Knee Surg Sports Traumatol Arthrosc
DOI 10.1007/s00167-011-1436-x

SHOULDER

Biomechanical evaluation of four different transosseous-equivalent/suture bridge rotator cuff repairs

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Received: 3 November 2010 / Accepted: 1 February 2011

Abstract

Purpose Evaluate the biomechanical behavior of four variants of the transosseous-equivalent/suture bridge (TOE/SB) repair.

Methods Four suture bridge (SB) constructs were created using 24 sheep infraspinatus tendon-humerus constructs ($n = 6$ per technique). The groups were (1) Knotted Standard Suture Bridge (Standard SB)—suture bridge with two medial mattress stitches, (2) Knotted Double Suture Bridge (Double SB)—four medial mattress stitches, (3) Untied Suture Bridge with Medial FT Anchors (Untied SB with FT)—two medial mattress stitches without knots, and (4) Untied Suture Bridge with PushLocks (Untied SB with Pushlocks)—two medial mattress stitches without knots. The contact area footprint was measured with an electronic pressure film prior to dynamic mechanical testing for gapping and testing to failure.

Results The Double SB produced the greatest contact area footprint compared to the other techniques, which did not differ. The Double SB repair with a mean failure load of 456.9N was significantly stronger than the Untied SB with Pushlocks repair at 300N ($P = 0.023$), the standard SB repair at 295N ($P = 0.019$), and lastly the Untied SB with FT repair at 284N ($P = 0.011$). No differences were detected between the two mattress stitch standard SB repair with knots and the knotless two mattress stitch repairs (Untied SB with FT and Untied SB with Pushlocks). Gaps developed during cyclic loading in all repairs apart from the Double SB repair.

Conclusions The transosseous-equivalent/suture bridge repair with 4 stitches tied in the medial row and maximal lateral suture strand utilization (Double SB) outperformed all other repairs in terms of failure load, tendon–bone contact, and gapping characteristics. The presence of knots in the medial row did not change tendon fixation with respect to failure load, contact area or gapping characteristics.

Keywords Rotator cuff · Shoulder · Suture bridge · Double row · Knot · Footprint

Introduction

The transosseous-equivalent/suture bridge (TOE/SB) rotator cuff repair was described by Park et al. [33]. The technique involves using medial row anchors at the humeral articular cartilage edge and tying mattress stitches to secure the cuff tissue. The free ends of the medial suture limbs are preserved and brought laterally over the bursal surface of the remaining unsecured cuff tissue. The suture limbs are fastened with anchors placed in a distal-lateral position over the side of the greater tuberosity to create downward pressure and recreated the rotator cuff footprint.

Rotator cuff repair integrity correlates with improved function and superior rotator cuff power postoperatively [3, 4, 12, 13, 15, 22]. Most patients with an intact rotator cuff ultimately have decreased pain and better function

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Published online: 24 February 2011

following surgery for rotator cuff tears [18, 44]. In contrast, patients with persistent symptoms following rotator cuff repair are more likely to have a recurrent tear [25, 45]. The surgeon should optimize the repair biomechanically which can potentially enhance healing biology by creating greater tendon to bone contact surface area and pressure [9]. Although work in animal models have shown promise in enhancing tendon healing biologically, [5, 20, 23, 27, 37] at present, surgeons still rely on the mechanical strength of a repair to allow tendon-bone healing to occur during rehabilitation.

Research into the optimal rotator cuff construct with the greatest strength at time zero has been done and continues. [7, 11, 15, 40, 42] Numerous studies report the superior initial rotator cuff repair characteristics of traditional double-row when compared to single-row fixation [24, 28, 29, 41]. As techniques have evolved through single row, transosseous repair, double-row repair, and finally transosseous-equivalent repairs, stronger constructs have appeared. Several versions of the TOE/SB technique exist and some have been tested biomechanically [34]. It is unclear however, if one suture bridge construct offers a biomechanical advantage over another. The null hypothesis for this study was that there would be no difference in the biomechanical properties of 4 different TOE/SB techniques.

