

American Journal of Sports Medicine

<http://ajs.sagepub.com>

Influence of Suture Material on the Biomechanical Behavior of Suture-Tendon Specimens: A Controlled Study in Bovine Rotator Cuff

Leslie J. Bisson, Leslie M. Manohar, Ryan D. Wilkins, Jennifer Gurske-Deperio and Mark T. Ehrensberger
Am. J. Sports Med. 2008; 36; 907 originally published online Mar 21, 2008;
DOI: 10.1177/0363546508314793

The online version of this article can be found at:
<http://ajs.sagepub.com/cgi/content/abstract/36/5/907>

Published by:

 SAGE Publications

<http://www.sagepublications.com>

On behalf of:



[American Orthopaedic Society for Sports Medicine](#)

Additional services and information for *American Journal of Sports Medicine* can be found at:

Email Alerts: <http://ajs.sagepub.com/cgi/alerts>

Subscriptions: <http://ajs.sagepub.com/subscriptions>

Reprints: <http://www.sagepub.com/journalsReprints.nav>

Permissions: <http://www.sagepub.com/journalsPermissions.nav>

Citations (this article cites 35 articles hosted on the
SAGE Journals Online and HighWire Press platforms):
<http://ajs.sagepub.com/cgi/content/abstract/36/5/907#BIBL>

Influence of Suture Material on the Biomechanical Behavior of Suture-Tendon Specimens

A Controlled Study in Bovine Rotator Cuff

Leslie J. Bisson,^{*†} MD, Leslie M. Manohar,[†] MD, Ryan D. Wilkins,[†]

Jennifer Gurske-Deperio,[†] MD, and Mark T. Ehrensberger,[‡] MS

From the [†]Department of Orthopaedics, University at Buffalo, Buffalo, New York, and

[‡]Department of Biomechanical Engineering, Syracuse University, Syracuse, New York

Background: Despite technical advances in rotator cuff surgery, recurrent or persistent defects in the repaired tendon continue to occur. Improved strength of sutures and suture anchors has resulted in the most common site of failure being the suture-tendon interface.

Hypothesis: The type of suture material used has a significant effect on the biomechanics of the suture-tendon interface.

Study Design: Controlled laboratory study.

Methods: Thirty-two bovine infraspinatus specimens were randomly assigned to simple suture fixation using No. 2 Fiberwire, Ultrabraid, Orthocord, or Ethibond. Each specimen was subjected to cyclic testing from 5 to 30 N for 30 cycles, followed by load-to-failure testing.

Results: Cyclic testing revealed significantly greater elongation with Ultrabraid, whereas peak-to-peak displacements were lowest for Fiberwire and greatest for Orthocord. Load-to-failure testing revealed no significant differences between any suture material for ultimate tensile load. Fiberwire and Orthocord repairs had the highest stiffness. The most common failure mode during load-to-failure testing was suture breakage in Ethibond specimens and suture cutting through the tendon in the polyblend suture specimens.

Conclusion: The type of suture material has a significant effect on the biomechanical behavior of the suture-tendon interface.

Clinical Relevance: The type of suture may influence early gap formation and ultimate healing of rotator cuff repairs.

Keywords: rotator cuff repair; polyblend suture; bovine rotator cuff; shoulder surgery

For many surgeons, rotator cuff surgery has progressed during the last 2 decades from a completely open surgical procedure to a mini-open procedure to a completely arthroscopic procedure. This technical advance in the performance of the surgery has been accompanied by a diminution

in postoperative pain and a decrease in residual stiffness when compared with traditional open surgery.²⁹

Despite the technical advances in rotator cuff surgery, however, authors have continued to note either persistent or recurrent defects after repair.^{2,7,9,17,18,31} One of the goals of surgery is to obtain a structurally sound repair that is capable of surviving early motion. Sites of failure can include the tendon, suture, bone, or anchor as well as the interfaces between bone and suture anchor, suture anchor and suture, or suture and tendon. Because of the introduction of stronger anchors and stronger suture material, the suture-tendon interface is the weak point of the initial repair construct.^{4,12} Many of the newer commercially available suture-anchor products include polyblend suture materials that incorporate ultra high molecular weight polyethylene (UHMWPE) into

*Address correspondence to Leslie J. Bisson, MD, University Orthopaedics, 4949 Harlem Road, Amherst, NY 14226 (e-mail: klbisson@aol.com).

