Muscle quality. I. Age-associated differences between arm and leg muscle groups

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quality. I. Age-associated differences between arm and leg
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determine the differences between arm and leg muscle qual-
ity (MQ) across the adult life span in men and women,
concentric (Con) and eccentric (Ecc) peak torque (PT) were
measured in 703 subjects (364 men and 339 women, age
range 19–93 yr) and appendicular skeletal muscle mass
(MM) was determined in the arm and leg in a subgroup of 502
of these subjects (224 men and 278 women). Regression
analysis showed that MQ, defined as PT per unit of MM, was
significantly higher in the arm (~30%) than in the leg across
age in both genders ($P < 0.01$). Arm and leg MQ declined at a
similar rate with age in men, whereas leg MQ declined ~20%
more than arm MQ with increasing age in women ($P \leq 0.01$
and $P < 0.05$ for Con and Ecc PT, respectively). Moreover, the
age-associated decrease in arm MQ was steeper in men than
in women whether Con or Ecc PT was used (both $P < 0.05$).
Arm MQ as determined by Con PT showed a linear age-
related decline in men and women (28 and 20%, respectively,
$P < 0.001$), whereas arm MQ as determined by Ecc PT
showed a linear age-related decline in men (25%, $P < 0.001$)
but not in women (not significant). In contrast, both genders
exhibited an age-related quadratic decline in leg MQ as
determined by Con PT (~40%) and Ecc PT (~25%; both $P <
0.001$), and the rate of decline was similar for men and
women. Thus MQ is affected by age and gender, but the
magnitude of this effect depends on the muscle group studied
and the type of muscle action (Con vs. Ecc) used to assess
strength.

concentric and eccentric peak torque; muscle strength; appen-
dicular skeletal muscle mass; gender differences

THE AGE-ASSOCIATED LOSS of muscle mass (MM) and
muscle function (sarcopenia) (7) has important health
and economic implications, because it is related to
functional disabilities (3, 27), risk of falling (19, 20),
and a higher rate of outpatient clinic visits in the
elderly (6). In the East Boston cohort of the Established
Populations for Epidemiologic Studies of the Elderly,
38% of the men and 59% of the women >65 yr of age
had difficulty stooping and 24% of the men and 29% of
the women had difficulty lifting their arm above the
shoulder (9). These findings suggest that older women
have greater muscular dysfunction than older men.

Muscle strength has been reported to reach peak
values between 25 and 35 yr of age, is maintained or is
slightly lower between 40 and 49 yr of age, and then is
~12–14%/decade less after 50 yr of age (2, 16, 18, 22).
These age-associated differences in strength are highly
correlated with age differences in MM (13, 21, 28).
Although the specific mechanisms for the age-related
decline in strength have not been identified, the major
underlying factor appears to be the decrease in MM
with age (10, 28).

The importance of expressing age-related strength
losses relative to MM was emphasized by a panel of
experts at the 1996 National Institute on Aging work-
shop "Sarcopenia and Physical Performance in Old
Age," in which it was concluded that there is a need for
more comprehensive evaluations of age-related changes
in muscle quality (MQ) (7). MQ, also known as specific
tension, refers to strength per unit of MM and may be a
better indicator of muscle function than strength alone
(7). We recently reported an age-related decline in MQ
of the leg in both genders when determined by concen-
tric (Con) peak torque (PT) (18). However, in our
previous study there was no measure of MQ in the arm
muscle groups. Investigators have emphasized the
need to obtain more information through aging re-
search on muscle groups in the arm (7). Information on
age and gender differences in MQ of the arm vs. leg
muscle groups determined from Con and eccentric (Ecc)
PT may help target interventions for sarcopenia to
specific muscle groups with specific muscle actions.

A gender difference in MQ with age has been sug-
gested in previous cross-sectional studies. For example,
no difference in MQ between young and older women has
been reported (33), but many studies have reported an
age-associated decline in MQ in men (13, 24, 28, 29, 34).
However, MQ in the arm and leg has not been compared
in men and women throughout the adult life span.

It has been reported that arm and leg muscle groups
are ~30–50% stronger in men than in women (2, 10, 23,
28) and that men tend to have a greater proportion of
their MM in the arms than women (14, 23). Nonethe-
less, Frontera et al. (10) reported that strength, cor-
rected for total body fat-free mass (FFM) estimated by
hydrodensitometry, remained significantly higher in
men than in women in the arm and leg. However, in the
same population the ratio of strength per kilogram of
MM, estimated by creatinine excretion, was higher in
men than in women for the arm but similar between
the genders in the leg (10). These findings suggest that
gender differences may exist in MQ, particularly in the
arm. Therefore, the purpose of this study was to

describe the age-associated differences in MQ in the arm and leg throughout the adult life span and to determine whether gender or muscle group affects the relationship between MQ and age.

