TECHNIQUE

Update on Repair Biomechanics for Rotator Cuff Fixation

Christopher S. Ahmad, MD and John-Erik Bell, MD
Center for Shoulder, Elbow, and Sports Medicine
Department of Orthopaedic Surgery
Columbia University
New York, NY

Neal S. ElAttrache, MD
Kerlan-Jobe Orthopaedic Clinic
Los Angeles, CA
Department of Orthopaedic Surgery
and Keck School of Medicine
University of Southern California
Los Angeles, CA

ABSTRACT

Biomechanical testing is a useful tool to compare rapidly evolving rotator cuff repair techniques. The methods of biomechanical testing have also evolved to better simulate the postoperative environment and actual failure modes. Initial biomechanical tests used a single load to failure of the repair, which poorly simulated the postoperative environment. Cyclic loading in a single direction was then introduced and improved our understanding of failure. Most recently, cyclic loading in multiple directions has been performed and better simulates the postoperative environment. The mechanics of the tendon repair attachment that may influence the biology of healing has also been evaluated. This includes the restoration of the native insertional footprint, pressurized contact of the tendon to the footprint, and interface motion at the footprint between the tendon and the bone. Because different anchor designs and configurations, suture materials, and suture passage techniques are rapidly changing, it is important to keep in mind that careful and high-quality biomechanical testing is a prerequisite for widespread clinical application.
Keywords: rotator cuff, repair, biomechanics

INTRODUCTION

The management of rotator cuff tears continues to challenge the orthopedic surgeon. Improvement in surgical techniques, including proper recognition of rotator cuff tear patterns, tendon mobilization techniques, suture passing instrumentation, and suture anchor implants, now enables all arthroscopic repair for even the largest rotator cuff tears.[1–3] The persistent tear rate after open and arthroscopic rotator cuff repair is concerning[4–8] and continues to stimulate innovation in rotator cuff repair techniques. Arthroscopic rotator cuff repair constructs have evolved from a single row of suture anchors to a double row and, most recently, to suture anchor configurations that create tissue compression against the greater tuberosity.

Important research has been devoted to the biomechanical properties of new and evolving rotator cuff repair techniques. The methods of biomechanical testing have become more sophisticated to better simulate the postoperative environment and actual failure modes. The mechanical environment of the bone-tendon interface is also under investigation, because properties such as contact area, contact pressure, and micromotion at the repair site have important consequences on the biology of healing. This article reviews the current methodology and available experimental data for rotator cuff repair biomechanics.

EVALUATION OF THE MECHANICAL QUALITY OF ROTATOR CUFF REPAIR

Selection of variations in techniques for rotator cuff repair has been supported by biomechanical analysis. The interpretation of these biomechanical evaluations, therefore, requires a critical analysis of study limitations. It would be ideal to have controlled data comparing fixation strength, footprint contact area, footprint

Reprints: Christopher S. Ahmad, MD, Department of Orthopaedic Surgery, Columbia University, 11th Floor, PH 1132, 622 West 168th St, New York, NY 10032 (e-mail: CSA4@columbia.edu).

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TABLE 1. *Summary of Biomechanical Factors That Influence Rotator Cuff Repair*

Suture-tendon interface
1. Suture material
2. Suture method

Tendon-bone interface
1. Suture anchor/bone tunnel fixation strength
2. Tendon-bone contact area
3. Tendon-bone interface motion
4. Tendon-bone footprint pressurization

contact pressure, and footprint micromotion for each construct, but the current literature does not supply this information. Furthermore, most of these in vitro studies do not directly evaluate the repair characteristics' impact of biological healing. Healing of the rotator cuff after repair is a competition between construct strength and durability and the biological process of healing. If no biological healing occurs, the repair construct will eventually fail from fatigue. Rotator cuff fixation strength has been extensively studied in an effort to improve rotator cuff tendon healing.[9–22] A summary of biomechanical factors affecting rotator cuff healing is presented in Table 1.

