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Age-related structural changes in upper extremity muscle tissue in a nonhuman primate model

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Background: Longitudinal studies of upper extremity aging in humans include logistical concerns that animal models can overcome. The vervet is a promising species with which to study aging-related processes. However, age-related changes in upper extremity muscle structure have not been quantified in this species. This study measured age-related changes to muscle structure, examined relationships between muscle structure and measures of physical performance, and evaluated the presence of rotator cuff tears.
Methods: Muscle structure (volume, optimal fiber length, and physiologic cross-sectional area (PCSA)) of 10 upper extremity muscles was quantified from the right upper limb of 5 middle-aged and 6 older adult female vervets.
Results: Total measured PCSA was smaller ($P = .001$) in the older adult vervets than in the middle-aged vervets. Muscle volume reduction predominate the age-related reductions in PCSA. Total measured PCSA was not correlated to any measures of physical performance. No rotator cuff tears were observed. Supraspinatus volume was relatively larger and deltoid volume relatively smaller in the vervet compared with a human.
Conclusions: The vervet is an appropriate translational model for age-related upper extremity muscle volume loss. Functional measures were not correlated to PCSA, suggesting the vervets may have enough strength for normal function despite loss of muscle tissue. Reduced relative demand on the supraspinatus may be responsible for the lack of naturally occurring rotator cuff tears.
Level of evidence: Basic Science Study, Anatomy, Animal Model.

Keywords: Aging; muscle; volume loss; function; primate

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Age-related changes to muscle structure and function in the upper limb are thought to be associated with progression to disability in humans, and thus, quantifying these features is important for providing context for healthy aging and also for other musculoskeletal disorders of the upper limb when they occur in an older patient group. Age-related changes to skeletal muscle are well known but have largely been evaluated in cross-sectional studies.[28] In the upper limb specifically, declines in muscle volume[1,36,43] and increased levels of fat and connective tissue[36] have been reported. Further, relationships between structural and functional changes are limited; longitudinal studies of the upper limb have primarily measured grip[8,16,26,35,41] or elbow strength,[3,10,15,34] but not more complex tasks, and corresponding measurements of skeletal muscle mass were not consistently measured or were not specific to the upper limb.[15,26]

Understanding longitudinal changes to muscle structure, function, and the interplay between the two would lend insight into early predictive factors for future disability that are difficult to assess in a cross-sectional study design. However high cost, long life span, and the need for invasive measurements to fully characterize skeletal muscle make longitudinal studies of the musculoskeletal system difficult to perform in humans. An animal model of upper extremity aging would more easily allow for longitudinal studies by limiting many of the logistical concerns associated with human subjects. Unfortunately, data regarding musculoskeletal degeneration in animals resulting strictly from normal aging are limited,[7,12,24,31,32] and many of the animal models are small, quadrupedal, or have bony geometry that is substantially different from that of a human.[9,22,31] A nonhuman primate model may offer a solution that mitigates many of these problems.[31]

Previous data suggest that the African vervet monkey (*Chlorocebus pygerythrus*) may be a promising species to use as a human surrogate to study age-related changes in physical function and in the upper extremity. Reductions in muscle fiber force in the vastus lateralis were present in older vervets,[7] although whether the upper extremity musculature experiences the same decline is unclear. Older vervets demonstrated age-related deteriorations of the shoulder similar to reports in older adult humans, including degeneration of the glenoid, increased glenoid retroversion, and decreased supraspinatus superficial cross-sectional area.[31] Similarly, measures of physical performance that incorporate the upper extremity were diminished in older vervets.[7,31,39] However, within this vervet species, age-related changes to the upper extremity musculature have not been evaluated, and degenerative rotator cuff tears, a common age-related injury affecting older adult humans,[44] have not been described.[31]

Quantifying age-related changes in the upper extremity musculature is necessary before the vervet can be appropriately evaluated as a human surrogate for longitudinal studies on upper extremity aging. To this end, we sought to expand upon the findings of age-related bony degeneration and decreased fiber cross-sectional area in the superficial portion of the supraspinatus in this vervet species by measuring the physiologic cross-sectional area (PCSA) of 10 upper extremity muscles important for upper limb function. PCSA combines measurements of volume and fiber length and is proportional to force-generating capacity. We also sought to determine how PCSA affects physical performance and the presence of rotator cuff tears.

