



Change in the pennation angle of the supraspinatus muscle after rotator cuff tear repair

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Background: The pennation angle is an important architectural and functional feature of pennate muscles. The purpose of this study was to investigate the change in the pennation angle of the supraspinatus muscle after rotator cuff tear repair.

Materials and methods: The study included 68 patients who underwent arthroscopic rotator cuff repair and magnetic resonance imaging. The size of the tear was measured under arthroscopic visualization. The pennation angle of the supraspinatus both preoperatively and postoperatively and the integrity of the repaired cuff were determined by magnetic resonance imaging.

Results: The preoperative pennation angle was significantly greater with enlargement of the tear size ($P < .0001$, analysis of variance). The retear rate was 29% in patients with medium tears and 59% in patients with large or massive tears. No retear was noted in patients with partial and small tears. The retear rate was 90.9% when the preoperative pennation angle was 20° or greater and was 12.3% when this angle was 19° or less, and the risk ratio for retear was 7.4 when this angle was 20° or greater. For repair-type tears, comparison between the preoperative and postoperative pennation angles showed a significant decrease in the mean value from $11.8^\circ \pm 3.7^\circ$ to $9.9^\circ \pm 3.0^\circ$ in the medium tear group ($P = .007$, paired t test) but no significant difference in the large or massive tear group (from $15.1^\circ \pm 7.0^\circ$ to $13.3^\circ \pm 5.8^\circ$) ($P = .33$). For retear-type tears, no significance was found between groups.

Conclusion: The preoperative pennation angle is directly correlated with the tear configuration and could be one of the prognostic factors for postoperative cuff integrity. To restore the pennation angle, primary repair is more appropriate in smaller rotator cuff tears than in medium-sized tears.

Level of evidence: Level IV; Case Series; Prognosis Study

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Rotator cuff tears are associated with structural and architectural alterations of the musculotendinous unit and cause dysfunction of the shoulder. To optimally treat rotator cuff tears, an accurate understanding of the cuff's musculotendinous architecture and sequence of change in relation to tendon pathology is needed. However, the musculotendinous

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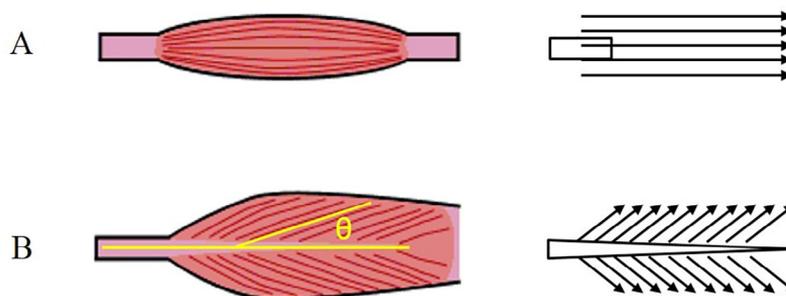


Figure 1 (A) Parallel muscle: Muscle fibers run parallel to the muscle's force-generating axis. (B) Pennate muscle: Muscle fibers run at a fixed angle relative to the muscle's force-generating axis. The characteristic of a pennate muscle is to permit packing of a larger number of fibers into a smaller cross-sectional area. θ , pennation angle.

architecture is frequently overlooked despite important insights that can be gained by noting the functional changes arising from tendon tears.^{2-4,9,10,19}

The supraspinatus is the structure most frequently involved in rotator cuff tears, and it is a pennate muscle, which consists of muscle fibers and an intramuscular tendon that run at an angle to the axis of traction. The pennation angle, defined as the angle between the intramuscular tendon and muscle fibers, is an important architectural and functional feature of pennate muscles (Fig. 1).