Fixation Strength

Single Load to Failure. Early attempts to evaluate repair strength used mechanical testing with single load to failure in cadaver models.[23–26] These studies typically used a material testing machine to apply a ramp load to the repaired supraspinatus. Although these studies were often designed well to directly compare different repair techniques, the rudimentary testing method has been criticized because of poor simulation of actual or in vivo rotator cuff failure mechanisms. Single load to failure accurately assesses the pull required to determine the ultimate load but does not evaluate the durability of the repair, that is, its resistance to fatigue failure. Cyclic loading has replaced single load to failure in more recent biomechanical studies because it better simulates the immediate postoperative environment and more accurately represent rotator cuff fixation failure that occurs in vivo.[27]

Cyclic Loading in a Single Plane. Burkhart et al introduced the technique of cyclic loading to evaluate rotator cuff repairs.[27] In his initial study, standardized 1 × 2 cm rotator cuff defects were created in cadaver shoulders and then repaired with transosseous simple sutures and cyclically loaded at physiological rates and loads on an MTS machine. Figure 1 demonstrates a typical cyclic loading experiment. Progressive gapping was measured during the cyclic loading. It was observed that the central suture always failed first and by the greatest amount. Because this correlated with the portion of the tendon repaired under the greatest tension, Burkhart et al coined the *tension overload* to describe the failure mechanism and suggested that repair techniques should focus on minimizing asymmetric tension and creating uniform stress distribution of the repair (Fig. 2). It should be noted, however, that clinically, the tension in the central suture is dependent on how much tension the surgeon puts on it and, although related, is not necessarily dependent on the shape of the tear or the presence of convergence sutures. In addition, the central suture does not always fail first, so other factors must be considered.

Burkhart et al[28] followed this initial cyclic loading study of transosseous repair with a similar study directly comparing transosseous repair with single-row suture anchor repair using identical biomechanical testing

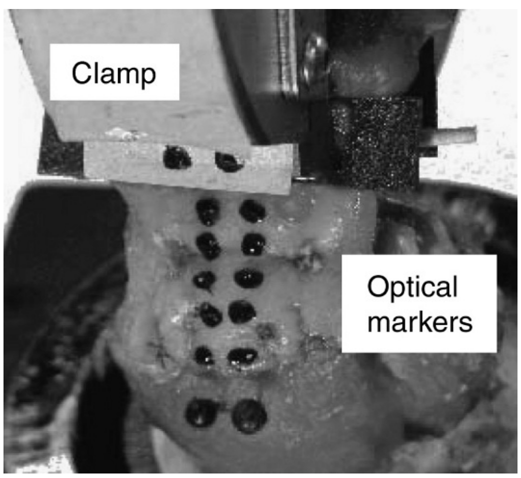

FIGURE 1. Typical cyclic loading experiment with clamp attached to rotator cuff and optical markers in place to measure gapping at repair site.

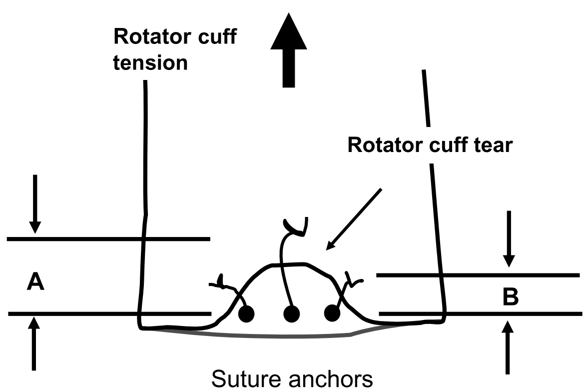

FIGURE 2. Tension overload concept when a U-shaped tear is repaired without margin convergence sutures. The central suture anchor must advance the rotator cuff (larger distance A) compared with the peripheral suture anchors that advance the tissue (shorter distance B). The central suture is under greater tension than the peripheral sutures and will fail first because of tension overload.

methods. This study demonstrated superior fixation of suture anchor constructs compared with transosseous tunnel constructs. The mode of failure also shifted from the bone-implant interface as reported in single load-to-failure models to the suture-tendon interface, as the transosseous tunnel constructs failed by the suture cutting through the bone and the suture anchor constructs failed by the suture cutting through tendon. After the work of Burkhart et al, many studies investigating fixation strength of various rotator cuff repair techniques have used cyclic loading to better simulate physiological conditions.[12,13,15,17,29]

Typically, studies testing rotator cuff repairs with cyclic loading measure gap formation, total energy absorbed or energy to failure, and modes of failure. Gap formation is measured between a point on the supraspinatus tendon and a fixed point on the humerus. “Failure” is defined as either complete pull-off of the tendon from the bone or as gapping of a certain magnitude, with 3 mm most often used. Energy absorbed by the repair or total energy to failure is also calculated from the load and displacement curve for many of these studies. Mode of failure refers to the site at which the failure occurred, such as the bone-implant, implant-suture, suture, or suture-tendon interface.

