Cyclic Loading of Transosseous Rotator Cuff Repairs: Tension Overload as a Possible Cause of Failure

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Summary: Previous experimental studies of failure of rotator cuff repair have involved a single pull to ultimate load. Such an experimental design does not represent the cyclic loading conditions experienced in vivo. We created 1 cm X 2 cm rotator cuff defects in 16 cadaver shoulders, repaired each defect with transosseous simple sutures, and cyclically loaded the repairs by a servohydraulic materials test system actuator at physiologic rates and loads (rate of 33 mm/sec to a load of 180 N.). A progressive gap was noted in each specimen, for a 100% rate of failure of the repairs. A 5 mm gap developed at an average of 25 cycles, and a 10 mm gap developed at an average of 188 cycles. The central suture always failed first and by the largest magnitude. This study suggests that rotator cuff tears that are repaired with a "tension overload" of a portion of the muscle-tendon units will undergo gradual failure with physiologic cyclic loading until the normal resting lengths of the muscle-tendon units are restored. This "controlled failure" of the repairs may explain residual defects that have been demonstrated by ultrasonography and by arthrography in patients with "successful" rotator cuff repairs. Clinical implications are that: 1) rotator cuff tears should be repaired without tension if possible; and 2) transosseous bone tunnels should ideally extend distal to the weak metaphyseal bone so that purchase is obtained into cortical bone for greater fixation strength. Key Words: Rotator cuff—Rotator cuff repair—Tendon repair—Biomechanical testing.

A variety of experimental studies have been conducted to investigate the factors that cause rotator cuff repairs to fail.1-7 These factors have gained increasing attention in view of the fact that recent clinical series have noted a high rate of residual defects in surgically repaired rotator cuffs. Harryman et al.8 have demonstrated these defects by ultrasonography, while Calvert et al.9 have shown them arthrographically. Liu and Baker10 reported that 50% of their rotator cuff repairs showed persistent cuff defects by postoperative arthrography.

We reviewed the literature on experimental investigations of rotator cuff fixation failure.1-7 All studies that we reviewed used an experimental model in which the rotator cuff repair was taken to failure by a single pull to the ultimate load. We could find no studies that used cyclic loading as a means of producing cuff fixation failure. Since cyclic loading is the mechanism by which rotator cuff fixation failure occurs in vivo, we elected to study failure modes of rotator cuff repair by means of cyclic loading. Load magnitudes and loading rates were chosen to be within the physiologic range. This physiologic cyclic loading study of the rotator cuff is, to the best of our knowledge, the first of its type.

MATERIALS AND METHODS

Sixteen fresh frozen human cadaveric shoulders were used in this investigation. The average age of the
specimens was 41.2 years, and the range was 18 to 63 years. In each case, the specimen consisted of a humeral head and an intact rotator cuff. There were no pre-existing rotator cuff tears in these specimens. A rotator cuff defect was created at the insertion of the supraspinatus and a portion of the infraspinatus. This defect measured $1 \times 2$ cm and comprised a portion of the rotator crescent (Fig 1). An actual defect was made rather than a simple detachment because the authors have observed that most rotator cuff tears involve degeneration at the tendon insertion, with actual loss of tendon substance. This experimental configuration was considered to better simulate the clinical situation. Transosseous bone tunnels were made so that there was a 2 cm bone bridge between the entrance and exit sites of each tunnel, and 8 mm between each pair of the three tunnel holes in the lateral humerus. In most cases, the distal hole was located in the metaphyseal bone, although in seven cases with small humeral heads the 2 cm bone bridge allowed placement of the lateral hole relatively more distally (because of the small specimen size) into cortical bone. The rotator cuff defect was closed using three simple sutures through transosseous tunnels. The sutures were placed 5 mm from the free margin of the tear, with eight specimens being repaired with No. 2 cottony Dacron and the other eight specimens being repaired with No. 2 Ethibond. The proximal end of the rotator cuff tendon was affixed to a looped nylon strap by means of multiple mattress sutures as a means of applying load to the repaired tendon.

