

Histologic and biomechanical characteristics of the supraspinatus tendon: Reference to rotator cuff tearing

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A bursal- or joint-side incomplete thickness tearing of the rotator cuff is clinically important, because it is known that this tearing has the potential to develop into a complete tendon disruption. Normal cadaveric supraspinatus tendons were analyzed histologically and biomechanically to clarify the differences in pathomechanical causation of bursal- and joint-side incomplete tears. Histologically, the bursal-side layer was composed of tendon bundles with a decreasing muscular component toward the insertion. The joint-side layer was a complex of tendon, ligament, and joint capsule without transitional areas. Biomechanically, the bursal-side layer had greater deformation and tensile strength. When each layer was divided into three portions of equal length, the middle segment of the bursal-side layer elongated the most, whereas the entire joint-side layer increased evenly in length. We conclude that the joint-side layer is more vulnerable to a tensile load than the bursal-side layer. (J SHOULDER ELBOW SURG 1994;3:79-87)

The cause of rotator cuff diseases, especially tears, has aroused much controversy. It has been thought that repetitive damage to the supraspinatus tendon occurs because of its anatomic position between the coracoacromial arch and the humeral head. Thus attrition, trauma, and subacromial impingement are most frequently cited as causative factors. They produce bursal-side, joint-side, or intratendinous incomplete tears and complete thickness rotator cuff tears. Meyer¹⁵ attributed rotator cuff tears to attrition. The cuff degenerates with aging, and most patients with cuff tears are older than 40 years. Codman³ suggested that trauma caused an incomplete thickness cuff tear within

the deep layer and that this tear progressed to a complete tear.

Neer¹⁸ comprehensively described the role of subacromial impingement in rotator cuff diseases. He also proposed three progressive stages of the impingement syndrome.¹⁹ In addition to impingement being a cause of cuff tears, the impingement concept has been recognized as offering some unification to understanding various pathologic changes in rotator cuff diseases. Fukuda et al.⁷ compared clinical findings and large histologic sections of incomplete thickness cuff tears demonstrating ongoing, pathologically identifiable processes. These authors emphasized that subacromial impingement produced a tear in bursal-side rotator cuff tendon layer (B-S) primarily and in joint-side layer (J-S) secondarily. In their study, the history of trauma was elicited more frequently in J-S than in B-S tears.⁸ Consequently, it is speculated that the pathomechanics of B-S and J-S incomplete thickness tears might be different. To clarify the differences in the inherent properties between B-S and J-S, we established an experimental condition excluding the effects of subacromial impingement. Histology of

