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Rotator cuff fatty infiltration and muscle atrophy: relation to glenoid deformity in primary glenohumeral osteoarthritis

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Background: Muscle atrophy (MA) and fatty infiltration (FI) are degenerative processes of the rotator cuff musculature that have incompletely understood relationships with the development of eccentric glenoid wear in the setting of primary glenohumeral osteoarthritis (GHOA).
Methods: All patients with GHOA and an intact rotator cuff who underwent both magnetic resonance imaging and computed tomography scans of the affected shoulder prior to total shoulder arthroplasty between 2015 and 2020 were identified from a prospectively maintained registry. Rotator cuff MA was measured quantitatively on sequential sagittal magnetic resonance images, whereas FI was assessed on sagittal magnetic resonance imaging slices using the Goutallier classification. Preoperative computed tomography scans were reconstructed using automated 3-dimensional software to determine glenoid retroversion, glenoid inclination, and humeral head subluxation. Glenoid deformity was classified according to the Walch classification. Univariate and multivariable regression analyses were performed to characterize associations between age, sex, muscle area, FI, and glenoid morphology.
Results: Among the 127 included patients, significant associations were found between male sex and larger overall rotator cuff musculature ($P < .01$), increased ratio of the posterior rotator cuff (PRC) to the subscapularis area ($P = .01$), and glenoid retroversion (19° vs. 14°, $P < .01$). Larger supraspinatus and PRC muscle size was correlated with increased retroversion ($r = 0.23$ [$P = .006$] for supraspinatus and $r = 0.25$ [$P = .004$] for PRC) and humeral head subluxation ($r = 0.25$ [$P = .004$] for supraspinatus and $r = 0.28$ [$P = .001$] for PRC). The ratio of PRC muscle size to anterior rotator cuff muscle size was not associated with evidence of eccentric glenoid wear ($P > .05$). After we controlled for confounding factors, increasing glenoid retroversion was associated with high-grade infraspinatus FI (β, 6.8; 95% confidence interval, 2.9-10.7; $P < .01$) whereas larger PRC musculature was predictive of a Walch type B (vs. type A) glenoid (odds ratio, 1.3; 95% confidence interval, 1.0-1.5; $P = .04$).
Conclusion: Patients with eccentric glenoid wear in the setting of primary GHOA and an intact rotator cuff appear to have both larger PRC musculature and higher rates of infraspinatus FI. Although the temporal and causal relationships of these associations remain ambiguous, MA and FI should be considered 2 discrete processes in the natural history of GHOA.
Level of evidence: Level III; Cross-Sectional Design; Epidemiology Study
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Keywords: Muscle atrophy; muscle volume; fatty infiltration; eccentric glenoid wear; glenoid deformity; shoulder arthritis; rotator cuff

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"Fatty infiltration" (FI) and "muscle atrophy" (MA) are terms that are often used interchangeably, but FI and MA are, in fact, 2 distinct degenerative processes of the rotator cuff musculature.[3,12,15] MA is defined as a reduction in the absolute size of a muscle, whereas FI represents the accumulation of adipose tissue within a muscle.[15] The etiology of both of these processes relates to mechanical unloading and denervation of the musculotendinous unit; however, MA appears to improve with restoration of native length-tension relationships and musculotendinous pennation angles whereas FI does not.[9,10] A growing interest has developed in understanding the role of these processes—originally studied in the setting of rotator cuff tears[11]—in the context of primary glenohumeral osteoarthritis (GHOA), specifically regarding the development of eccentric glenoid wear.[1,6]

Both rotator cuff FI and MA have been shown to be associated with eccentric glenoid wear among patients with an intact rotator cuff, albeit in distinct ways. Aleem et al[1] (2019) demonstrated that asymmetrical atrophy of the rotator cuff in the transverse plane (larger posterior rotator cuff [PRC] muscle size relative to anterior rotator cuff muscle size) was associated with a type B2 glenoid deformity. Conversely, Donohue et al[6] (2018) reported a link between type B3 glenoids and high-grade infraspinatus FI. Although these results initially appear contradictory, it is unclear whether these processes develop simultaneously and whether they are a cause or an effect of the described glenoid deformity. It is possible that MA and FI develop separately and have independent associations with bony deformity among patients with primary GHOA.