The purposes of this study were to determine whether progressive fixation failure of the repaired rotator cuff occurred with cyclic loading; if fixation failure occurred, to measure the number of cycles required to reach 50% failure (a 5 mm gap) and 100% failure

FIG 1. Photograph showing a representative cadaver specimen in which a $1 \times 2$ cm rotator cuff defect was created at the insertion of the supraspinatus and a portion of the infraspinatus. Repair was by three simple transosseous sutures. Nylon straps were sutured to the cuff tendon involved in the defect for attachment to the MTS actuator.

The humerus was fixed by means of an adjustable vise so that the repaired tendon could be longitudinally loaded in the anatomic direction of the repaired muscle-tendon unit. The nylon strap that had been sutured to the tendon was affixed over a horizontal bar that was connected to the vertical actuator of a servohydraulic materials test system (MTS Model 858 Bionix, MTS Corp, Minneapolis, MN). Each specimen was then cyclically loaded to 180 N. at a rate of 33 mm/second. The duration of each cycle was 5 seconds. The load of 180 N represented approximately two thirds the load that could be delivered by a maximal contraction of the muscles that subtended the cuff defect so the load was considered to be well within the physiologic range. The rate of 33 mm/second has been previously reported as a loading rate that occurs in normal daily activities.

Each specimen was cyclically loaded and observed for failure of the cuff repair. Calipers were used to measure gap formation at the repair site. The repair was deemed to have reached 50% of complete failure when a 5 mm gap had developed (the original defect had a width of 10 mm) and complete failure when a 10 mm gap developed. The extent to which failure occurred through bone or tendon was also observed and measured.

Three control specimens without rotator cuff defects or repairs were cyclically loaded with an arbitrary cut off at 3,500 cycles. That is, if failure had not occurred by 3,500 cycles, we considered that failure would be unlikely to occur with further cycling, and we stopped loading that specimen.

Donor variability and the effects of suture repair material (Ethibond and Dacron) on the number of cycles for 5 mm gap creation and 10 mm gap creation were examined using analysis of variance (ANOVA). Fisher’s Least Significant Difference (FLSD) multiple comparisons test of the means was applied when the F-test in ANOVA was significant ($P > .05$). Unpaired Student's t-test was performed to look at the differences between donor height, weight, age, cycles for 5 mm gap and cycles for 10 mm gap for the two suture materials. The statistical significance level was set at $P < .05$ for all tests.

RESULTS

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FIG 2. (A) Diagrammatic representation of the cuff tear. Muscle-tendon units are referenced to an arbitrary plane of origin through the medial scapula. The undisturbed muscle-tendon unit has a length $L_1$. The shortened muscle-tendon unit at the apex of the cuff tear has a length $L_2$, which is less than $L_1$. (B) Repair of the rotator cuff defect can be accomplished either by releasing the origin of the muscle-tendon units that comprise the defect and repairing the defect without undue tension or by closing the defect under tension, thereby creating a "tension mismatch" between $L_1$ fibers and $L_2$ fibers. (C) The bone bed should be prepared so that the rotator cuff is repaired under minimal or no tension, respecting to some extent the crescent-shaped margin of the tear.

(a 10 mm gap); and to observe the location of the failure (bone, tendon, suture). All specimens eventually failed to a 10 mm gap. The specimens reached 50% failure at an average of 25 cycles (33.00 cycles for cottony Dacron and 16.88 for Ethibond). The difference in cycles to failure between the Dacron and Ethibond were found not to be statistically significant ($P > .05$). The specimens reached 100% failure (10 mm gap) at an average of 188 cycles (195.88 for cottony Dacron and 169.63 for Ethibond). Again, the difference between Dacron and Ethibond was not statistically significant ($P > .05$). No failure of rotator cuff attachments occurred in the three control specimens that underwent 3,500 cycles.

Donor height, weight, and age were found not to show statistically significant differences between repair groups and control groups. There was also no significant difference between Dacron and Ethibond in regard to the number of cycles required to form 5 mm and 10 mm gaps. However, there was a significant difference between both Dacron and Ethibond versus the controls in reaching 5 mm and 10 mm gaps ($P = .0001$). That is, the consistent failure of the repaired specimens was statistically significant at $P = .0001$.