METHODS

Subjects. Volunteers ($n = 703$, 364 men and 339 women, age range 19–93 yr) from the Baltimore Longitudinal Study on Aging participated in the study. However, only 502 subjects (224 men and 278 women) underwent assessment of arm and leg MM. The physical characteristics and PT measurement of this subgroup did not deviate significantly from the participants who did not undergo arm and leg MM assessment. All subjects received a complete medical history and physical examination. Those with clinical cardiovascular or musculoskeletal disease were excluded. Also, subjects were excluded if they had active neck and back pain, frequent and severe joint pain, any surgery in the past 6 mo, prior bone scan below normal for their age (<0.72 g/cm² for femoral neck and lumbar spine bone mineral density in women and 0.59 and 0.76 g/cm² for femoral neck and lumbar spine bone mineral density, respectively, in men), or any other condition that might be aggravated by strength testing. Subjects responded to a questionnaire concerning weight training over the past 2 yr. The average number of minutes per week of weight training participation was recorded, analyzed, and compared among various age groups. Only a very small percentage of subjects ($<1\%$) participated in any type of regular weight training program, and there was no significant difference in participation by age group or gender (18). After receiving a complete explanation of the procedures and the risks of the study, all subjects gave their written informed consent. The experimental protocols of this study were approved by the Institutional Review Board for Human Subjects at Johns Hopkins Bayview Medical Center (Baltimore, MD) and the University of Maryland (College Park, MD).

Body composition assessment. Body mass and height were measured to the nearest 0.1 kg and 0.5 cm, respectively, with a Detecto medical beam scale. A total body scan was performed using dual-energy X-ray absorptiometry (model DPX-L, Lunar Radiation, Madison, WI) to determine percent body fat, nonosseous arm FFM, and leg FFM of the dominant arm and leg. Arm FFM encompassed soft tissue extending from the center of the arm socket to the phalange tips, and leg FFM consisted of soft tissue extending from an angled line drawn through the femoral neck to the phalange tips (11). Nonosseous appendicular FFM derived from these regional measurements was then assumed to be a valid estimation of appendicular skeletal MM for the arm and leg on the basis of the work of Gallagher et al. (11) and Wang et al. (30). All scans were analyzed using the LUNAR software program (version 3.6/1.3y) for body composition analyses. Reliability was assessed by performing two total body scans, 6 wk apart, on 12 older men (>65 yr). Serial values were 52.94 ± 1.23 vs. 53.03 ± 1.36 kg for MM and 22.99 ± 1.46 vs. 22.88 ± 1.43 kg for fat mass, representing a difference between the two scans of $\sim 0.01\%$ for MM and fat mass. The scanner was calibrated daily before testing.

PT assessment. An isokinetic dynamometer (Kinetic Communicator model 125E Plus, Chattecx, Chattanooga, TN; Kin-Com) was used to measure PT. Con and Ecc PT (PT_{Con} and PT_{Ecc}, respectively) were measured in the dominant elbow flexors and elbow extensors at an angular velocity of 0.79 rad/s (45°/s) and in the dominant knee flexors and knee extensors at an angular velocity of 0.52 rad/s (30°/s). Participants were positioned sitting with the backrest at an angle of 1.83 rad (105°) and with hip angle between 1.40 and 1.48 rad (80 and 85°) and were stabilized using chest, waist, and thigh straps. The rotational axis of the dynamometer was aligned to the lateral epicondyle of the distal humerus with the resistance arm positioned in alignment with the forearm. The rotational axis of the dynamometer was aligned with the lateral femoral epicondyle of the subject's knee with the resistance pad positioned proximally to the lateral malleolus of the ankle joint. The length of the resistance arm was recorded for the elbow and knee. A goniometer was used to measure the anatomic joint angle to calibrate the Kin-Com angle readings. Gravity corrections to torque were calculated by the gravity correction program in the Kin-Com software package (version 3.2) on the basis of the weight of the arm in the horizontal position at 2.62 rad (150°) and the leg at 2.97 rad (170°; 3.13 rad = straight leg). The force threshold required for movement of the lever arm was set at 50 N, but when necessary the force threshold was adjusted for arm strength measurement to a minimum of 2 N. The joint arc of the elbow was limited to 1.05 rad (60°), and the maximal elbow extension angle was set at 2.62 rad (150°). The joint arc of the knee was limited to 1.13 or 1.22 rad (65 or 70°), and the maximal knee extension angle was set at 2.97 rad (170°). Accuracy of the force movement was determined weekly by using the internal Kin-Com diagnostic check and force calibration programs. For force calibrations the lever arm was positioned parallel to the floor at 3.14 rad (180°) and known weights of 45 and 110 N (10 and 25 pounds) were hung directly on the load cell. The force reported by the Kin-Com was compared with the actual weights, and force outputs were calibrated when necessary. Reliability of strength testing with use of this Kin-Com dynamometer and protocol was tested in 10 older men on two occasions with a 1-wk interval between trials. Intraclass correlation coefficients were between 0.96 and 0.99 for leg tests. Mean coefficient of variation for leg tests was 5% (range 1.5–7.5%).

