REVIEW ARTICLE

Biomechanical Factors in Rotator Cuff Pathology

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Abstract: The rotator cuff provides dynamic stability and is critical to normal shoulder function. Forces generated by the rotator cuff facilitate the motions involved in activities of daily living and the more demanding movements of athletics and manual labor. Injury and pathology of the rotator cuff are common and the unique anatomical and biomechanical characteristics of the cuff contribute to the etiology of its injury. This review provides a biomechanical and anatomic context to understanding normal rotator cuff function and summarizes recent work describing biomechanical implications of cuff pathology.

Key Words: rotator cuff, tendon, muscle, collagen, biomechanics, mechanical load, mechanical strain

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ANATOMIC FORM OF THE ROTATOR CUFF

Clark and Harryman[1] microscopically examined the rotator cuff and capsular-soft tissue complex to elucidate the orientation of fiber groups, blood supply of the rotator cuff and purvey evidence of degeneration. Their histologic characterization showed the rotator cuff-capsule complex to be composed of 5 semidistinct layers within which collagen fibers from the capsule, surrounding ligaments (such as the coracoacromial ligament), and rotator cuff tendons, interdigitate. Gohlke[2] confirmed this 5-layer configuration of the cuff-capsule complex and observed that collagen fibers become increasingly interdigitated and ribbon-like as opposed to round as they course from the musculotendinous junction to the humeral insertion.

The anterior and posterior aspects of the supraspinatus are characterized by their distinct musculotendinous anatomy. The posterior, quadrangular-shaped tendon blends with fibers from the joint capsule. This posterior supraspinatus tendon has an average width and length of approximately 1.6 and 2.9 cm,[3] respectively. The anterior supraspinatus tendon is more cord-like, also blends with the joint capsule, and is both narrower (0.8 cm) and longer (6.1 cm) than its posterior counterpart.[3] The anterior portion of the supraspinatus tendon is thicker and more robust than the wider but flatter posterior tendon.[4] With respect to medial-lateral tendon collagen ultrastructure, it has recently been reported that the mean collagen fibril diameter and fibril area density is significantly greater medially when compared with the lateral aspect of the intact tendon ($P < 0.05$) (Fig. 1).[5] Furthermore, the estimated physiologic cross-sectional area of the anterior supraspinatus muscle is nearly 2.5 times larger than that of the posterior, allowing for more force contraction. Functionally, the anterior supraspinatus can both internally and externally rotate the humerus, whereas the posterior subregion can generate external rotation only (Fig. 2).[6] In human cadaveric studies, tears have been consistently noted to initiate on the anterior aspect of the supraspinatus.[3,7] In contrast, a recent in vivo ultrasound study by Kim et al[8] suggests that rotator cuff tears commonly initiate in the posterior portion of the tendon between the suprapinatus and the infraspinatus. These investigators postulate that the posterior region corresponds to the approximate center of the rotator crescent; an area on the cuff that Burkhart et al[9] suggest bears high load and which degenerates with age.

Fibers of the infraspinatus interdigitate with the supraspinatus approximately 1.5 cm from its insertion on the greater tuberosity and thus cannot be readily distinguished close to the insertion. The teres minor, originating at the lateral aspect of the scapular blade, inserts onto the inferior aspect of the greater tuberosity and also interdigitates, distally on the humeral shaft, with the infraspinatus. Finally, the subscapularis muscle originates on the anterior surface of the scapula and its tendon inserts distally onto the lesser tuberosity and the humeral shaft.