Several studies have estimated the pennation angle of the supraspinatus from cadaveric specimens,^{8,13,20} magnetic resonance imaging (MRI),¹⁵ and ultrasonography^{6,7}; however, few studies have reported the pennation angle of the ruptured supraspinatus. Notably, little has been mentioned regarding the change in pennation angle after rotator cuff repair. Preoperative and postoperative investigation of muscle architecture may provide greater insight into when and how repair of the tendon has influenced the musculotendinous unit and thus its function.

The purposes of this study were first to investigate the change in pennation angle of the supraspinatus muscle after rotator cuff tear repair and second to evaluate the association between the pennation angle and cuff integrity after repair.

Materials and methods

Patients

Arthroscopic rotator cuff repair (ARCR) was performed in 107 consecutive patients by our senior surgeon between November 2005 and March 2014. The criterion for inclusion in the study was the ability to perform an evaluation by MRI both preoperatively and at a minimum of 6 months after the repair. The criterion for exclusion was poor scan image quality due to artifact creation. Finally, 68 patients were enrolled. The mean age of all 68 patients (37 men and 31 women) was 63.5 years (range, 30-80 years) at the time of ARCR. In addition, we chose 33 control patients (25 male and 8 female patients; mean age, 30.9 years; age range, 17-54 years) who had intact rotator cuffs and had undergone arthroscopic Bankart repair for recurrent instability in the same period.

Arthroscopic findings

The size of the rotator cuff tear was measured under arthroscopic visualization. By use of the maximum values of either the length or width, full-thickness tears were classified as small (<1 cm), medium (1-3 cm), large (3-5 cm), or massive (>5 cm) according to the classification of Cofield et al.¹ Tears with incomplete exposure of their rotator cuff footprints were defined as partial-thickness tears. Large and massive tears were grouped because a tear over 3 cm also includes the infraspinatus tendon according to the anatomic study by Mochizuki et al.¹²

Magnetic resonance imaging

Shoulder MRI scans were analyzed in the T2-weighted axial and oblique coronal planes. The scans were performed with a 3-T machine (Discovery MR750w; GE Healthcare, Pollards Wood, UK). The coil was an 8-channel shoulder coil. The thickness of axial slices was 3 mm, and the gap (space) measured 0.3 mm. The matrix frequency was 320 with a phase of 224. The patients were imaged supine, with the arm at the side and the thumb pointing upward. The pennation angle (the angle subtended by the central axis of the intramuscular tendon and anterior muscle fiber in the supraspinatus) was measured in a specific region extending from the articular surface of the glenoid to 30 mm medially in the axial plane by MRI preoperatively and postoperatively (Fig. 2). The mean interval from surgery to postoperative MRI was 11.1 months (range, 6-13 months). Repaired cuff integrity was evaluated using the criteria established by Sugaya et al.¹⁴ Types 1, 2, and 3 were defined as the repair types, whereas types 4 and 5 were defined as the retear types. All scans were blindly reviewed by 3 orthopedic surgeons. The interclass correlation coefficient of the pennation angle was 0.972.

Arthroscopic rotator cuff repair

All rotator cuff tears were repaired by 1 of 3 methods as follows: single row in 20 shoulders, double row in 42, and suture bridging in 6. In 2 massive tear cases, the tears were repaired with margin convergence. In 2 large tear cases, a suture anchor was placed on the humeral head within 1 cm of the medial edge of the footprint. No partial repair or patch procedure was used in any case. Rehabilitation consisted of wearing an abduction sling for the initial 6 weeks. Passive and active-assisted motion was started at 6 weeks.