Subjects warmed up on a stationary cycle with light resistance for 3–5 min. The dominant arm and leg were tested to assess upper and lower body strength, respectively. Testing order was arm Con then Ecc PT followed by leg Con then Ecc PT. The rest period between the arm and leg tests was ≥ 5 min. Three submaximal practice repetitions preceded three maximal efforts for each specific test. All maximal efforts were separated by a ≥ 30-s rest period. PT was determined for each maximal effort with use of the Kin-Com's Torque vs. Angle program (KC772.047). The trial yielding the highest PT for each test was used in the analysis. Arm PT_{Con} was defined as the sum of Con elbow flexor and extensor PT, arm PT_{Ecc} as the sum of Ecc elbow flexor and extensor PT, leg PT_{Con} as the sum of Con knee flexor and extensor PT, and leg PT_{Ecc} as the sum of Ecc knee flexor and extensor PT.

Arm and leg MQ. Arm MQ_{Con} and arm MQ_{Ecc} ($N \cdot m \cdot kg^{-1}$) were calculated by dividing arm PT_{Con} ($N \cdot m$) and arm PT_{Ecc} ($N \cdot m$), respectively, by arm MM (kg). Leg MQ_{Con} and leg MQ_{Ecc} were calculated by dividing leg PT_{Con} ($N \cdot m$) and leg PT_{Ecc} ($N \cdot m$), respectively, by leg MM (kg).

Arm and leg difference. To determine whether the arm and leg showed similar changes with increasing age, the difference between arm and leg PT (Diff arm-leg PT_{Con} and Diff arm-leg PT_{Ecc}) and the difference between arm and leg MQ (Diff arm-leg MQ_{Con} and Diff arm-leg MQ_{Ecc}) were calculated.

Statistical analysis. One-way ANOVA was used to compare age decade and gender differences for the following physical characteristics and peak torques: height, body mass, percent body fat, arm MM, leg MM, arm PT_{Con}, arm PT_{Ecc}, leg PT_{Con}, and leg PT_{Ecc} (Tables 1 and 2). Significant main effects for age decade were followed up with Dunnett's multiple comparison

Table 1. *Physical characteristics and peak torques for each age group in men*

	Group						
	20–29 yr	30–39 yr	40–49 yr	50–59 yr	60–69 yr	70–79 yr	>80 yr
Age, yr	26.8 ± 2.3 (23)	34.8 ± 2.7 (36)	45.5 ± 2.9 (66)	54.0 ± 3.1 (65)	65.3 ± 3.2 (81)	74.8 ± 3.2 (58)	84.5 ± 3.2 (35)
Height, cm	180.5 ± 6.9 (22)	177.7 ± 7.4 (34)	179.5 ± 7.4 (66)	178.2 ± 5.8 (64)	176.7 ± 6.6 (79)	174.9 ± 6.3 (56)*	171.1 ± 5.2 (35)*
Body mass, kg	83.9 ± 20.0 (22)	83.1 ± 13.1 (34)	88.1 ± 19.0 (66)	89.2 ± 12.4 (64)	84.3 ± 15.2 (79)	83.1 ± 10.2 (56)	74.2 ± 11.6 (34)*
%Body fat	20.7 ± 8.5 (16)	23.6 ± 8.9 (22)	25.0 ± 6.2 (47)	30.7 ± 7.1 (43)*	27.5 ± 7.2 (54)*	29.5 ± 3.8 (29)*	29.9 ± 7.1 (13)*
MM, kg							
Arm	3.6 ± 0.4 (14)	3.6 ± 0.5 (19)	3.7 ± 0.5 (36)	3.7 ± 0.4 (28)	3.3 ± 0.4 (45)*	3.1 ± 0.4 (26)*	2.9 ± 0.5 (10)*
Leg	10.7 ± 1.1 (16)	10.2 ± 1.4 (22)	10.3 ± 1.5 (47)	10.3 ± 1.1 (43)	9.4 ± 1.2 (54)*	9.2 ± 1.0 (29)*	8.5 ± 0.9 (13)*
Arm PT_{Con}, N·m	190 ± 40 (19)	184 ± 51 (32)	186 ± 43 (63)	164 ± 33 (61)	141 ± 34 (77)*	123 ± 28 (51)*	103 ± 26 (31)*
Arm PT_{Ecc}, N·m	217 ± 46 (19)	227 ± 62 (32)	217 ± 50 (63)	203 ± 41 (62)	175 ± 40 (74)*	162 ± 41 (51)*	139 ± 34 (29)*
Leg PT_{Con}, N·m	339 ± 93 (23)	337 ± 69 (35)	340 ± 86 (63)	304 ± 55 (62)	260 ± 64 (75)*	220 ± 52 (53)*	176 ± 44 (31)*
Leg PT_{Ecc}, N·m	429 ± 117 (21)	401 ± 118 (36)	409 ± 100 (61)	383 ± 74 (64)	337 ± 87 (72)*	289 ± 62 (55)*	257 ± 56 (31)*

Values are means $\pm$ SD of number of participants in parentheses. Arm MM, arm muscle mass; leg MM, leg muscle mass; arm PT_{Con}, arm concentric peak torque; arm PT_{Ecc}, arm eccentric peak torque; leg PT_{Con}, leg concentric peak torque; leg PT_{Ecc}, leg eccentric peak torque. * Significant age-associated change compared with young adults (20–39 yr), $P < 0.05$.

technique. Dunnett's test was used to determine the specific age decades that were significantly different from the young (20- to 39-yr-old) adults.