Materials and methods

The right upper limbs of 5 middle-aged and 6 older adult female African vervets were obtained from a previously studied population of vervets (Table I). The current reports list vervets aged older than 20 years as elderly, with the 26.4-year-old in the current study the oldest known female vervet in captivity originating from the original colony.[31] Briefly, all animals were housed in social groups at the Wake Forest Primate Center and were allowed to traverse the inside/outside pens at their own leisure. Feeding was ad libitum. Physical performance (walking speed, percentage of time hanging, and percentage of time climbing) was measured for the animals as described previously.[7,31,39] Euthanasia was performed as part of a larger experiment exploring immunologic and physiologic parameters and their relationship to aging. All procedures were conducted in compliance with state and federal laws, standards of the U.S. Department of Health, and Human Services, and regulations and guidelines established by the Institutional Animal Care and Use Committee. After euthanasia, the right upper extremity was removed from the torso and frozen.

Each limb was thawed over a period of 24 hours, skinned, and fixed in 10% phosphate-buffered formalin for 24 hours. Before fixation, the limb was placed in a neutral shoulder and wrist posture with 90° of elbow flexion and attached to an aluminum plate via the spine. Each limb was removed from the formalin and placed in a 70% ethanol solution for a minimum of 24 hours to preserve the fixation and rinse any excess formalin. Measurements of arm length (acromion to lateral epicondyle) and forearm length (lateral epicondyle to ulnar styloid) were made using digital calipers.

The muscle-tendon unit of the 4 rotator cuff muscles (subscapularis, infraspinatus, supraspinatus, and teres minor), teres major, deltoid, biceps, triceps, coracobrachialis, and brachialis were dissected from the skeleton. Care was taken to ensure the entire muscle-tendon unit was removed from the skeleton. Before dissection, rotator cuff tendons were visually inspected for tears. Subscapularis, infraspinatus, deltoid, triceps, and biceps were divided into subsections according to previous descriptions of muscle architecture[13,42] for a total of 18 muscle-tendon units (Table II). After dissection, excess connective tissue and fat was removed from the muscle-tendon unit, and each muscle-tendon unit was stored in a 70% ethanol solution.

Measurements of muscle length and volume were made for each of the 18 muscle-tendon units. The tendon was removed at the muscle-tendon junction and the muscle belly length was measured using digital calipers and defined as the distance from the most proximal point to the most distal point. The 70% ethanol solution was placed in a graduated cylinder, and muscle volume was determined as the difference in volume with and without the muscle. Location of the meniscus was determined from high-

Table I Characteristics of vervet specimens

Age (y)	Age group (MA/OA)	Body mass (kg)	Arm length (mm)	Forearm length (mm)
11.76	MA	6.57	119.55	108.80
9.43	MA	4.68	112.15	100.69
11.53	MA	5.87	114.01	105.99
11.63	MA	4.92	108.18	100.17
11.53	MA	7.08	113.99	109.99
21.48	OA	6.14	119.42	109.21
25.75	OA	4.00	107.67	103.71
26.41	OA	4.93	127.48	114.22
23.73	OA	5.51	111.17	108.51
19.86	OA	4.63	113.80	107.99
21.55	OA	5.12	111.46	106.15

MA, middle-aged; *OA*, older adult.

resolution photos (57.37 pixels/mL) of each cylinder and calculated using ImageJ software (National Institutes of Health, Bethesda, MD, USA).[38]

After fixation and gross muscle measurements, thin strips of muscle fibers were dissected from the interior of the muscle using fine sharp dissection,[18] and fiber length (l^f) was measured using digital calipers. Fibers were dissected from different locations within the muscle belly to ensure the entire muscle belly was represented. A microscope was used to dissect the fibers into smaller bundles. These bundles were mounted on a microscope slide for sarcomere length measurements, and a cover slip was added.