One or more authors has declared a potential conflict of interest: Dr Bisson has received funds from Arthrex for an unrelated research project.

the suture in varying configurations. Although investigators have tested the strength of damaged polyblend suture,³³ its abrasiveness to articular cartilage,³⁴ and its ability to hold knots,^{16,24} minimal data are available with respect to the effect of suture material on the biomechanical properties of the suture-tendon interface. A recent report documented the propensity for polyblend suture to damage surgical gloves.¹⁹ If these newer sutures also have an increased propensity to damage the rotator cuff, this could have a deleterious effect on the structural integrity of the repair.

The primary purpose of our study was to test the effect of suture type on the biomechanics of the rotator cuff–suture interface under both cyclic and load-to-failure conditions. We chose to test these sutures in bovine rotator cuff because of the relative ease of availability as well as the greater consistency of tendon material when compared with that found in human cadaveric specimens, and we chose to compare the biomechanical characteristics of constructs using the polyblend sutures with those using Ethibond (Ethicon Inc, Johnson and Johnson, Piscataway, NJ), a commonly used first-generation suture. The secondary purpose of the study was to test the biomechanical properties of the sutures themselves under identical cyclic followed by load-to-failure conditions. Our null hypotheses were (1) that there would be no difference in the biomechanical performance of suture-tendon constructs using the newer polyblend sutures when compared either with each other or with Ethibond under both cyclic and load-to-failure conditions in the bovine rotator cuff specimens and (2) that there would be no difference in the biomechanical characteristics of the polyblend sutures when compared with each other or with Ethibond.

METHODS

Bovine Specimens

Sixteen fresh bovine disarticulated shoulders with the infraspinatus attached to the proximal humerus were obtained from a local meat processing company. All animals were mature at the time of slaughter. The infraspinatus tendon was sharply detached from the proximal humerus at its insertion and split longitudinally, yielding 32 specimens. No visible abnormalities were noted on any specimen, and all were kept moist with saline solution as necessary during testing. Specimens were then randomized to biomechanical testing of the suture-tendon interface using a simple stitch of either Ethibond, Fiberwire (Arthrex Inc, Naples, Fla), Ultrabraid (Smith and Nephew Inc, London, England), or Orthocord (DePuy Mitek Inc, Johnson and Johnson, Piscataway, NJ), all of size No. 2, with each configuration tested 8 times. The experiment was designed to specifically test the suture-tendon interface; for this reason, bone and suture anchors were not used. Each suture was passed in simple fashion through the tendon at 1 cm from the insertion, and a 3-cm loop was tied in the suture using at least 5 square knots. The simple suture technique is still in clinical use (particularly in the lateral row of double-row repairs) and was chosen to minimize contamination of the results attributable to unavoidable differences in surgical technique from specimen to specimen. The 3-cm loop was used to

