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CT-based volumetric assessment of rotator cuff muscle in shoulder arthroplasty preoperative planning

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Aims

The aim of this study was to describe a quantitative 3D CT method to measure rotator cuff muscle volume, atrophy, and balance in healthy controls and in three pathological shoulder cohorts.

Methods

In all, 102 CT scans were included in the analysis: 46 healthy, 21 cuff tear arthropathy (CTA), 18 irreparable rotator cuff tear (IRCT), and 17 primary osteoarthritis (OA). The four rotator cuff muscles were manually segmented and their volume, including intramuscular fat, was calculated. The normalized volume (NV) of each muscle was calculated by dividing muscle volume to the patient's scapular bone volume. Muscle volume and percentage of muscle atrophy were compared between muscles and between cohorts.

Results

Rotator cuff muscle volume was significantly decreased in patients with OA, CTA, and IRCT compared to healthy patients ($p < 0.0001$). Atrophy was comparable for all muscles between CTA, IRCT, and OA patients, except for the supraspinatus, which was significantly more atrophied in CTA and IRCT ($p = 0.002$). In healthy shoulders, the anterior cuff represented 45% of the entire cuff, while the posterior cuff represented 40%. A similar partition between anterior and posterior cuff was also found in both CTA and IRCT patients. However, in OA patients, the relative volume of the anterior (42%) and posterior cuff (45%) were similar.

Conclusion

This study shows that rotator cuff muscle volume is significantly decreased in patients with OA, CTA, or IRCT compared to healthy patients, but that only minimal differences can be observed between the different pathological groups. This suggests that the influence of rotator cuff muscle volume and atrophy (including intramuscular fat) as an independent factor of outcome may be overestimated.

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Keywords: rotator cuff muscle, muscle volume, 3D CT scan, atrophy, fatty infiltration, volumetric analysis, tangent sign, occupation ratio, shoulder arthroplasty

Introduction

Preoperative 3D planning based on 3D CT reconstructions has been demonstrated to allow more accurate placement of the glenoid implant in shoulder arthroplasty,[1] which is known to be an important factor in the survival of the implants.[2,3] Preoperative planning continues to evolve and allows surgeons to virtually position shoulder implants on the glenoid and on the humerus to obtain the best fixation in bone and hopefully the best function possible. However, accurate evaluation of the rotator cuff muscles is important in the decision process between total shoulder arthroplasty (TSA) and reverse shoulder arthroplasty (RSA), and to determine expected outcomes. Indeed, fatty infiltration and muscle atrophy have been identified as predictive factors for functional outcomes after shoulder surgery,[4,5] with muscle atrophy being reversible and fatty infiltration being irreversible.[4,6–9] It has been shown that muscle atrophy is an

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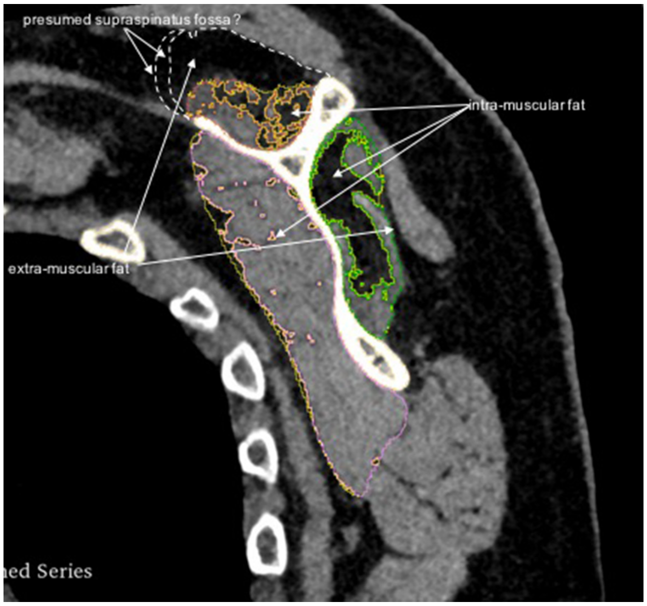

Fig. 1

Sagittal view of a right shoulder in a cuff tear arthropathy patient with severe fatty infiltration of the supraspinatus, infraspinatus and teres minor. The contours of the different muscles and their intramuscular fat can be seen. This example shows the difficulty to define precisely the contour of the presumed supraspinatus fossa.

