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Human Kinetics
TECHNICAL NOTE

Upper Limb Strength and Muscle Volume in Healthy Middle-Aged Adults

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Our purpose was to characterize shoulder muscle volume and isometric moment, as well as their relationship, for healthy middle-aged adults. Muscle volume and maximum isometric joint moment were assessed for 6 functional muscle groups of the shoulder, elbow, and wrist in 10 middle-aged adults (46–60 y, 5M, 5F). Compared with young adults, shoulder abductors composed a smaller percentage of total muscle volume ($P = .0009$) and there was a reduction in shoulder adductor strength relative to elbow flexors ($P = .012$). We observed a consistent ordering of moment-generating capacity among functional groups across subjects. Although total muscle volume spanned a 2.3-fold range, muscle volume was distributed among functional groups in a consistent manner across subjects. On average, 72% of the variation in joint moment could be explained by the corresponding functional group muscle volume. These data are useful for improved modeling of upper limb musculoskeletal performance in middle-aged subjects, and may improve computational predictions of function for this group.

Keywords: biomechanics, isometric, MRI, muscle volume, strength

Aging bears significant consequences for muscle function, including muscle atrophy, increased cocontraction, and decreased voluntary neural drive.[1–8] Even with healthy aging, loss of strength associated with these changes can contribute to difficulty performing everyday tasks necessary for independent living.[2,4,5,9] Many functional tasks require strength and coordination of the upper extremity,[10] so age-related changes to the upper limb are of particular interest.

Significant reductions in strength have been previously identified at major upper limb joints in older adults compared with young adults.[1,7,11,12] For example, declines in isometric strength for the 6 functional shoulder groups have been reported for a large group of subjects between ages 20 and 78.[13] Another study,[14] in which both muscle volume and strength were assessed, also reported reduced absolute isometric shoulder moment-generating capacity in older adults (> 65 y). The observed declines in strength were correlated to reduced shoulder muscle volumes.

Notably, changes in relative strength of shoulder functional groups (that is, ratios of strength among functional groups) have also been reported, both relative to one another[15] and to other upper limb joints.[14] Changes in relative strength are important because balanced agonist and antagonist shoulder strength is required to maintain shoulder stability, and imbalance may be associated with injury.[15] Further, changes in strength among joints may alter coordination required to perform tasks. In other studies, it was also evident that volume distribution changed with age. For example, elbow extensors had larger volume reductions with age than did flexors.[7]

Despite the importance of aging for muscle function, relatively few studies characterize either upper limb isometric strength or muscle size in middle-aged adults. In some cases, comparisons of upper limb isometric strength have been reported for different age groups. However, these studies tend to focus on single joints.[1,7,11–13,15–17] With regard to muscle size, historically, muscle architecture studies are conducted in cadaveric specimens,[18–21] an approach that is innately more restrictive in terms of demographics available for study. Overall, neither upper limb muscle function nor muscle structure are well documented for a middle-aged cohort. This is problematic because changes in isometric strength and muscle size could result in changes to coordination and task performance well before the onset of disability.

The purpose of this work was to characterize: (1) absolute muscle volume and isometric moment-generating capacity of upper limb functional groups, (2) distribution of muscle volume and relative moment-generating capacity of the functional groups, and (3) the relationship between these parameters in a group of healthy middle-aged adults. We further sought to place these values in the context of previously-measured values for young adults. To do so, we quantified muscle volumes and maximum isometric joint moments for 10 middle-aged adults for 6 major functional groups of the shoulder, elbow, and wrist.

Methods

Ten subjects (5F, 5M, 46–60 y, 163–185 cm, 64–100 kg) with no history of upper limb injury or pathology were studied (Table 1). Subjects were not engaged in an exercise program or significant upper limb activities. All subjects provided informed consent in accordance with institutional guidelines. The dominant arm of each subject was tested (9R, 1L).