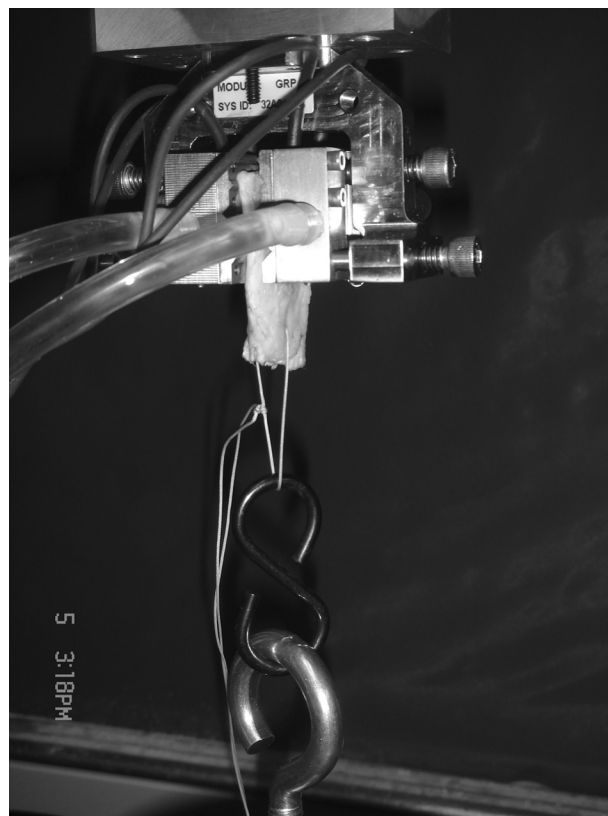


Figure 1. Bovine rotator cuff specimen held with a cryoclamp with a single loop of suture placed through the tendon.

approximate the portion of suture that would be passed through or over the greater tuberosity in a transosseous repair technique. Microcalipers were used to measure the exact distance from the edge of the tendon to the entry site of the suture as well as the thickness of the tendon at the site of the suture. Cross-sectional area was calculated using the measured distance multiplied by the thickness of the tendon at the site of suture passage. The loop was then placed over the load cell of a Bionix Mini MTS machine (MTS Systems Corp, Eden Prairie, Minn), and the tendon was frozen into a cryoclamp 1 cm medial to the site of suture passage (Figure 1).

Cyclic Loading Test

A cyclic loading test was performed to evaluate the performance of the different sutures under repeated loading conditions.²⁶ The construct was preloaded to 5 N for 30 seconds, followed by 30 cycles from 5 to 30 N at 0.25 Hz using a half-sinusoidal waveform. The maximum load for cycling was set at 30 N based on preliminary testing, showing that this would be approximately 25% of the maximum load to failure, and 30 cycles were chosen based on the observation that the slope of the displacement versus time curve appeared to become stable between 20 and 30 cycles. This cyclic protocol has been used by other investigators.^{25-27,30} Elongation and peak-to-peak displacement were determined in the cyclic loading test (Figure 2). Elongation was defined as the difference

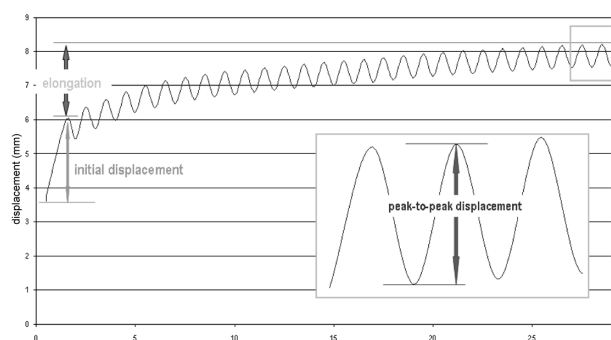


Figure 2. Graph of displacement versus cycles, illustrating how initial displacement, elongation, and peak-to-peak displacement were determined during cyclic testing.

in y-displacement between the 1st cyclic peak and the 30th cyclic peak. Peak-to-peak displacement was defined as the average of the local minimum to maximum of the 28th, 29th, and 30th cycles.

Load-to-Failure Tensile Test

After cyclic loading, each tendon specimen was loaded to failure at 1 mm/s.²⁶ Load versus displacement was recorded until failure. Ultimate tensile load was considered to be the peak force recorded. Stiffness was calculated by determining the slope of the best fit line on the load versus displacement curve. Failure mechanism was recorded for each specimen.

Suture Specimens

A 3-cm loop of each suture was created using at least 5 square knots and was connected to the load cell of the MTS machine. Four sets of each suture were then tested using a cyclic loading followed by a load-to-failure protocol identical to that described for the bovine specimens.

Statistical Analysis

A 1-way analysis of variance was used to determine the effect of the suture type on the biomechanical properties of the suture-tendon specimens. Post hoc comparisons were tested on all significant analysis of variance findings with a Tukey honestly significant difference. Statistical analysis of distance from tendon edge to suture entry, tendon thickness, area, elongation, peak-to-peak displacement, ultimate tensile load, and stiffness was performed. Significance was set at $P < .05$. All statistical analyses were performed using SPSS version 14 (SPSS Inc, Chicago, Ill).