CONTRIBUTIONS OF THE ROTATOR CUFF TO SHOULDER MOTION AND STABILITY

Several cadaveric studies have described the changes in moment arms and hence the torque-generating capacity of each rotator cuff muscle through varying angles of abduction and positions of flexion-extension.[10–12] In elevation, Kuechle et al[10] found that the magnitude of the anterior deltoid and middle deltoid moment arms were twice that of the supraspinatus, and all 3 had a significantly larger moment arm than the infraspinatus and subscapularis. In elevation, the moment arms for these muscles were larger in the coronal plane than in the sagittal plane. Liu et al[11] compared the deltoid and supraspinatus moment arms and concluded that abduction moment arms change in a nonlinear manner with glenohumeral angle. In the latter study, the investigators posited that the supraspinatus may play a larger role in elevation at higher glenohumeral angles whereas the deltoid may be more effective than previously thought[12] during initiation of elevation because its large force producing capability compensates for its small moment arm at lower glenohumeral angles. In addition to being external and internal rotators respectively, the infraspinatus and subscapularis, were also found to play a role in abduction.[12]

Role of RC in Normal Shoulder Function

Dynamic compression of the humeral head against the glenoid cavity, termed "concavity compression," is the primary mechanism by which the rotator cuff dynamically

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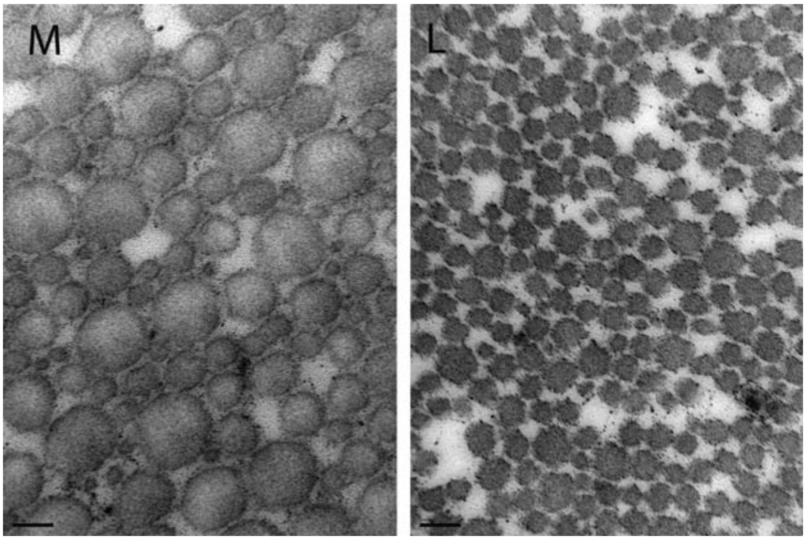

FIGURE 1. Transmission electron microscopy images of collagen fibrils of the medial (M) and lateral (L) regions of intact supraspinatus tendon (magnification: ×150,000). Mean collagen fibril diameter and area density were greater in the medial region of the tendon relative to the lateral region ($P < 0.05$). Scale bar=100 nm.

stabilizes the glenohumeral joint.[13,14] In a normal shoulder, the combined force of the subscapularis anteriorly and the infraspinatus and teres minor posteriorly provide antagonistic forces that compress the humeral head onto the glenoid.[15,16] In simulated rotator cuff paralysis of the infraspinatus, subscapularis and teres minor tendons, cadaveric analysis showed glenohumeral instability superiorly.[17] Simulation of a massive cuff tear (supraspinatus and infraspinatus tendons) led to decreased abduction angle relative to a native joint and increased reaction forces.[18]

A primary role of the rotator cuff in the normal shoulder is that of conferring dynamic stability.[19–22] Superior translation of the humeral head has consistently been noted as a biomechanical consequence of rotator cuff injury.[23,24] Evidence is seen clinically with superior humeral migration in massive rotator cuff tears and cuff tear arthropathy.[25,26] Over time, this superior migration of the humeral head can result in "acetabularization" of the undersurface of the acromion as the latter structure then articulates with the humeral head. In several cadaveric studies Halder et al[19,20,27] systematically assessed the individual and combined stabilizing effect of selected muscles. With respect to humeral head depression, the latissimus dorsi and teres major were most effective. In these studies, the infraspinatus and subscapularis proved more effective in humeral head depression than did the supraspinatus. The supraspinatus also proved to be less effective than the lateral deltoid, coracobrachialis and short head of the biceps with regard to providing stability in the superior direction.