Multiple regression analysis was performed on PT variables (arm PT_{Con}, arm PT_{Ecc}, leg PT_{Con}, and leg PT_{Ecc}), MQ variables (arm MQ_{Con}, arm MQ_{Ecc}, leg MQ_{Con}, and leg MQ_{Ecc}), and the difference between arm and leg variables (Diff arm-leg PT_{Con}, Diff arm-leg PT_{Ecc}, Diff arm-leg MQ_{Con}, and Diff arm-leg MQ_{Ecc}) by age and gender. Previous studies have shown a nonlinear quadratic relationship between strength and age (2, 11, 14, 20). Thus polynomial regression was used by adding a quadratic age term (age^2) to the regression equation. The linear model was used when the quadratic term did not significantly improve the r^2. Men and women were analyzed separately when a significant age-by-gender interaction or gender main effect was observed.

Assumptions for independence for all variables were examined by standardized residual plots and standardized residual vs. predicted value plots. Data were checked for the existence of outliers and/or influential data points. Two outliers were identified; however, the influence of these points did not affect the results. Thus the outliers remained in the sample. No violations of regression assumptions were identified in these data, and all data analyses were completed using SPSS for Windows.

RESULTS

Physical characteristics. Physical characteristics of the men and women by age group are reported in Tables 1 and 2, respectively. Men were significantly taller and heavier and had lower percent body fat and greater arm and leg MM than women throughout the entire adult life span (all $P < 0.01$). An age-related reduction in height from the young adults became apparent for the men in their 70s and for the women in their 60s ($P < 0.01$). Body mass was significantly lower in the oldest decade than in the young adults among the men ($P < 0.05$); however, there were no differences in body mass in women across the adult life span. In men, percent body fat showed a significant increase beginning in their 50s, and in women it was significantly higher than in the young adults in their 40s, 50s, and 60s ($P < 0.01$). Men had significantly lower arm and leg MM in their 60s and older decades ($P < 0.01$). Arm MM was significantly lower in their 60s and older decades in women ($P < 0.01$); however, leg MM reductions began as early as the 40s ($P < 0.05$). There were no significant differences in age, height, weight, percent body fat, or PT measurements between the total population ($n = 703$) and the subgroup ($n = 502$) in which arm and leg MM were measured.

Arm and leg PT. Age-associated declines were observed for arm PT_{Con} (Tables 1 and 2, Fig. 1A), leg PT_{Con} (Tables 1 and 2, Fig. 1B), arm PT_{Ecc} (Tables 1 and 2, Fig. 2A), and leg PT_{Ecc} (Tables 1 and 2, Fig. 2B; all $P < 0.05$). In $\geq$50-yr-old men, arm PT_{Con} and leg PT_{Con} were

Table 2. *Physical characteristics and peak torques for each age group in women*

	Group						
	20–29 yr	30–39 yr	40–49 yr	50–59 yr	60–69 yr	70–79 yr	>80 yr
Age, yr	27.3 ± 2.3 (31)	34.7 ± 3.2 (47)	46.0 ± 2.7 (105)	53.2 ± 3.0 (70)	64.2 ± 3.0 (44)	74.7 ± 3.0 (24)	83.7 ± 3.6 (18)
Height, cm	166.1 ± 7.2 (31)	166.3 ± 7.4 (46)	165.1 ± 5.4 (104)	164.9 ± 6.5 (68)	161.9 ± 5.5 (43)*	158.9 ± 6.1 (23)*	156.0 ± 7.5 (18)*
Body mass, kg	63.1 ± 10.2 (31)	69.5 ± 14.6 (46)	68.8 ± 13.2 (104)	68.6 ± 11.9 (68)	69.1 ± 12.7 (43)	63.1 ± 11.7 (23)	60.6 ± 10.1 (18)
%Body fat	31.6 ± 7.8 (24)	33.6 ± 8.2 (31)	36.3 ± 8.1 (97)*	37.2 ± 7.8 (62)*	39.9 ± 6.1 (38)*	37.7 ± 9.2 (19)	38.3 ± 6.0 (15)
MM, kg							
Arm	2.1 ± 0.3 (22)	2.3 ± 0.3 (29)	2.1 ± 0.3 (88)	2.1 ± 0.3 (53)	2.0 ± 0.3 (34)*	1.7 ± 0.3 (15)*	1.7 ± 0.3 (13)*
Leg	6.9 ± 1.1 (24)	7.5 ± 1.0 (30)	6.7 ± 0.9 (95)*	6.7 ± 0.9 (60)*	6.4 ± 0.9 (37)*	6.2 ± 0.7 (18)*	5.7 ± 0.4 (15)*
Arm PT_{Con}, N·m	81 ± 19 (27)	94 ± 23 (41)	83 ± 21 (86)	75 ± 19 (62)*	71 ± 14 (38)*	65 ± 17 (22)*	51 ± 13 (16)*
Arm PT_{Ecc}, N·m	98 ± 23 (27)	118 ± 27 (41)	101 ± 25 (87)	96 ± 23 (61)	96 ± 21 (38)	93 ± 22 (22)	67 ± 17 (17)*
Leg PT_{Con}, N·m	200 ± 46 (30)	215 ± 49 (44)	192 ± 42 (105)	179 ± 39 (65)*	147 ± 38 (41)*	138 ± 32 (23)*	97 ± 28 (15)*
Leg PT_{Ecc}, N·m	240 ± 53 (29)	264 ± 66 (45)	242 ± 56 (101)	236 ± 59 (64)	204 ± 54 (42)*	176 ± 35 (22)*	146 ± 39 (12)*