RESULTS

Bovine Specimens

Specimen Consistency. There was no significant difference between mean specimen thickness at the site of suture penetration, mean distance from tendon edge to

TABLE 1
Measurements of Rotator Cuff Specimens^a

Suture Group	Tendon Thickness, mm	Distance From Edge to Suture Entry, mm	Area of Tendon Spanned by Suture, mm ²
Ethibond ^a	8.75 (1.52)	12 (1.89)	96.7 (14.2)
Fiberwire ^a	8.62 (1.50)	12 (1.90)	103 (14.9)
Orthocord ^a	9.43 (1.54)	10.1 (0.68)	95.5 (20.1)
Ultrasraid ^a	8.98 (1.75)	11.4 (1.55)	96 (20.3)
<i>P</i>	.756	.075	.829

^aValues are mean (SD).

suture entry site, or cross-sectional area of tendon in any group of specimens (Table 1).

Cyclic Loading. The cyclic loading test revealed no significant difference between Ethibond, Fiberwire, or Orthocord with respect to elongation but did show significantly greater elongation for Ultrasraid. Peak-to-peak displacements were lowest for Fiberwire and highest for Orthocord, with these differences being significant (Table 2).

Load to Failure. Load-to-failure testing showed no significant differences between any suture material with respect to ultimate tensile load. There was a significant difference in stiffness between several suture-tissue specimens, with Ethibond constructs being less stiff than Orthocord and Fiberwire but not significantly different than Ultrasraid. Fiberwire was stiffer than Ultrasraid but was not significantly stiffer than Orthocord (Table 2).

Mechanism of Failure. All Fiberwire and Ultrasraid specimens failed as a result of suture pulling through the tendon. Three Ethibond and 6 Orthocord specimens failed by suture pulling through the tendon; the remaining 5 Ethibond and 2 Orthocord specimens failed by suture breakage away from the knot.

Suture Material

Cyclic Loading. Cyclic testing showed significantly lower elongation for Fiberwire than Ultrasraid, but the magnitude of the differences between suture materials was minimal (<0.1 mm). Peak-to-peak displacement was significantly greater for Ethibond and Orthocord, but once again the magnitude of this difference was relatively small (approximately 0.3 mm) (Table 3).

Load-to-Failure Testing. Ultimate tensile load was highest in Fiberwire, followed by Ultrasraid, Orthocord, and finally Ethibond. Stiffness was greatest for Fiberwire and Ultrasraid, followed by Orthocord and finally by Ethibond (Table 3).

DISCUSSION

Surgical treatment of rotator cuff tears has progressed over the last 2 decades from open to mini-open to all-arthroscopic repairs, and this progression has been accompanied by an explosion in the number of devices available for fixation of the tendon to the greater tuberosity. Despite the progress in surgical technique, however, there is still a significant incidence of

TABLE 2
Biomechanical Behavior of Suture-Tendon Specimens^a

Variable	Ethibond	Fiberwire	Orthocord	Ultrasbraid
Cyclic loading test				
Elongation, mm	0.98 (0.29)	0.95 (0.40)	1.04 (0.18)	1.48 (0.30) ^b
Peak-to-peak displacement, mm	0.87 (0.09) ^c	0.55 (0.12) ^b	1.02 (0.08) ^b	0.74 (0.08) ^c
Load-to-failure test				
Ultimate tensile load, N	133 (15)	152 (56)	181 (55)	165 (49)
Stiffness, N/mm	9.2 (2.3) ^c	16.5 (3.8) ^d	14.8 (2.5) ^e	12.2 (2.5) ^f

^aValues are mean (SD).

^bSignificantly different versus all others.

^cSignificantly different versus Fiberwire and Orthocord.

^dSignificantly different versus Ethibond and Ultrasbraid.

^eSignificantly different versus Ethibond.

^fSignificantly different versus Fiberwire.