Currently, the relationship between MA, FI, and glenoid deformity is incompletely understood. This may partly be attributed to the fact that many of the existing studies on this topic assessed either MA or FI without evaluating the relative associations of both processes in concert. Furthermore, prior studies have used a single imaging modality (computed tomography [CT] scan or magnetic resonance imaging [MRI]) to characterize both rotator cuff degeneration and glenoid deformity. More granular relationships may be elucidated if these parameters are assessed with their respective gold-standard imaging technique (eg, MRI for MA and FI and CT scan for glenoid deformity).[17,21,22]

Using both MRI and CT scans, we sought to characterize the relative associations of MA and FI with eccentric glenoid wear among patients with primary GHOA and an intact rotator cuff. We hypothesized that MA and FI would have independent associations with the progression of eccentric glenoid wear.

Materials and methods

Patient population

We performed a retrospective review of all patients who underwent either reverse total shoulder arthroplasty or anatomic total shoulder arthroplasty between 2015 and 2020 for a diagnosis of primary GHOA performed by a single fellowship-trained shoulder surgeon. Patients were included in our analysis if they had MRI and CT scans of the affected shoulder for preoperative surgical planning. The exclusion criteria included an indication for surgery other than primary glenohumeral arthritis, the presence of a full-thickness tear of any rotator cuff tendon on the preoperative MRI scan (confirmed by a radiology read, as well as manual review), the inability to obtain appropriate MRI or CT scan sequences for radiologic assessment, and a history of arthroplasty on the examined shoulder. During the study period, 127 patients were identified for inclusion. Demographic characteristics including age, sex, and body mass index (BMI) were obtained from medical records.

Radiographic assessment

Muscle atrophy

MA was assessed quantitatively for the rotator cuff musculature. The area of each muscle was assessed on T1-weighted MRI sequences without fat suppression in the sagittal plane. Assessment of muscle area has been shown to be highly predictive of muscle volume.[16,21] To account for potential variation in appraising muscle size using 2-dimensional software, muscle area was calculated by summing the area of the muscle on 2 separate MRI slices.[21] The first slice was measured on the most lateral image where the scapular spine was in contact with the scapular body, whereas the second slice was obtained at a point equidistant from the first image and the glenoid. The area of the muscle (excluding surrounding fat) was outlined on each of the 2 images and summed to obtain the final muscle area. Muscle area is presented in square centimeters per meter. The muscle areas of the infraspinatus and teres minor muscles were combined to represent a single unit (PRC), as previously described, given the difficulty in accurately discriminating their borders from each other.[7] The ratio of the PRC (infraspinatus and teres minor) to the subscapularis muscle area was calculated for each patient to assess for a transverse force couple imbalance in the axial plane.[1]

Fatty infiltration

FI was determined for each rotator cuff muscle individually using T1-weighted non–fat-suppressed MRI sequences in the sagittal plane. An MRI slice just medial to the spinoglenoid notch was obtained to assess FI.[6] Three orthopedic surgeons determined FI grades for each muscle via consensus methodology. Grading was performed using the FI grading system described by Goutallier et al[11] and later adopted for MRI by Fuchs et al.[7] FI scores were classified into 2 groups as previously described, where a Goutallier score of 0 or 1 represents low-grade FI, and a score ≥ 2 represents high-grade FI.[6,13,19] PRC FI was calculated by summing the scores of the infraspinatus and teres minor. A score ≥ 4 was considered high-grade FI.[6]

Glenohumeral bony deformity

Glenohumeral bony deformity was assessed using a preoperative CT scan of the affected shoulder. Glenoid retroversion, glenoid inclination, and humeral head subluxation were quantified for each patient using an automated 3-dimensional software program (Blueprint; Wright Medical Group, Memphis, TN, USA).[1] No attempt to manually determine glenoid parameters was made at the extremes of retroversion. Glenoid morphology was characterized using the modified Walch classification.[4,23] Each CT scan was reviewed by 2 orthopedic surgeons and characterized using consensus methodology. Because of low numbers of Walch type B1 and C glenoids ($n \leq 5$), these patients were excluded from our analysis.