Values are means $\pm$ SD of number of participants in parentheses. See Table 1 footnote for definition of abbreviations. * Significant age-associated change compared with young adults (20–39 yr), $P < 0.05$.

significantly lower than in younger men ($P < 0.05$). In ≥60-yr-old men, arm PT_{Ecc} and leg PT_{Ecc} were significantly lower than in younger men ($P < 0.01$). In ≥50-yr-old women, arm PT_{con} and PT_{Ecc} were significantly lower, whereas in ≥40-yr-old women leg PT_{Con} was significantly lower than in younger women (all $P < 0.05$). In addition, in ≥60-yr-old women, leg PT_{Ecc} was significantly lower than in younger women (all $P < 0.05$). Changes in arm and leg PT were curvilinear with age, such that declines were modest or nonexistent until the 40s, and thereafter more robust declines were present. Age-associated declines in PT were greater for men than for women in all muscle locations (all age-by-gender interactions, $P < 0.001$).

Leg PT_{Con} was significantly higher than arm PT_{Con}, and leg PT_{Ecc} was higher than arm PT_{Ecc} in both genders ($P < 0.001$). Diff arm-leg PT_{Con} and Diff arm-leg PT_{Ecc} were significantly less with advancing age, indicating that leg PT_{Con} and PT_{Ecc} declined more with age than arm PT_{Con} and PT_{Ecc}, respectively (Figs. 1 and Fig. 2; both $P < 0.001$). In addition, although Diff arm-leg PT_{Con} and Diff arm-leg PT_{Ecc} were greater for men than
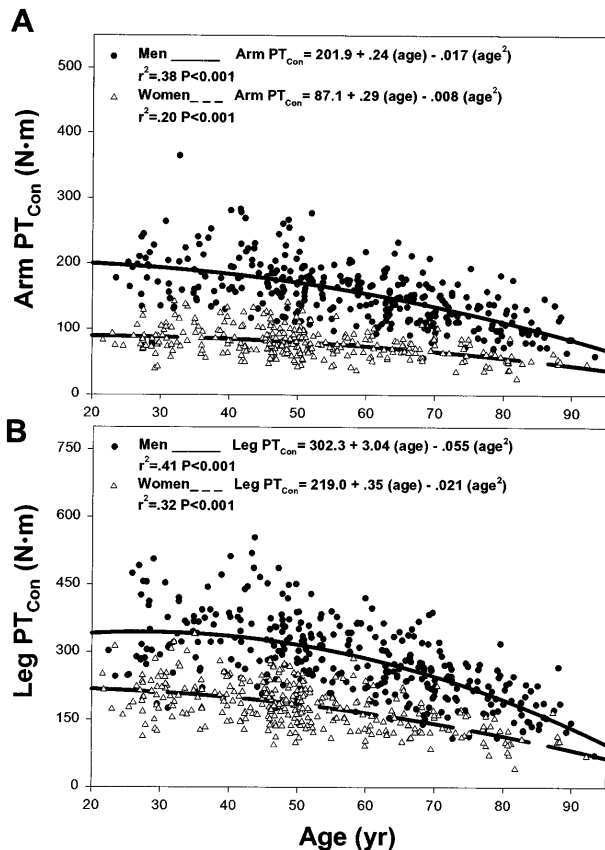

Fig. 1. Concentric (Con) peak torque (PT) in arm (arm PT_{Con}) and leg (leg PT_{Con}) with advancing age. Significant quadratic age declines were observed in arm PT_{Con} and leg PT_{Con} for men and women ($P < 0.001$). Different rates of age-associated change were observed for men and women in arm PT_{Con} and leg PT_{Con} (both age-by-gender interactions, $P < 0.001$). Leg PT_{Con} was significantly higher than arm PT_{Con} across age in both genders ($P < 0.001$). Difference between arm PT_{Con} and leg PT_{Con} narrowed with age in men and women ($P < 0.001$).
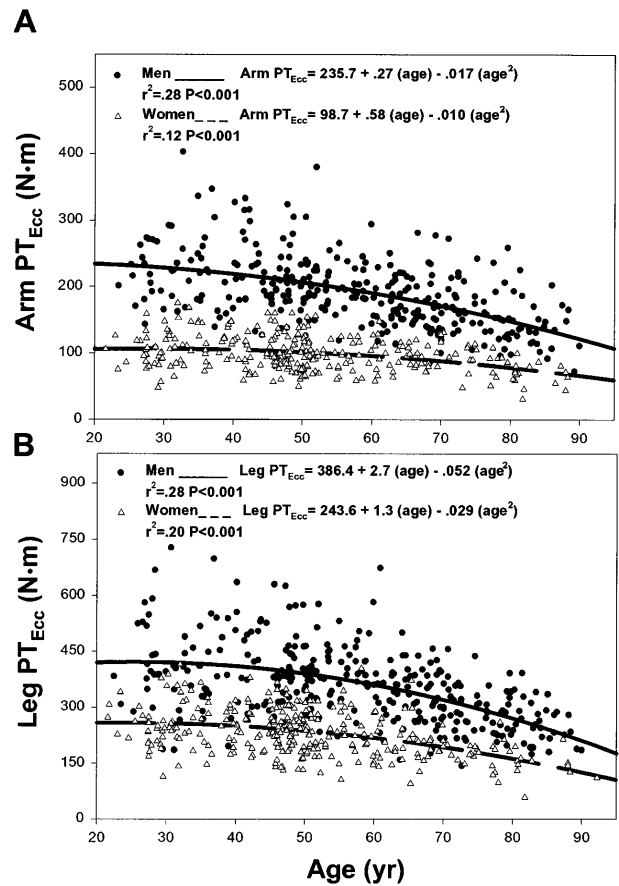