TABLE 3
Biomechanical Behavior of Isolated Suture Specimens^a

Variable	Ethibond	Fiberwire	Orthocord	Ultrasbraid
Cyclic loading test				
Elongation, mm	0.14 (0.019)	0.12 (0.023) ^b	0.18 (0.017)	0.20 (0.063) ^c
Peak-to-peak displacement, mm	0.35 (0.005) ^d	0.20 (0.006) ^e	0.56 (0.016) ^d	0.20 (0.008) ^e
Load-to-failure test				
Ultimate tensile load, N	141 (8.0) ^d	335 (20.2) ^e	275 (19) ^d	325 (24) ^e
Stiffness, N/mm	21.5 (3.1) ^d	59.9 (5.65) ^e	36.2 (1.66) ^d	59.9 (5.01) ^e

^aValues are mean (SD).

^bSignificantly different compared with Ultrasbraid.

^cSignificantly different compared with Fiberwire.

^dSignificantly different compared with all.

^eSignificantly different compared with Ethibond and Orthocord.

persistent or recurrent defects of the repaired cuff after surgery.^{2,7,9,17,18,31} Multiple failure modes have been reported and examined in rotator cuff surgery including suture failure, knot failure, suture pull through soft tissue, failure of the suture-anchor interface, and anchor pull-out of bone. With the introduction of stronger anchors and suture material, the suture-tendon interface has been implicated as the weakest link in the repair of the rotator cuff.^{4,12}

One significant advance in the design of suture material has been the introduction of polyblend sutures that incorporate UHMWPE into the suture. These sutures have been shown to be stronger than standard polyester sutures both when intact and when damaged.³³ Fiberwire is a nonabsorbable, polyester suture with a UHMWPE multifilament core and a braided polyester jacket. The nonbraided core resists elongation and is further protected by the polyester jacket. Orthocord combines an absorbable polydioxanone (PDS) core coated with polyglactin 910 and a nonabsorbable UHMWPE sleeve with the goal of leaving a lower profile suture once the PDS has dissolved. Ultrasbraid has braided, nonabsorbable polyethylene fibers without a longitudinal core. Prior biomechanical studies have examined the suture-anchor interface,^{13,14,23,34} the anchor-bone interface,^{5,6} and the individual properties of suture and suture configurations.[§] However, few have specifically examined the suture-tendon

interface,^{26,35} and few have examined the polyblends Orthocord and Ultrasbraid. A recent article reported the increased incidence of glove tears attributable to the use of polyblend suture in rotator cuff surgery,¹⁹ which creates the concern that these sutures may also damage rotator cuff tendon. We are aware of no study that specifically compares the effect of different polyblend sutures on the suture-tendon interface. To address this question, we compared the biomechanical behavior of these 3 polyblend sutures to that of Ethibond, a braided polyester suture. Our purpose in this initial study was not to determine the optimal suture type and repair method for rotator cuff surgery but rather to determine whether different suture materials would cause differences in the biomechanical behavior of suture-tendon specimens and whether further study using human specimens and clinically relevant repair methods would be worthwhile.

With respect to our first hypothesis, our study revealed significant differences in elongation, peak-to-peak displacement, and stiffness when different suture materials were compared in bovine rotator cuff using a single simple stitch. These differences, although statistically significant, were small in magnitude. However, they were much greater than those differences found when the sutures were tested in isolation, suggesting that the differences occurred at the suture-tendon interface and were not simply attributable to differences in the biomechanical behavior of the sutures themselves. We demonstrated a significant effect of suture

[§]References 1, 3, 4, 10, 11, 15, 20-22, 26, 28, 30, 32

material on biomechanical behavior of suture-tendon specimens after only 30 cycles. We did not measure elongation after hundreds or thousands of cycles, as would occur in a clinical setting, and we consider this to be an important area for future research. It is possible that the differences in elongation found after 30 cycles would be much greater with a more clinically relevant number of cycles. We found no significant difference in ultimate tensile load but did find significant differences in stiffness. The finding of no difference in ultimate tensile load suggests that these sutures do not cause a significant weakening at the suture-tendon interface compared with Ethibond, at least in the model tested. However, the tendency for the polyblend sutures to fail by cutting through the tendon at loads much lower than their ultimate tensile load may partially reduce the advantage conferred by their greater tensile strength compared with Ethibond. Our inability to demonstrate a suture-related difference in ultimate tensile load may also be attributable to our small sample size, and the lack of a significant difference should be interpreted with caution. Studies with larger numbers of specimens may indeed reveal differences in this factor as well. We therefore demonstrated that the choice of suture material can affect some of the biomechanical parameters of the suture-tendon interface, at least in a bovine model. Further studies in human cadaveric tissue using more complex suture methods and greater numbers of cycles are necessary to determine whether these differences are clinically important.