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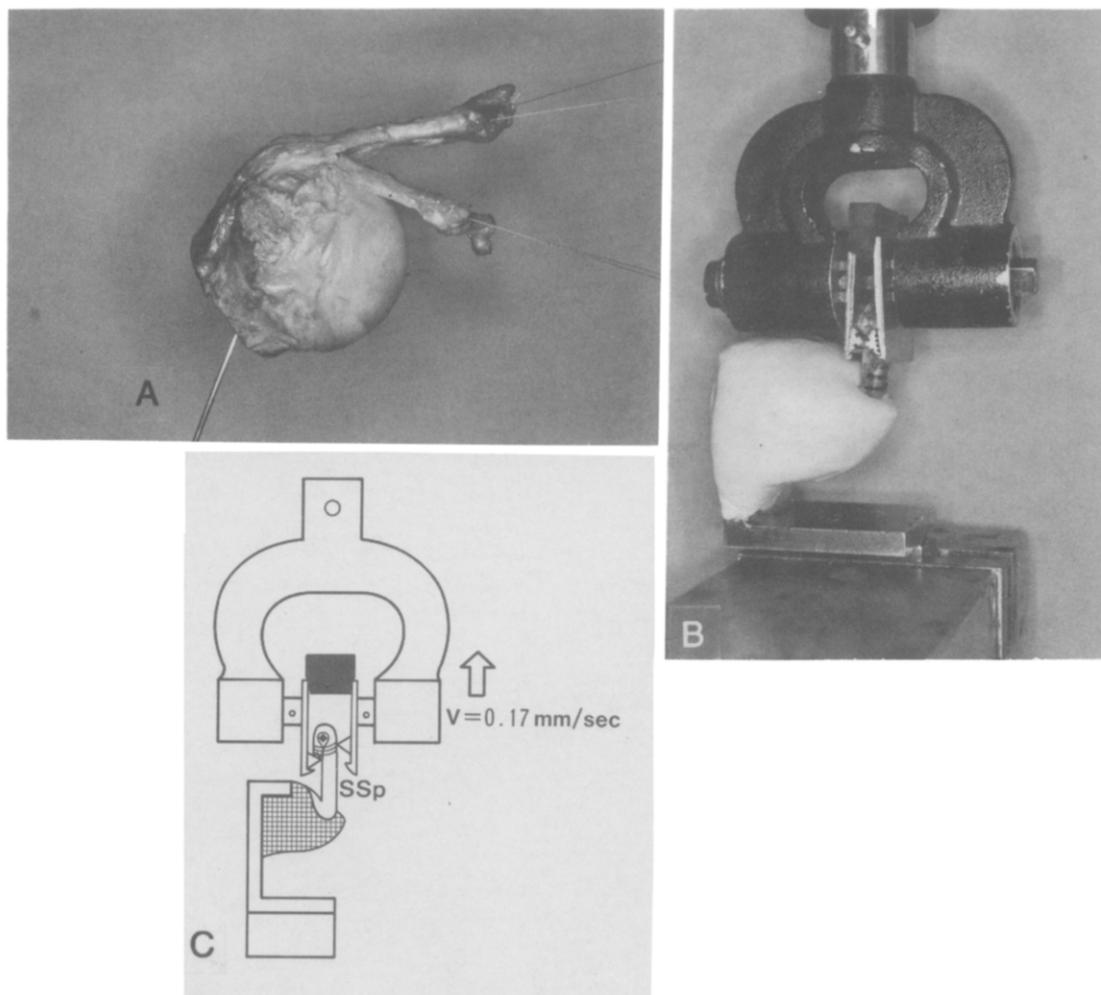


Figure 1 **A**, Supraspinatus tendon was sharply divided horizontally into bursal-side and joint-side layers of equal thickness; **B, C**, Proximal part of humerus, including greater tuberosity, was fixed to L-shaped metal device with methylmethacrylate. Muscle belly of supraspinatus was coiled around rod and held with rubber compression clamp. Each tendon was marked into three portions of equal length; distal, middle, and proximal portions. Quasi-static tensile test (velocity of cross-head, 0.17 mm/sec) was performed with Instron 1000 Tension Analyzer.

cross-sections of normal rotator cuff tendons was studied, and the biomechanical properties of the supraspinatus tendon were analyzed with cadaveric specimens.

MATERIAL AND METHODS

Histologic study. Twenty normal rotator cuffs were obtained at autopsy; age at death ranged from 28 to 73 years (two patients in twenties, one in thirties, three in forties, four in

fifties, eight in sixties, two in seventies). Mean age at death was 58.2 years; 10 male and 10 female cadavers were studied. Cross-sections were examined 2, 7, 12, and 17 mm from the insertion of the supraspinatus tendon on the humeral head. Staining was done with hematoxylin-eosin, and Azan in Mallory's solution. The size and structure of fibers in B-S and J-S were compared, excluding the subacromial bursa from analysis.