Cyclic Loading in Different Planes. Although cyclic loading has improved the simulation of the postoperative environment compared with single load to failure, loading of the supraspinatus in only one direction does not take into account rotation of the humerus, which is often incorporated into postoperative physical therapy regimens and is an instinctive motion of by patients, despite postoperative restrictions. Ahmad et al[30] has introduced the concept of cyclic loading in different planes to further improve the simulation of the postoperative environment. The postoperative motion of the shoulder has 3 degrees of rotational freedom, including internal/external rotation, flexion/extension, and abduction/adduction. As an initial study, the effect of humeral internal and external rotation on the biomechanical characteristics of single- and double-row rotator cuff repair was evaluated (Fig. 3). Increased gapping and decreased energy to failure were found when cyclic loading was performed in positions of internal and external rotation compared with neutral position. This suggests that when the humerus is in neutral position, the line of pull of the supraspinatus is perpendicular to a line connecting the anterior and posterior anchors. This position allows for an even distribution of tension between the anterior and posterior anchors. However, when the humerus is rotated, the tension is not symmetrically distributed, and there is greater tension on the further lateral suture anchor. It is postulated that internal/external rotation creates a tension overload similar to the theory proposed by Burkhart et al. Clinically, the finding that the repair exhibits greater amounts of gapping in rotation raises concerns with immediate humeral rotation used in postoperative rehabilitation. Future studies will evaluate more complex shoulder motion that includes flexion/extension and abduction/adduction.

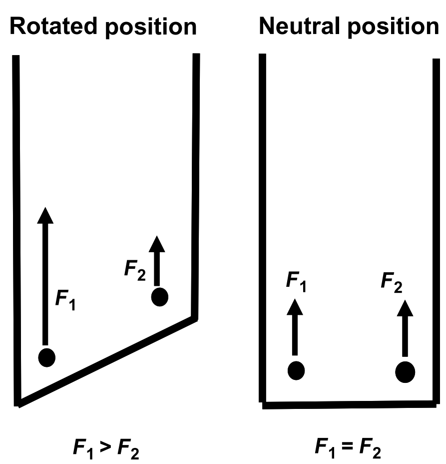

FIGURE 3. Schematic illustration indicating nonuniform force distribution that is created when the humerus is in a rotated position compared with neutral position.

Tendon-Bone Interface Mechanics

The biological process of tendon healing to bone continues to be studied in different clinical and animal models. It is important to keep in mind when studying the biomechanics of rotator cuff repair that the ultimate goal is biological healing and that even the strongest repair will ultimately fail if healing does not occur. Nevertheless, these 2 essential aspects of repair are intertwined, for the mechanical microenvironment of the rotator cuff “footprint,” which is the portion of the tendon in contact with the greater tuberosity, must be optimized to maximize the healing potential of the repair.[31–36] Important aspects of this biomechanical environment include restoration of footprint contact area, uniform footprint contact pressurization, and minimization of footprint tendon-bone interface motion.

Footprint Interface Motion. Several studies have shown that healing of soft tissue to bone occurs by formation of a fibrovascular interface tissue between the tendon and bone.[31,37,38] This is followed by progressive bone ingrowth into this interface tissue as collagen fiber continuity is gradually created between the tendon and bone. Excessive motion at the tendon-bone interface may disrupt the forming fibrovascular interface tissue and compromise the healing process. Again, it is useful to extrapolate information gained from anterior cruciate ligament (ACL) research to the healing of the rotator cuff. Soft tissue graft motion relative to bone has been studied for different ACL reconstruction techniques. The EndoButton linked with tape has motion of the graft in the tunnel of up to 3 mm under physiological cyclic loads.[39] This longitudinal motion has been associated with concerning tunnel expansion in clinical trials.[40,41]

