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Quantitative Measurements of Muscle Degeneration in Volumetric Shoulder Muscle Models

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Qualitative image-based Goutallier grading system is popular to examine fatty degeneration of shoulder muscles, but may not provide consistent results to describe the true status of the muscles due to observer-dependent variabilities and limitations of using one cross-sectional image. We calculated occupation ratio (ratio between the supraspinatus muscle and the fossa), single-image and volumetric fat contents to quantitatively describe the degree of muscle atrophy and fatty infiltration in the supraspinatus muscle and compared them with conventional Goutallier grading system. We retrospectively examined the MR images of 33 symptomatic patients. Significant differences were found in the occupation ratio ($p < 0.01$, Kruskall-Wallis H test) and volumetric fat contents ($p < 0.05$) among different grading groups while no differences were found in single-image fat contents. Correlations of the occupation ratio with single-image and volumetric fat contents were found to be moderate suggesting that muscle atrophy and fatty infiltration might be independent factors. Quantitative measurements of occupation ratio and threshold-based volumetric fat contents may be useful to provide consistent information describing both atrophy and fatty infiltration of the supraspinatus muscle which are important predictors of degenerative muscles.

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1. Introduction

Degeneration and tear of the rotator cuff tendons are among the most common conditions causing pain and disability in aging shoulders. Although surgical repair of the torn rotator cuff tendons is one of the most common and effective treatments, the outcome of which is believed to be influenced by the baseline muscle quality.[1-4] Fatty muscular degenerations are known to be an important predictor of physiologic and functional alterations in the rotator cuff muscles.[5-8] Thus, an accurate and reliable method examining fatty degeneration in the muscles is necessary to predict potential outcome of repair surgeries.

Image-based qualitative grading system by Goutallier et al. has been widely used to evaluate the degree of fatty degenerations in the rotator cuff muscles.[9] For the supraspinatus muscle which is one of the main muscles in the rotator cuff muscle group, an oblique T1-weighted sagittal image of the muscle at the level of coracoid process is examined by estimating the degree of muscle atrophy and fatty infiltration. Supraspinatus muscle atrophy was estimated by the cross-sectional occupation ratio of the supraspinatus muscle against the supraspinatus fossa. Although a healthy supraspinatus muscle is shown to fill most of the fossa, a degenerative muscle only occupies the central portion of the fossa while the peripheral space is replaced by the fat.[10,11] Fatty infiltration of the supraspinatus muscle was evaluated by estimating the portion of the fat in the muscle. Although clinical relevance of this grading system has been reported.[5,7,8,12-17] there have been studies indicating inter- and intra-observer variabilities in this method due to the subjectiveness and limitation of using one cross-sectional image.[18-21] Goutallier grading system may not accurately describe the true status of the muscle outside of the selected images because the selected slices may not accurately represent the quality of the whole muscle and it may also be difficult to find a consistent slice position before and after repair surgery.

In this study, we aimed to develop quantitative methods to provide more reliable information for muscle degeneration and aid in the prediction of surgical outcome. We quantified 1) the occupation ratio of the supraspinatus muscle in the fossa, 2) the amount of fatty infiltration

Table 1 MR Imaging parameters

Imaging Parameters	TR / TE (ms)	Section Thickness (mm)	Resolution (μm^2)
Coronal-oblique T2	3000-4500 / 80-100	2	0.55 × 0.55
Coronal oblique T1	500-1000 / 20	2	0.55 × 0.55
Sagittal oblique T2	3000-4500 / 100	2	0.55 × 0.55
Sagittal oblique T1	450-610 / 8-11	2 or 3	0.55 × 0.55
Fox axial T1 with fat suppression	440-600 / 9-40	2.0	0.55 × 0.55

in a selected image which was used in Goutallier grading system and 3) the amount of volumetric fatty infiltration in a whole muscle volume, independent of slice position. Finally, these quantitative measurements were compared with conventional Goutallier grades to examine if new quantitative approaches can effectively represent the status of supraspinatus muscle degenerations.