Regarding our second hypothesis, we found significant differences between suture material in all biomechanical parameters studied. The differences in cyclic loading performance when testing the sutures in isolation were likely too small to be clinically relevant. The load-to-failure testing of sutures in isolation showed that the polyblend sutures were much stronger and stiffer than Ethibond, a finding that has been reported by other authors.⁶

We acknowledge several important limitations of our study. First, the use of a bovine model limits the direct extrapolation of our results to human rotator cuff repairs. We chose to use bovine rotator cuff specimens because of their availability and relative consistency compared with human specimens. Although other investigators have used bovine infraspinatus to test various methods of rotator cuff repair,²² differences including tendon thickness, muscle pennation, and collagen fiber orientation between bovine infraspinatus and human supraspinatus may have influenced our results in unknown ways. Second, although we randomized the specimens before assigning them to a group, there may have been differences in the specimens themselves that influenced our findings. We attempted to control for this by calculating the area of the tendon spanned by the suture and using only mature animals, but differences in tendon degeneration may have been present despite the randomization process and may have affected our results. Third, we tested only a single, simple suture, which may be rarely used in current practice, and incorporated a 3-cm loop to approximate the amount of suture that would be passed over or through the greater tuberosity in a transosseous repair. Most authors recommend multiple sutures, often in locking fashion, during rotator cuff repair, and the use of suture anchors would result in a much smaller loop and decrease the overall contribution of the suture material to the biomechanical behavior of the construct. We chose

a simple suture because of its ease and reproducibility, and we thought it would be the suture method least likely to influence our results because of surgical technique. The fact that essentially all of our means had very low standard deviations attests to the reproducibility of this technique, but the choice of a suture method that is rarely used alone clinically means that our results should not be extrapolated to other suture methods or to repairs using anchors. We attempted to test a modified Mason-Allen stitch as well but found that this changed the mode of failure during load-to-failure testing to suture breakage rather than pulling through the tendon in all specimens, and we thought that this failure mode poorly reflected that seen clinically. We plan to compare suture materials using the modified Mason-Allen stitch in human cadaveric tissue. Fourth, we did not directly document the site of elongation in our specimens. It is possible that the differences in elongation were attributable to different degrees of knot slippage rather than differences at the suture-tendon interface; however, direct observation during the cycling process as well as inspection of the samples after load-to-failure testing failed to reveal evidence of knot slippage in any specimen. Also, the differences in elongation and peak-to-peak displacement when the sutures were tested in isolation, although significant, were quite small, which further supports the conclusion that the differences in the suture-tendon specimens were occurring at the suture-tendon interface rather than at the knot or in the 3-cm loop. Finally, as mentioned above, we terminated cyclic testing after only 30 cycles. We did this to duplicate the methods used by other authors.^{16,25,26,30} However, this limits the conclusions that we can draw regarding the performance of the specific sutures after a more clinically relevant number of cycles.

We are in the process of publishing a study on repair of the distal biceps tendon⁸ that shows inferior performance of No. 5 Fiberwire when compared with No. 5 Ethibond when a repair using a Bunnell stitch in human cadaveric specimens is cycled 3000 times using loads up to 100 N. This is in direct contrast to the current study, which shows superior performance of No. 2 Fiberwire when compared with No. 2 Ethibond (as well as the other polyblend sutures) in bovine rotator cuff when cycled 30 times using loads of up to 30 N. These differences are probably explained by some combination of differences in species; tendon location, strength, age, and structure; complexity of suture technique; diameter of suture; loads during cycling; number of cycles; and biomechanical parameters measured; however, the contrasting results in these studies should stimulate further investigation using clinically applicable models for each repair situation. One recent publication that compared different suture materials noted minimal gap formation of cyclically loaded bovine gastrocnemius tendon repairs when the investigators used polyblend suture placed in a single locking configuration but showed increased gap formation compared with braided polyester when polyblend suture was used in other configurations.³⁵