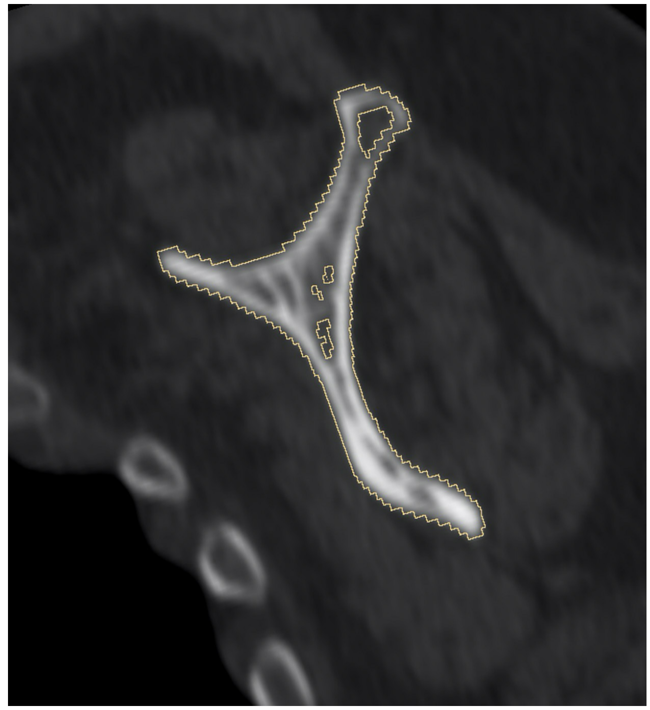

Fig. 2

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series. Sagittal view of a right shoulder in a cuff tear arthropathy patient.

independent factor associated with poorer outcome after TSA[10] and RSA.[11]

Although quick and fairly reproducible, existing methods, such as measurement of the occupation ratio,[12] measurement of the cross-sectional areas, or assessment of the tangent sign[13] fail to quantify precise rotator cuff muscle atrophy for several reasons: 1) these 2D measurements can be affected by tendon retraction;[14] 2) they have not been validated to measure infraspinatus or teres minor atrophy; 3) calculation of the occupation ratio requires an estimation of the pre-atrophy area of the supraspinatus which is subjective and which cannot be applied to the other rotator cuff muscles (Figure 1); and 4) measurement of muscle atrophy as a ratio between the cross-sectional area of the muscle, and the cross-sectional area of its fossa relies on the assumption that as muscle atrophy occurs, the space created is replaced by extramuscular fat. This explanation, however, is not supported by science, as the literature has demonstrated that extramuscular fat is greater than the expected volume and weight filling the defect subsequent to muscle atrophy.[15] As such, the objective of this study was to compare rotator cuff muscle volume and atrophy in healthy controls and three pathological shoulder cohorts using a novel quantitative 3D CT-based method. We hypothesized that rotator cuff muscle volume and atrophy would differ significantly between healthy and pathological patients. Additionally, muscle volume would also differ among pathological groups, specifically between massive rotator cuff tear/cuff tear arthropathy and primary osteoarthritis (OA).

Methods

Study cohort. We retrospectively reviewed shoulder CT scans performed between 2015 and 2020 and obtained from a database incorporating four institutions (Lyon, Nice, and Paris, France; and Belo Horizonte, Minas Gerais, Brazil). The CT scan exams had been performed using one of two CT scan systems (Revolution CT; GE Healthcare, USA, or Siemens Somatom CT Scanner; Siemens Healthcare, Germany) with the patient positioned supine on the CT table. CT scan exams of healthy shoulders and shoulders with primary OA, cuff tear arthropathy (CTA), and irreparable rotator cuff tears (IRCT) were included provided they had been obtained using the following acquisition parameters: slice thickness < 1.2 mm, number of slices > 200, field of view: whole scapula, X-Y resolution < 0.5 mm, matrix size: 512 × 512, kV140, mA > 300, and both bone and soft-tissue algorithms.

Our final study sample included a total of 102 CT scans (46 healthy shoulders, 21 CTA, 18 ICRT, and 17 OA shoulders). The CT of healthy shoulders had been obtained from patients aged older than 18 years without shoulder pathology or injury in the setting of: 1) polytrauma; 2) traumatic head injury; or 3) unilateral shoulder trauma with a contralateral normal shoulder. The CT scan images of patients with CTA, IRCT, or OA were preoperative CT scans performed prior to shoulder arthroplasty. Shoulders with full-thickness rotator cuff tears were classified as

Fig. 3

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series: the threshold draw tool in the editor module of the Slicer version 4.10.0 software (Slicer Community, USA) is used to draw a line along the contour of the supraspinatus.

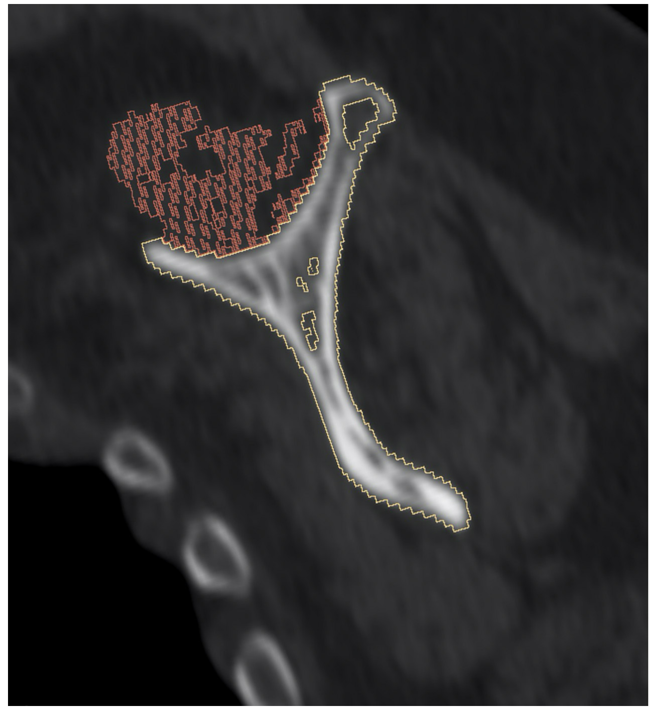

Fig. 4

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series: a preset range of muscle tissue is used to select specifically muscle tissue.