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Table 1 Subject characteristics

Subject	Age	Height (cm)	Height (Percentile)	Body Mass (kg)	Body Mass (Percentile)	Humerus Length (cm)	Radius Length (cm)	Arm Length (cm)	Arm Circum. (cm)	Forearm Circum. (cm)
MF1	49	172.7	95.0	88.5	99.0	31.2	24.6	55.8	41.7	30.4
MF2	58	162.6	50.0	81.6	98.0	27.6	20.1	47.7	40.6	28.8
MF3	46	167.6	75.0	63.5	60.0	28.8	21.3	50.1	30.2	25.7
MF4	54	170.2	90.0	78.0	95.0	30.3	21.6	51.9	36.8	28.4
MF5	58	175.3	97.0	99.8	99.0	29.4	24.9	54.3	41.7	31.5
MM1	46	172.7	35.0	90.7	85.0	31.2	24.9	56.1	42.2	33.8
MM2	59	185.4	90.0	80.3	60.0	31.8	24.0	55.8	37.1	29.9
MM3	48	165.1	5.0	65.8	10.0	29.4	23.4	52.8	34.6	27.1
MM4	54	177.8	60.0	79.4	55.0	33.3	23.7	57.0	37.5	30.2
MM5	60	180.3	75.0	88.5	80.0	34.5	24.9	59.4	38.3	32.6
Female, mean (SD)	53.0 (5.4)	169.7 (4.9)	81.4 (19.6)	82.3 (13.4)	90.2 (17.0)	29.5 (1.4)	22.5 (2.1)	52.0 (3.2)	38.2 (4.9)	29.0 (2.2)
Male, mean (SD)	53.4 (6.3)	176.3 (7.7)	53.0 (33.7)	80.9 (9.8)	58.0 (29.7)	32.0 (2.0)	24.2 (0.7)	56.2 (2.4)	38.0 (2.7)	30.7 (2.6)
All, mean (SD)	53.2 (5.5)	173.0 (7.0)	67.2 (30.0)	81.6 (11.1)	74.1 (28.4)	30.8 (2.1)	23.3 (1.7)	54.1 (3.5)	38.1 (3.8)	29.8 (2.4)

Abbreviations: MF = middle-aged female; MM = middle-aged male; Circum. = circumference.

Isometric joint moments produced during maximum voluntary contraction were quantified for 6 muscle groups using a Biodex System3 (Biodex Medical Systems, Shirley, NY) using a previously-described protocol used to study strength capability in young[22] and older[14] adults. Briefly, maximum shoulder abduction and adduction moments were assessed in 60° shoulder abduction, elbow extension and flexion were assessed with 90° elbow flexion, and wrist extension and flexion moments were measured with a neutral wrist. The subject was seated with the torso restrained, the hand braced to the hand grip, and joints distal to the joint of interest braced. For each functional group, we collected 3 trials of maximum voluntary contraction 3 seconds in duration, sampled at 100 Hz. To minimize fatigue, subjects rested 60 seconds between trials, and test order was randomized. Maximum moment produced by a functional muscle group was determined by averaging over the 0.5 second window during which the largest moment was maintained. The peak moment produced in any of the 3 trials was used for analysis.

The same subjects were imaged in a 1.5T magnetic resonance imaging (MRI) scanner (GE Healthcare, Milwaukee, WI), and three-dimensional surface reconstructions of muscles crossing the shoulder (glenohumeral joint), elbow, and wrist were created and used to calculate muscle volume of functional groups of muscles and total muscle volume.[23] Some wrist extensors and wrist flexors were segmented as a group due to close association of forearm muscles.[14] Total upper limb muscle volume was calculated by summing all volumes. Segmented muscles were grouped and volumes summed by functional group based on the muscles' moment arms at their joint of primary action in the postures used for isometric joint moment assessments.[14,22] Volume distribution for each functional group was calculated as functional group volume as a percent of total muscle volume.

We compared outcomes for the middle-aged subjects to data generated by a young adult cohort (n = 10) using the same protocol.[22,23] Mixed-effects models for repeated measures were used to evaluate age group differences for absolute and relative joint moment, muscle volume, and percent muscle volume, adjusting for sex and body mass. Within these models, age group variation was explored by assessing differences between functional groups. Due to our small sample size, males and females were evaluated together with covariate adjustments for sex. Holm-sequential Bonferroni[24] was used to control type I error at the 0.05 level for comparisons of young and middle-aged adults for each outcome. To compare relative strengths at each joint, we also used the Wilcoxon signed-ranks test (n = 10), with an experiment-wide $P < .05$, adjusted for multiple comparisons using the Bonferroni correction to $P < .0033$ for individual comparisons. To evaluate the relationship between joint moment and muscle volume in middle-aged adults, we compared functional group muscle volume to the corresponding maximum moment measured for each subject using the coefficient of determination (r^2). Results were considered significant for $P < .05$. We used SAS software (Cary, NC) for all analyses.