Fig. 2. Eccentric (Ecc) peak torque (PT) in arm (arm PT_{Ecc}) and leg (leg PT_{Ecc}) with advancing age. Significant quadratic age declines were observed in Arm PT_{Ecc} and Leg PT_{Ecc} for men and women ($P < 0.001$). Different rates of age-associated change were observed for men and women in arm PT_{Ecc} and leg PT_{Ecc} (both age-by-gender interactions, $P < 0.001$). Leg PT_{Ecc} was significantly higher than arm PT_{Ecc} across age in both genders ($P < 0.001$). Difference between arm PT_{Ecc} and leg PT_{Ecc} narrowed with age in men and women ($P < 0.001$).

for women ($P < 0.001$), the age-associated regression patterns were the same for men and women.

PT and appendicular MM. PT for Con and Ecc and appendicular MM were highly related in all body regions ($P < 0.001$). Arm MM accounted for 44 and 50% of the variance in arm PT_{Con} and 38 and 46% in arm PT_{Ecc} for men and women, respectively. Leg MM accounted for 36 and 39% of the variance in leg PT_{Con} and 32 and 39% in leg PT_{Ecc} for men and women, respectively.

Arm and leg MQ. MQ as a function of age for men and women is presented in Figs. 3 and Fig. 4. A linear age-associated decline was observed in arm MQ_{Con} for men and women ($P < 0.001$; Fig. 3A). Arm MQ_{Ecc} declined linearly with age in men; however, no age-related decline was observed in women (Fig. 4A). A significant age-by-gender interaction was observed for arm MQ_{Con} and arm MQ_{Ecc} ($P < 0.05$). For example, as reflected in Fig. 3A, arm MQ_{Con} was ~10 $N \cdot m \cdot kg^{-1}$ more in men than in women at 30 yr of age. However, at 90 yr of age the gender difference in arm MQ_{Con}

narrowed to $\sim 4\,\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$. Furthermore, the difference between men and women decreased with advancing age in arm MQ_{Con} and arm MQ_{Ecc}.

In contrast to the differences observed in arm MQ, age-related differences in leg MQ_{Con} (Fig. 3*B*) and leg MQ_{Ecc} (Fig. 4*B*) were curvilinear, with modest or no decline until the 50s, and thereafter reductions were accelerated in men and women ($P < 0.001$). Leg MQ was significantly higher in men than in women ($P < 0.001$), yet the rate of change with age in leg MQ_{Con} and leg MQ_{Ecc} was the same in men and women.

Arm MQ_{Con} was significantly higher than leg MQ_{Con} (Fig. 3), and arm MQ_{Ecc} was significantly higher than leg MQ_{Ecc} in men and women (both $P < 0.01$; Fig. 4). In addition, Diff arm-leg MQ_{Con} and Diff arm-leg MQ_{Ecc} varied with age between men and women [age-by-gender interaction, $P < 0.01$ (Con PT) and $P < 0.05$ (Ecc PT); Figs. 3 and 4]. Specifically, arm and leg MQ changed at the same rate across age in men as deter-
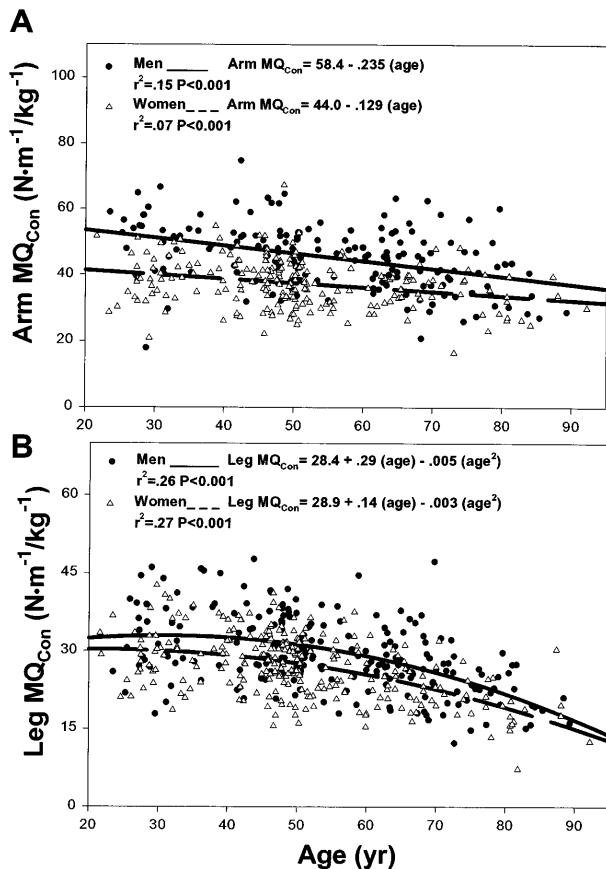