A custom-built laser diffractometer (HRP050-1, 5.0 mW at 633 nm; Thor Labs, Newton, NJ, USA) was used to determine the sarcomere lengths for each dissected fiber.[45] Digital calipers were used to measure the width of the first-order diffraction band (y), which was used to calculate the sarcomere length (l^s) (Eq. 1, Eq. 2), where λ is the laser wave-length (633 nm) and L is the distance from the microscope slide to the diffraction surface.

$$l^s = \frac{\lambda}{\sin\theta} \qquad \text{Equation 1}$$

$$\tan\theta = \frac{y}{L} \qquad \text{Equation 2}$$

Repeatability of the caliper measurements was ±0.32 mm, corresponding to ±0.048 μm for sarcomere lengths. Optimal fiber length (l_o^f) was calculated for each sarcomere measurement by normalizing the measured sarcomere length by the optimal sarcomere length (2.8 μm) determined for mammalian muscle (Eq. 3).[21] Optimal muscle length (l_o^m) was calculated in the same manner to normalize muscle belly length. Optimal fiber length (Eq. 4) and optimal muscle length (Eq. 5) were also calculated for the whole muscle for muscles with multiple sections: where t equals the number of subsections (subscapularis = 3, infraspinatus = 2, deltoid = 3, triceps = 3, biceps = 2). Relative length (Eq. 6) of the rotator cuff muscles was calculated to facilitate comparisons between vervet and other animal species.

$$l_o^f = l^f \frac{2.8}{l^s} \qquad \text{Equation 3}$$

$$l_o^f = \frac{\sum_{j=1}^{t} PCSA_j * \left(l_o^f\right)_j}{\sum_{j=1}^{t} PCSA_j} \qquad \text{Equation 4}$$

$$l_o^m = \frac{\sum_{j=1}^{t} CSA_j * \left(l_o^m\right)_j}{\sum_{j=1}^{t} CSA_j} \qquad \text{Equation 5}$$

$$\text{Relative length} = \frac{l_o^f}{l_o^m} \qquad \text{Equation 6}$$

PCSA was calculated by dividing the muscle volume by optimal fiber length.[27] A representative cross-sectional area (CSA) was calculated by dividing muscle volume by optimal muscle length. For muscles with multiple subsections (subscapularis, infraspinatus, deltoid, triceps, and biceps) whole-muscle PCSA was calculated by adding the PCSA from each section.[27] Total measured PCSA was calculated by adding the PCSA for every muscle.

The primary outcome of this study was to evaluate whether there are differences between old and middle-aged animals in total measured PCSA; a Student t test was used for this purpose. The effect of total measured PCSA on measures of physical performance previously measured in the same animals was quantified for all animals and each age group using linear regression models. The t tests were used to compare the components of PCSA (volume and optimal fiber length) for each muscle between the groups. Total rotator cuff PCSA was compared between groups using a t test. The PCSA fraction for each rotator cuff muscle (subscapularis, infraspinatus, supraspinatus, teres minor) and the deltoid was calculated by dividing the PCSA of the muscle by the total rotator cuff PCSA and compared between groups using Student t tests. Volume fraction was calculated and compared in the same way. All statistical tests were performed in SAS software (SAS Institute Inc, Cary, NC, USA), and statistical significance was defined as $P < .05$. Because of the exploratory nature of this study, corrections for multiple comparisons were not performed.