BIOMECHANICAL PROPERTIES OF THE ROTATOR CUFF

An understanding of the mechanical properties of the individual tendinous components of the rotator cuff provides perspective for understanding their relative functional capacity and propensity for injury (eg, bursal vs. articular sides of the supraspinatus). Among the rotator cuff tendons, the supraspinatus has been most extensively

FIGURE 2. Illustrations of the supraspinatus subregion footprint orientation at different humeral rotation positions (A, anterior supraspinatus; B, posterior supraspinatus; C, humeral head; D, acromion). Reprinted with permission from *J Orthop Res.* 2010;28:12–17.

characterized with respect to its structural and material properties. To date, published data on mechanical properties of the entire subscapularis and infraspinatus tendons (ie, tested as an entire unit in its intact state) are scarce. Further studies of viscoelastic (particularly strain-rate sensitive properties) and comparative studies of the rotator cuff tendons using similar biomechanical assays (eg, cyclic loading or material testing of regional properties) would likely provide greater insight into the role of biomechanics in cuff injury.

Supraspinatus

The supraspinatus tendon exhibits structural and mechanical properties which vary by anatomic region, through its thickness, and with glenohumeral abduction angle. Itoi et al[28] divided the human supraspinatus into anterior, central, and posterior thirds and observed significantly greater ultimate load, ultimate stress, and tensile modulus for the anterior region. Tensile modulus (computed from optical strain measurements) was not found to differ between the bursal and articular aspect of any of the 3 regions. Nakajima et al[29] isolated the articular and bursal portions of the tendon and found significantly higher tensile strength but lower modulus of elasticity for the bursal aspect. Very recently, Lake et al[30] compared the material properties of tissue samples harvested from the medial, anterior, and posterior locations of both the bursal and articular side of supraspinatus tendons (Fig. 3). Although no differences were detected between bursal and articular moduli at each location, comparisons within the bursal and articular groups each showed that samples from the medial region were stiffer than those of the anterior, which in turn showed higher moduli than the posterior samples.

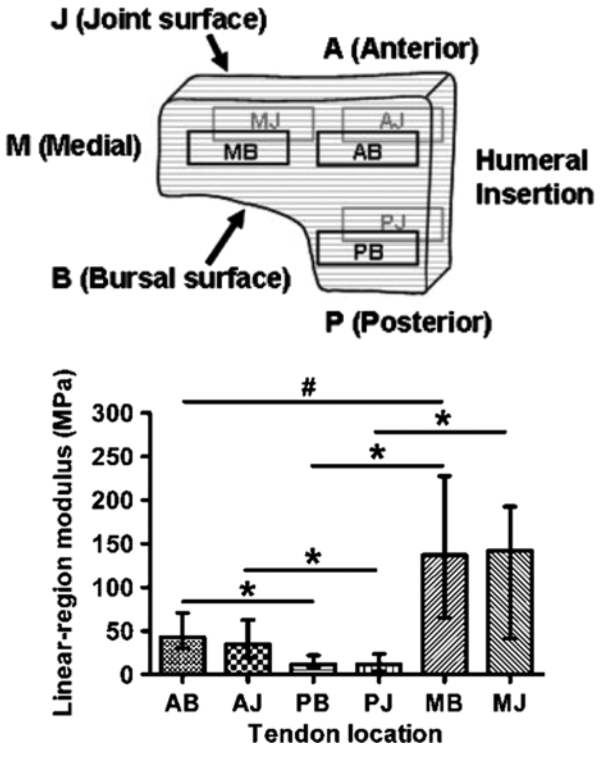

FIGURE 3. Top: Harvest locations of 6 human supraspinatus tendon samples used for comparison of mechanical properties (schematic represents tendon harvest locations in a right shoulder). Bottom: Linear region modulus results depict inhomogeneous tensile properties of the supraspinatus tendon (*significant; $^{\#}$trend). Reprinted with permission from *J Orthop Res.* 2009;27:1596–1602.