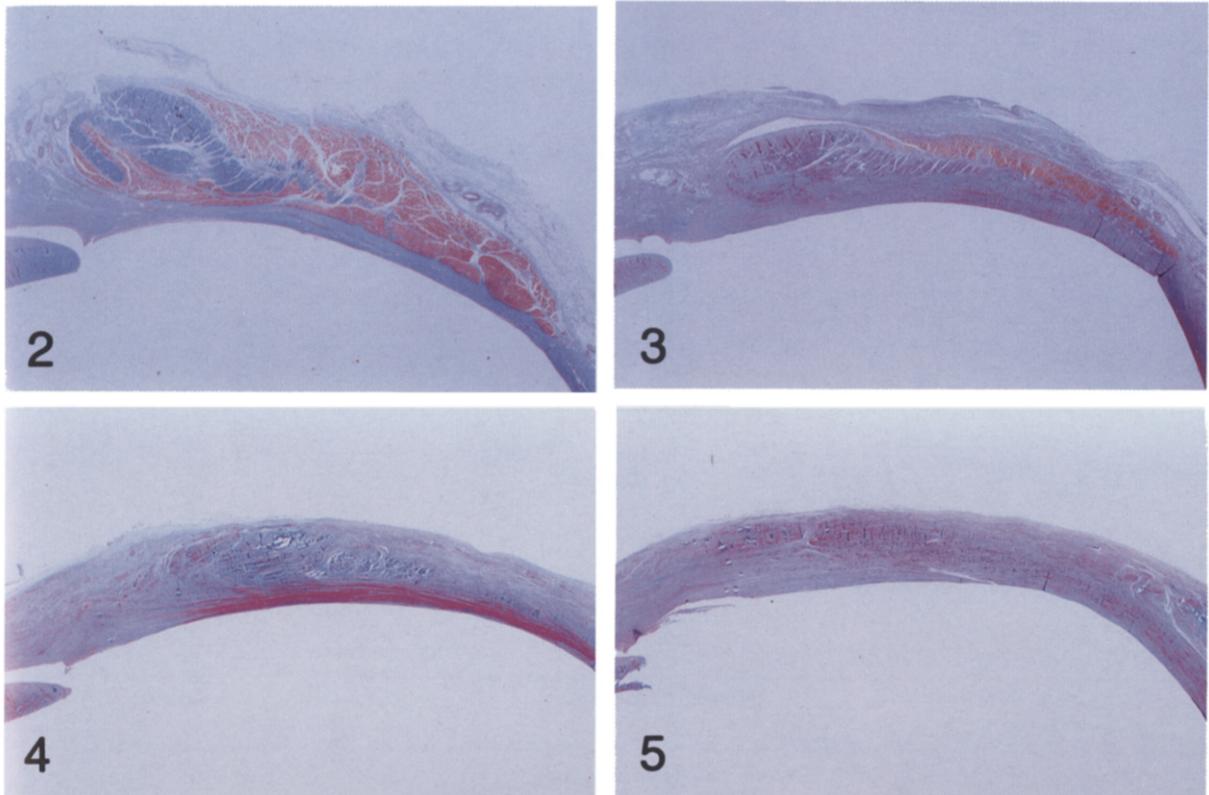


Figure 2 Cross-section 17 mm from insertion of supraspinatus tendon (Azan stain $\times 10$). Bursal-side layer was mixture of muscle and tendon fibers running longitudinally. Longitudinal fibers in joint-side layer were stratified.

Figure 3 Cross-section 12 mm from insertion of supraspinatus tendon (Azan stain $\times 10$). Critical portion of Codman. Fibers predominantly were in bursal-side tendon bundles, which joined with some muscle fibers. Transverse fibers interlaced with superficial layer of longitudinal capsular fibers in joint-side.

Figure 4 Cross-section 7 mm from insertion of supraspinatus tendon (Azan stain $\times 10$). Bursal-side layer was composed of group of tendon bundles and were thicker than fibers in joint-side. Joint-side layer was complex of tendon, ligament, and capsule. Deep extensions of coracohumeral ligament united tendon bundles and joint capsule.