Results

Despite no differences in body mass, upper arm length, and forearm length between the middle-aged and older vervets (Table I), the older vervets had significantly smaller total

Table II Mean (standard deviation) of anatomic parameters

Muscle	PCSA, cm^2		Volume, cm^3		Optimal fiber length, mm		Optimal muscle length, mm	
	OA	MA	OA	MA	OA	MA	OA	MA
Superior subscapularis[‡]	2.14 (0.35)[†]	2.66 (0.29)	4.32 (1.15)[†]	5.83 (0.65)	20.37 (3.29)	22.30 (1.86)	62.05 (9.19)	64.74 (11.55)
Middle subscapularis[*,‡]	2.62 (0.65)	3.20 (0.33)	4.19 (1.28)[†]	5.87 (0.99)	16.17 (2.84)	18.44 (2.45)	67.53 (15.32)	75.95 (8.06)
Inferior subscapularis[‡]	1.10 (0.32)	1.35 (0.23)	2.16 (0.65)	2.62 (0.17)	19.79 (2.07)	20.02 (2.65)	71.80 (7.78)	65.13 (3.27)
Subscapularis[*,‡]	5.87 (0.60)[†]	7.21 (0.42)	10.67 (2.17)[†]	14.32 (1.59)	18.36 (2.91)	20.07 (1.67)	65.84 (9.66)	68.37 (5.71)
Superior infraspinatus[‡]	1.74 (0.27)	2.01 (0.24)	4.47 (0.82)	5.32 (0.61)	26.15 (3.66)	26.97 (2.05)	78.70 (9.65)	82.10 (7.91)
Inferior infraspinatus[‡]	1.47 (0.30)	1.81 (0.39)	3.82 (0.92)	4.91 (0.98)	26.40 (2.90)	27.49 (2.97)	81.12 (9.52)	78.07 (13.14)
Infraspinatus[*,‡]	3.20 (0.41)	3.82 (0.59)	8.30 (1.44)	10.23 (1.40)	26.22 (3.28)	27.23 (2.36)	79.86 (9.63)	79.66 (9.84)
Supraspinatus[‡]	2.42 (0.47)	2.77 (0.55)	6.47 (1.65)	8.12 (1.45)	26.94 (3.36)	29.80 (3.07)	74.22 (4.98)	78.11 (9.96)
Teres minor	0.76 (0.12)[†]	0.98 (0.14)	1.28 (0.14)[†]	1.63 (0.23)	17.27 (2.11)	16.77 (1.40)	44.70 (6.15)	45.89 (3.22)
Anterior deltoid	0.85 (0.18)[†]	1.25 (0.28)	4.70 (0.96)[†]	7.31 (1.26)	56.06 (3.06)	59.86 (5.14)	67.37 (5.39)[†]	77.17 (4.90)
Middle deltoid	1.97 (0.63)[†]	2.91 (0.52)	5.08 (1.50)[†]	7.50 (1.50)	26.45 (2.95)	26.29 (2.09)	50.62 (3.07)	55.22 (6.82)
Posterior deltoid	0.89 (0.20)	1.12 (0.20)	3.02 (0.61)[†]	4.74 (1.36)	34.55 (2.25)[†]	42.65 (8.13)	53.91 (5.54)	62.53 (8.49)
Deltoid[*]	3.71 (0.90)[†]	5.28 (0.76)	12.79 (2.89)[†]	19.55 (3.62)	35.13 (2.29)	37.48 (1.81)	56.36 (1.66)[†]	63.53 (3.97)
Teres major	1.64 (0.37)[†]	2.15 (0.21)	6.29 (1.11)[†]	8.98 (1.80)	39.10 (3.96)	42.41 (6.88)	74.50 (6.67)	79.00 (12.19)
Long triceps	5.59 (0.71)[†]	8.66 (0.97)	16.88 (1.99)[†]	24.72 (3.73)	30.68 (1.35)	29.14 (2.83)	120.85 (8.52)[†]	109.39 (4.48)
Lateral triceps	2.83 (0.43)[†]	4.63 (0.89)	11.96 (1.92)[†]	17.30 (2.59)	42.91 (3.47)	38.32 (4.03)	112.79 (8.10)	104.50 (7.68)
Medial triceps	2.18 (0.42)	2.71 (0.77)	7.52 (1.14)	9.05 (2.10)	35.25 (1.68)	34.41 (4.58)	108.82 (3.33)	108.55 (10.65)
Triceps[*]	10.59 (1.39)[†]	16.00 (2.35)	36.36 (4.55)[†]	51.06 (8.29)	34.85 (1.66)	32.52 (2.93)	115.35 (6.01)[†]	107.26 (4.45)
Long biceps	1.92 (0.42)[†]	2.46 (0.46)	9.03 (2.01)	11.61 (2.10)	47.34 (2.41)	47.41 (4.59)	90.08 (3.73)	93.00 (11.75)
Short biceps	0.59 (0.05)[†]	0.88 (0.19)	3.12 (0.36)[†]	4.81 (1.14)	53.22 (3.91)	54.86 (6.13)	90.81 (3.01)	93.47 (12.85)
Biceps[*]	2.52 (0.44)[†]	3.34 (0.35)	12.15 (2.27)[†]	16.42 (2.87)	48.68 (2.43)	49.36 (4.88)	90.25 (3.43)	93.17 (11.40)
Coracobrachialis	0.36 (0.12)	0.47 (0.14)	0.60 (0.20)	0.80 (0.23)	17.32 (2.31)	17.35 (1.14)	54.36 (10.55)	61.86 (11.15)
Brachialis	1.47 (0.25)[†]	1.81 (0.25)	4.82 (1.02)	5.86 (0.95)	33.17 (2.29)	32.78 (3.32)	71.74 (2.79)	69.35 (9.11)