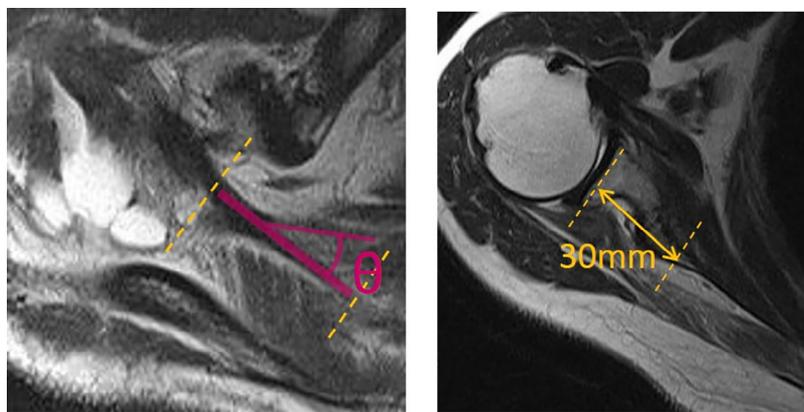


Figure 2 The pennation angle (θ) is subtended by the anterior muscle fiber (*thin line*) and the central axis of the intramuscular tendon (*thick line*). The measured region extends 30 mm medially from the articular surface of the glenoid.

postoperatively. Active elevation was permitted at 8 weeks postoperatively, and resistive shoulder strengthening was started at 12 weeks.

Statistical analysis

Paired *t* tests were used to compare the preoperative and postoperative pennation angles of the supraspinatus. The configuration of the tear and the pennation angle were analyzed by 1-way analysis of variance. Statistical analysis was performed using StatView software (version 5.0; SAS Institute, Cary, NC, USA); $P < .05$ was considered statistically significant. Power analysis was performed using the free G*Power program (version 3.1.7; Franz Faul, Christian-Albrechts-Universität zu Kiel, Kiel, Germany).

Results

Tears were assessed as partial in 17 patients (articular-sided tears in 7, bursal-sided tears in 2, and intratendinous tears in 8), small in 10, medium in 24, and large or massive in 17. All tears involved the supraspinatus. The mean preoperative pennation angle was $6.3^\circ \pm 1.6^\circ$ in controls and $8.6^\circ \pm 2.6^\circ$, $10.0^\circ \pm 3.2^\circ$, $11.9^\circ \pm 3.9^\circ$, and $20.2^\circ \pm 8.1^\circ$ in patients with partial, small, medium, and large or massive tears, respectively (Fig. 3). The preoperative pennation angle increased significantly with enlargement of the tear size ($P < .0001$, analysis of variance; effect size [f] = 1.170; power = 1.000). Retears occurred in 29% and 59% of patients with medium tears and large or massive tears, respectively, but not in patients with partial or small tears. The re-tear rate was 90.9% when the preoperative pennation angle was 20° or greater and was 12.3% when this angle was 19° or less, and the risk ratio for re-tear was 7.4 when this angle was 20° or greater (Table I).

Regarding tears with repair types, the preoperative to postoperative decrease in the mean pennation angle was significant in the medium tear group (from $11.8^\circ \pm 3.7^\circ$ to $9.9^\circ \pm 3.0^\circ$; $P = .007$, paired *t* test; effect size [d] = 0.755; power = 0.832) but not in the large or massive tear group (from $15.1^\circ \pm 7.0^\circ$ to $13.3^\circ \pm 5.8^\circ$, $P = .33$; Fig. 4). Regarding tears with re-tear types, we found an increase in the mean pennation angle from $12.3^\circ \pm 4.6^\circ$ to $13.7^\circ \pm 5.6^\circ$ in the medium tear group but not

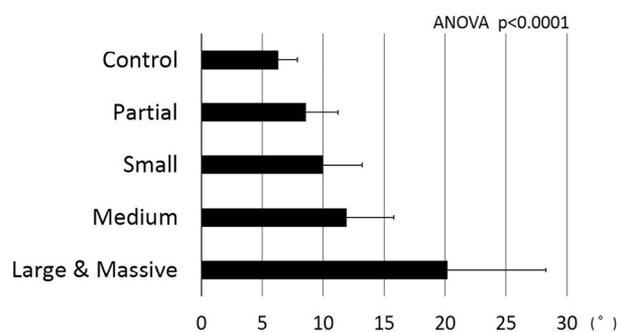


Figure 3 The pennation angles of the supraspinatus before rotator cuff repair were significantly greater with enlargement of the tear size. $P < .0001$ by analysis of variance (ANOVA).