CONCLUSIONS

The type of suture material significantly influenced the elongation, peak-to-peak displacement, and stiffness but

not the ultimate tensile load of bovine rotator cuff/simple suture specimens. Suture material tested in isolation also had cyclic and load-to-failure performance that varied significantly according to type of suture material. If a surgeon wanted to choose a suture material that when used in a rotator cuff repair combined the lowest peak-to-peak displacement and elongation with the greatest stiffness, then our study would support Fiberwire as the suture material of choice for this surgery. However, because of conflicting conclusions between this study and our study of distal biceps repairs, as well as the specific repair method used in this study, we recommend that further studies be done in human cadaveric specimens using more complex suture techniques under physiologic loads and clinically relevant numbers of cycles before a specific suture material is recommended.

ACKNOWLEDGMENT

We thank Cathy Buyea for help with the statistical analysis of our data and Craig Howard for assistance with the biomechanical testing.

REFERENCES

- Abbi G, Espinoza L, Odell T, Mahar A, Pedowitz R. Evaluation of 5 knots and 2 suture materials for arthroscopic rotator cuff repair: very strong sutures can still slip. *Arthroscopy*. 2006;22:38-43.
- Anderson K, Boothby M, Aschenbrenner D, van Holsbeeck M. Outcome and structural integrity after arthroscopic rotator cuff repair using 2 rows of fixation: minimum 2-year follow-up. *Am J Sports Med*. 2006;34:1899-1905.
- Baleani M, Ohman C, Guandalini L, et al. Comparative study of different tendon grasping techniques for arthroscopic repair of the rotator cuff. *Clin Biomech (Bristol, Avon)*. 2006;21:799-803.
- Baleani M, Schrader S, Veronesi CA, Rotini R, Giardino R, Toni A. Surgical repair of the rotator cuff: a biomechanical evaluation of different tendon grasping and bone suture fixation techniques. *Clin Biomech (Bristol, Avon)*. 2003;18:721-729.
- Barber FA, Coons DA, Ruiz-Suarez M. Cyclic load testing of biodegradable suture anchors containing 2 high-strength sutures. *Arthroscopy*. 2007;23:355-360.
- Barber FA, Herbert MA, Richards DP. Sutures and suture anchors: update 2003. *Arthroscopy*. 2003;19:985-990.
- Bishop J, Klepps S, Lo IK, Bird J, Gladstone JN, Flatow EL. Cuff integrity after arthroscopic versus open rotator cuff repair: a prospective study. *J Shoulder Elbow Surg*. 2006;15:290-299.
- Bisson LJ, Gurske de Perio J, Weber AE, Ehrensberger MT, Buyea C. Is it safe to perform aggressive rehabilitation after distal biceps tendon repair using the modified two-incision approach? A biomechanical study. *Am J Sports Med*. 2007;35:2045-2050.
- Boileau P, Brassart N, Watkinson DJ, Carles M, Hatzidakis AM, Krishnan SG. Arthroscopic repair of full-thickness tears of the supraspinatus: does the tendon really heal? *J Bone Joint Surg Am*. 2005;87:1229-1240.
- Coons DA, Barber FA, Herbert MA. Triple-loaded single-anchor stitch configurations: an analysis of cyclically loaded suture-tendon interface security. *Arthroscopy*. 2006;22:1154-1158.
- Cummins CA, Appleyard RC, Strickland S, Haen PS, Chen S, Murrell GA. Rotator cuff repair: an ex vivo analysis of suture anchor repair techniques on initial load to failure. *Arthroscopy*. 2005;21:1236-1241.
- Cummins CA, Murrell GA. Mode of failure for rotator cuff repair with suture anchors identified at revision surgery. *J Shoulder Elbow Surg*. 2003;12:128-133.