Figure 5 Cross-section 2 mm from insertion of supraspinatus tendon (Azan stain $\times 10$). Tendon bundles in bursal-side were more compact. Joint-side fibers at this level were thinner and associated with large amount of interfibrillar space, much more so than in other tendon segments.

Biomechanical study. Forty other grossly intact specimens were resected and cut into strips 25 mm in width. Age of these specimens ranged from 28 to 79 years (two patients in twenties, two in thirties, four in forties, six in fifties, 17 in sixties, nine in seventies). Mean age was 59.3 years; 18 male and 22 female cadavers were studied. The tendon was frozen at

-80°C and tested at room temperature immediately after thawing.¹³ The tendon was divided horizontally into B-S and J-S of nearly equal thickness with a sharp blade (Figure 1, A). The length and thickness of both layers were measured with a caliper. The proximal part of the humerus, including the greater tuberosity, was fixed to an L-shaped metal device

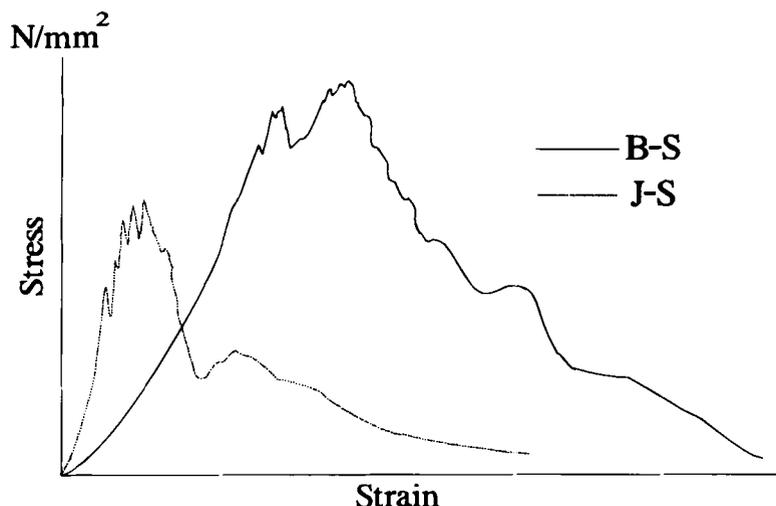


Figure 6 Typical stress-strain curves of supraspinatus tendon. Bursal- and joint-side layers (B-S and J-S) of tendon showed nonlinear deformation initially, followed by elastic elongation. Two curves were distinctly different.

Table I Histologic differences between the bursal- and joint-side layers ($n = 20$)

From the insertion (mm)	Bursal-side layer (B-S)	Joint-side layer (J-S)
17	A mixture of the longitudinal fibers of muscles and tendons	A stratified structure composed of the longitudinal fibers
12 (critical position)	Some muscle fibers within predominant tendon bundles	The transverse and longitudinal fibers interlacing
7	A group of tendon bundles, being thicker than the J-S fibers	A complex of tendon, branch of coracohumeral ligament, and joint capsule
2	The most compact portion of the tendon bundles	The thinnest transverse fibers with the largest interfibrillar spaces

with methylmethacrylate. The muscle belly of the supraspinatus was then coiled around a square aluminum rod and held with a rubber compression clamp. Care was taken not to twist the specimen or to hold the tendon or joint capsule directly. Each specimen was marked into three portions of equal length: distal (2 to 7 mm from the insertion), middle (7 to 12 mm), and proximal (12 to 17 mm) portions. A quasistatic tensile test (velocity or cross-head, 0.17 mm/sec) was performed separately for each layer with the Instron Universal Testing Instrument (model 1000, Boston, Massachusetts; Figure 1, B, C). To ensure that B-S and J-S were subjected to an equal tensile load, the load was

applied at a fixed angle of 90° to the anatomic neck of the humerus. The behavior of both layers was recorded with a camera, and the strain in each portion was calculated. The Student *t* test was used to compare ultimate failing stress, strain to yield point, and elastic modulus for each layer. After the tensile test, the distal part of the specimen was sectioned longitudinally for histologic examination, examining for ruptures caused by the tensile load.