2. Method

2.1 Patients

We have retrospectively examined the supraspinatus muscle on MR images of 33 symptomatic patients who visited the outpatient shoulder clinic during January-December in 2009, and January-December in 2012. The study population included 20 female (62.65 ± 9.55 years old and an age range of 37-76) and 13 male (51.00 ± 17.83 years old and an age range of 23-79) patients. Diagnoses regarding supraspinatus (SSP) pathology varied from normal (n = 4), tendinopathy (injuries in the supraspinatus tendon, n = 4), articular-sided low grade (n = 4) and bursal-sided high grade (n = 4) partial thickness tears, and full thickness tears (n = 17). The study was approved by the institutional review board and informed consent was waived due to the retrospective nature of the study.

2.2 MR imaging

MR imaging was performed with a 3.0T imager (Achieva; Philips, Netherlands) with a shoulder array coil. For the MR arthrography protocol, coronal-oblique T2 and T1-weighted fast spin-echo images (FSE) with and without fat saturation, sagittal-oblique T2 and T1-weighted FSE images with fat saturation, and transverse T1-weighted FSE images with fat suppression were obtained. Imaging parameters were summarized in Table 1.

2.3 Goutallier grading

Among the series of sagittal oblique shoulder images, an image including a triangular shape of the supraspinatus fossa surrounded by the coracoid base and acromial spine representing the so-called scapular Y view was selected (Fig. 1(a)). Qualitative image-based Goutallier grading system was then applied to estimate the degree of fatty degeneration of the supraspinatus muscle for each patient. A musculoskeletal staff radiologist with 11 years of experience in interpretation of musculoskeletal imaging examined the selected sagittal shoulder image and scored the degree of fatty degeneration using the grading system by Goutallier et al. from 0 to 4.

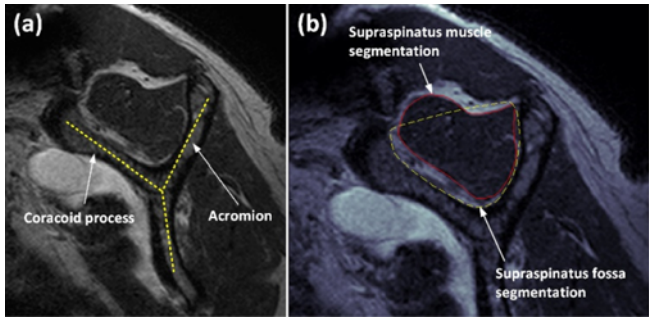

Fig. 1 (a) An example of scapular Y view, and (b) the areas of supraspinatus muscle and fossa in a sagittal MR image were shown

2.4 Occupation ratio and fatty infiltration measurements

To accurately evaluate the degree of muscle atrophy, occupation ratio was measured by calculating the cross-sectional ratio between the supraspinatus muscle (red solid line in Fig. 1(b)) and fossa (yellow dotted line in Fig. 1(b)) by using a custom segmentation program.

We also developed a custom thresholding algorithm to quantitatively estimate the amount of fatty infiltration in the supraspinatus muscle. Conventional thresholding methods assumed that an image contains two different types of pixels (foreground (bright) and background (dark) pixels) and calculated the optimum pixel value separating foreground and background pixels.[22,23] These thresholding methods provided successful results when the images were bi-modally distributed with two distinct peaks of foreground and background pixels in the histogram of pixel values (Fig. 2(a)).

Unfortunately, the distribution of pixel values in our segmented supraspinatus muscle did not display two distinct peaks but a single peak was present in the histogram because the muscle tissue (dark) was the most abundant tissue in the segmented area. A common histogram profile of a heavily degenerated muscle is shown in Fig. 2(b). The histogram resembled a Gaussian distribution but had a larger histogram area in the right-side of the apex representing a large portion of bright pixels in the segmented muscle. Our thresholding approach was to identify the histogram profile of background pixels rather than calculating an optimum value between foreground and background peaks. The profiles of foreground and background peaks were assumed to be normally distributed. The histogram in the left-side of the apex was used to be fitted with a Gaussian function because the histogram in the left-side of the apex was dominantly influenced by background pixels. The fitted curve was then considered as the distribution of background pixels (Fig. 2(b)). Finally, the pixel values abnormally greater than the fitted function (= three standard deviation away from the center of the Gaussian function) was defined as the threshold value for the selection of pixels representing the fat tissue. Fig. 2(c) presented thresholding results from a conventional method (Otsu' thresholding) and our new Gaussian fitting method. Conventional thresholding underestimated the amount of the muscle tissue while new thresholding method successfully separated the muscle (black) from the fat tissues (white). The amount of fatty infiltration was then calculated as the ratio between the number of pixels greater than the threshold value and the total pixels in the segmented area.