Results

When compared with young adult subjects, muscle volume distribution and relative strength of shoulder muscles were reduced in middle-aged subjects. Shoulder abductors composed a smaller volume as a percentage of total muscle volume in middle-aged adults than young adults ($P = .0009$) (Figure 1). Similarly, mixed-effects analyses revealed that the difference between isometric moment-generating capacity of shoulder adductors compared with that of elbow flexors was significantly smaller ($P = .012$) in middle-aged adults than in previously studied young adults (Figure 2).

While we observed differences in volume distribution and relative strength of shoulder adductors and abductors, respectively, we did not observe significant decreases in absolute volume and joint moment-generating capacity. The mixed-effects models revealed no significant differences between age groups for functional group muscle volumes for any group except wrist extensors ($P = .029$), which were smaller for young adults.

We observed an ordering of moment-generating capacity among functional groups that was consistent both across subjects and compared with what has been previously observed in young adults. Overall, isometric shoulder adduction strength was greater than shoulder abduction ($P = .0039$), elbow extension ($P = .002$), wrist flexion ($P = .002$), and wrist extension ($P = .002$) (Figure 3). Shoulder abduction was greater than both wrist extension and flexion ($P < .002$). Elbow flexion was significantly greater than

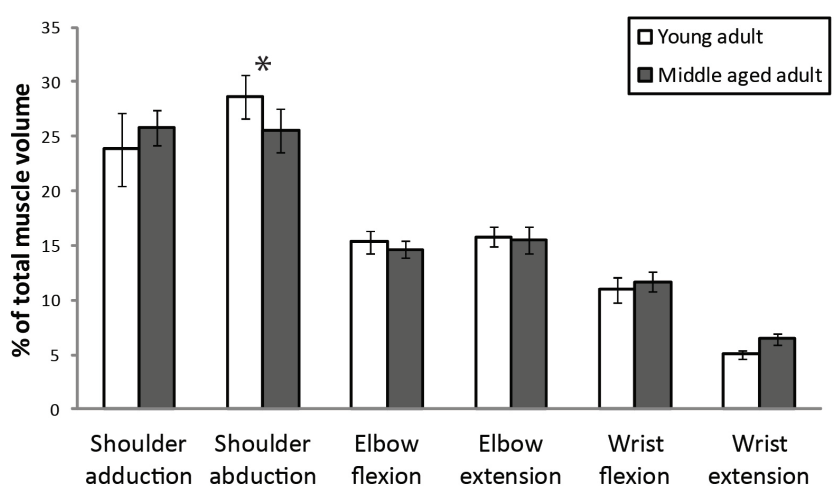

Figure 1 — Relative muscle volume for the 6 primary functional muscle groups, expressed as a percentage of the total muscle volume in the upper limb. Shoulder abductors were the only group to demonstrate a significant difference from the distribution of muscle volumes in the young adults ($P = .0009$). Middle-aged adults (dark grey) showed a decrease in the relative volume of the shoulder abductors compared with young adults (white). Error bars indicate one standard deviation. *Indicates significance $p < .05$.