Table I Risk ratio for re-tear in patients with preoperative pennation angle of 20° or greater

Pennation angle, °	Repair group, n	Re-tear group, n	Re-tear rate, %	Risk ratio
≥ 20	1	10	90.9	7.4
< 20	50	7	12.3	

in the large or massive tear group (which changed from $23.8^\circ \pm 7.0^\circ$ to $23.8^\circ \pm 11.4^\circ$). None of these changes was statistically significant (Fig. 5).

Discussion

The rotator cuff is formed by the tendons of the supraspinatus, infraspinatus, teres minor, and subscapularis muscles, and these pennate muscles are composed of central tendon and muscle fibers. Characteristically, pennate muscles have short lengths and large numbers of muscle fibers. Therefore, pennate muscles are much more powerful than other muscles. We commonly evaluate tendon retraction, muscle atrophy, and fatty degeneration in rotator cuff tears by preoperative imaging. However, little attention is paid to morphologic change in pennate muscles, which seems to influence muscle function.

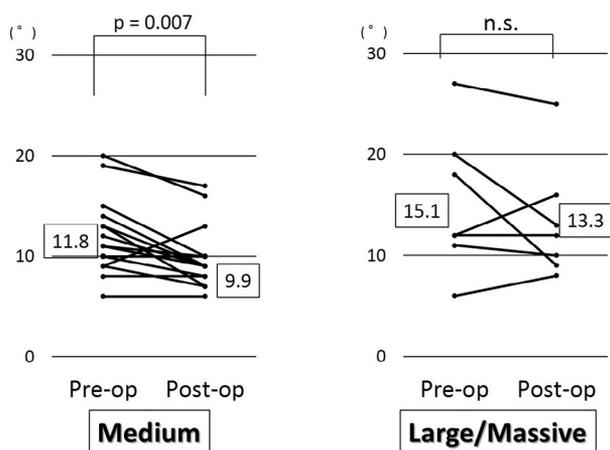


Figure 4 Change in pennation angle in repair group (paired *t* test) from preoperatively (*Pre-op*) to postoperatively (*Post-op*). *ns*, not significant.

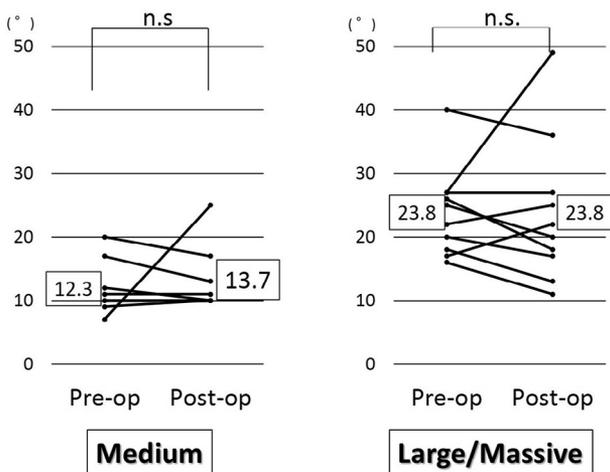


Figure 5 Change in pennation angle in retear group (paired *t* test) from preoperatively (*Pre-op*) to postoperatively (*Post-op*). *ns*, not significant.

The physiological basis of muscle force production and movement is determined by the muscle architecture. The muscle architecture is defined as the macroscopic arrangement of muscle fibers, which is an important element in mechanical function.⁹ Large muscle groups have 2 main muscle architectures: parallel and pennate. The physiological cross-sectional area (PCSA) is a measure of the muscle cross section perpendicular to the fibers and, hence, in pennate muscle (Eq. 1); it depends on the pennation angle:

$$PCSA \text{ (in square centimeters)} = M \text{ (in grams)} \times \cos\theta / (\rho \text{ [in grams per cubic centimeter]} \times L_f \text{ [in centimeters]})$$

in which *M* is muscle mass, θ is the pennation angle, ρ is muscle density, and L_f is the normalized muscle fiber length. As mentioned earlier, the pennation angle is an important factor related to the maximum force production and to range of motion. Therefore, attention should be paid to the pennation

angle change when diagnosing and performing surgery on rotator cuff tears.