Materials and methods

Twenty-four (24) infraspinatus tendon-humerus constructs were harvested from 12 (2-year old) sheep. The infraspinatus was detached from its insertion using a scalpel and the exposed 10 mm × 20 mm footprint burred. Four different TOE/SB rotator cuff repairs were randomly performed 6 times by the same surgeon (MM). The first repair type (Fig. 1) was a Knotted Standard Suture Bridge (Standard SB) and utilized two medial 5.5 mm Bio-Corkscrew FT Anchors (Arthrex, Napes FL) with one No 2 FiberWire suture (Arthrex, Napes FL) from each anchor, passed through the tendon with a Mayo needle, and tied in a mattress fashion. A Weston Knot (sliding knot) was used to simulate an arthroscopic repair. Two 3.5-mm PushLock Anchors (Arthrex, Naples, FL) were used to secure the 4 suture strands laterally after crossing one strand from each medial anchor. The spacing between the anchors was 1.5 cm. The second repair type (Fig. 1) was a Knotted Double Suture Bridge (Double SB) and was similar to the first except that both sutures from each double-loaded medial anchor were used to produce 4 medial mattress stitches. A Weston knot was utilized to tie the medial row. All 8 suture strands were passed laterally and secured with two 3.5 mm PushLock Anchors after crossing half of the

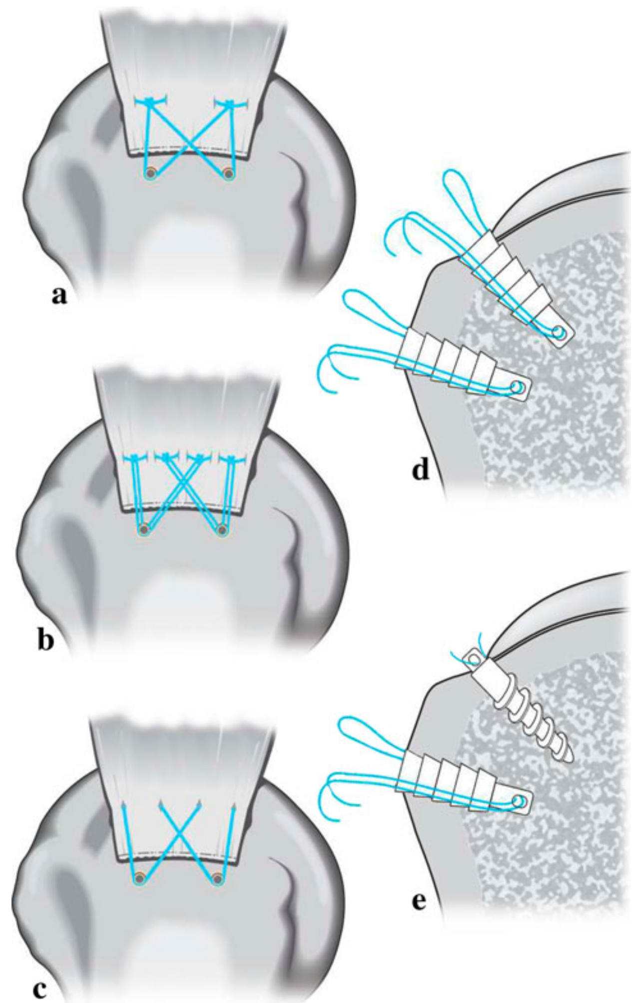

Fig. 1 Suture Constructs tested in this study. **a** Standard SB—standard suture bridge with knots tied medially. **b** Double SB—double suture bridge with knots tied medially. **c** Untied Suture Bridge representing the construct with either FT Anchors or PushLocks. **d** Detail showing PushLock suture fixation used for Untied SB with Pushlocks. **e** Detail showing PushLock and FT anchor configuration used for all other constructs

sutures. Spacing between the anchors was 1.5 cm. The third repair (Fig. 1) was a knotless repair. This construct was an Untied Suture Bridge with Medial FT Anchors (Untied SB with FT) and utilized two medial 5.5 mm Bio-Corkscrew FT Anchors (Arthrex, Naples, FL) single-loaded with No. 2 FiberWire. The sutures from the medial row anchors were not tied, but simply passed through the infraspinatus tendon creating a mattress stitch without a knot. One strand from each medial anchor was crossed over and secured laterally with two 3.5 mm PushLock Anchors with spacing of 1.5 cm between anchors. The fourth repair (Fig. 1) was an Untied Suture Bridge with PushLocks (Untied SB with Pushlocks). The Untied SB with Pushlocks was also a completely knotless construct and used two 3.5 mm PushLock Anchors medially and two 3.5 mm

PushLocks laterally, with all other aspects of the repair identical to repair type three (Untied SB with FT). The only difference between type three (Untied SB with FT) and four (Untied SB with Pushlocks) repairs other than the medial row anchor type was that the suture did not slide through the eyelet of the medial row anchors in group four (Untied SB with Pushlocks) due to the anchor design.