CTA if they were ≥ grade 4 in the Hamada classification,[16] and as IRCT if they had at least two irreparable rotator cuff tendons but no glenohumeral arthritis (Hamada < 4).

Volumetric reconstruction. Soft tissue DICOM (Digital Imaging and Communications in Medicine) series sequences were manually segmented using the Slicer software version 4.10.0 (Slicer Community, USA). The software was used to identify and manually segment the muscle boundaries of the supraspinatus, subscapularis, infraspinatus, and teres minor on each image slice from muscle origin to insertion. Segmentations were either performed by a shoulder fellowship-trained orthopaedic surgeon (JDW) or by trained technicians, in which case, the segmentations were all verified by the orthopaedic surgeon. Published threshold values were used to identify muscle and fat tissue.[17] The threshold draw tool in the editor module of the software allows selecting only the tissues within a preset range. The tool was used to draw a line around the contour of each rotator cuff muscle (Figures 2 to 7). In several previous publications, the infraspinatus and teres minor have been segmented as one muscle because they have analogous functions and the fascial boundaries between them are often indistinct.[18–22] However, as our segmentation was performed simultaneously on every plane (axial, sagittal, or coronal), it was possible to verify muscle boundaries simultaneously in the two other planes, and therefore to distinguish the different rotator cuff muscle from one another. This was especially helpful to distinguish infraspinatus from teres minor (Figures 8 and 9). A smoothing tool in the Slicer software was then used to include the intramuscular fat within the borders of the muscle tissue (Figures 5 and 6). We chose to incorporate intramuscular fat in our measurement of muscle volume to mimic the most commonly used and validated methods of assessment of atrophy (tangent[13] and occupation ratio).[12] The volume for each muscle including intramuscular fat was calculated in cm^3 (global muscle volume).

Bone DICOM series sequences were then automatically segmented using a validated software (BluePrint, v2.1.6; Tornier, France) that renders 3D models of the scapula allowing us to calculate scapular bone volume in cm^3. Each global muscle volume was then normalized to the patient's scapular bone volume to account for the effect of body size on muscle volume.[23] This allowed us to calculate the normalized volume (NV) of each rotator cuff muscle:

$$NV = \frac{V_{muscle}}{V_{scapula}}$$

Data analysis. Mean muscle volumes and mean NV were calculated for each muscle in the four patient cohorts (healthy control, IRCT, CTA, OA). The mean NV of the healthy cases was used to determine a reference NV

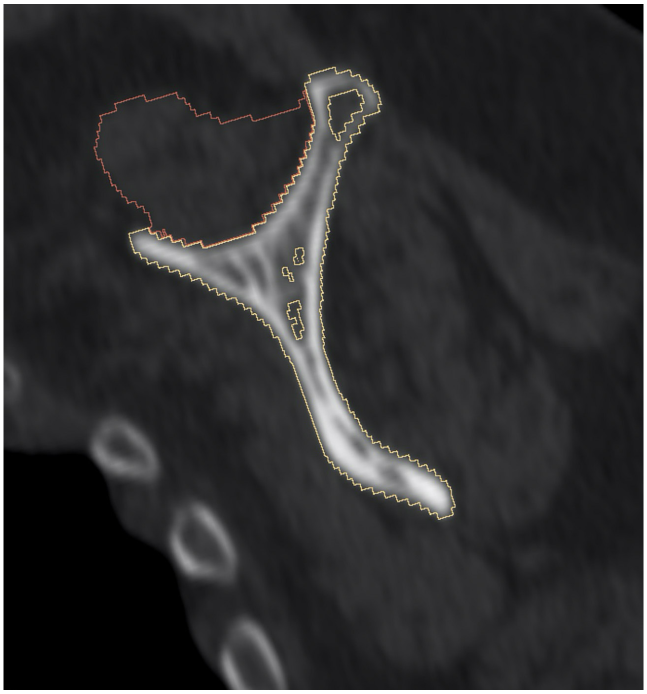

Fig. 5

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series: a smoothing tool is then used to include the intramuscular fat within the borders of the supraspinatus muscle tissue.