Several reports have distinguished between the anterior and posterior portions of the supraspinatus muscle belly.^{8,16-18} According to Roh et al,¹³ the average PCSA of the anterior muscle is almost 2.5 times greater than that of the posterior muscle. They also stated that rotator cuff tendon repairs should incorporate the anterior tendon whenever possible, inasmuch as it functions as the primary contractile unit. Considering these facts, we decided to measure the pennation angle formed by the central axis of the intramuscular tendon and anterior muscle fiber in the supraspinatus.

Zuo et al²⁰ reported that the pennation angle of the supraspinatus was 10.2° in controls (no tears), 12.5° in partial-thickness tears, and 18.6° in full-thickness tears and that there was a strong positive correlation between the normalized length of the tear and the pennation angle. Similarly, the pennation angle increased significantly with enlargement of the tear size in our study. Our results indicate the usefulness of evaluating the morphologic change in the intramuscular tendon and muscle fibers by MRI. We speculate that the reason for the petty variation in angle between the study by Zuo et al and our study is the difference between the objects of investigation. We measured the pennation angle of the supraspinatus in living patients by MRI; on the other hand, Zuo et al examined the pennation angle in embalmed human cadaveric shoulders.

In our study, the muscles with a preoperative pennation angle of 20° or greater had a relatively high risk of retear. Many studies describing factors affecting outcome in primary rotator cuff repair have been published. Heerspink et al⁵ stated in their systematic review that there is insufficient evidence for tissue quality having an influence on cuff integrity at follow-up, despite the different methods (fatty infiltration and muscle atrophy with MRI, intraoperative degeneration) used for assessing tissue quality. Therefore, they commented that a decrease in tissue quality would obviously increase the risk of retear. Although little attention has been paid to measuring the preoperative pennation angle before now, we think that it could be a prognostic factor for postoperative cuff integrity.

To our knowledge, no previous study has measured the change in pennation angle after rotator cuff repair. In this study, successful rotator cuff tear repair resulted in a significantly decreased mean pre- to post-ARCR pennation angle in the medium tear group but not in the large or massive tear group. An experimental study by Gerber et al³ using sheep suggested that continuous elongation can lead to restoration of normal muscle architecture, to partial reversal of muscle atrophy, and to arrest of the progression of fatty infiltration. In addition, the pennation angle of the infraspinatus that had increased owing to tendon release was restored by successful repair but not by failed repair.^{2-4,11} Our results suggest that continuous traction could be one of the useful methods to restore the pennation angle in large or massive tears but would not be needed in smaller than medium tears. Early repair is

therefore recommended to recover the musculotendinous architecture and muscle force production needed for further improvement of postoperative outcomes in rotator cuff tear patients.

This study has some weaknesses. First, the pennation angle is not reproducible when it is difficult to distinguish the anterior muscle fiber of the supraspinatus by MRI. However, the intraclass correlation coefficient among the 3 raters was 0.972, so the pennation angle could be reliable for the imaging evaluation. Second, we did not investigate functional and patient-reported outcomes. It is possible to explain logically that shoulder function improves when the pennation angle is restored, but this was not shown clinically in this study. Further investigation is needed to elucidate the correlation of clinical outcomes (eg, improved muscle strength or activities of daily life) with change in the pennation angle.

Conclusion

The preoperative pennation angle is directly correlated with the tear configuration and could be a prognostic factor for postoperative cuff integrity. To restore an enlarged pennation angle, primary repair is more appropriate in smaller than medium-sized tears, but procedures such as continuous traction should be considered in large or massive tears.

Disclaimer

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