Statistical analysis

We performed univariate analyses to characterize associations between age, sex, muscle area, FI, glenoid type according to the Walch classification, glenoid retroversion, glenoid inclination, and humeral head subluxation. To adjust for potential confounding factors, a multivariable linear regression model was performed to determine factors independently associated with glenoid retroversion. The results are presented with a standardized β coefficient and 95% confidence interval (CI) for each variable. Similarly, to determine factors independently associated with a Walch type B (vs. Walch type A) glenoid, we performed a multivariable logistic regression analysis. The results are presented in the form of odds ratios (ORs) and 95% CIs. Variables with $P \leq .05$ on univariate analysis were inserted into these models.

All statistical analysis was performed using SPSS statistical software (version 11.5; IBM, Armonk, NY, USA). A P value of .05 was selected to denote statistical significance.

Results

A total of 127 shoulders (127 patients) met the final inclusion criteria. There were 66 male patients (54.1%), the average age was 66.3 ± 7.9 years, and the average BMI was 31.2 ± 7.4.

Rotator cuff MA

On univariate analysis, age was associated with Walch glenoid type (A1, 66.3 ± 9.0 years; A2, 72.3 ± 7.0 years; B2, 66.8 ± 7.9 years; and B3, 64.4 ± 6.7 years) ($P = .04$), supraspinatus area ($r = -0.376$, $P < .01$), PRC area ($r = -0.375$, $P < .01$), and subscapularis area ($r = -0.254$, $P < .01$) (Table I). Male sex was associated with glenoid retroversion (19° in male patients vs. 14° in female patients, $P < .01$), supraspinatus area (4.2 cm^2/m vs. 3.4 cm^2/m, $P < .01$), PRC area (11 cm^2/m vs. 7.7 cm^2/m, $P < .01$), and subscapularis area (11 cm^2/m vs. 9.0 cm^2/m, $P < .01$), as well as the ratio of PRC muscle size to anterior rotator cuff muscle size (1.0 vs. 0.9, $P = .01$) (Table I).

Walch glenoid type was associated with supraspinatus muscle size (A1, 3.8 ± 1.3 cm^2/m; A2, 2.9 ± 1.2 cm^2/m; B2, 4.1 ± 1.2 cm^2/m; and B3, 4.1 ± 1.3 cm^2/m) ($P = .005$), PRC muscle size (A1, 8.8 ± 3.0 cm^2/m; A2, 7.7 ± 2.7 cm^2/m; B2, 9.9 ± 3.2 cm^2/m; and B3, 10.4 ± 3.6 cm^2/m) ($P = .01$), and subscapularis muscle size (A1, 10.0 ± 3.82 cm^2/m; A2, 9.4 ± 3.0 cm^2/m; B2, 10.2 ± 2.7 cm^2/m; and B3, 12 ± 3.4 cm^2/m) ($P = .034$) (Table II). Larger supraspinatus and PRC muscle size was correlated with increased retroversion ($r = 0.23$ [$P = .006$] for supraspinatus and $r = 0.25$ [$P = .004$] for PRC) and humeral head subluxation ($r = 0.25$ [$P = .004$] for supraspinatus and $r = 0.28$ [$P = .001$] for PRC). Larger PRC musculature was also negatively correlated with glenoid inclination ($r = -0.19$, $P = .029$) (Table III). The ratio of PRC muscle size to anterior rotator cuff muscle size was not associated with glenoid type, humeral head subluxation, or glenoid retroversion ($P > .05$) (Tables II and III).

After we controlled for potential confounding factors on multivariable regression modeling, larger PRC musculature was independently predictive of a Walch type B (vs. type A) glenoid (OR, 1.3; 95% CI, 1.0-1.5; $P = .04$). Furthermore, increasing BMI values were negatively predictive of a Walch type B glenoid (OR, 0.94; 95% CI, 0.89-0.99, $P = .03$) (Table IV).

Rotator cuff FI

On univariate analysis, FI of individual rotator cuff musculature was not associated with Walch glenoid type ($P > .05$) (Table II). Patients with high-grade FI of the infraspinatus demonstrated increased glenoid retroversion compared with patients with low-grade FI (18° vs. 14°, $P = .05$). No other associations were found between individual muscle FI and glenoid retroversion, glenoid inclination, or humeral head subluxation ($P > .05$) (Table V). After we controlled for potential confounding factors on multivariable analysis, high-grade infraspinatus FI was independently predictive of increasing glenoid retroversion (β, 6.8; 95% CI, 2.9-10.7; $P < .01$) (Table VI).