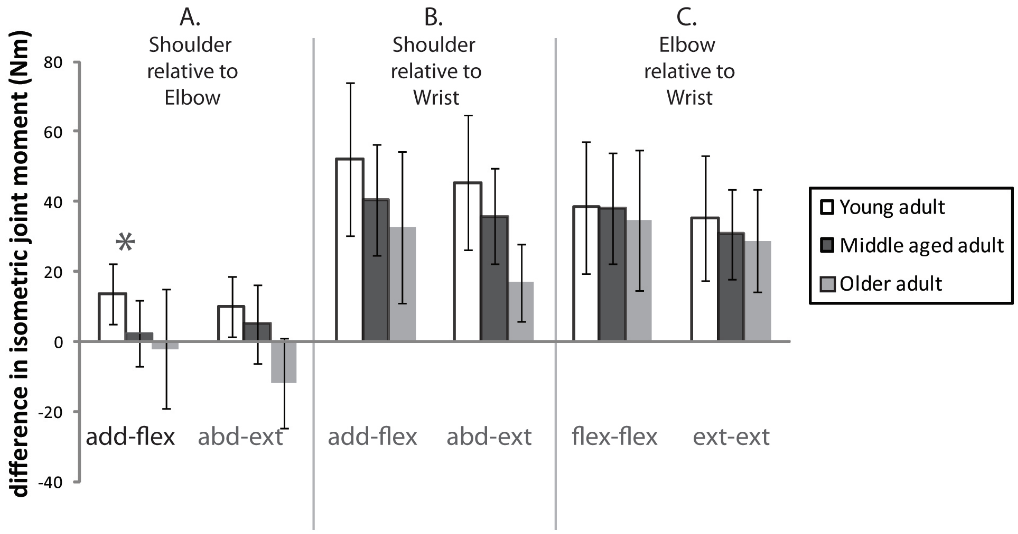

Figure 2 — Differences in isometric moment-generating capacity between functional muscle groups at the (A) shoulder and elbow, (B) shoulder and wrist, and (C) elbow and wrist. The relative moment-generating capacity of the shoulder adductors relative to the elbow flexors significantly decreased ($P = .012$) in middle-aged adults (dark gray) compared with the young adults (white). Differences between the remaining muscle groups were not significantly different from young adults. Differences observed in older adults[14] are shown in light gray bars. Error bars indicate one standard deviation. *Indicates significance $p < .05$.

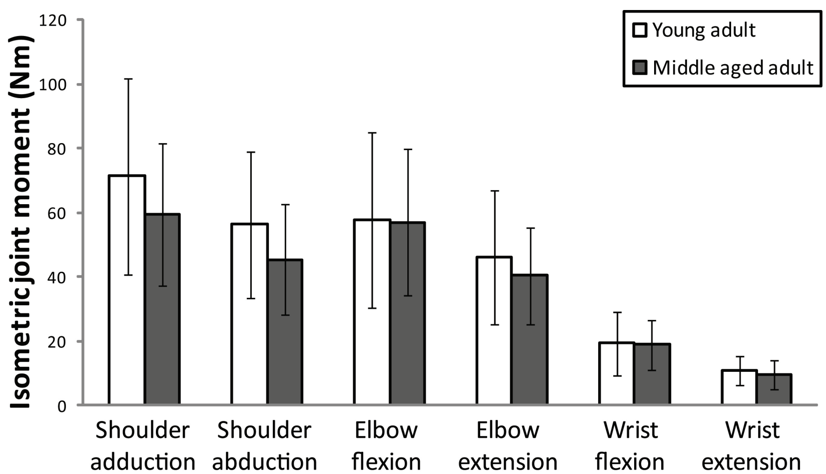

Figure 3 — Isometric moment-generating capacity for each functional muscle group. We observed a consistent ordering of moment-generating capacity among functional groups across subjects. Overall, isometric shoulder adduction strength was greater than shoulder abduction ($P = .0039$), elbow extension ($P = .002$), wrist flexion ($P = .002$), and wrist extension ($P = .002$). Shoulder abduction was greater than both wrist extension and flexion ($P < .002$). Elbow flexion was significantly greater than elbow extension ($P = .002$), which was greater than wrist flexion ($P = .002$), followed by wrist extension ($P = .002$). Error bars indicate one standard deviation.

elbow extension ($P = .002$), which was greater than wrist flexion ($P = .002$), followed by wrist extension ($P = .002$).

Variation in moment-generating capacity accounted for by muscle volume in this middle-aged cohort was comparable to what has been observed in young adults (Figure 4). The linear relationship between isometric moment-generating capacity and muscle volume was significant ($P < .02$) for shoulder abduction and adduction, elbow flexion and extension, and wrist flexion, with an average of 79% of variation accounted for by muscle volume in these 5 functional groups. Wrist extensor volume explained 35% of the variation for wrist extension moment ($P = .07$). When wrist extension is included, the average variation in joint moment accounted for by functional group muscle volume is 72%. Thus, whether wrist extensors are considered or not, variability in isometric strength accounted for by muscle volume in these middle-aged subjects was within 8% of what has been observed in young adults (80%[22]). Similarly, for all muscle groups, the slope relating joint moment and muscle volume for middle-aged adults was within the 95% confidence interval observed for young adults.