PCSA, physiologic cross-sectional area.

[*] PCSA and volume were calculated from the summation of PCSA and volume from the subsections. Optimal fiber length and optimal muscle length were calculated from Eq. 4 and 5.

[†] Statistically significant differences ($P < .05$) between groups.

[‡] Indicates a rotator cuff muscle.

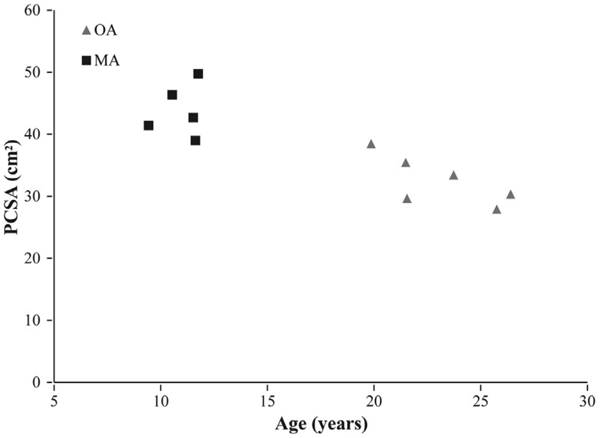

Figure 1 Total measured physiologic cross-sectional area (*PCSA*) vs age for the older adult (*OA*) and middle-aged (*MA*) vervets.

measured PCSA than the middle-aged vervets ($P = .001$; Table II, Fig. 1). Older PCSA was smaller for every individual muscle studied, and 10 of the 18 muscles exhibited significant decreases. The lateral head of the triceps exhibited the largest reduction in PCSA between groups (38.97%), and the supraspinatus exhibited the smallest reduction in PCSA (12.55%; Fig. 2). The total measured PCSA was not significantly correlated to any of the physical performance measures when the middle-aged and older adults were considered together for statistical analysis for walking speed ($r^2 = 0.0843$, $P = .3863$), percentage of time hanging ($r^2 = 0.0247$, $p = 0.644$), and percentage of time climbing ($r^2 = 0.0736$, $P = 0.420$). Similarly, when the same analysis was repeated for each age group separately, PCSA was not correlated to any physical performance measure for either age group.

Mean muscle volume in the older adults was numerically smaller for every muscle studied and was statistically different in 10 of the 18 muscles (Table II). The posterior portion of the deltoid (36.25%) and the superior portion of the infraspinatus (15.88%) exhibited the largest and smallest volumes reductions, respectively. Optimal fiber length for the posterior portion of the deltoid was significantly shorter for the older vervets due to a decrease in measured fiber length; no other muscles exhibited a significant difference in optimal fiber length.