Discussion

MA and FI are both degenerative processes of the rotator cuff musculature that may have independent relationships with the pathogenesis of eccentric glenoid wear in the setting of primary glenohumeral arthritis. In this study, we sought to characterize the relative associations of MA and FI with glenoid deformity among patients with GHOA and an intact rotator cuff using both MRI and CT scans. Our primary findings reveal that larger absolute PRC muscle size is independently predictive of a Walch type B glenoid whereas high-grade infraspinatus FI is independently related to increased glenoid retroversion. The results of our study support the notion that MA and FI are both associated with eccentric glenoid wear but should be considered separate and potentially independent processes in the setting of GHOA.

FI of the rotator cuff represents the accumulation of fatty tissue within a muscle. Unlike MA, FI appears to be an irreversible process.[8,15] An interest in understanding this process—initially described in the setting of rotator cuff

Table I Univariate analysis for age and sex association with radiographic parameters

Parameter	Data	*P* value
Age		
Type A1, mean (SD), yr	66.3 (9.0)	.04*
Type A2, mean (SD), yr	72.3 (7.0)	
Type B2, mean (SD), yr	66.8 (7.9)	
Type B3, mean (SD), yr	64.4 (6.7)	
Glenoid inclination	$r = 0.015$	.863
Glenoid retroversion	$r = -0.051$	.55
Humeral head subluxation	$r = -0.037$	.67
Supraspinatus area	$r = -0.376$	<.01*
Posterior cuff area	$r = -0.375$	<.01*
Subscapularis area	$r = -0.254$	<.01*
Posterior-subscapularis ratio†	$r = -0.14$	.1
Male sex		
Type A1, n (%)	13 (44.8)	.13
Type A2, n (%)	3 (46.15)	
Type B2, n (%)	22 (58.9)	
Type B3, n (%)	28 (65.1)	
Glenoid inclination, mean (SD)		
Male	7.7 (6.6)	.89
Female	7.6 (4.9)	
Glenoid retroversion, mean (SD)		
Male	19 (9.4)	<.01*
Female	14 (9.3)	
Humeral head subluxation, % (SD)		
Male	74 (12)	.08
Female	70 (14)	
Supraspinatus area, cm^2/m		
Male	4.2 (1.3)	<.01*
Female	3.4 (1.3)	
Posterior cuff area, cm^2/m		
Male	11 (3.2)	<.01*
Female	7.7 (2.6)	
Subscapularis area, cm^2/m		
Male	11 (3.2)	<.01*
Female	9.0 (2.8)	
Posterior-subscapularis ratio†		
Male	1.0 (0.4)	.01*
Female	0.9 (0.3)	

SD, standard deviation.
* Statistically significant at $P < .05$.
† Ratio of muscle area of posterior rotator cuff muscles to subscapularis.

tears[11]—among patients with GHOA and an intact rotator cuff has recently developed. Our results demonstrate that the presence of high-grade infraspinatus FI is independently associated with increased glenoid retroversion. We did not, however, find any associations between rotator cuff FI and eccentric glenoid bone loss (Walch type B glenoids), humeral head subluxation, or glenoid inclination on univariate or multivariable analyses. The results of our study largely corroborate those of prior work. Donohue et al[6] (2018), using CT scan assessments of FI, demonstrated that high-grade infraspinatus FI was more likely to be present in type B3 glenoids compared with type B2 glenoids. Furthermore, another recent study found that a higher posterior cuff relative to subscapularis FI percentage was associated with >75% humeral head subluxation (compared with 60%-75% subluxation) and >25° of glenoid retroversion (compared with <15° of retroversion).[1] When our results are considered in the setting of these other studies' findings, a trend emerges suggesting that high-grade FI of the PRC is associated with more severe forms of posterior eccentric wear of the glenoid (relative to milder forms of eccentric wear).