Fig. 3. Muscle quality as determined by concentric peak torque in arm (arm MQ_{Con}) and leg (leg MQ_{Con}) with increasing age. Arm MQ_{Con} declined linearly with age in both genders (both $P < 0.001$), with a steeper decline in men than in women (age-by-gender interactions, $P < 0.05$). Leg MQ_{Con} declined at a similar rate in men and women. Both genders showed a significant quadratic age decline in leg MQ_{Con} ($P < 0.001$), and leg MQ_{Con} was significantly higher in men than in women across age ($P < 0.001$). Arm MQ_{Con} was significantly higher than leg MQ_{Con} across age in both genders ($P < 0.001$). Difference between arm MQ_{Con} and leg MQ_{Con} remained constant across age for men, but this difference was greater in older than in younger women ($P < 0.05$).
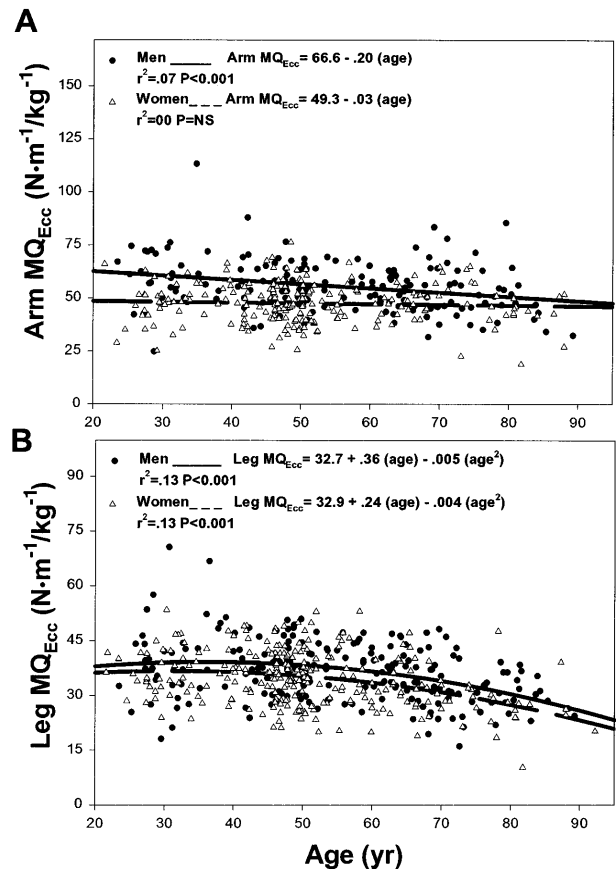

Fig. 4. Muscle quality as determined by eccentric peak torque in arm (arm MQ_{Ecc}) and leg (leg MQ_{Ecc}) with increasing age. Arm MQ_{Ecc} declined linearly with age in men ($P < 0.001$) but remained constant across age in women, resulting in a narrowing of gender difference in arm MQ_{Ecc} with advancing age (age-by-gender interaction, $P < 0.05$). Leg MQ_{Ecc} declined at a similar rate in men and women. Both genders showed a significant quadratic age decline in leg MQ_{Ecc} ($P < 0.001$), but leg MQ_{Ecc} was significantly higher in men than in women across age ($P < 0.001$). Arm MQ_{Ecc} was significantly higher than leg MQ_{Ecc} across age in both genders ($P < 0.001$). Difference between arm MQ_{Ecc} and leg MQ_{Ecc} remained constant across age for men, but this difference was greater in older than in younger women ($P < 0.05$).

mined by Con and Ecc PT; however, MQ of the leg declined more than that of the arm with increasing age in women as determined by Con and Ecc PT.

DISCUSSION

The major new findings from this study are as follows. *1*) Age-associated differences in arm MQ declined more in men than in women; however, leg MQ declined with age at the same rate in both genders. *2*) Arm MQ was higher than leg MQ across age for men and women. *3*) Arm MQ declined at the same rate across age as leg MQ in men; however, the age-related decline was greater in leg MQ than in arm MQ for women. Finally, leg PT was higher than arm PT across age, but this difference decreased across the adult life span in both genders.