Ahmad et al[42] introduced the concept of evaluating tendon-bone interface motion to characterize the stability of the rotator cuff repair. Tendon motion relative to the insertional footprint on the greater tuberosity was determined optically using a digital camera rigidly connected to the humerus, with the humerus positioned at 60 degrees of internal rotation and 60 degrees of external rotation. Testing was performed for the intact tendon, a complete supraspinatus tear, a suture anchor repair, and a transosseous tunnel repair. Transosseous suture repair compared with suture anchor repair demonstrated superior tendon fixation with reduced motion at the tendon-to-tuberosity interface. As shown in the Figure 4, with internal rotation of the humerus, the muscle force of the supraspinatus has a force component vector directed anterior and with external rotation of the humerus, the supraspinatus has a force component vector directed posterior relative to the tuberosity. With the changing direction of the force vectors, loose fixation may allow motion of the tendon relative to the tuberosity as measured in our model. The transosseous tunnel repair configuration results in a broad fixation of the tendon against the tuberosity as thereby limiting the motion. The tensioning of suture in the suture anchor repair technique results in the increase of the circumferential pressure on the tendon with limited fixation against the tuberosity as depicted in Figure 6. The suture anchor repair, therefore, allows for greater tendon motion relative to the tuberosity. Development of new fixation techniques for arthroscopic and open rotator cuff repairs should attempt to minimize interface motion of the tendon relative to the tuberosity.

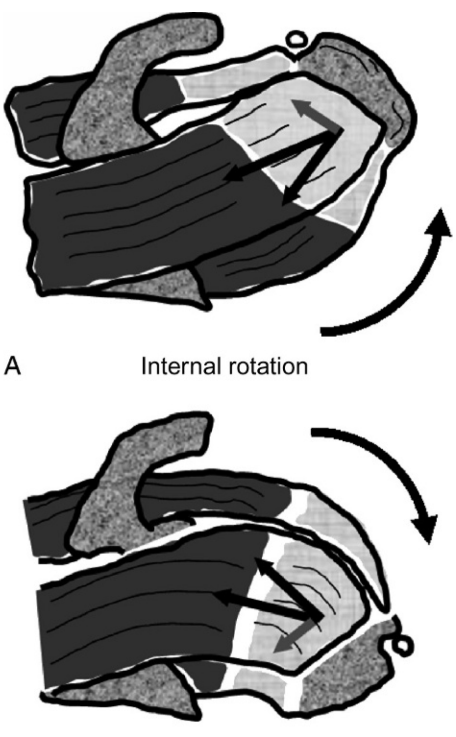

FIGURE 4. Humeral rotation creates (A) anterior and (B) posterior force components on the rotator cuff that contributes to tendon-bone interface motion. Reprinted with permission from Am J Sports Med.[42] Copyright 2005, American Orthopaedic Society for Sports Medicine.

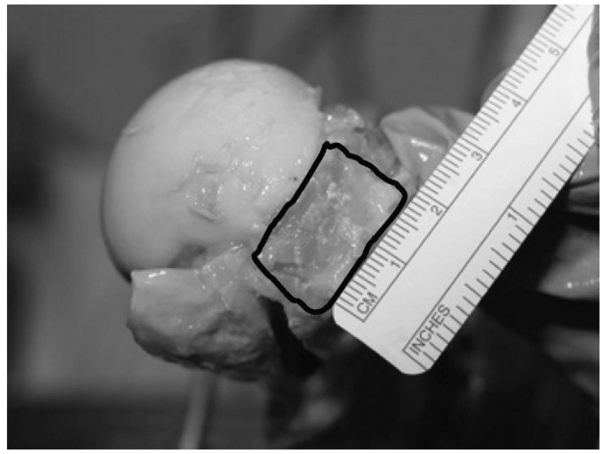

FIGURE 5. Supraspinatus footprint outlined.

Footprint Contact Area. Ruotolo et al[43] studied the normal rotator cuff thickness at its bony attachment. The mean anteroposterior dimension of the supraspinatus insertion was 25 mm. The mean superior to inferior tendon thickness at the rotator interval was 11.6 mm, 12.1 mm at midtendon, and 12 mm at the posterior edge. The distance from the articular cartilage margin to the bony tendon insertion was 1.5 to 1.9 mm, with a mean of 1.7 mm. Similar finding were observed by Dugas et al.[44] (Fig. 5).