The contact area between the tendon and the bone was measured using an electronic pressure sensor technique [2, 19, 21] (I-Scan 6900, TekScan, South Boston) followed by mechanical testing. A single sensing tab of the model 6900 sensor was placed at the interface between the tendon and bone during the repair with transmission exiting distally between the lateral row. Data were taken for 30 s after completion of the repair. This pressure film has a sensing area of 14 mm x14 mm. The maximum contact area was obtained for 4 samples from each technique.

Mechanical testing was performed on 6 reconstructions from each group. The humerus was fixed in a low melting point alloy and the muscle belly of the infraspinatus secured using brass grips and liquid carbon dioxide (cryogrips) to freeze the muscle belly [31, 32]. Mechanical testing was performed using a calibrated servohydraulic testing machine (MTS, Eden Prairie, MN). The repairs were loaded between 10 and 100N at 1 Hz for 500 cycles to see if any gaps developed at the interface. The gapping was assessed with a digital calliper at the tendon–bone interface on the bursal side following testing. Cyclic creep was also assessed based on changes in actuator position throughout testing. Samples were tested in uniaxial tension to failure at a rate of 33 mm/sec following cyclical testing. Failure was defined as decreasing load with increasing displacement. The peak load, stiffness in the linear region, and failure mechanism were noted.

Statistical analysis

Contact area and mechanical data for all constructs were reviewed using an analysis of variance (ANOVA) followed by post hoc testing using the Games Howell criterion for multiple comparisons. All statistical analysis was performed with SPSS for Windows (SPSS Inc., Chicago, IL) and differences were considered significant where $P < 0.05$.

Results

The mean contact area of the Untied SB with Pushlocks was similar to the contact area of the Untied SB with FT. The standard SB contact area was slightly higher although no significant differences were detected between any of these three constructs (Fig. 2). The Double SB repair produced a contact area of 1.47 cm^2, which was greater than all other repairs ($P < 0.05$).

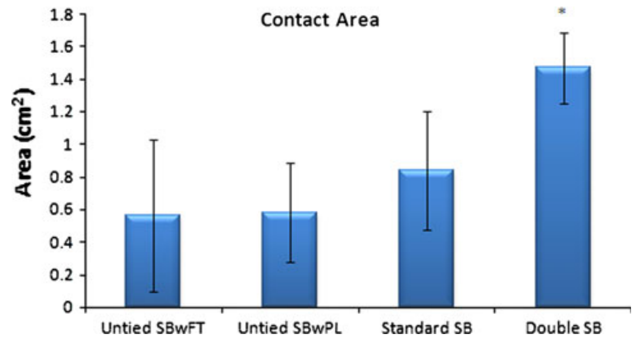

Fig. 2 Footprint contact area between tendon and bone. $*P < 0.05$, when compared to all other repairs