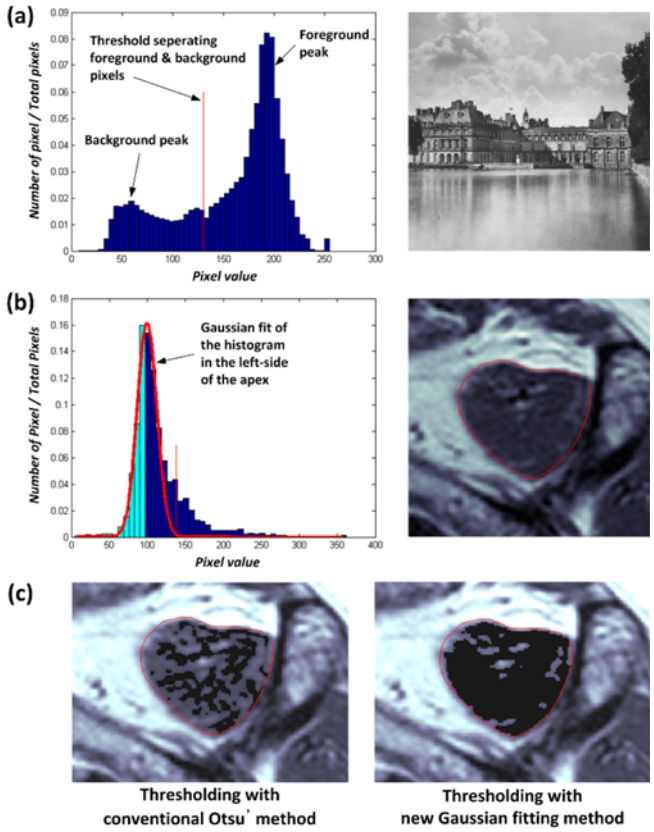

Fig. 2 (a) Two distinct peaks of foreground and background pixels presented in a sample image, and a threshold value separating foreground and background pixels was shown. However, (b) only one distinct peak was present in a supraspinatus MR image. New thresholding method utilized Gaussian fitting of the histogram in the left-side of the apex (cyan bars). (c) Conventional thresholding method (Otsu' thresholding) underestimated the amount of the muscle tissue while new thresholding method successfully separated the muscle (black) from the fat tissues (white)

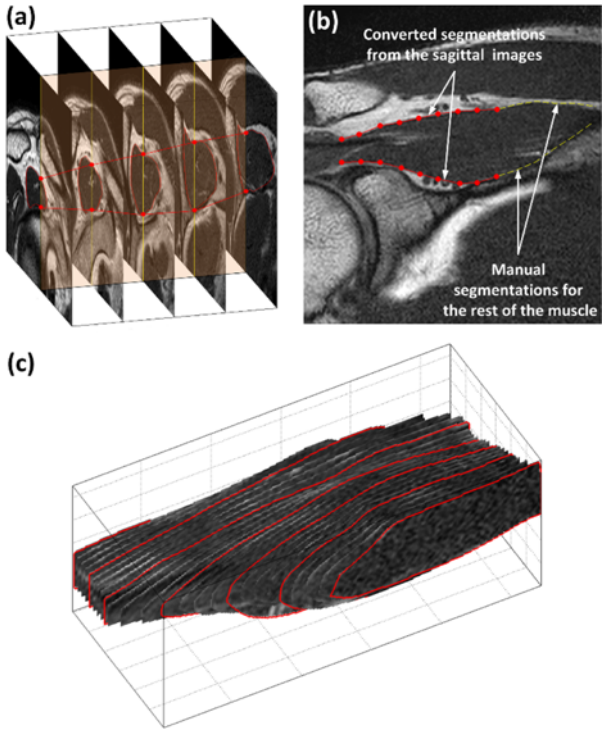

Fig. 3 Boundaries of a supraspinatus muscle were segmented in (a) sagittal and (b) coronal MR images. (c) All segmented supraspinatus muscles in each imaging plane were combined and a complete 3D volume data of a whole supraspinatus muscle was created