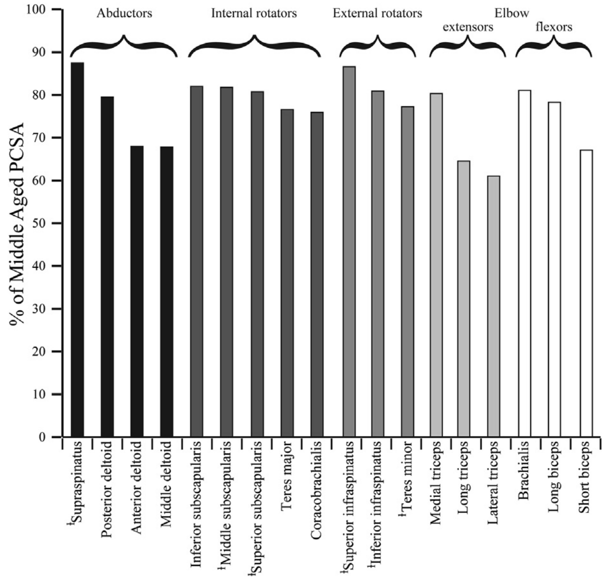

Figure 2 Older adult individual muscle physiologic cross-sectional area (PCSA) as a percentage of middle-aged PCSA. There was not a preferential decrease in PCSA of any muscle group in the older adults. Of the rotator cuff muscles (indicated by †), the teres minor had the largest decrease in PCSA (22.7%) and the supraspinatus had the smallest (12.5%).

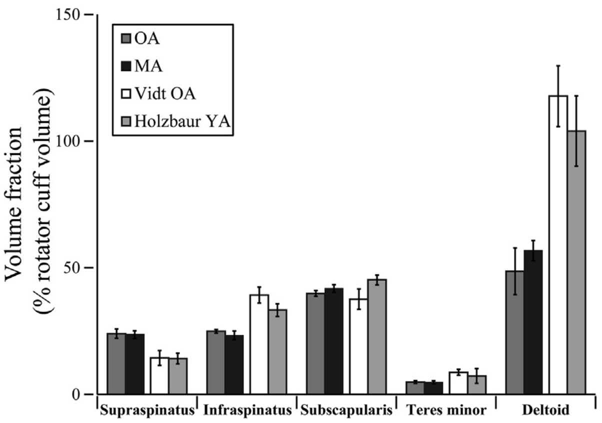

Figure 3 Volume fraction for vervet and female young adult (*Holzbaur YA*) and older adult (*Vidt OA*) humans as determined by a percentage of the total rotator cuff volume.[14,43] There were no statistical differences between the older adult (*OA*) and middle-aged (*MA*) vervet volume fractions for any muscle. When combined, the vervet supraspinatus volume fraction (24%) was larger than the humans (14%), and the vervet deltoid volume fraction (52%) was smaller than the humans (112%). The *range bars* indicate the standard deviation.

Despite significant differences in total rotator cuff (supraspinatus, infraspinatus, subscapularis, and teres minor) PCSA ($P = .008$), there were no significant differences in the rotator cuff PCSA fraction between the older and middle-aged vervets for any muscle. The same was true for volume fraction (Fig. 3). The subscapularis made up the largest proportion of the rotator cuff PCSA for the older (48.03% ± 3.75%) and middle-aged vervets (48.96% ± 3.39%), and the teres minor made up the smallest (older: 6.22% ± 0.84%; middle-aged: 6.70% ± 1.04%; Table III). The deltoid measured 30.11% ± 4.94% and 35.64% ± 2.34% of the rotator cuff PCSA for the older and middle-aged vervets, respectively. Visual inspection of the articular and bursal side (Fig. 4) showed no rotator cuff tears were present. Unlike hominoids, such as humans, chimpanzees, and orangutans, the vervets do not have a "true" rotator cuff in which the supraspinatus, infraspinatus, subscapularis, and teres minor share a common insertion site (Fig. 4).[40]

Table III Comparison of vervet, capuchin, and chimpanzee

Muscle	Rotator cuff PCSA, %			Relative length		
	Vervet	Capuchin*	Chimpanzee*	Vervet	Capuchin*	Chimpanzee*
Subscapularis	48.45	49.15	47.23	0.29	0.25	0.39
Infraspinatus	25.94	21.57	26.62	0.34	0.26	0.28
Supraspinatus	19.16	23.18	21.12	0.37	0.38	0.30
Teres minor	6.44	6.09	5.04	0.38	0.31	0.45

PCSA, physiologic cross-sectional area.