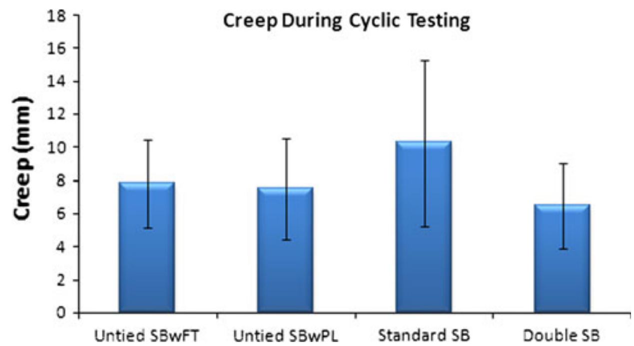

Fig. 3 Results of creep measurements during cyclic loading

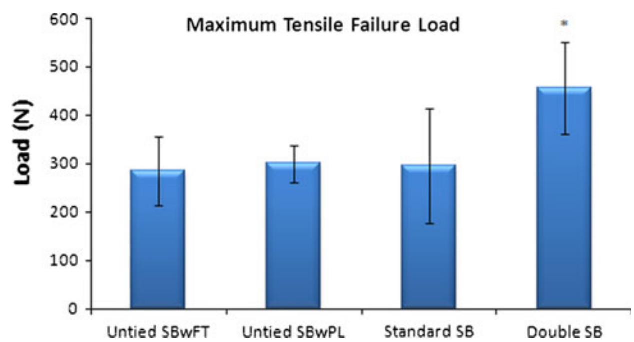

Fig. 4 Mechanical testing results; failure loads. $*P < 0.05$, when compared to all other designs

Cyclical testing of the repairs did not reveal any differences between the 4 groups with mean creep values between 6.47 mm and 10.2 mm for all constructs (Fig. 3). Gap formation on the bursal side was not visible in the Double SB repairs during cyclical testing while small gaps (1-3 mm) were noted in the other groups.

Destructive failure did however reveal significant findings. The Double SB repairs with all medial suture limbs tied were the strongest (Fig. 4). The Double SB repair failed at 457N and was significantly stronger than the Untied SB with Pushlocks, standard SB, and Untied SB

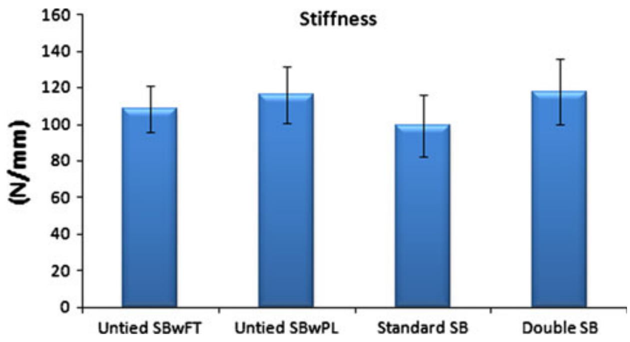

Fig. 5 Stiffness within the linear region of load–displacement curve

with FT which failed at 300N, 295N, and 284N, respectively ($P < 0.05$). No differences were detected between the Untied SB with Pushlocks, standard SB, and Untied SB with FT repairs (n.s.). While the stiffness (Fig. 5) of the Double SB was greatest, no statistical differences were noted between any of the repair techniques (n.s.). The predominate failure mode was tendon tearing through the suture material. In one of the Double SB repairs, the sutures pulled free of one PushLock Anchor and tore through the tendon on the other side. No statistical differences were noted (n.s.).

Discussion

The present study has two primary findings. These are the increased failure loads achieved with the Double SB repair when compared to the other three repairs and the similarities in the performance of the Untied SB with Pushlocks & Untied SB with FT repairs.

One of the goals of any reconstructive surgery should be to restore anatomy. Mechanical factors which may alter tendon healing include footprint coverage, contact pressure [1], and decreased motion at the bone–tendon interface [36]. All of these factors can potentially be controlled by the surgeon using a TOE/SB repair [9]. In order to achieve biological healing, a rotator cuff repair must be able to withstand the inherent forces generated by the muscle as well as during the rehabilitation process. The maximal force reported to be generated by the supraspinatus is 302N [6]. While many repairs do not achieve this static load threshold, Park et al. [34] report the TOE/SB repair to achieve failure load of 443N with cadaveric shoulders. Spang et al. [42] have used the ovine model to evaluate suture bridge repairs. The results of stiffness were similar to the current study and failure loads fell between those of the present Double SB and the other three repairs. Pauly et al. [35] have recently utilized a porcine model to show greater failure loads of double mattress constructs. The ovine model presented here demonstrates continuity of results with slightly higher failure loads. We have included untied constructs to investigate the influence of knots in our measured parameters. The Double SB was the superior construct in terms of load to failure while all were equivalent in stiffness and cyclical testing. The superior load to failure of the quadruple knotted Double SB may be related to utilizing all 4 mattress stitches medially providing a more secure grasping of the tendon. The tendon suture interface has been shown to be the weak link in rotator cuff repair [16, 38] and was again confirmed by this study.