Reilly et al[31] placed differential variable reluctance transducers within the supraspinatus "critical zone" and reported, both for the anterior and posterior regions, increasing tensile strain on the articular side of the tendon and compressive strain on the bursal aspect with progressive shoulder abduction. Huang et al[7] measured strain simultaneously on the bursal and articular tendon surfaces during displacement-controlled testing of the supraspinatus at different elevation angles. A strain gradient across the tendon thickness was noted, whereby the articular surface exhibited greater strain at 22 and 63 degrees of glenohumeral abduction and the bursal surface experienced greater strain at 90 degrees.[7] Higher tensile strains for the insertional region was noted at all abduction angles as compared with more proximal regions. Bey et al[32] developed a novel magnetic resonance image-based approach for quantifying intratendinous strain in human cadaveric supraspinatus specimens. A primary advantage of this technique is the ability to measure strain variations through the thickness (depth) of the tissue. Their results indicate that intratendinous strain significantly increased with joint angle and that strain was considerably more sensitive to joint position rather than tendon region (superior, middle, and inferior locations within the critical zone).[32]

Inconsistencies in strain magnitudes in the above-cited studies may be due to factors such as differing donor age and sex distribution, measurement techniques and mechanical loading parameters and protocols. Collectively, results from the aforementioned studies suggest that the mechanism of biomechanical load transmission through the supraspinatus tendon is complex and there exist mechanical predispositions to injury at the insertion site with either the articular or bursal surfaces, depending on humeral elevation. Additional factors may include duty cycle (frequency of loading) of the supraspinatus and the accompanying cellular responses to these mechanical inputs.

Subscapularis Tendon

Halder et al[33] quantified structural properties of 4 discrete regions (superior, mid-superior, mid-inferior, and inferior) of the human subscapularis tendon by conducting tensile testing at 0 and 60 degrees of glenohumeral abduction. Geometrically, the mean cross-sectional area of the superior region (40.3 mm^2) well exceeded that of the inferior region (27.3 mm^2). Although statistical trends differed between properties obtained at the 2 abduction angles, stiffness and ultimate load were higher for the superior and mid-superior tendon portions.

Infraspinatus Tendon

Halder et al[19] reported on geometric and structural properties of the teres minor and 4 regions of the infraspinatus tendon. Specimens were randomly assigned to testing either at 0 or 60 degrees of glenohumeral abduction and the infraspinatus was divided into 4 distinct superior-inferior anatomic units. The tensile modulus was significantly higher for specimens tested at 60 degrees of abduction, but all remaining mechanical outcomes were similar between the 2 angles. The cross-sectional area of the infraspinatus tendon (range of mean values across 4 regions: 20.8 to 29 mm^2) was significantly lower than that of the teres minor (mean, 49 mm^2). Interestingly, the mid-superior and inferior regions of the infraspinatus generally exhibited higher ultimate load, stiffness, ultimate stress, and tensile modulus compared with the superior and mid-inferior regions. Furthermore, both structural and material properties of infraspinatus regions were dramatically greater than those of the teres minor. As is the case with the subscapularis tendon, further study is required to better clarify implications of these findings to rotator cuff injury (specifically in the setting of massive cuff tears).

EFFECTS OF INJURY AND MECHANICAL LOADING

Rotator cuff injury and tears may be attributable to extrinsic and/or intrinsic factors. Extrinsic factors include subacromial impingement of the bursal aspect of the tendon by the overlying acromion and/or internal impingement of the superior glenoid on the articular aspect of the supraspinatus tendon. Intrinsic factors which may include vascular, biologic, and morphologic tendon properties. The etiology is likely multifactorial.[34,35]

Neer and Poppen[36] first described the theory of subacromial impingement in an intraoperative study of 400 patients with rotator cuff tears. They postulated that the etiology of the rotator cuff tears in 95% of their patients was subacromial impingement on the cuff by the anterior third of the acromion.[36] The degree of impingement beneath the acromion was later hypothesized to correlate with acromial shape.[37] However, it is unclear as to whether impingement induces cuff damage or if weakness and dysfunction of the rotator cuff (eg, resulting in superior humeral translation) lead to subacromial impingement. Regardless of cause, the functional manifestation of tears in the rotator cuff is increased anterior and superior humeral head translation and decreased external and upward rotation.[38–41]