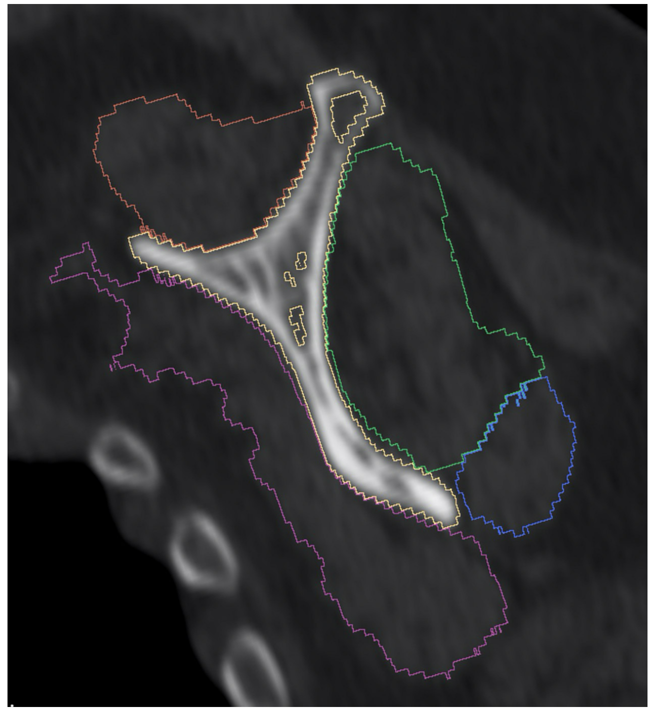

Fig. 6

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series: the operation described in Figures 4 to 6 is repeated for each of the rotator cuff muscle and their volume including intramuscular fat can then be included.

value for each of the rotator cuff muscles and for each sex. Muscle atrophy was calculated by dividing the NV of a given muscle by the reference NV of that muscle. For example, an atrophied infraspinatus of a female was determined to have a normalized volume of 0.77. The reference NV of the infraspinatus was calculated to be 1.29 for females (Table I). In this case, the theoretical remaining muscle volume is 0.77/1.29 = 60%. Therefore, the calculated atrophy is 100% to 60% = 40%.

The relative volume of each muscle with respect to the global volume of the rotator cuff muscles was calculated as this allows an easier comparison with the data available in the literature by neglecting the effect of body size on muscle volume.

Shoulder balance. The difference between the NV of the anterior cuff (subscapularis) and the posterior cuff (infraspinatus and teres minor) was compared between the four patient cohorts (control, IRCT, CTA, OA) to assess the horizontal balance of the "healthy" shoulder and to identify any possible horizontal shoulder imbalance in pathological states.[20,24]

Statistical analysis. One-way analysis of variance was used to test the difference between the means of several qualitative subgroups (diagnosis: healthy, CTA, IRCT, OA) of a continuous variable (which can be volume, normalized volume, global muscle atrophy, or muscle atrophy). Levene's test was used to check equality of

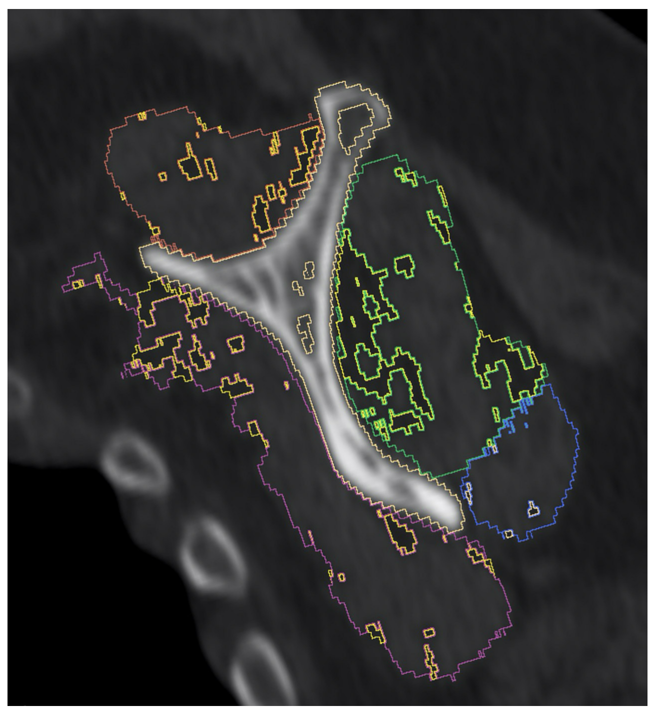

Fig. 7

Example of rotator cuff muscle segmentation on a sagittal view from the soft tissue DICOM (Digital Imaging and Communications in Medicine) series: muscle tissue and intramuscular fat are then separated using the threshold tool.

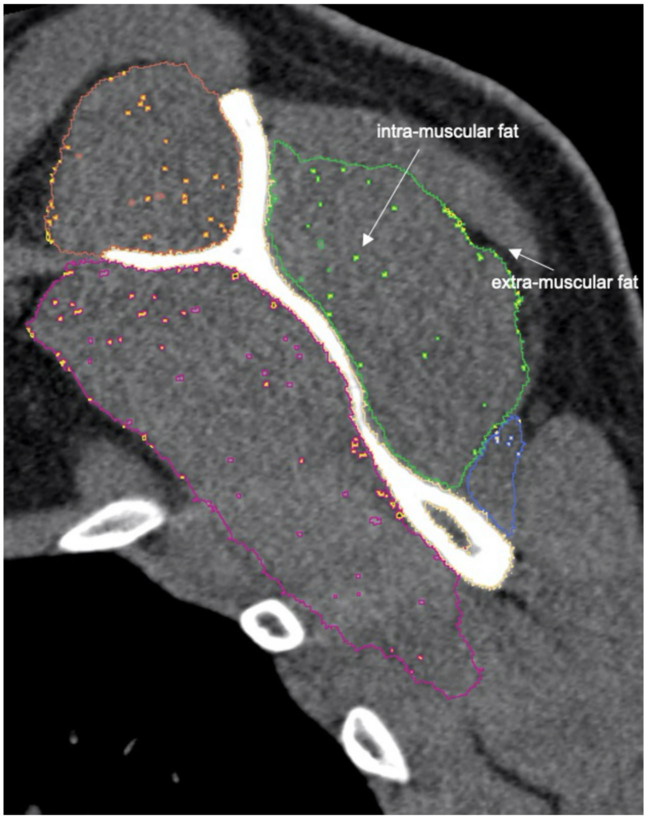

Fig. 8

Intramuscular fat, extra-muscular fat, and muscle size on the sagittal view of a healthy patient.