RESULTS

Histologic findings. In the cross-section 17 mm from the insertion, B-S contained a mixture of the muscle and tendon fibers running longi-

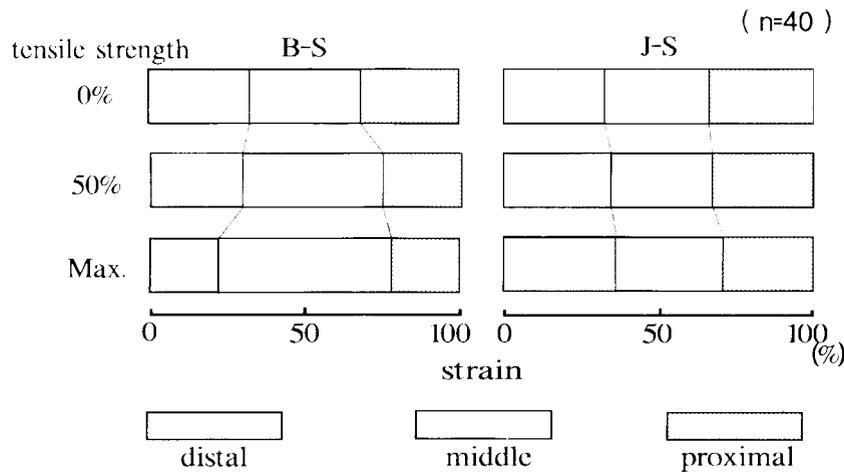


Figure 7 Average elongation in bursal-side layer (B-S) was greater in following order: the middle > proximal > distal portions. However, each portion of joint-side layer (J-S) showed almost same degree of deformation.

Table II Biomechanical properties of supraspinatus tendon on a tensile load ($n = 40$, mean \pm standard deviation)

	Bursal-side layer (B-S)	Joint-side layer (J-S)	
Modulus of elasticity*	7.2 ± 0.3	8.2 ± 0.2	($\times 10^{-3}$ N/mm ² · strain)
Strain to yield point	0.15 ± 0.04	0.07 ± 0.03	(Strain)
Ultimate failing stress	6.3 ± 1.1	2.8 ± 0.7	(N/mm ²)

The Student *t* test was used to compare the values of B-S and J-S.

*At half of ultimate failing stress

tudinally. Longitudinal fibers in J-S had a stratified structure (Figure 2).

In the cross-section 12 mm from the insertion (the critical portion of Codman), the B-S fibers were thicker than the J-S fibers. They formed predominant tendon bundles surrounded by endotenonous sheaths. Some muscle fibers joined with those bundles. In J-S, transverse fibers interlaced with a superficial layer of longitudinal fibers (Figure 3).

In the cross-section 7 mm from the insertion, B-S was composed of a group of tendon bundles, and J-S was primarily transverse fibers of a smaller diameter than B-S. Some fibrous tissue, originating from the coracohumeral ligament, ensheathed the group of tendon bundles. The deep branches of the ligament mingled with the transverse fibers in J-S (Figure 4).

In the cross-section 2 mm from the insertion, the tendon bundles in B-S were united and compact. In J-S, the fibers were thin with a large

amount of interfibrillar space, among the four portions examined (Figure 5).

The differences of histology between B-S and J-S at the four separate levels are summarized in Table I. They were similar in the autopsy specimens of all decades.

Biomechanical properties. B-S and J-S of the supraspinatus tendon typically showed different stress-strain curves (Figure 6). The modulus of elasticity in B-S was lower than that in J-S ($p = 0.05$). In contrast, strain to yield point and ultimate failing stress in B-S were twice those observed in J-S ($p < 0.001$) (Table II). The average elongation in B-S was greater in the following order: middle > proximal > distal portions. However, each portion of J-S showed almost the same degree of deformation ($p = 0.01$) (Figure 7). Biomechanical properties of the two layers were similar to those illustrated in specimens of differing decades.