Total muscle volume varied substantially across middle-aged subjects, spanning a 2.3-fold range. Despite large variation in absolute volume among subjects, total muscle volume was distributed among functional groups in a consistent manner across subjects. Specifically, the coefficient of variation (standard deviation/mean)

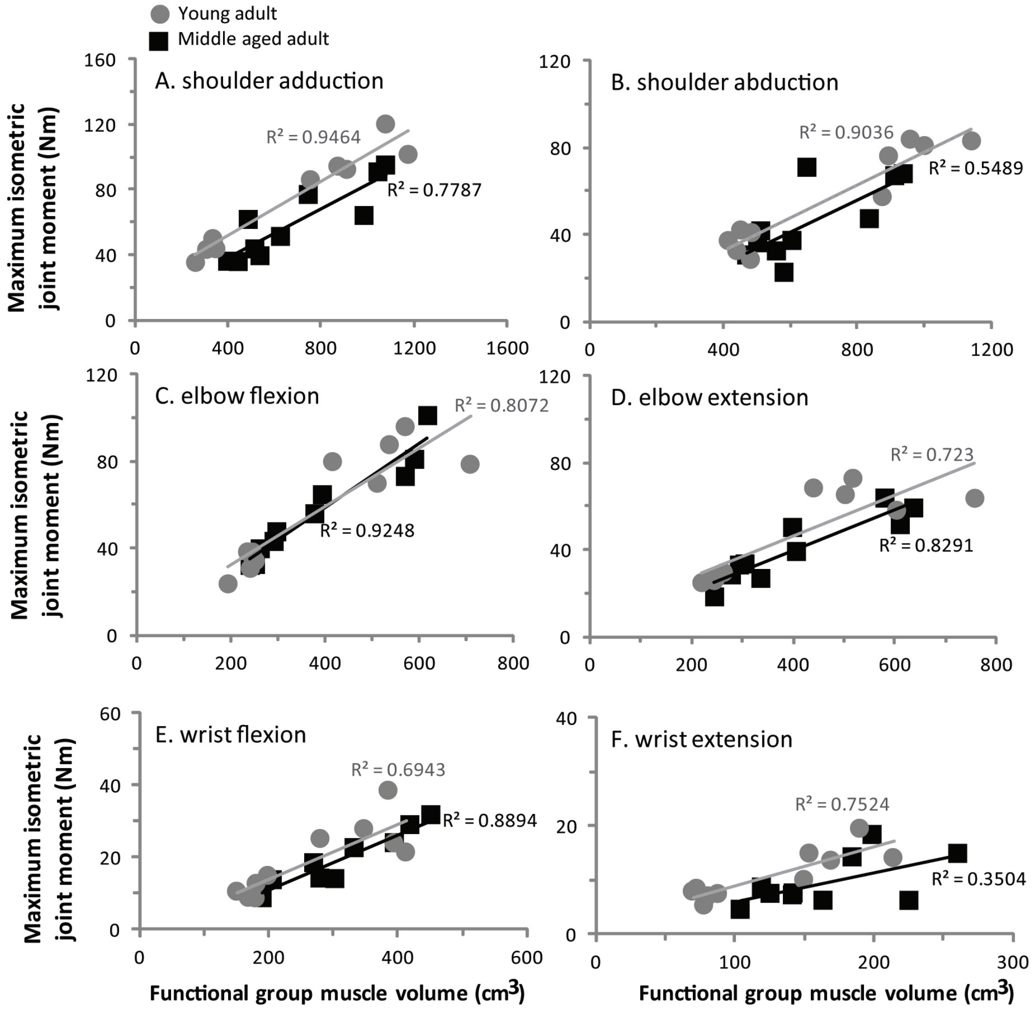

Figure 4 — Maximum isometric moment versus total volume of muscles in the corresponding functional group. Middle-aged subjects (black squares) show a significant linear relationship for shoulder adduction (A) and abduction (B), elbow flexion (C) and extension (D), and wrist flexion (E) ($P < .02$), and a trend for wrist extension (F) ($P = .07$). Slopes for the middle-aged subjects fall within the 95% confidence interval for each functional group, as measured in young adult subjects (gray circles).[22] An average of 72% of joint moment variation is accounted for by functional group muscle volume across all 6 functional groups for middle-aged adults, compared with approximately 80% in young adults.

of volume distribution for each functional group ranged from 0.05 to 0.08 (Table 2). Coefficients of variation for absolute muscle volume in each functional group were 3 to 7 times larger than those for volume distribution (Table 2). The consistency of volume distribution within the upper limb across subjects of different sizes replicates observations from the young adults.