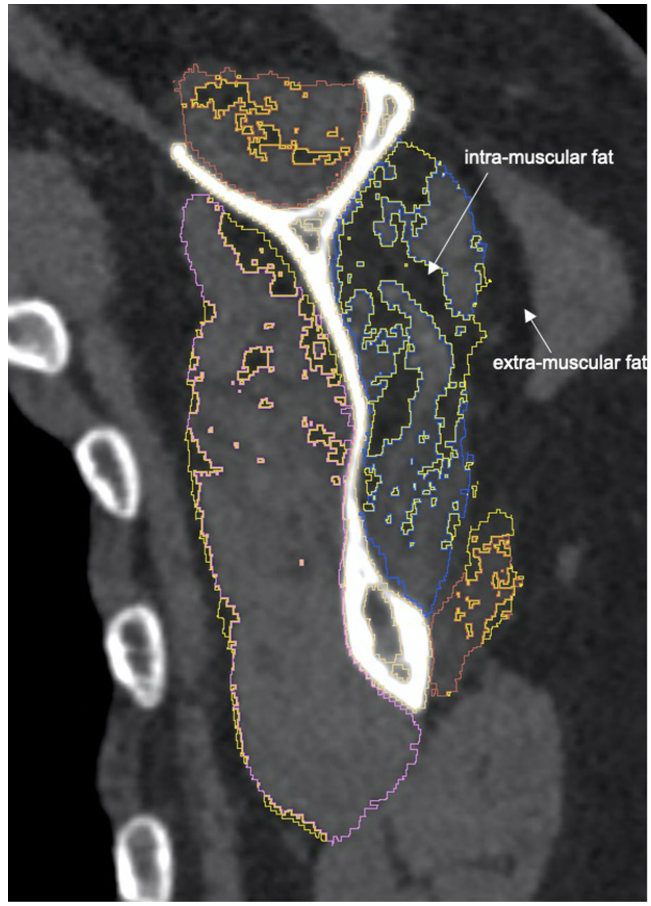

Fig. 9

Intramuscular fat, extra-muscular fat, and muscle size on the sagittal view of a patient with a cuff tear arthropathy.

variances. The hypothesis that the means of at least two of the subgroups differ significantly is accepted if the p-value of the F statistic is less than 0.05, which is our chosen significance level. Pairwise comparison of subgroups was then calculated using Tukey-Kramer test. Shapiro-Wilk test was finally performed to check the normal distribution of the residuals.

If the Levene test is positive ($p < 0.05$), then the variances in the different groups are different and we used a non-parametric statistic. In that case, the Kruskal-Wallis test (H-test) was used with a significance level of 0.05. The post-hoc test used for pairwise comparison of subgroups was the test according to Dunn.[25] Statistical analyses were performed using MedCal (v19.4.0; MedCalc Software, Belgium).

Results

Patient demographics are detailed in Table II.

Scapular bone volumes. The mean scapular volume was 95 cm^3 (56 to 180) for the entire study group. The mean scapular volume did not differ significantly between healthy (101 cm^3; standard deviation (SD) 21), CTA (87 cm^3; SD 28), IRCT (99 cm^3; SD 29), and OA (102 cm^3; SD 37) patients ($p = 0.113$, Kruskal-Wallis one-way analysis of variance (ANOVA)). Mean scapular volumes were significantly smaller ($p < 0.001$, independent samples *t*-test) in females (77 cm^3; SD 12) than in males (118 cm^3; SD 22).

Rotator cuff muscles volumes and normalized volumes (NV). Mean muscle volumes for each patient group (healthy, CTA, IRCT, and OA) are detailed in Table III. All four rotator cuff muscle volumes were significantly greater in the healthy control cohort than in the three diseased cohorts ($p < 0.0001$, Kruskal-Wallis one-way ANOVA, post-hoc analysis (Dunn)), but did not differ between CTA, IRCT, and OA patients ($p > 0.175$, Kruskal-Wallis one-way ANOVA). Similarly, after normalization by the scapular volume (Table I), all four rotator cuff muscles had a significantly greater NV in the healthy cohort than in the three others ($p < 0.0001$, Kruskal-Wallis one-way ANOVA, post-hoc analysis (Dunn)) and did not differ between pathological groups except for the NV of the supraspinatus, which was significantly greater in OA patients than in CTA patients ($p = 0.012$, Kruskal-Wallis one-way ANOVA).

The relative volume of each muscle with respect to the global volume of the rotator cuff muscles is reported in Table IV. The relative volume of each muscle was comparable in the four different groups with the supraspinatus

Table I. Normalized muscle volume per pathology.