Apreleva et al[45] introduced the concept of insertional footprint restoration with rotator cuff repair. They determined the footprint repair site contact areas after repair of a simulated supraspinatus tear. A larger footprint contact area for a transosseous technique was observed compared with a single-row suture anchor technique. The authors suggests that this technique provides better healing potential and, ultimately, greater strength of repair after healing. Tuoheti et al[46] found that double-row repairs produced a contact area 42% greater than transosseous and 60% greater than single-row and that the transosseous contact area was 31% greater than that for single row. It is theoretically

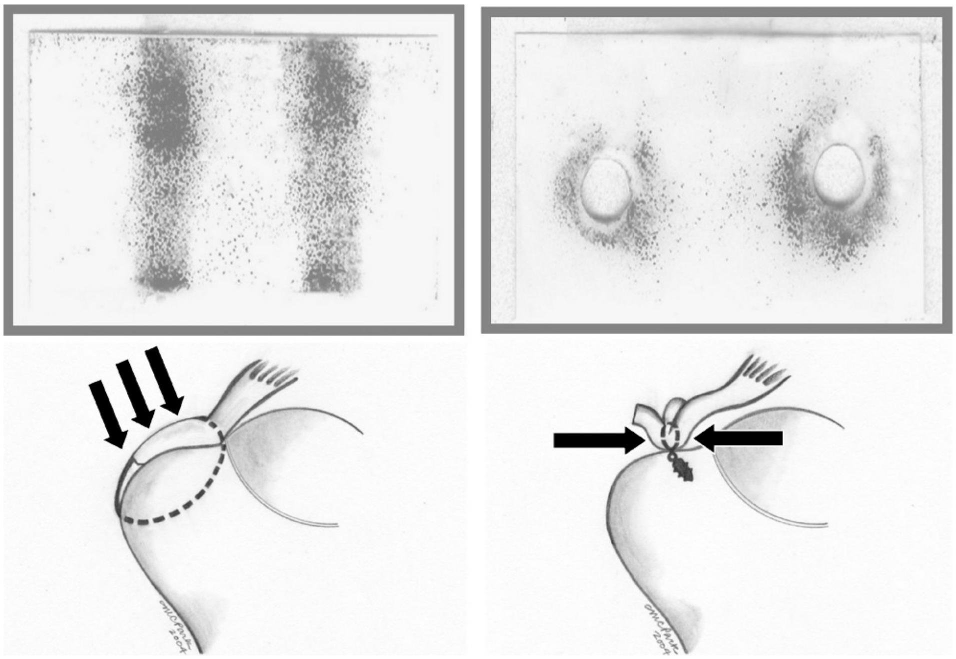

FIGURE 6. Pressurized contact is increased for (A) transosseous repair compared with (B) suture anchor repair. Reprinted with permission from Am J Sports Med.[56] Copyright 2005, American Orthopaedic Society for Sports Medicine.

important to maintain a large area of contact between tendon and bone, allowing more fibers to participate in the healing process. Although these hypotheses still must be tested in vivo, it is safe to conclude that attention should be paid to the 3-dimensional geometry of the repair site and the ability of the procedure to restore the original tendon insertion and, in turn, increase the area available for tendon attachment.

Footprint Contact Pressure. Numerous studies have demonstrated that tendon-to-bone interface pressure influences the biology of tendon healing within a bone tunnel.[47–54] Weiler et al[55] showed that a local pressure environment created with interference fit fixation is beneficial for direct tendon-to-bone healing using autologous Achilles tendon in ACL surgery. It is, therefore, extrapolated from the tendon-bone healing situation in the rotator cuff that local pressure between the bone and tendon may be important for healing.

Park and coworkers[56] introduced the concept of measuring pressurized contact area at the rotator cuff repair site. This study confirmed the conclusion of Apreleva et al that transosseous repair technique provides greater contact area for potential healing, but also found greater mean pressurized contact over a defined tuberosity footprint when compared with either of the suture anchor techniques (Fig. 6). The suture anchor repair demonstrated "spot welding" type of pressurized contact. The transosseous sutures provide greater compressive force over a larger area, when compared with suture anchor repair techniques. The suture tension for the transosseous technique provides a more direct tendon-to-bone compression vector. In contrast, the sutures for the suture anchor technique predominantly provide circumferential tension around the tendon while providing relatively little compression between tendon and bone. Park et al[57] also found that when using anchors, a simple suture configuration provides significantly more pressurized contact area between tendon and bone than the mattress suture configuration. The technique of measuring pressurized contact area has also demonstrated superior properties for the new repair techniques that create suture bridges over the repair site (Fig. 7). Although increased pressurization may enhance local healing of the tendon to bone, concern exists regarding compromise to tendon vascularity from excessive pressure. At this time, vascular compromise to the tendon has not been studied with different rotator cuff repair techniques. Given the necessity for optimal vascularity required for healing, rotator cuff repair should balance the goals of achieving high restoration of the footprint interface mechanics without strangulating the tissue with vascular compromise.