Discussion

This study provides a resource of primary multijoint musculoskeletal data describing absolute and relative muscle size and strength in the upper limb of a healthy middle-aged population that was not previously available. Prior observations in older adults (> 65 years) suggest that age-related effects are most pronounced at the shoulder; in one study, absolute muscle volume and both absolute and relative strength deficits were most pronounced at the shoulder, to the extent that the shoulder was not stronger than the elbow (Figure 2).[14] In the current study, the only evidence of age-related declines in this group of middle-aged adults was a statistically significant proportional loss of strength and muscle volume at the shoulder, although the shoulder remained stronger than the elbow, as in young adults.[22] Reduced relative shoulder strength may have implications for coordination and function. For example, shoulder strength and muscle volumes are better predictors of maximal strength when performing more complex movements compared with those of other functional groups.[25] The extent to which variability in moment-generating capacity was explained by functional group muscle volume in these middle-aged adults remained comparable to that of young adults (79%).

Limited data describing upper limb strength or muscle size for middle-aged individuals is available. Previously, relationships between muscle size and strength have been reported for the middle-aged for elbow flexors only,[17] with reported significant correlations between calculated elbow flexor force and muscle thickness for a single group including both middle-aged and elderly individuals. Isometric strength assessments of shoulder abduction and adduction in the same posture in individuals aged 50 to 59 years reported strength of 37 ± 10 N·m and 75 ± 11 N·m, respectively,[13] while we report 58.1 ± 14.9 N·m and 75.7 ± 18.3 N·m in our group aged 46 to 60 years.