Research into double-row rotator cuff repair suggests the medial row contributes most to the overall strength [39, 43]. Certainly, increasing the number of suture strands across tendon repairs improves the strength of repair by sharing tensile load as shown in our Double SB. This repair also exhibited the greatest contact area, with a significant difference noted between the Untied SB with FT repair and approaching significance for the Untied SB with Pushlocks repair ($P = 0.072$). The downside to this repair however is whether the multiple mattress stitches and increased number of bursal sided compressive strands could be detrimental to the vascularity of the cuff tendon [8], this however is beyond the scope of our study.

Spang et al. [42] have suggested that knot tying may not be necessary for arthroscopic procedures and have recommended future work to evaluate the need for knots in this type of construct. In the present study, tying two stitches in the medial row of the standard SB did not affect the cyclic data, or contact area compared to the similar but knotless medial Untied SB with Pushlocks & Untied SB with FT repairs. The ultimate load of the knotless medial row repairs did not differ. These data do not clearly demonstrate whether medial row knot tying provides any advantage in "Suture Bridge" repairs when comparing the three standard two-stitch suture bridge constructs used in this study. The Double SB however, with its increased number of suture strands (8 versus 4 for all other repairs) and knots (4 medial tied stitches versus 2 stitches in all other repairs) was biomechanically superior. The 4 knots of Double SB TOE/SB repair appeared to be a more stable construct with no discernable tendon movement or bursal sided gap formation during loading.

There were several limitations to this study. The sheep infraspinatus-humerus construct was used as a model of the human supraspinatus tendons. The sheep infraspinatus tendon is however well described by Gerber [14] and others [10, 26, 30] as a good model for rotator cuff repair. We chose this as an alternative to cadaveric tissue which is often of varying age and quality. The sheep infraspinatus tendon has similar size, shape, and mechanical properties to the human supraspinatus tendon and is almost indistinguishable on histological examination, making it a realistic model for evaluating surgical techniques of rotator cuff repair as applicable to humans [17]. The absolute values for load to failure may however be different compared to humans considering differences in activity and levels and tissue quality. It should be noted that the failure loads generated with healthy rotator cuff tissue without degeneration is likely to be higher than that of a more likely clinical scenario, with degeneration. Additionally, due to the bony anatomy and the fact that the infraspinatus was used, the lateral anchors were not placed in an extreme over the edge position as described by Park et al. [33]. This positioning may have affected the strength of the repairs. Finally, the superior repair construct of four medial stitches with knot tying unfortunately was not compared directly to a similar construct with four stitches without knot tying. This technique was not considered in the current study as it was not used in our surgical practices. Six reconstruction from each group were tested mechanically while only four were evaluated for contact area, raising the number of shoulders could have identified more differences between contact area characteristics. While an increase in sample size could have been performed, statistical evaluations revealed a large sample size would have been required to detect difference between the 4 knot repairs (approximately 162 with an alpha of 0.05 and beta of 0.8) which was considered unrealistic.

Our findings show the superior failure load and greater contact area when tying 4 stitches in the medial row. When comparing standard suture bridge constructs with untied constructs our findings follow on from Sprang's work and suggestions for future evaluation, demonstrating that there is no significant difference in strength, gap formation, and footprint stability whether the medial row has tied knots or simply passed through the tendon and been anchored laterally. For those surgeons performing a double-row cuff repair without tying the medial row sutures as a horizontal mattress, our study offers reassurance that the fixation of the rotator cuff tendon has not been compromised, despite the surgical technique being easier and quicker to perform.

Conclusions

It has been proposed that the goals of rotator cuff repair are as follows: (1) an initially strong construct with, (2) minimal gap formation, and (3) footprint stability that will allow the tendon to heal to bone during the rehabilitation period. Based on the results of this study, the transosseous-equivalent/suture bridge repair with 4 stitches tied in the medial row and maximal lateral strand utilization (Double SB TOE/SB) is the strongest and has the greatest contact area between the tendon and bone. The null hypothesis of no differences in the biomechanical properties of these 4 TOE/SB techniques was rejected. The Double SB also appeared to have no bursal sided gap formation compared to the other techniques. Tying of the medial row on similar suture constructs did not enhance tendon fixation as measured by this study.

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