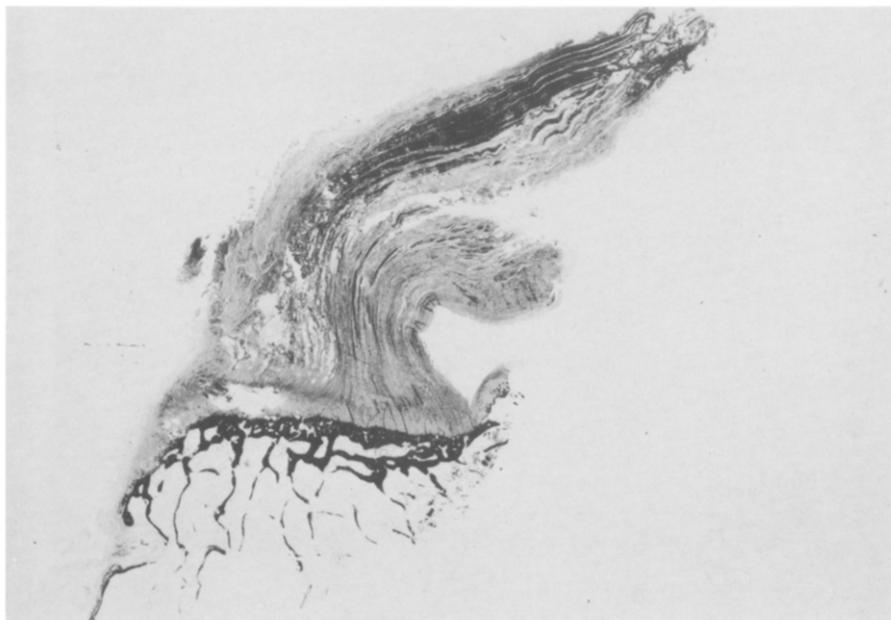


Figure 8 Coronal-section of distal part of specimen after tensile testing ($\times 2$). Macroscopic complete ruptures, occurring in proximal portions of B-S and J-S layers, were defined as "gross" ruptures. Incomplete intratendinous ruptures, observed histologically near insertions of both layers, were defined as "concealed" ruptures.

Table III Sites of "gross" and "concealed" ruptures ($n = 40$)

	Insertion	"Gross" ruptures			"Concealed" ruptures
		Distal	Middle	Proximal	
Bursal-side layer (B-S)	6	3	18	13	24
Joint-side layer (J-S)	8	18	10	4	19

"Concealed" ruptures occurred in both layers of 12 supraspinatus tendons.

Tendon ruptures caused by a tensile load. "Ruptures" caused by tensile loading were distinguished from premorbid "tears" of the supraspinatus tendon by the absence of fibrinoid material on the ruptured surface. Macroscopic complete ruptures were defined as "gross" ruptures, and incomplete intratendinous ruptures, observed histologically, were defined as "concealed" ruptures (Figure 8). Approximately 80% of the gross ruptures in B-S occurred in the middle or proximal portion (7 to 17 mm from the insertion). However, 70% of J-S was grossly torn in the distal or middle portion (2 to 12 mm). All the J-S fibers ruptured simultaneously (Table III). The incidence of concealed ruptures, which occurred near the in-

sertions or in the distal portions of both layers, was not distinctly different between B-S and J-S. While the concealed ruptures in B-S were disseminated, those in J-S were solitary (Figure 9, A, B). These patterns of gross and concealed ruptures did not vary with the age of the specimens.