Table 2 Muscle volumes and joint moments by functional group

		Functional Group Volume (CM^3)						Functional Group Percent Volume						Maximum Isometric Joint Moment (N·m)					
Subject	Total Volume (cm^3)	SAD Vol.	SAB Vol.	EF Vol.	EE Vol.	WF Vol.	WE Vol.	%SAD Vol.	% SAB Vol.	%EF Vol.	%EE Vol.	%WF Vol.	%WE Vol.	SAD Max.	SAB Max.	EF Max.	EE Max.	WF Max.	WE Max.
MF1	2097.0	487.0	558.1	291.7	336.6	271.0	141.9	23.2	26.6	13.9	16.1	12.9	6.8	61.7	32.5	43.1	26.8	18.5	7.3
MF2	1768.5	444.0	501.9	252.3	245.7	190.8	126.0	25.1	28.4	14.3	13.9	10.8	7.1	35.8	36.2	32.5	18.3	12.5	7.6
MF3	1925.2	515.5	511.0	262.4	305.4	207.0	119.8	26.8	26.5	13.6	15.9	10.8	6.2	43.6	41.7	39.7	33.5	13.8	8.7
MF4	1688.6	398.6	468.8	241.1	278.6	191.4	104.4	23.6	27.8	14.3	16.5	11.3	6.2	36.0	30.7	32.1	28.4	8.8	4.6
MF5	2141.4	537.8	580.8	297.6	294.6	280.6	142.6	25.1	27.1	13.9	13.8	13.1	6.7	39.4	22.7	47.5	33.0	14.3	7.6
MM1	3941.1	1078.3	937.2	617.8	580.5	452.5	260.8	27.4	23.8	15.7	14.7	11.5	6.6	95.0	68.0	101.0	63.8	31.8	14.9
MM2	2717.4	745.9	649.0	394.3	398.9	333.7	184.9	27.4	23.9	14.5	14.7	12.3	6.8	77.0	71.0	64.6	50.2	22.7	14.3
MM3	2491.1	626.1	604.4	378.2	406.6	304.0	164.0	25.1	24.3	15.2	16.3	12.2	6.6	51.3	37.3	55.9	39.2	14.1	6.3
MM4	3765.8	1045.3	911.5	590.2	610.8	396.0	199.3	27.8	24.2	15.7	16.2	10.5	5.3	90.9	67.1	80.9	51.5	24.1	18.4
MM5	3691.6	986.1	835.6	570.2	637.1	420.1	225.8	26.7	22.6	15.4	17.3	11.4	6.1	64.1	47.3	73.0	59.2	29.1	6.3
Female, mean (SD)	1924.1 (198.0)	476.6 (55.9)	524.1 (45.0)	269.0 (24.7)	292.2 (33.5)	228.2 (44.1)	126.9 (16.0)	24.8 (1.4)	27.3 (0.8)	14.0 (0.3)	15.2 (1.3)	11.8 (1.2)	6.6 (0.4)	43.3 (10.7)	32.7 (7.0)	39.0 (6.7)	28.0 (6.1)	13.6 (3.5)	7.2 (1.5)
Male, mean (SD)	3321.4 (665.7)	896.3 (199.4)	787.5 (152.3)	510.2 (114.5)	526.8 (115.0)	381.2 (61.3)	207.0 (37.6)	26.9 (1.0)	23.8 (0.7)	15.3 (0.5)	15.8 (1.1)	11.6 (0.7)	6.3 (0.6)	75.7 (18.3)	58.1 (14.9)	75.1 (17.2)	52.8 (9.4)	24.3 (6.8)	12.0 (5.5)
All, mean (SD)	2622.8 (869.9)	686.5 (260.8)	655.8 (174.6)	389.6 (149.2)	409.5 (147.2)	304.7 (95.1)	167.0 (50.2)	25.8 (1.6)	25.5 (2.0)	14.6 (0.8)	15.5 (1.2)	11.7 (0.9)	6.4 (0.5)	59.5 (22.2)	45.4 (17.3)	57.0 (22.7)	40.4 (15.1)	19.0 (7.6)	9.6 (4.6)
COV	0.33	0.38	0.27	0.38	0.36	0.31	0.30	0.06	0.08	0.05	0.08	0.08	0.08	0.37	0.38	0.40	0.37	0.40	0.48

Abbreviations: MF = middle-aged female; MM = middle-aged male; COV = coefficient of variation; SAD = shoulder adduction; SAB = shoulder abduction; EF = elbow flexion; EE = elbow extension; WF = wrist flexion; WE = wrist extension; Vol. = volume; Max. = maximum.

An important limitation of our work is the relatively small cohorts of subjects (n = 10) for each age group. Similarly, within each cohort, subject size and strength varied substantially. Thus, we acknowledge that reductions in volume or joint moment may not have been detected here because absolute differences in the 2 populations were small compared with the variability across the subjects. We note that subject anthropometry, including height and body mass, was an intentional inclusion criterion for subject recruitment for the current study to match groups (percentile body mass: young adults 5th–90th; middle-aged adults 10th–99th). We sought to replicate anthropometrics of the original study to better explore differences between groups that result from aging. Because of the high computational burden of obtaining and analyzing muscle volumes, evaluating a larger number of subjects was not feasible. Despite this shortcoming, these novel data provide new potential to design future studies appropriately so that smaller changes in absolute upper limb muscle volume and strength can be quantified with statistical confidence.[26] Due to the sample size limitations, males and females were evaluated in the same analyses. Sex-based differences warrant further study. In addition, we evaluated strength in only a single posture and for only 2 functional groups at each joint. Wrist deviation and shoulder rotation and flexion strength are also important for functional performance, and changes in these roles with age warrant attention.

This is a cross-sectional study; longitudinal studies of age-related changes are more powerful. Longitudinal examinations of muscle volume and joint strength with age exist, but these are often in the context of effects of strength training, rather than effects of age alone.[25,27] Muscle function and structure would be difficult to assess longitudinally over a time period consistent with the mean age difference between our 2 cross-sectional cohorts (~25 years).

Models that incorporate muscle volumes and strength profiles that represent the subject or population of interest better represent experimental measurements of function.[28] These data provide a useful foundation for improved modeling of upper limb musculoskeletal performance in middle-aged subjects, and may improve computational predictions of function for this group.

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