MA of the rotator cuff represents a decrease in the absolute size of a muscle. Our results demonstrate that a

Table II Associations between rotator cuff muscle area, presence of high-grade FI, and Walch glenoid classification

	Supraspinatus		Infraspinatus FI, n (%)	Teres minor FI, n (%)	Infraspinatus and teres minor		Subscapularis		Infraspinatus and teres minor/ subscapularis* MA, mean (SD), cm²/m
	FI, n (%)	MA, mean (SD), cm²/m			FI, n (%)	MA, mean (SD), cm²/m	FI, n (%)	MA, mean (SD), cm²/m	
Glenoid type									
A1 (n = 29)	25 (86.2)	3.75 (1.28)	18 (62.1)	8 (27.6)	8 (27.6)	8.78 (3.01)	16 (55.2)	10.03 (3.82)	0.95 (0.35)
A2 (n = 10)	10 (100)	2.89 (1.15)	9 (90)	4 (40)	4 (40)	7.72 (2.68)	8 (80)	9.35 (2.97)	0.87 (0.35)
B2 (n = 45)	34 (75.6)	4.06 (1.24)	26 (57.8)	8 (17.8)	9 (20)	9.88 (3.20)	19 (42.2)	10.23 (2.66)	0.99 (0.31)
B3 (n = 43)	37 (86)	4.13 (1.27)	31 (72.1)	17 (39.5)	17 (9.5)	10.38 (3.62)	21 (48.8)	11.64 (3.4)	0.91 (0.26)
P value	.22	.005†	.18	.13	.21	.01†	.17	.034†	.33

FI, fatty infiltration; *MA*, muscle area; *SD*, standard deviation.
* Ratio of muscle atrophy of posterior rotator cuff muscles to subscapularis.
† Statistically significant.

Table III Correlations between rotator cuff muscle area and glenoid measurements

Muscle	Retroversion		Inclination		HH subluxation	
	R	*P* value	*R*	*P* value	*R*	*P* value
Supraspinatus	0.23	.006*	0.006	.95	0.25	.004*
Infraspinatus and teres minor	0.25	.004*	−0.19	.029*	0.28	.001*
Subscapularis	0.14	.11	−0.11	.21	0.11	.22
Infraspinatus and teres minor–to–subscapularis ratio	0.11	.2	−0.07	.4	0.16	.07

HH, humeral head; *R*, Pearson correlation coefficient.
* Statistically significant.

Table IV Multivariable logistic regression of patient factors associated with Walch type B (vs. Walch type A) glenoids

Parameter	OR	95% CI	*P* value
Male sex	0.97	0.4-1.2	.95
BMI	0.94	0.89-0.99	.03*
Age	1	0.94-1.1	.86
Supraspinatus muscle area	1.1	0.73-1.8	.57
Posterior cuff muscle area	1.3	1.0-1.5	.04*
Subscapularis muscle area	1	0.86-1.2	.93

OR, odds ratio; *CI*, confidence interval; *BMI*, body mass index
* Statistically significant at $P < .05$.

larger PRC (infraspinatus and teres minor) is independently associated with Walch type B glenoids (relative to Walch type A glenoids). We did not, however, find a difference in the size of the PRC relative to the subscapularis in any of our analyses—suggesting that the transverse plane force couple remains in balance among Walch type B glenoids. Previous studies assessing the relationship between MA and eccentric wear of the glenoid have shown conflicting results. Aleem et al[1] (2019) and Chalmers et al[5] (2020) both reported preferential atrophy of the subscapularis relative to the PRC in Walch type B glenoids. However, more recently, Arenas-Miquelez et al[2] (2021), using 3-dimensional volumetric CT reconstructions, found the transverse force couple to be in balance among patients with Walch type B glenoids. Similarly to our results, this group did find, however, that larger PRC musculature was predictive of Walch type B glenoids and humeral head subluxation.[2] Although our results support the notion that patients with eccentric glenoid wear have a balanced rotator cuff in the axial plane, eccentric wear appears to be more likely to develop in patients with larger absolute PRC musculature—even when we control for age, sex, and BMI.