There was one pure suture failure. Of the 15 remaining specimens, six were primarily cuff failures characterized by the suture pulling through the tendon substance; six were primarily bone failures character-
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FIG 3. (A) U-shaped rotator cuff tear. (B) Partial side-to-side repair causes a “margin convergence” of the tear toward the greater tuberosity. This increases the cross-sectional area and decreases the length of the tear, thereby decreasing strain (since elongation is directly proportional to the length of the tear and inversely proportional to the cross-sectional area).

ized by the transosseous sutures cutting through the bone bridge; the other three showed failure of both cuff and bone. Seven distal bone holes were into cortical bone and nine were into metaphyseal bone. When the distal bone hole was clearly in cortical bone, six of seven showed primarily cuff failure. When the distal bone hole was primarily in metaphyseal bone, six of nine showed primarily bone failure.

All repaired specimens showed progressive failure to a 10 mm gap. The central suture always failed first and by the largest magnitude.

DISCUSSION

Failure of all or a portion of rotator cuff repairs must be a frequent occurrence, judging from the high rate of residual cuff defects that have been demonstrated in postoperative cuff repair patients. Clinical investigators have reported good function in many patients with residual postoperative cuff defects. Even so, most clinical series of rotator cuff repairs have credited the repair for the good postoperative results, even though there is no evidence that the repair held up.

Most studies of rotator cuff fixation involve a single-pull load to failure. This type of load is not physiologic. Since we move our shoulders repetitively in daily activities, it is apparent that cyclic loading better represents the type of load to which the shoulder will be subjected.

It is disturbing that the specimens in this study reached 50% failure (a 5 mm gap) at only 24.94 cycles. This indicates that a patient doing pendulum exercises in the early postoperative period might disrupt his repair with a very small number of pendulum swings. Yet we recognize the value of early motion in preventing postoperative stiffness. Passive motion would of course be preferable, but many patients can be observed to involuntarily contract their shoulder muscles even during “passive” exercises.

We propose “tension overload” as a likely mechanism of failure in rotator cuff repair. To understand “tension overload,” we must go back to the length-tension relationships that are so important to muscle-tendon units. For each muscle-tendon unit, there is an optimal fiber length for which maximal tension can be generated by that unit. In most rotator cuff tears, there is a degenerative factor that results in loss of tissue substance at the distal end of the torn fibers. The effect of this tissue loss is that the muscle-tendon units comprising the tear are shortened in comparison to the intact muscle-tendon units at the margins of the tear (Fig 1). Because of this shortening, there are only two ways that a degenerative rotator cuff tear can be repaired. The first technique is to free the muscle origins, allowing the tension in the shortened fibers to remain equal, as in the Debeyre supraspinatus slide (Fig 2). The second technique is to pull the torn fibers under tension to the repair site on the greater tuberosity.

The results of this study support “tension overload” as a mechanism of failure in rotator cuff repair. One may postulate, in view of this “tension overload” phenomenon, that some good clinical results that have been attributed to successful repairs are not due to successful repairs at all. In effect, these “successful repairs” are better described as “controlled failures.”

Two clinical implications are apparent from this study. The first implication is that rotator cuff tears should not be repaired under significant tension or they will fail. In this study, there was a 100% failure rate with cyclic loading of tears that were repaired under tension. Therefore, we should try to achieve a relatively tensionless apposition of the free margin of the cuff to a bone bed beneath it, even if that bone bed is a bit medial to the anatomic insertion of the tendon (Fig 2). Even so, we should try not to extend our bone bed into the articular surface. In the case of a large U-shaped tear extending far medially, one can do a partial side-to-side repair and utilize the principle of “margin
convergence” to converge the margin of the tear closer to the tuberosity where a bone bed can be prepared (Fig 3). This “margin convergence” will also decrease the strain in our new construct, and this strain reduction should be protective to the margins of our repair.

The second clinical implication is that transosseous bone tunnels should extend distally into cortical bone if possible, as previously demonstrated by Caldwell et al. In the present study, the specimens that had a bone bridge extending distally into cortical bone had a lower rate of bone failure. Because even our open transosseous repairs do not routinely achieve cortical fixation, one should consider a small accessory subaxillary nerve incision or arthroscopic portal (11 to 12 cm distal to the acromial margin) as previously described by the senior author (SSB) for insertion of a distal drill guide that can predictably obtain a wide bone bridge that goes distally into cortical bone.

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REFERENCES