DISCUSSION

Histologic cross-sections of the rotator-cuff showed predominantly a group of tendon bundles in B-S. Almost all B-S fibers seemed to be running parallel to the direction of the tensile load in this study. In the critical portion, which was defined by Codman³ as the portion 0.5 inch proximal to the tendon insertion, some muscle

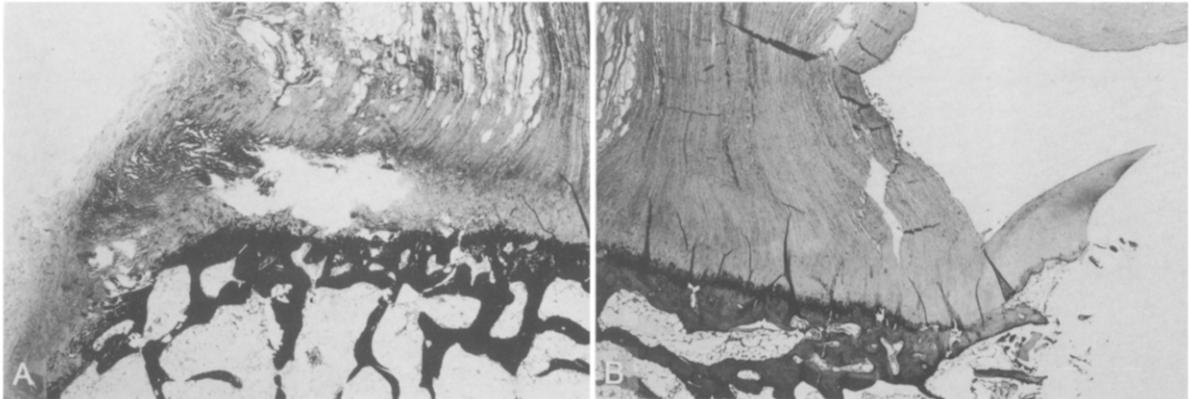


Figure 9 "Concealed" ruptures of supraspinatus tendon caused by tensile loading ($\times 20$). Concealed ruptures in bursal- and joint-side layers (B-S [A] and J-S [B]) were observed mostly near insertion. While concealed ruptures in bursal-side were disseminated, those in joint-side were solitary.

fibers were still observed adjacent to the longitudinal tendon fibers. They were ensheathed by deep branches of coracohumeral ligament. Because it has two heterogeneous tissues, the critical portion of B-S may be damaged more easily by a tensile load than the other portions. On the other hand, the histologic component in each portion of J-S was almost homogeneous with no transitional area; the directions of the J-S fibers were not always the same. The distal portion of J-S had thinner fibers than the other portions.^{6, 10, 11, 28} Based on these findings, it is concluded that a tensile load concentrates on the distal portion of J-S. Clark² clarified the anatomy of the composite structure of the rotator cuff and identified a thick sheet of fibrous tissue from the coracohumeral ligament reinforcing the supraspinatus tendon.

Biomechanically, it has been reported that the supraspinatus tendon (19 mm wide and 3 mm thick) can endure a tensile load of about 454 kg.^{5, 16} However, its ultimate failing stress in our study was about 9 N/mm², approximately an eighth of the previously mentioned value. In the past studies, the preservation of specimens was not consistent, and the loading rates or ages of the subjects were not clearly noted. A quasi-static tensile test was performed to clarify the differences of biomechanical properties between B-S and J-S. It is well known that ultimate failing stress of a ligament is smaller at a lower loading rate.^{9, 22} Furthermore, although normal autopsy specimens were tested, their average age at death was 59.3 years. Similar to other

reports,²³ the ultimate failing stress we obtained must have included the effects of aging. Our result may also have been affected by the horizontal splitting of the supraspinatus tendon. These experimental conditions, which were not equivalent to an extrinsic load in vivo, appeared to be responsible for the low ultimate failing stress observed. However, they should have influenced B-S and J-S similarly and can be ignored when comparing the biomechanical properties of the two layers. Therefore, we conclude that J-S is more easily ruptured by a tensile load than is the B-S. These biomechanical differences between B-S and J-S are thought to relate to their histologic differences. Being composed primarily of a group of longitudinal tendon bundles, B-S could disperse a tensile load and generate greater resistance and elongation than J-S. In contrast, the J-S fibers interlaced lengthwise and crosswise and were thinner than the B-S fibers. These histologic characteristics render J-S more vulnerable to a tensile load.