The reason that eccentric wear develops in certain patients in the setting of primary GHOA is currently ambiguous. Although this process is likely multifactorial (eg, muscular forces and premorbid bony anatomy),[2] we hypothesize that muscle size plays a larger role than FI. Specifically, we believe that a large PRC pulls the humeral head posteriorly, beginning this process, whereas infraspinatus FI develops in the later stages of eccentric arthritic progression owing to factors such as changes in its length-tension relationship[9,10] and stiffness. Presuming that a type B3 glenoid is a more advanced form of eccentric wear

Table V Associations between rotator cuff FI and glenoid parameters

Muscle	Retroversion		Inclination		HH subluxation	
	Mean (SD), °	*P* value	Mean (SD), °	*P* value	Mean (SD), %	*P* value
Supraspinatus						
Low-grade FI (n = 21)	15 (8)	.55	7 (6)	.53	72 (12)	.89
High-grade FI (n = 106)	16 (10)		8 (5)		72 (13)	
Infraspinatus						
Low-grade FI (n = 43)	14 (8)	.05*	7 (6)	.66	71 (12)	.62
High-grade FI (n = 84)	18 (10)		8 (5)		72 (13)	
Teres minor						
Low-grade FI (n = 90)	16 (9)	.42	8 (5)	.87	71 (13)	.58
High-grade FI (n = 37)	18 (10)		7 (6)		73 (12)	
Infraspinatus and teres minor						
Low-grade FI (n = 89)	15 (9)	.22	8 (5)	.88	71 (13)	.38
High-grade FI (n = 38)	18 (11)		7 (6)		73 (12)	
Subscapularis						
Low-grade FI (n = 63)	18 (10)	.23	8 (5)	.98	74 (13)	.11
High-grade FI (n = 64)	15 (10)		8 (5)		70 (13)	

FI, fatty infiltration; *HH*, humeral head; *SD*, standard deviation.
* Statistically significant.

Table VI Linear regression model for variables associated with increasing glenoid retroversion

Parameter	β*	Standardized β†	95% CI	*P* value
Male sex	1.6	0.08	−2.3 to 5.5	.41
BMI	−0.03	−0.02	−0.28 to 0.22	.83
Infraspinatus FI	6.8	0.33	2.9 to 10.7	<.01‡
Supraspinatus muscle area	1.6	0.22	−0.11 to 3.4	.07
Posterior cuff muscle area	0.48	0.17	−0.31 to 1.3	.23

CI, confidence interval; *BMI*, body mass index; *FI*, fatty infiltration.
* β Coefficient values with 95% CIs signify the strength of association between the dependent variable and the variable of interest.
† Standardized β coefficients were weighted to allow for comparison of the relative strength of association with the dependent variable between the variables of interest.
‡ Statistically significant at $P < .05$.

relative to type B1 and B2 glenoids,[24] our hypothesis is supported by the fact that FI appears to be primarily related to later stages of arthritic progression. It should be noted, however, that our results cannot establish temporal or causal relationships, and longitudinal studies are necessary to answer this question.

Although MA and FI are often discussed in the same context,[15] it is important to discern that these may be separate and potentially independent processes in the setting of GHOA and an intact rotator cuff. Whereas the development of MA and FI is associated with tendon rupture in the setting of rotator cuff tears,[3] patients with primary GHOA do not have rotator cuff tears. As such, the natural history and etiology of these processes may be different within this population. Our primary results demonstrate a poor correlation between MA and FI as these variables were found to have differing associations with pathologic glenoid measurements. In fact, previous cervical spine literature has demonstrated that FI and cross-sectional paraspinal muscle area are not correlated among patients undergoing anterior cervical discectomy and fusion for cervical spine degeneration[18]—lending support to the notion that these processes may not be closely tied when a muscle is intact.

The primary strength of our study was the use of both MRI and CT scans to characterize our variables of interest, whereas previous studies have used a single imaging modality to assess both muscle degeneration and glenoid deformity. Previous work has demonstrated that the optimal assessment of glenoid morphology and rotator cuff muscle degeneration is with CT and MRI scans, respectively.[17,20-22] Furthermore, our automated measurement of glenoid retroversion, glenoid inclination, and humeral head subluxation allowed for precise analysis of glenoid deformity.