Variable	Sex	Healthy, mean (SD)		CTA, mean (SD)		IRCT, mean (SD)		OA, mean (SD)	
		General population	Per sex	General population	Per sex	General population	Per sex	General population	Per sex
Supraspinatus	M	0.66 (0.1)	0.68 (0.1)	0.28 (0.1)	0.33 (0.1)	0.30 (0.1)	0.34 (0.1)	0.39 (0.1)	0.35 (0.1)
	F		0.59 (0.1)		0.27 (0.1)		0.28 (0.1)		0.41 (0.1)
Subscapularis	M	1.91 (0.4)	2.00 (0.3)	1.14 (0.3)	1.08 (0.4)	1.11 (0.2)	1.18 (0.2)	1.08 (0.2)	1.00 (0.2)
	F		1.64 (0.2)		1.16 (0.3)		1.07 (0.2)		1.14 (0.3)
Infraspinatus	M	1.39 (0.2)	1.43 (0.2)	0.82 (0.2)	0.80 (0.3)	0.83 (0.2)	0.95 (0.1)	0.95 (0.3)	0.93 (0.2)
	F		1.29 (0.2)		0.80 (0.2)		0.74 (0.2)		0.96 (0.2)
Teres minor	M	0.30 (0.1)	0.32 (0.1)	0.21 (0.1)	0.26 (0.1)	0.22 (0.1)	0.21 (0.1)	0.20 (0.1)	0.20 (0.1)
	F		0.26 (0.1)		0.20 (0.1)		0.22 (0.1)		0.20 (0.1)

IRCT, irreparable rotator cuff tear; OA, osteoarthritis; SD, standard deviation.

Table II. Patient demographics.

Variable	Healthy (n = 46)	CTA (n = 21)	IRCT (n = 18)	OA (n = 17)	All
Mean age, yrs (SD)	36 (16)	77 (8)	71 (8)	69 (8)	56 (22)
Mean age females, yrs (SD)	46 (19)	78 (8)	73 (7)	69 (8)	67 (17)
Mean age males, yrs (SD)	33 (14)	73 (8)	68 (8)	70 (8)	46 (22)
Left:right, n	25:21	9:12	4:14	9:8	47:55
Females:males, n	12:34	16:5	11:7	10:7	49:53

CTA, cuff tear arthropathy; IRCT, irreparable rotator cuff tear; OA, osteoarthritis; SD, standard deviation.

Table III. Muscle volume (cm^3) per pathology and comparison with the literature.

Method	Present study				Holzbauer et al[26]	Juul-Kristensen et al[27]	Juul-Kristensen et al[27]	Piepers et al[28]	Vidt et al[29]	Matsumura et al[30]	Henninger et al[31]	Jeong et al[32]
	CT				MRI	MRI	Dissection	CT	MRI	MRI	MRI	MRI
Subjects	Healthy	CTA	IRCT	OA	Healthy	Healthy	Cadaveric specimens	Healthy	Healthy	Healthy	Cadaveric specimens	Healthy
Age, yrs	36	77	71	69	29	40	79	57	75	72	N/A	43
Supraspinatus volume, mean (SD)	67 (19)	25 (12)	30 (14)	38 (13)	50 (20)	48 (8)	30 (12)	N/A	40 (15)	28 (6)	41 (21)	15 (6)
Subscapularis volume, mean (SD)	195 (62)	98 (40)	111 (40)	107 (36)	165 (64)	154 (22)	90 (20)	123 (36)	103 (32)	95 (26)	107 (45)	30 (15)
Infraspinatus volume, mean (SD)	141 (42)	68 (25)	83 (36)	95 (35)	119 (47)	125 (16)	84 (9)	119 (30)	102 (28)	74 (19)	116 (41)	21 (9)
Teres minor volume, mean (SD)	31 (12)	19 (11)	21 (10)	20 (11)	28 (14)				25 (8)	13 (6)		13 (15)

CTA, cuff tear arthropathy; IRCT, irreparable rotator cuff tear; OA, osteoarthritis; SD, standard deviation.

representing 14% (12 to 15), the subscapularis 45% (42 to 47), the infraspinatus 34% (3 to 37), and the teres minor 8% (7 to 9) of the global volume of the rotator cuff.

Quantitative measure of atrophy. Quantitative atrophy for each rotator cuff muscle and for each patient group (healthy, CTA, IRCT, OA) is detailed in Table V. Muscle atrophy was comparable for all rotator cuff muscles between CTA, IRCT, and OA patients, except for the supraspinatus, which was significantly ($p = 0.002$, one-way ANOVA) more atrophied in CTA (53%) and IRCT (52%) than in OA (37%).

Shoulder horizontal balance. In healthy shoulders, the mean NV of the anterior cuff was greater than that of the posterior cuff with a mean difference of 0.22 (SD 0.28). This did not differ significantly in CTA or IRCT patients, where the mean differences between anterior and posterior cuff were 0.11 (SD 0.34) and 0.06 (SD 0.18), respectively. However, OA patients had a significantly different balance compared to healthy patients ($p = 0.014$, one-way ANOVA) with a mean NV of the posterior cuff greater than that of the anterior cuff, leading to a mean difference of -0.07 (SD 0.27).