* Data adapted from Mathewson et al[23] (2014).

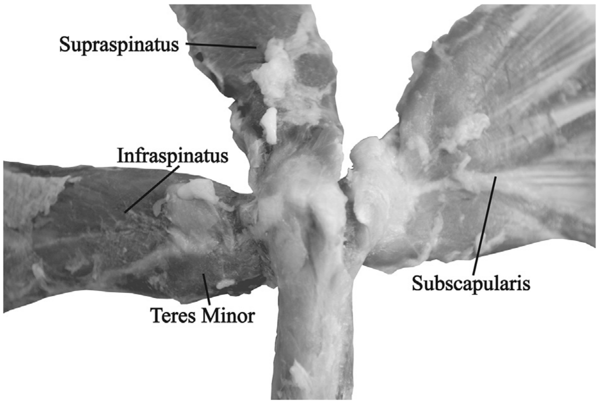

Figure 4 Representative bursal-surface view shows the rotator cuff muscle-tendon units and their anatomic insertion sites. Unlike hominoids, such as humans, chimpanzees, and orangutans, the vervets do not have a "true" rotator cuff, which is indicated by a lack of distinction between the tendon insertion sites of the supraspinatus, infraspinatus, subscapularis, and teres minor.[40] No tears were discovered during dissection.

Discussion

We examined age-related differences in the PCSA of 18 muscles of the right upper extremity in a cohort of 5 middle-aged and 6 older adult female vervet monkeys. We observed that the total measured PCSA was significantly smaller in the older vervets despite similarities in body mass and arm length. Reduced PCSA was driven by an overall loss of muscle volume rather than by changes in optimal fiber length, which were not observed. Multiple cross-sectional studies in human volunteers have demonstrated reduced upper extremity muscle volume in older adults.[1,36,43] Although age-related muscle volume loss has been established in the lower limb of animal models,[12,24] to our knowledge, the current study is the first to observe age-related upper extremity muscle volume loss in an animal model. This observation provides support for the vervet monkey as an animal model for age-related upper extremity muscle volume loss.

The prevalence of rotator cuff tears in humans increases with advancing age, with the incidence reaching 50% in adults aged older than 70.[44] Older vervets presented with no grossly detectable rotator cuff tears. This extends previous findings of the left upper limb of the same vervets.[31] Vervet monkeys use the supraspinatus, the most commonly torn rotator cuff muscle-tendon unit,[37] as a dynamic stabilizer, similar to humans.[19] However, our results indicate that the vervet supraspinatus represents a much larger proportion of the total rotator cuff volume (24%) than in a human (14%).[14,43] In addition, the vervet deltoid volume is only 52% of the total rotator cuff volume, whereas the human deltoid is 112% (Fig. 3). Similarly to a previous study in knuckle-walking nonhuman primates (*Pan troglodytes*),[33] these 2 findings suggest a reduced relative demand on the supraspinatus in this vervet model. In humans, a lifetime of increased demand on a proportionally smaller supraspinatus from the action of a proportionally larger deltoid may predispose the supraspinatus to age-related tearing. Owing to the lack of naturally occurring rotator cuff tears, it would be necessary to inflict a tear in a vervet model, as is done in other animal models used to study rotator cuff injury. However, the vervet may be a useful model of atrophy and fatty infiltration, common muscle changes associated with rotator cuff tears,[25] because these changes may be exaggerated and occur more quickly in the supraspinatus due to its large PCSA and subsequently increased role in movement.