There were, however, several notable limitations to our study. First, given the cross-sectional nature of our study, we were not able to determine the temporal relationships of our findings. Longitudinal studies with serial scans of the same patient cohort are necessary to more precisely elucidate the natural history of primary GHOA, as well as its relationship with MA and FI. Second, our cohort was biased by the fact that all patients underwent either anatomic or reverse shoulder arthroplasty and MRI and CT scans were ordered for preoperative planning purposes. Although the senior author will regularly order a CT scan for preoperative planning in most patients, preoperative MRI scans are also ordered to assess the integrity of the rotator cuff in patients who may be candidates for anatomic total shoulder arthroplasty. Consequently, our patient cohort may be limited by selection bias. Third, given the low numbers of type B1 and C glenoids in our study population, we were unable to perform a meaningful analysis in these subpopulations. Fourth, this study was performed at an urban specialty orthopedic hospital in the United States. Our results may not be applicable to all patient populations. Finally, although we assume that muscle size represents a reasonable proxy for muscle force, this relationship is incompletely understood.[14] For example, the relative strength of a muscle with a large cross-sectional area but high-grade FI vs. a smaller sized muscle with no infiltration is unclear.

Conclusion

Patients with eccentric glenoid wear in the setting of primary GHOA and an intact rotator cuff appear to have both larger PRC musculature and higher rates of infraspinatus FI. Although the temporal and causal relationships of these associations remain ambiguous, MA and FI should be considered 2 discrete processes in the natural history of GHOA.

Disclaimer

Ryan W. Churchill is a paid consultant for DePuy Synthes.

Andrew Jawa is a paid speaker and consultant for DJO Global, is a paid consultant for Ignite Orthopedics, receives royalties from DePuy Synthes, and has equity in Boston Outpatient Surgical Suites.

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References

1. Aleem AW, Chalmers PN, Bechtold D, Khan AZ, Tashjian RZ, Keener JD. Association between rotator cuff muscle size and glenoid deformity in primary glenohumeral osteoarthritis. J Bone Joint Surg Am 2019;101:1912-20. https://doi.org/10.2106/JBJS.19.00086
2. Arenas-Miquelez A, Liu VK, Cavanagh J, Graham PL, Ferreira LM, Bokor DJ, et al. Does the Walch type B shoulder have a transverse force couple imbalance? A volumetric analysis of segmented rotator cuff muscles in osteoarthritic shoulders. J Shoulder Elbow Surg 2021. [Epub ahead of print]. https://doi.org/10.1016/j.jse.2021.02.005
3. Barry JJ, Lansdown DA, Cheung S, Feeley BT, Ma CB. The relationship between tear severity, fatty infiltration, and muscle atrophy in the supraspinatus. J Shoulder Elbow Surg 2013;22:18-25. https://doi.org/10.1016/j.jse.2011.12.014
4. Bercik MJ, Kruse K II, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. J Shoulder Elbow Surg 2016;25:1601-6. https://doi.org/10.1016/j.jse.2016.03.010
5. Chalmers PN, Beck L, Miller M, Stertz I, Henninger HB, Tashjian RZ. Glenoid retroversion associates with asymmetric rotator cuff muscle atrophy in those with Walch B-type glenohumeral osteoarthritis. J Am Acad Orthop Surg 2020;28:547-55. https://doi.org/10.5435/JAAOS-D-18-00830
6. Donohue KW, Ricchetti ET, Ho JC, Iannotti JP. The association between rotator cuff muscle fatty infiltration and glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:381-7. https://doi.org/10.2106/JBJS.17.00232
7. Fuchs B, Weishaupt D, Zanetti M, Hodler J, Gerber C. Fatty degeneration of the muscles of the rotator cuff: assessment by computed tomography versus magnetic resonance imaging. J Shoulder Elbow Surg 1999;8:599-605.
8. Gerber C, Fuchs B, Hodler J. The results of repair of massive tears of the rotator cuff. J Bone Joint Surg Am 2000;82:505-15.
9. Gerber C, Meyer DC, Frey E, von Rechenberg B, Hoppeler H, Frigg R, et al. Neer Award 2007: reversion of structural muscle changes caused by chronic rotator cuff tears using continuous musculotendinous traction. An experimental study in sheep. J Shoulder Elbow Surg 2009;18:163-71. https://doi.org/10.1016/j.jse.2008.09.003
10. Gerber C, Meyer DC, Schneeberger AG, Hoppeler H, von Rechenberg B. Effect of tendon release and delayed repair on the structure of the muscles of the rotator cuff: an experimental study in sheep. J Bone Joint Surg Am 2004;86:1973-82. https://doi.org/10.2106/00004623-200409000-00016
11. Goutallier D, Postel JM, Bernageau J, Lavau L, Voisin MC. Fatty muscle degeneration in cuff ruptures. Pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res 1994:78-83.
12. Hamrick MW, McGee-Lawrence ME, Frechette DM. Fatty infiltration of skeletal muscle: mechanisms and comparisons with bone marrow adiposity. Front Endocrinol (Lausanne) 2016;7:69. https://doi.org/10.3389/fendo.2016.00069
13. Ho JC, Amini MH, Entezari V, Jun BJ, Alolabi B, Ricchetti ET, et al. Clinical and radiographic outcomes of a posteriorly augmented glenoid component in anatomic total shoulder arthroplasty for primary osteoarthritis with posterior glenoid bone loss. J Bone Joint Surg Am 2018;100:1934-48. https://doi.org/10.2106/JBJS.17.01282
14. Jones EJ, Bishop PA, Woods AK, Green JM. Cross-sectional area and muscular strength: a brief review. Sports Med 2008;38:987-94. https://doi.org/10.2165/00007256-200838120-00003
15. Kuzel BR, Grindel S, Papandrea R, Ziegler D. Fatty infiltration and rotator cuff atrophy. J Am Acad Orthop Surg 2013;21:613-23. https://doi.org/10.5435/JAAOS-21-10-613
16. Lehtinen JT, Tingart MJ, Apreleva M, Zurakowski D, Palmer W, Warner JJ. Practical assessment of rotator cuff muscle volumes using shoulder MRI. Acta Orthop Scand 2003;74:722-9. https://doi.org/10.1080/00016470310018270