Brewer¹ and Pettersson²⁵ clinically pointed out that the resiliency of the supraspinatus tendon decreased with age. Macnab¹² showed in his experiments that the insertion of supraspinatus tendon was damaged by the compression effect of humeral head in repeated shoulder motions. In the present study, however, the middle portion of B-S showed the greatest strain among all portions, and the distal aspect of the J-S had almost the same elongation ratio as the other segments of the tendon, despite the presence of premorbid histologic degeneration in this seg-

ment. These results suggest that the elasticity of both layers depends strongly on their inherent histologic structures; i.e., the middle portion of B-S, which appears tendinous, includes some muscle fibers, whereas each portion of J-S is a homogeneous composite structure of tendon, ligament, and joint capsule. These findings are one of the reasons the difference in elasticity between B-S and J-S was greatest in the middle portion. Furthermore, this difference may cause a shearing force within the supraspinatus tendon. Lindblom¹¹ suggested that during abduction there was a difference in tension between B-S and J-S, which might act as a shearing force. The branches of coracohumeral ligament appears to prevent these two layers from separation by uniting them.^{2, 10}

The site of rupture in a tendon usually depends on the loading rate and the quality of the tendon. Kennedy⁹ and Noyes et al.,^{21, 22} using human anterior cruciate ligaments, showed that the greater the loading rate was, the more likely the ligamentous portion ruptured. In McMaster's study on tensile strength of rabbits' extensor tendons,¹⁴ normal tendinous portions were more resistant to rupture than tendon insertions or musculotendinous junctions. In the present study, despite a quasistatic tensile test with normal cadaveric supraspinatus tendons, all specimens ranging from 20 to 79 years at death were grossly injured in their tendinous portion, especially, the middle portion of B-S and the distal aspect of J-S. Therefore, the rupture patterns in the two layers were distinctly different, possibly because (1) the middle portion of B-S contained the transitional area between muscle fibers and tendon bundles and was more elastic than the others, and (2) the J-S fibers, which elongated evenly in each portion, became more slender toward the insertion where transverse fibers were predominant. However, the middle portion of B-S, containing the critical portion, is also affected by attrition^{6, 10, 15} and impingement^{4, 18, 20, 24} as well as by ischemic changes.^{11, 17, 26, 27} The distal portion of J-S becomes fibrillated as age progressed.^{11, 28} Our results may have been influenced to some degree by the intrinsic and extrinsic factors occurring on each tendon before death, and the diversity of the tear patterns may be explained by these individual alterations.

Gross and concealed ruptures in both layers of the supraspinatus tendon are based on these

histologic characteristics and biomechanical properties. In B-S, even if some tendon bundles had disseminated concealed ruptures, the remaining ones could resist a greater tensile load with larger strain than in J-S. On the contrary, when a solitary concealed rupture occurred in J-S, it progressed easily to a gross rupture in the distal portion because of the "notch effect" demonstrated by Macnab's experiment.¹² Therefore, it is concluded that J-S is more vulnerable to a tensile load.

SUMMARY

Histologic differences exist between the bursal- and joint-side layers of the supraspinatus tendon, and these two layers were found to have different biomechanical properties. For example, B-S, composed primarily of tendon bundles, increased in length to a tensile load but was resistant to rupture. J-S, on the other hand, a complex of tendon, ligament, and joint capsule, elongated poorly but tore more easily. We conclude that J-S is more vulnerable to a tensile load than B-S.

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