Effects of Rotator Cuff Tears

After simulating anterior, bursal-sided partial tears in cadaveric supraspinatus tendons, Yang et al[42] reported a 23.8% increase in tensile strain in the posterior tendon after a tear of 60% of the tendon thickness, relative to the intact tendon. Bey et al,[43] using magnetic resonance image to quantify intratendinous strain, reported that simulated rotator cuff tears at the inferior aspect of the articular side of the tendon resulted in significantly increased strain in the middle and superior portions of the supraspinatus. Results from these 2 studies support the notion that partial thickness tears may predispose the remaining rotator cuff to further damage, and that surgical repair should strongly be considered in these situations.

Andarawis-Puri et al[44] examined mechanical interactions between the supraspinatus and infraspinatus tendons during simulated rotator cuff defects. They found that a simulated tear of 66% of the supraspinatus tendon width increased the average apparent maximum principal strain and decreased the average apparent minimum principal strain in the infraspinatus tendon. In addition, by progressively increasing supraspinatus tendon loading on an intact tendon, an increase in apparent maximum strain and decrease in apparent minimum principal strain in the infraspinatus tendon was found. They, therefore, showed an interaction between rotator cuff tendons in both intact and pathologic states and suggested that this interaction should be considered when treating rotator cuff tears (Fig. 3).[44]

Of relevance to biomechanical performance after suture repair, Wang et al[5] observed superior resistance to pullout of medially versus laterally placed tendon sutures in torn human supraspinatus tendons. The investigators concluded that these suture retention properties may provide a strain shielding effect for the lateral row after double-row repair. In contrast, no regional differences in suture retention properties were apparent among intact tendons. Biomechanically, the inferior suture pullout characteristics of the lateral supraspinatus tendon may, in part, explain the high retear or failure-to-heal rates after primary rotator cuff repair.

In Vivo Animal Models

In vivo animal models of tendinopathy facilitate the rigorous investigation of temporal changes in biomechanical, histological, and compositional properties of pathologic rotator cuff tendons. In general, tendinopathy models can be classified as those reliant on alteration of either the mechanical (eg, overuse) or chemical environment (eg, collagenase).[45,46] At present, there does not appear to exist a consensus regarding the most translationally relevant injury model for studying rotator cuff tendinopathy. Rather, most investigators agree that specific animal models have utility in specific instances such as dogs and horses for strain induced tendinopathy and that their results should not be generalized across different pathologies and anatomic sites.[45,46]

Overuse (through mechanical loading) has long been implicated in rotator cuff tendon pathology. Mechanical overuse of the supraspinatus was explicitly tested by Soslowsky[47] by examining tendon alterations in a rat model of decline treadmill running. The supraspinatus tendon in their overuse model exhibited an increased cross-sectional area, hypercellularity, and collagen disorganization. Biomechanically, maximum stress and elastic modulus were significantly lower in the overuse group when compared with cage control rats. These finding suggested that overuse of the rotator cuff can lead to compromised tendon properties and may predispose the rotator cuff to tearing.[47,48]

Perry et al[49] provided in vivo evidence that rotator cuff tears negatively affect the adjoining intact tendons. Specifically, after simulated full thickness supraspinatus tendon tears in rats, the infraspinatus and subscapularis tendons showed increased cross-sectional area and decreased modulus of elasticity. These findings became more pronounced with time (4 vs. 8 wk) and also as the number of damaged tendons increased. These results support the notions that chronic rotator cuff tears may ultimately lead to additional cuff pathology, and furthermore, combined supraspinatus/infraspinatus tendon tears are more detrimental to subscapularis tendon properties than a supraspinatus tear alone.[49]

CONCLUSIONS

Musculotendinous tissue structure and biomechanical properties, and mechanical interactions between the tendons themselves contribute prominently to function and dysfunction of the rotator cuff. Clinically translational approaches, likely using advanced noninvasive imaging technology, electromyography, and/or in vivo anatomical reconstruction, are needed ito further advance our understanding of the role of biomechanical factors in rotator cuff pathology.

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