2.5 Volumetric fatty infiltration measurements

We also calculated the volumetric fat content of the whole supraspinatus muscle by using sagittal and coronal T1-weighted muscle images. The sagittal images were available from the lateral end of shoulder to the middle of the supraspinatus muscle while the coronal muscle images were scanned almost entirely. Segmentation of the supraspinatus muscle was started from the sagittal images due to the relatively clearer muscle boundaries in the sagittal plane (Fig. 3(a)). Sagittal segmentation results were converted into the coronal imaging plane, but the coronal segmentation data were partially created (red solid lines in Fig. 3(b)) because of the incomplete sagittal images for the whole muscle. The rest of the muscle (medial half of the supraspinatus) was manually segmented by following the converted segmentation lines from the sagittal images (yellow dotted lines in Fig. 3(b)). All segmented supraspinatus muscles in each imaging plane were finally combined and a complete 3D volume data of a whole supraspinatus muscle was created (Fig. 3(c)). The data between each coronal image were mathematically interpolated.[24,25]

2.6 Statistical analysis

Kruskall-Wallis H test was used to examine the differences in occupation ratio, single-image fatty infiltration, and volumetric fatty infiltration measurements among different Goutallier grades. Relationships of occupation ratio with single-image and volumetric fatty infiltration measurements were tested by Pearson correlation.

3. Results

Goutallier grading was completed for all patients. The patients with normal supraspinatus muscles had a wide range of Goutallier grades (grade 0, n = 2; grade 2, n = 1; grade 3, n = 1). The grades of the tendinopathy group were also inconsistent (grade 0, n = 2; grade 1, n = 1, grade 2, n = 1). The patients with partial tears were all graded as either 1 or 2 (grade 1, n = 4; grade 2, n = 4) while the patients with full thickness tears had the highest grades (grade 0, n = 1; grade 2, n = 5; grade 3, n = 5; grade 4, n = 6).

The grading results were also compared with occupation ratio, single-image fat content, and volumetric fat content measurements (Table 2). Significant differences were found in the occupation ratio and volumetric fat contents ($p < 0.05$, Kruskall-Wallis H test) among the different grading groups while the differences in single-image fat contents were not significant ($p > 0.05$, Kruskall-Wallis H test).

Correlations of the occupation ratio with single-image and volumetric fat contents were found to be moderate while volumetric fat contents

Table 2 Occupation ratio, single-image fat content, and volumetric fat content in different Goutallier grades (Kruskall-Wallis H test)

Goutallier grades	n	Occupation ratio	Single-image Fat (%)	Volumetric Fat (%)
Grade 0	5	1.18 ± 0.08	4.62 ± 2.38	3.60 ± 2.37
Grade 1	5	0.93 ± 0.13	6.40 ± 6.51	7.15 ± 6.60
Grade 2	11	0.80 ± 0.12	9.13 ± 6.60	10.15 ± 6.86
Grade 3	6	0.74 ± 0.14	11.71 ± 8.03	9.03 ± 3.63
Grade 4	6	0.33 ± 0.10	14.51 ± 9.86	13.84 ± 7.80
p-value		< 0.01	0.227	0.039

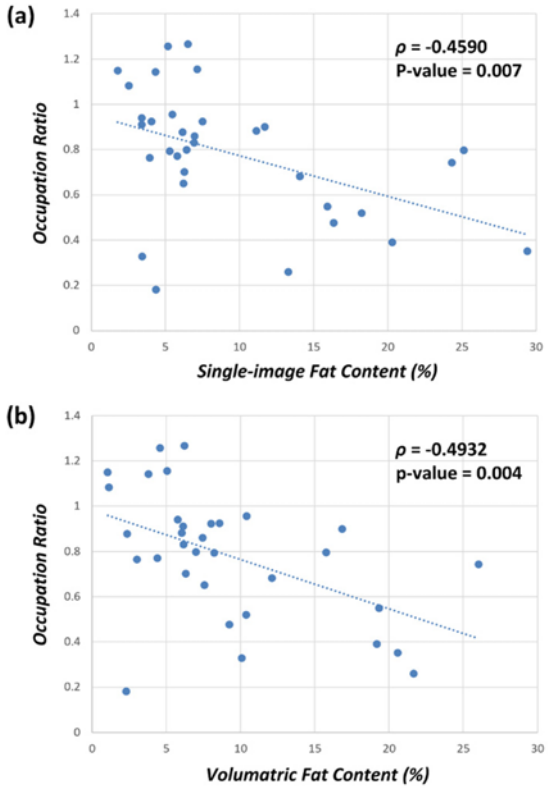

Fig. 4 Relationships of the occupation ratio with single-image fatty infiltration and volumetric fatty infiltration measurements were examined by Pearson correlation

showed a better correlation (ρ = -0.507) than the correlation of single-image fat contents (ρ = -0.425) with the occupation ratio (Fig. 4).