Conflicting results have been reported in previous studies regarding the relationship between MQ and age. Alway et al. (1) reported that isometric torque per

unit muscle cross-sectional area (CSA), measured by magnetic resonance imaging (leg MQ), was not significantly different between young and older men. Overend et al. (24) reported no age-related difference when leg MQ was estimated by isometric strength per CSA as measured by computed tomography but lower MQ in the elderly than in the young men when MQ was expressed as Con isokinetic strength per CSA of the leg. Reed et al. (28) found a significant age-associated loss in cumulative MQ (combined strength of the arm and leg per kg of total body lean MM); however, they used a bioelectrical impedance analysis to estimate total body lean MM and concluded that more accurate measures of regional MM are needed in future studies. Frontera et al. (10) showed age-related declines in MQ of the arm and leg when using FFM estimated by hydrostatic weighing but no change in MQ when using MM estimated from urinary creatinine excretion. However, these results are difficult to interpret, because hydrostatic weighing was performed without the measurement of residual volume and PT was performed using the Cybex II with no gravity correction. Each of these factors can lead to significant errors (31, 32). Thus the various techniques used in previous studies to estimate MM may explain some of the inconsistent findings regarding the effects of age on MQ. This is the first study in which age-related MQ comparisons in the arm vs. leg were made using reliable techniques for assessing strength and limb MM (8, 11, 30).

In addition to differences in measurement techniques, some of the conflicting results from previous studies may be explained by differences in age, gender, or the muscle group tested. For example, previous studies have reported that although men were stronger than women, MQ was the same in men and women (23, 28, 33, 34). In contrast, the present study shows a higher MQ in men than in women in the arm and leg. In addition, Young et al. (33, 34) reported that MQ was lower in older than in younger men but was the same in older and younger women. In the present study, MQ was lower with advancing age in men and women in all muscle locations, except arm MQ_{Ecc} in women. Furthermore, the age-associated rate of change differed between men and women for arm MQ. Arm MQ appears to decline more with age in men than in women, although it is important to note that because men begin with more MQ at a young age, they have more MQ to lose over the adult life span. In contrast to arm MQ, the age-associated rate of change in MQ of the leg was similar for men and women.

The finding of a significant age-related decline in leg MQ_{Ecc} in women is in contrast to our previous report, which did not show a decline in women (18). There were almost four times as many women >65 yr of age in the current study as in the previous study. Thus the greater sample size for this variable increased the statistical power for detecting a significant age effect. Although our previous (18) study did not report arm MQ data, we have since examined the relationship between arm and leg MQ from the previous study's sample and found the same relationship reported in this study.

This is the first study to report a gender difference in the decline of arm and leg MQ with advanced age. As shown in Fig. 3, the difference between arm and leg MQ was unchanged with age in men but increased in women, indicating that leg MQ declined more with advancing age than arm MQ in women. This suggests that in women arm muscles may not experience as much age-related change in contractile properties, connective tissue, or architectural components, such as pennation angles, as leg muscles. Qualitative changes in contractile properties (17) and increases in connective tissue (25) have been associated with aging. In addition, increases in muscle fiber pennation angle in hypertrophied muscle (15) suggest that pennation angle is likely to decrease with aging. An additional novel finding from this study is that MQ of the arm was significantly higher than MQ of the leg across the entire adult life span in both genders. Thus more strength is produced per unit of MM in the arm than in the leg in men and women. In addition, the variance in arm PT accounted for by arm MM was greater than the variance in leg PT accounted for by leg MM. Therefore, MM may be more important in explaining arm strength loss than leg strength loss. Although other age-related factors to explain this difference have not been identified, possible mechanisms include neural activation, muscle fiber type distribution, and muscle pennation angle differences between the arm and leg.

In general, muscle strength has been reported to peak in the 20s and 30s, remain stable or decline slowly into the 40s, and decline ~12–14%/decade after 50 yr of age (2, 16, 22). Overall, our results support previous findings describing the age-associated loss of strength. Moreover, our findings appear to be in partial agreement with those of previous investigators who also report a greater age-related loss of Con than Ecc strength (12, 26). An age-related decline in Ecc strength was not observed in these studies; however, we observed a significant age-related decline in Con and Ecc strength in all muscle locations and in both genders. However, the variance accounted for by age was higher for Con than for Ecc measurements in both genders and in the arm and leg. In addition, results from this study confirm previous reports that showed a greater age-related loss of strength in the leg than in the arm (4, 28, 29). A possible explanation for the greater leg strength loss may be related to increased disuse in the legs, but no physiological or biochemical mechanisms have been identified.

There were several limitations of this study in addition to the cross-sectional design. For example, there was no measure of contractile or mechanical properties of the muscle groups studied to help explain our findings. In addition, future studies should investigate age-related differences in muscle architecture, such as fiber pennation angles, so that this information can be related to losses in strength and MM.

In conclusion, the results of this study indicate that there are age-related declines in arm and leg MQ in men and women, except for arm MQ_{Ecc}, which remained stable across age in women. MQ was greater in the arm

than in the leg as determined by Con and Ecc PT in men and women throughout the adult life span. Furthermore, there was a greater age-related decline in leg than in arm MQ in women; however, arm and leg MQ declined at the same rate with age in men. Finally, leg PT was higher and declined more with advancing age than arm PT in men and women.

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