Previous architectural analyses of other primate species suggest that chimpanzee (*Pan troglodytes*) and capuchin (*Cebus apella*) have rotator cuff muscle architecture more similar to the human rotator cuff than that of large and small quadrupedal animals.[23] Specifically, the volume fraction of the muscles of the rotator cuff and the relative length of the muscles (Eq. 6) were similar to that of humans. The same parameters for the vervet rotator cuff muscles in this study are similar (Table III). However, the relative deltoid PCSA was not determined for the capuchin or the chimpanzee in the previous study, which may be an important factor for establishing the appropriateness of a rotator cuff model with regard to tear propensity. Further, it should be noted that the vervet is an Old World monkey, and that the capuchin and chimpanzee are considered New World monkeys and advanced primates, respectively. New World monkeys and advanced primates exhibit a tendinous connection between rotator cuff tendons, whereas the vervet (Fig. 4) and other Old World monkeys do not.[40] This suggests that other factors beyond architectural parameters should be taken into consideration when considering an animal model for the rotator cuff.

In humans, the relationship between joint strength and overall function is important for understanding upper extremity disability and associated therapies. Because PCSA is proportional to muscle force-generating capacity,[20] we expected that reduced PCSA would be associated with a corresponding reduction in functional performance. Contrary to this hypothesis, the total measured PCSA was not significantly correlated with walking speed, percentage of time climbing, or percentage of time hanging within either age group or when all vervets were considered together. Any strength capacity that exists above the strength requirements of a task is referred to as reserve strength.[5] In humans, small reductions in strength have been reported to result in large functional declines only when strength falls below the minimum required strength to perform a task and reserve strength is zero.[5] We hypothesize that the older vervets, despite the substantial reduction in PCSA, retained reserve strength above the strength requirements of the measured functional tasks. Retaining reserve strength would indicate that to successfully perform the tasks, it is unnecessary for all of the available motor units to be recruited or unnecessary for all of the recruited motor units to be fully activated.

A previous study of these vervets demonstrated that these functional measures are significantly correlated to degenerative bony changes,[31] suggesting that discomfort due to age-related degenerative changes in the joint, rather than reduced strength, may impair function in these animals. Accurate measurements of strength and functional measures that include fatigue may prove more sensitive to reductions in PCSA and should be explored. Inclusion of other upper extremity musculature, including the pectoralis and latissimus dorsi, in the total PCSA calculation is prudent in determining the full extent of the effect of age-related PCSA reductions on functional performance.

This current study has some limitations that should be considered. Architectural parameters were not measured for all of the upper extremity muscles due to the method of upper extremity removal from the torso after euthanasia. Although the inclusion of more muscles would not be expected to significantly alter the weak relationships between total PCSA and functional performance, future characterization of these architectural parameters would provide a more complete picture of age-related PCSA loss and would allow for additional comparison of the vervet muscle structure to those obtained for other nonhuman primates.[2,6,11,17,29,30,33]

Only female vervets were included in this study. Although it is unclear whether hormonal imbalances due to aging or menstrual cycle phase affect the results of this study, previous work found that lean body mass in adult women was approximately 64% of that in men regardless of decade of life, indicating that women and men lose muscle mass at approximately the same rate.[28] Further, functional performance in macaque monkeys and human women do not vary based on menstrual cycle phase.[4] However, future work should include male vervets to ensure any sex differences in the age-related decline of PCSA are captured.

Conclusions

The results of this study suggest that the vervet monkey provides an appropriate translational model for studying longitudinal age-related muscle volume loss in the upper extremity. Future work relating the muscle volume changes to functional performance should consider additional measurements of strength or functional measures that include fatigue. Although naturally occurring age-related rotator cuff tears have not been observed in the vervets, the large size of the supraspinatus may make it an adequate muscle-tendon unit in which to study fatty infiltration and atrophy associated with naturally occurring rotator cuff tears. Furthermore, when considering an appropriate rotator cuff tear translational model, the relative size of the deltoid should be taken into consideration. The similarities to humans in the anatomic features and age-related musculoskeletal changes suggest that there may be a benefit for the use of the vervet in translational research involving healthy aging of the upper extremity.

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