■ SPECIFIC ROTATOR CUFF REPAIR TECHNIQUES

Anchor Considerations

In general, suture anchors are required for all arthroscopic rotator cuff repair. There are many anchor

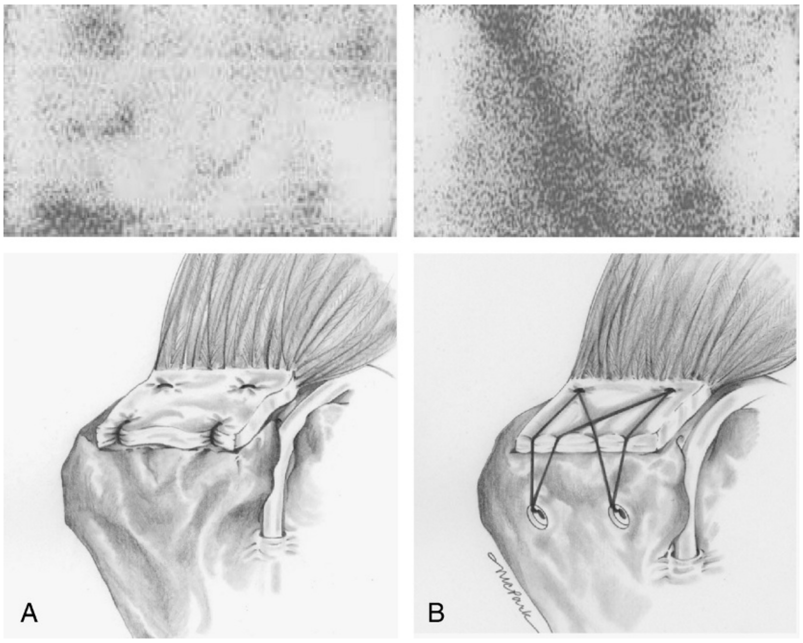

FIGURE 7. Pressurized contact is decreased for (A) double-row suture anchor repair compared with (B) suture bridge repair. Reprinted with permission from Park MC, ElAttrache, NS, Tibone JE, et al. Part I: Footprint contact characteristics for a "transosseous-equivalent" rotator cuff repair technique compared to a double-row technique, J Shoulder Elbow Surg. 2007 Feb 21; [Epub ahead of print].

designs and materials, including metal and bioabsorbable tack-and-screw configurations. Most anchors rely on fixation in the cancellous bone of the greater tuberosity, and it is possible that some of the gapping observed in cyclic loading experiments is because of the motion of the anchor beneath the cortical bone. In one unidirectional cyclic loading study, a fully threaded screw-type anchor with cortical fixation resulted in decreased tendon gapping and decreased anchor motion under fluoroscopy.[58]

The position of the anchor within the bone has important biomechanical consequences. In a study comparing metallic screw-type anchors inserted deep, proud, or at the recommended standard depth, unidirectional cyclic loading was performed.[59] It was found that the anchors placed deeper than the recommended depth reached clinical failure, defined as formation of a 3-mm gap, after the least number of cycles, with the mode of failure as suture cutting through bone. However, although the anchors placed at proud or at standard depth reached clinical failure after more cycles, they experienced "catastrophic" failure more rapidly, as a result of suture abrasion and breakage against the anchor eyelet.