When looking at relative volumes, in healthy shoulders the anterior cuff represented 45% of the entire cuff, while the posterior cuff represented 40%. A similar partition between anterior and posterior cuff was also found in both CTA and IRCT patients. However, in OA patients, the relative volume of the anterior (42%) and posterior cuff (43%) were similar (Table IV).

Discussion

This study shows that rotator cuff muscle volume is significantly decreased in patients with OA, CTA, or IRCT compared to healthy patients. In addition, the analysis of global muscle atrophy per pathological group shows significantly more atrophy in CTA/IRCT patients in the

Table IV. Relative volume of each muscle with respect to the global volume of the rotator cuff muscles per pathology and comparison with the literature.

Variable	Present study				Holzbauer et al[26]	Juul-Kristensen et al[27]	Juul-Kristensen et al[27]	Vidt et al[29]	Matsumura et al[30]	Henninger et al[31]	Jeong et al[32]
Method	**CT**				**MRI**	**Dissection**	**MRI**	**MRI**	**MRI**	**MRI**	**MRI**
Subjects	**Healthy**	**CTA**	**IRCT**	**OA**	**Healthy**	**Healthy**	**Cadaveric specimens**	**Healthy**	**Healthy**	**Cadaveric specimens**	**Healthy**
Age, yrs	36	77	71	69	29	40	79	75	72	N/A	43
Supraspinatus, %	15	12	12	15	14	15	13	15	13	16	19
Subscapularis, %	45	47	45	42	46	47	44	38	45	41	38
Infraspinatus, %	33	33	34	37	33	38	43	38	35	44	27
Teres minor, %	7	9	9	8	8			9	6		16

CTA, cuff tear arthropathy; IRCT, irreparable rotator cuff tear; OA, osteoarthritis.

Table V. Normalized quantitative atrophy.

$$Atrophy_{male} = \frac{NV}{mean_{healthyMale}(NV)}\%$$

$$Atrophy_{female} = \frac{NV}{mean_{healthyFemale}(NV)}\%$$

Muscle atrophy was comparable for all rotator cuff muscles between CTA, MRCT, and OA patients, except for the supraspinatus which was significantly more atrophied in CTA and MRCT than in OA.

Variable	Healthy, %	CTA, %	IRCT, %	OA, %
Supraspinatus	0	53	52	37*
Subscapularis	0	33	37	38
Infraspinatus	0	39	38	29
Teres minor	0	21	22	29

*Values significantly different (p = 0.002).
CTA, cuff tear arthropathy; IRCT, irreparable rotator cuff tear; OA, osteoarthritis.

supraspinatus muscle than in OA patients. However, this difference was surprisingly not observed for the subscapularis, the infraspinatus, and the teres minor, suggesting that maybe stiffness and the lower utilization of the shoulder observed in OA can lead to muscle atrophy despite intact tendons, or possibly that increasing age may be more important to explain muscle atrophy than rotator cuff tearing. Indeed, there was a great difference in the mean age of the pathological and healthy shoulders. This is in agreement with a recent study from Choate et al,[33] which showed that severe rotator cuff atrophy was observed in the absence of full-thickness rotator cuff tear in 22% of a cohort of patients who had undergone TSA for OA. However, as above, this finding may be due to the fact that OA patients are older and that muscle atrophy is more affected by age than by pathology.[33]

It is commonly believed that a healthy shoulder should be balanced in the horizontal plane[34] with the force generated by the anterior cuff (subscapularis) being equal to the force generated by the posterior cuff (infraspinatus and teres minor).[35] The volume of a healthy muscle is a well-established surrogate marker for the force produced by the muscle,[19,36] and it was therefore expected that the NV of the anterior cuff would match the NV of the posterior cuff in healthy patients. This, however, was not the case in our study as we found that the anterior cuff represents 45% of the entire cuff in healthy shoulders versus only 40% for the posterior cuff, and this appears to be comparable to the data we were able to calculate from the literature (Table IV). Surprisingly, a similar repartition between anterior and posterior cuff was also found in both CTA and IRCT patients (46% vs 42% in both groups). However, in OA patients, shoulders appeared to be significantly "more balanced" in the horizontal plane than the other three groups as the relative volume of the posterior cuff increased (43%) to the detriment of the anterior cuff (42%). This finding is in agreement with two recent studies[37,38] showing significantly increased cross-sectional areas of the posterior cuff with increased retroversion. However, although the differences observed in our study are statistically significant, the actual differences among the four groups in muscle volumes, in percentage of muscle atrophy or in rotator cuff balance, and relative volume remain very minimal and much less than what we are used to observe when analyzing fatty infiltration.