17. Lowe JT, Testa EJ, Li X, Miller S, DeAngelis JP, Jawa A. Magnetic resonance imaging is comparable to computed tomography for determination of glenoid version but does not accurately distinguish between Walch B2 and C classifications. J Shoulder Elbow Surg 2017; 26:669-73. https://doi.org/10.1016/j.jse.2016.09.024
18. Pinter ZW, Wagner S, Fredericks D Jr, Xiong A, Helgeson M, Currier B, et al. Cervical paraspinal muscle fatty degeneration is not associated with muscle cross-sectional area: qualitative assessment is preferable for cervical sarcopenia. Clin Orthop Relat Res 2021;479: 726-32. https://doi.org/10.1097/CORR.0000000000001621
19. Simovitch RW, Helmy N, Zumstein MA, Gerber C. Impact of fatty infiltration of the teres minor muscle on the outcome of reverse total shoulder arthroplasty. J Bone Joint Surg Am 2007;89:934-9. https://doi.org/10.2106/JBJS.F.01075
20. Tenbrunsel TN, Whaley JD, Golchian D, Malone DL, Lima DJL, Sabesan VJ. Efficacy of imaging modalities assessing fatty infiltration in rotator cuff tears. JBJS Rev 2019;7:e3. https://doi.org/10.2106/JBJS.RVW.18.00042
21. Tingart MJ, Apreleva M, Lehtinen JT, Capell B, Palmer WE, Warner JJ. Magnetic resonance imaging in quantitative analysis of rotator cuff muscle volume. Clin Orthop Relat Res 2003:104-10. https://doi.org/10.1097/01.blo.0000092969.12414.e1
22. Unal E, Karaosmanoglu AD, Akata D, Ozmen MN, Karcaaltincaba M. Invisible fat on CT: making it visible by MRI. Diagn Interv Radiol 2016;22:133-40. https://doi.org/10.5152/dir.2015.15286
23. Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. J Arthroplasty 1999; 14:756-60.
24. Walker KE, Simcock XC, Jun BJ, Iannotti JP, Ricchetti ET. Progression of glenoid morphology in glenohumeral osteoarthritis. J Bone Joint Surg Am 2018;100:49-56. https://doi.org/10.2106/JBJS.17.00064