The angle of anchor insertion is also important for fixation strength. Burkhart[60] and Burkhart and Lo[61] introduced the concept of the "deadman angle," referring to a 45-degree angle between the line of pull of the tendon and the angle of anchor insertion into the bone, which is analogous to a mechanism used to stabilize corner fence posts (Fig. 8). The rotation and angle of the anchor also contribute to the likelihood of suture abrasion against the eyelet causing suture breakage.[62,63]

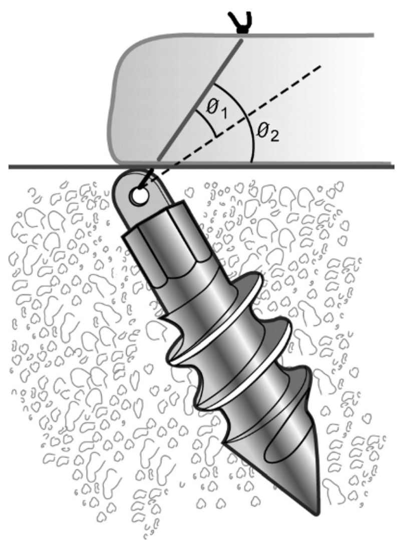

FIGURE 8. Proper anchor insertion at the deadman angle. θ_1 is the pullout angle for the anchor, which is the angle the suture makes perpendicular to the anchor. θ_2 is the tension-reduction angle, which is the angle the suture makes with the direction of pull of the rotator cuff. Ideally, θ_1 and θ_2 should both be 45 degrees or less. Reproduced with permission from J Am Acad Orthop Surg.[61] Copyright 2006, American Academy of Orthopaedic Surgeons.

Anchors are dependent on bone quality, and it has been shown through a unidirectional cyclic loading study that the strongest bone within the greater tuberosity is within the proximal-anterior and proximal-middle aspects of the tuberosity.[64] Especially in osteoporotic patients, the anchors should be placed in these zones.

Suture Considerations

The suture-tendon interface has been identified as the weakest link in rotator cuff repair.[65] In addition, the type of suture can significantly affect the biomechanical properties of the repair, changing the energy to failure and the mode of failure, because sutures with a core strand achieve more cycles and absorb more energy before failure.[66] The introduction of these new super sutures have significant improvements in strength compared with previously standard nonabsorbable braided sutures. The configuration of suture passage through tendon also plays a role in the biomechanical strength of the repair. Ma et al[67] showed that a modified Mason-Allen and a configuration referred to as the “massive cuff” stitch were stronger in unidirectional cyclic loading compared with simple and mattress suture configurations.

Tear Considerations: The Massive Retracted Tear

It is critical to minimize tension in the repair.[68] In massive rotator cuff tears, it may be impossible to bring the retracted margin of the rotator cuff down to its attachment site on the greater tuberosity under reasonable tension, even after performing all indicated soft tissue releases. Burkhart has described 2 techniques for reducing the tension on these repairs. The first is known as “margin convergence,” in which sutures are passed from the anterior to posterior edges of the tear, bringing them together. Several of these stitches may be required before the new “edge” of the rotator cuff can be secured to the tuberosity without undue tension via suture anchors.[69] This has been shown to decrease tension on the repair and restore the force transmission capability of the rotator cuff.[70] In some cases, there is not sufficient tissue to perform margin convergence suture technique, and in these cases, Burkhart advocates a partial repair, focusing on restoration of the “force couple” between the anterior and posterior rotator cuff and reestablishing a fulcrum for elevation of the arm.[71]

Transosseous Tunnels

Controversy exists regarding the superiority of either suture anchors or transosseous tunnels. Several investigators reported that suture anchors were comparable or weaker to transosseous tunnels.[19,21,22] Other investigators report higher fixation strength with suture anchor repairs.[20,72] Traditionally, transosseous tunnels have been used for open and miniopen rotator cuff repairs with good to excellent clinical results. There is no current arthroscopic means of achieving true transosseous tunnels. Biomechanical evaluation of transosseous tunnels has revealed distinct advantages and disadvantages. Although controversial, most studies have found that, in terms of fixation strength, transosseous tunnels tend to be inferior to suture anchor constructs because of increased gapping and decreased energy to failure under cyclic loading conditions.[28] The primary mode of failure is at the suture-bone interface, with the sutures cutting out of the bone with increasing cycles. Strength is improved when small plates are placed between the sutures and the lateral aspect of the greater tuberosity.[23] In terms of the microenvironment of the footprint, transosseous tunnels are superior to single-row suture anchor constructs in restoring the maximum tendon contact area on the tuberosity,[45] achieving the greatest mean pressure over the largest area,[56] and minimizing motion at the bone-tendon interface[42] when compared with single-row suture anchor techniques. Other work has shown that the contact area of transosseous tunnels is second to double-row suture and that contact pressure is lower than both single- and double-row repairs.[46] Transosseous repairs have clinically been shown to provide sufficient strength to allow early range of motion.[73,74]