Atrophy of the shoulder muscles (especially of the infraspinatus, which is located just under the skin) is a common finding during physical examination in patients with an indication of shoulder arthroplasty.[32] Numerous authors have tried to correlate this clinical atrophy with radiological atrophy observed on CT or MR imaging. Published results have been variable, and it still remains unclear whether this muscle atrophy is reversible,[4,28,30,39–41] and its precise influence, if any, on outcome.[4,10,42,43] Current methods used to evaluate rotator cuff muscle atrophy are insufficient as they only provide a 2D assessment on a single area of the muscle[12,13,44] which does not capture the entire muscle volume.[14,29,45,46] Therefore, several authors have reported on segmentation techniques to calculate rotator cuff muscle volume,[26,27,47,48] and the values from these studies are detailed in Table I along with the results our study. Overall, our results are comparable to the literature; however, large differences can be observed especially when comparing ethnic groups, such as Europeans to Asians. Additionally, it has been reported that the size of rotator cuff muscles is correlated to the area of the supraspinatus fossa;[13] therefore, it seems important to normalize rotator cuff volumes to patient morphology in order to understand the significance of muscle atrophy.

In this study, a novel method was used to normalize the rotator cuff muscle volumes to the volume of the bony scapula to accurately reflect patient size. This method in its current form is not applicable in routine clinical practice, but this data provided the basis for development of computer algorithms that, in the near future, will incorporate automatic muscle segmentation using statistical models and deep machine learning techniques.[49,50] Normalization to the scapular volume is possible given the fact that despite the glenoid and/or acromial erosion observed in severe OA or CTA cases; no significant difference in scapular volume was observed in the four different groups.

Most studies that analyze muscle volume have been based on MR imaging, using techniques such as fat-selective imaging, T2-based water-fat separation, single-voxel MR spectroscopy, spectroscopic gradient echo imaging, two-point Dixon imaging, or water-fat imaging techniques, which enable the generation of accurate quantitative fat-fraction maps.

For the present study, we elected to use CT imaging with a soft-tissue algorithm for several reasons. First, our objective is to use this method in the setting of preoperative planning for shoulder arthroplasty and CT is the exam of choice for this purpose. Second, it has been demonstrated that both MRI and CT are equally effective in assessing supraspinatus atrophy[51] and in the measurement rotator cuff cross-sectional area.Third, CT imaging allowed us to segment scapular bones automatically using a validated 3D software (BluePrint, v2.1.6; Tornier, France) allowing us to calculate scapular volume in cm^3. Finally, CT is widely available, fast, and is used routinely in preoperative planning of shoulder arthroplasty,[52] and the addition of soft tissue algorithms to the bone algorithms is simple, quick, and cheap.

In 2D quantitative methods, the measurement of the cross-sectional area of a rotator cuff muscle is not sufficient to calculate atrophy, and one needs to divide the cross-sectional area to the presumed area of the entire supraspinatus fossa to obtain the occupation ratio. Similarly, in 3D, the measurement of a rotator cuff muscle volume is not sufficient to calculate atrophy quantitatively and a reference needs to be determined. To address this, we measured rotator cuff volumes in a cohort of healthy patients to obtain healthy normalized volumes for each muscle, which could then be used as a reference to determine a quantitative 3D measure of muscle atrophy (Table V).

Our study allows quantitative 3D measurement of muscle volume and muscle atrophy of the rotator cuff muscles including intra-muscular fat similarly to previous 2D methods such as the tangent sign,[13] the occupation ratio,[12,53,54] or measures of the cross-sectional area.[14,29,31] The minimal differences between the different pathological groups observed in our study suggest that the influence of rotator cuff muscle volume and atrophy (including intramuscular fat) as an independent factor of outcome is probably overestimated and this potentially explains why it has been so difficult in the literature to determine whether muscular atrophy is reversible[28,30,40] or not.[4,39,41]

This study has several limitations. First, the size of the cohort of pathological shoulders was relatively small. This was due to the difficulty in obtaining CT scans with both bone and soft tissue algorithms and with the entire scapula, which was unfortunately often truncated at its medial or distal tip. With the recent push for high-quality CT protocols for use in preoperative planning software, future CT scan exams will likely cover the entire scapula. Second, at present, this method is time-consuming (around three hours per muscle) as it requires manual segmentation of muscles; however, algorithms are being developed for automatic segmentation using either statistical shape modelling or deep learning techniques.

We propose a novel 3D quantitative adaptation of previous 2D qualitative and quantitative methods to assess rotator cuff muscle atrophy. Our results indicate that, on average, the volume of the supraspinatus represents 14% of the cuff, the subscapularis 45%, the infraspinatus 33%, and the teres minor 8%. Additionally, rotator cuff muscle volume is significantly decreased in patients with OA, CTA, or IRCT compared to healthy patients, but that only minimal differences can be observed between the different pathological groups. This suggests that the influence of rotator cuff muscle volume and atrophy (including intramuscular fat) as an independent factor of outcome may be overestimated. As such, atrophy should not be calculated as an isolated parameter without taking intramuscular fat into account.

Take home message

- This study provides a novel 3D quantitative adaptation of previous 2D qualitative and quantitative methods to assess rotator cuff muscle atrophy.
- On average, the volume of the supraspinatus represents 14% of the cuff, the subscapularis 45%, the infraspinatus 33%, and the teres minor 8%.
- Rotator cuff muscle volume is significantly decreased in patients with osteoarthritis, cuff tear arthropathy, or irreparable rotator cuff tear compared to healthy patients, but only minimal differences can be observed between the different pathologic groups.
- The influence of rotator cuff muscle volume and atrophy (including intramuscular fat) as an independent factor of outcome may be overestimated.

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