4. Conclusions

In this study, we developed quantitative methods to estimate the degree of fatty degenerations in the supraspinatus muscle. The cross-sectional occupation ratio between the supraspinatus muscle and the fossa was accurately calculated by using a custom segmentation program and the fat contents in a single image and a whole muscle model were also successfully quantified by using a novel thresholding method. These quantitative measurements allowed us to avoid inconsistencies in the qualitative Goutallier grading system which were caused by the inter- and intra-observer variabilities and the limitations of using one cross-sectional image. We then retrospectively examined shoulder MR images of 33 symptomatic patients and correlated these new measurements with conventional Goutallier grades to test the efficacy of the new methods in estimating fatty degeneration of the supraspinatus muscle.

The results showed that the occupation ratio (p < 0.01) among different grading groups were found to be significantly different, but the differences in the single-image fat content among different groups were not significant (p > 0.2). It seems that conventional Goutallier grading system tends to reflect the degree of supraspinatus muscle volume reductions which was described by the decreases in occupation ratio rather than fatty infiltration. Although radiologists consider the degree of fatty infiltration during the process of Goutallier grading, the final grading might be biased toward the degree of muscle atrophy because the volume reduction of the muscle is more eminent in the sagittal MR images due to the relatively greater volume of the fat surrounding the muscle when compared with the volume of the fat inside the muscle.

Although muscle atrophy was a well-known aspect of supraspinatus tears, fatty infiltration was also shown to be an important predictor of surgical outcomes. Moderate correlations between the occupation ratio and the single-image and volumetric fat contents suggested that muscle atrophy and fatty infiltration might be independent factors in the evaluation of muscle degenerations (Fig. 4). Our results showed that occupation ratio was an effective indicator of degenerative muscles. However, the occupation ratio may not successfully reflect the degree of fatty infiltration in the supraspinatus muscle. We found that our threshold-based volumetric fat contents might be a better indicator to describe fatty degenerations in the supraspinatus muscle than single-image fat contents as volumetric fat contents in different Goutallier grades were found to be significantly different while the variations in single-image fat contents were not significant. This result suggested that the degree of fatty infiltration was various in different image locations and the examination of fatty infiltration needed to be performed in at least multiple MR images.

There were limitations to our study. Our volumetric muscle models created by T2-weighted sagittal and coronal images may contain errors in fat content calculation. Because the muscle values between each slice were mathematically interpolated from the existing scanned slices, our model may have missed some information of the muscle in inter-slice gaps. However, it is unlikely that the distribution of the supraspinatus fatty degeneration would be substantially different in the approximately 2 mm gap between each slice even though it has been known that fatty changes of the muscle are not uniformly distributed after a tendon tear. Moreover, we did not compare our quantitative measurements with real muscle degeneration levels such as a histologic proof of lipid composition in the supraspinatus muscle. Unfortunately, we were not allowed to obtain tissue samples of the muscle from the patients just to prove the results of this study due to ethical issues. Thus, we decided to compare our occupation ratio and fat contents measurements with Goutallier grade system which was the only clinically proven method to evaluate muscle degenerations although the Goutallier method had some limitations.

In conclusion, we calculated occupation ratio, single-image and volumetric fat contents to quantitatively describe the degree of muscle

atrophy and fatty infiltration in the supraspinatus muscle and compared them with clinically proven Goutallier grading system. We found that the image-based grading system tended to reflect the degree of muscle atrophy around outer muscle, but the influence of single-image fatty infiltration measurements on the muscle grading was found to be minimal. However, threshold-based volumetric fat content measurement seemed to well represent fatty infiltration in the supraspinatus muscle by exhibiting significant differences with different Goutallier grades. Both muscle atrophy and fatty infiltration in the rotator cuff muscles are known to be important signs of muscle degeneration and may be correlated with higher incidence of re-tear of the tendon after repair surgery. Quantitative measurements of occupation ratio and threshold-based volumetric fat content may be useful to provide consistent information describing both atrophy and fatty infiltration of the supraspinatus muscle which are important predictors of degenerative muscles.

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