Single- Versus Double-Row Repair

Single-row repair constructs consist of a single row of suture anchors in the greater tuberosity, and double-row repairs add a second, more medial row at the lateral margin of the articular cartilage of the humeral head.[75] In single-row repairs, sutures are placed in simple, modified Mason-Allen, or other configurations to minimize suture failure through the tendon. In double-row repairs, the medial row sutures are typically placed in mattress configuration, and the lateral row sutures are placed in simple configuration.

Recent biomechanical studies have compared single- and double-row rotator cuff repair constructs directly using unidirectional cyclic load to failure.[76–78] Mazzocca et al[77] found that there was no significant difference between single- and double-row repairs in load to failure, cyclic displacement, or gap formation in a well-designed study, whereas Ma et al[76] showed that double-row fixation was significantly stronger that 3 different configurations of single-row repair, including simple, Mason-Allen, and “massive cuff” suture configuration. Kim et al[78] also found that double-row repairs significantly decreased gap formation and that adding the medial row increased the stiffness of repair by 46% and the ultimate failure load by 48%. Kim et al also studied the strain of the repair and found that the strain of the double-row repair was only one third of that for the single-row repair.

After Apreleva et al[45] showed that single-row repair restored only 67% of the original rotator cuff footprint compared with 85% for transosseous repair, Lo and Burkhart[75] proposed the concept of double-row repair as a way to improve the footprint contact area characteristics of suture anchor repair. Multiple studies have since confirmed that the double-row repair constructs more accurately reproduce the anatomic dimensions of the supraspinatus footprint.[46,77] Another advantage of double-row repair over single-row repair is the ability to place medial row anchors in the best-quality bone just lateral to the articular cartilage.[64,79] This may be advantageous, especially in elderly patients with poor bone quality in the metaphyseal bone of the greater tuberosity.

Suture Bridge Repair

New rotator cuff repair techniques have been introduced to create a mechanical environment that enhances the biology of healing by limiting interface motion and improving contact area and pressure. We refer to these techniques suture bridge repairs. Millett et al[80] reported a technique of shuttling suture limbs from the medial row through the lateral row suture eyelet, allowing compression of the tissue between anchor rows against the tuberosity. Park et al[81] has described use of specialized interference screws that can be placed on the far lateral aspect of the greater tuberosity that captures medial sutures creates suture bridges.

New implants have been developed to greater facilitate placement of compression sutures and reduce knot tying. For the Push Lock (Arthrex, Naples, Fla) device, standard medial suture anchors and suture passing is performed as would be performed for a double-row repair. The medial sutures to be used for compression (one suture from the anterior medial anchor and one suture from the posterior medial anchor) are then passed through the eyelet of the implant outside the cannulae. Manual tension is then applied to the suture bridge sutures as they are delivered into the tunnel to achieve the desired compression. The implant is then advanced over the inserter and captures the eyelet, which fixes the sutures in place and eliminates the need for knot tying.

Park and coworkers[57] compared suture bridge rotator cuff repairs to double-row rotator cuff repairs that are currently used clinically. For strength of fixation, the 4 suture-bridge technique had significantly higher ultimate load to failure with no difference in gap formation to cyclic loading. Furthermore, the suture bridge rotator cuff repair provided more pressurized contact area and mean pressure over the repaired rotator cuff tendon insertion when compared with a double-row technique (Fig. 7).

■ SUMMARY

In conclusion, many techniques now exist for repair of the rotator cuff to the greater tuberosity. Significant advances have been made in biomechanical testing methods of fixation strength and durability. New appreciation of the importance of the biomechanical microenvironment of the repair site is also an advancement. As more and more constructs consisting of different anchor designs and configurations, different sutures materials, and different suture passage techniques are reported in the literature, it is important to keep in mind that careful and high-quality biomechanical testing is a prerequisite for widespread clinical application. Relative advantages and disadvantages exist for all current techniques of rotator cuff repair, and it is important to keep in mind the ultimate goal of tendon-to-bone healing with excellent postoperative pain relief and functional restoration.

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