- De Carli A, Vadala A, Monaco E, Labianca L, Zanzotto E, Ferretti A. Effect of cyclic loading on new polyblend suture coupled with different anchors. *Am J Sports Med*. 2005;33:214-219.
- Deakin M, Stubbs D, Bruce W, Goldberg J, Gillies RM, Walsh WR. Suture strength and angle of load application in a suture anchor eyelet. *Arthroscopy*. 2005;21:1447-1451.
- Demirhan M, Atalar AC, Kilicoglu O. Primary fixation strength of rotator cuff repair techniques: a comparative study. *Arthroscopy*. 2003;19:572-576.
- Elkousy H, Hammerman SM, Edwards TB, et al. The arthroscopic square knot: a biomechanical comparison with open and arthroscopic knots. *Arthroscopy*. 2006;22:736-741.
- Flurin PH, Landreau P, Gregory T, et al. Cuff integrity after arthroscopic rotator cuff repair: correlation with clinical results in 576 cases. *Arthroscopy*. 2007;23:340-346.
- Galatz LM, Ball CM, Teefey SA, Middleton WD, Yamaguchi K. The outcome and repair integrity of completely arthroscopically repaired large and massive rotator cuff tears. *J Bone Joint Surg Am*. 2004;86:219-224.
- Kaplan KM, Gruson KI, Gorczyński CT, Strauss EJ, Kummer FJ, Rokito AS. Glove tears during arthroscopic shoulder surgery using solid-core suture. *Arthroscopy*. 2007;23:51-56.
- Kim DH, Elattrache NS, Tibone JE, et al. Biomechanical comparison of a single-row versus double-row suture anchor technique for rotator cuff repair. *Am J Sports Med*. 2006;34:407-414.
- Klinger HM, Steckel H, Spahn G, Buchhorn GH, Baums MH. Biomechanical comparison of double-loaded suture anchors using arthroscopic Mason-Allen stitches versus traditional transosseous suture technique and modified Mason-Allen stitches for rotator cuff repair. *Clin Biomech (Bristol, Avon)*. 2007;22:106-111.
- Koganti AK, Adamson GJ, Gregersen CS, Pink MM, Shankwiler JA. Biomechanical comparison of traditional and locked suture configurations for arthroscopic repairs of the rotator cuff. *Am J Sports Med*. 2006;34:1832-1838.
- Lo IK, Burkhart SS, Athanasiou K. Abrasion resistance of two types of nonabsorbable braided suture. *Arthroscopy*. 2004;20:407-413.
- Lo IK, Burkhart SS, Chan KC, Athanasiou K. Arthroscopic knots: determining the optimal balance of loop security and knot security. *Arthroscopy*. 2004;20:489-502.
- Ma CB, Comerford L, Wilson J, Puttlitz CM. Biomechanical evaluation of arthroscopic rotator cuff repairs: double-row compared with single-row fixation. *J Bone Joint Surg Am*. 2006;88:403-410.
- Ma CB, MacGillivray JD, Clabeaux J, Lee S, Otis JC. Biomechanical evaluation of arthroscopic rotator cuff stitches. *J Bone Joint Surg Am*. 2004;86:1211-1216.
- Park MC, Tibone JE, Elattrache NS, Ahmad CS, Jun BJ, Lee TQ. Part II: biomechanical assessment for a footprint-restoring transosseous-equivalent rotator cuff repair technique compared with a double-row repair technique. *J Shoulder Elbow Surg*. 2007;16:469-476.
- Schlegel TF, Hawkins RJ, Lewis CW, Turner AS. An in vivo comparison of the modified Mason-Allen suture technique versus an inclined horizontal mattress suture technique with regard to tendon-to-bone healing: a biomechanical and histologic study in sheep. *J Shoulder Elbow Surg*. 2007;16:115-121.
- Severud EL, Ruotolo C, Abbott DD, Nottage WN. All-arthroscopic versus mini-open rotator cuff repair: a long-term retrospective outcome comparison. *Arthroscopy*. 2003;19:234-238.
- Sileo MJ, Ruotolo CR, Nelson CO, Serra-Hsu F, Panchal AP. A biomechanical comparison of the modified Mason-Allen stitch and massive cuff stitch in vitro. *Arthroscopy*. 2007;23:235-240, 240.e1-2.
- Verma NN, Dunn W, Adler RS, et al. All-arthroscopic versus mini-open rotator cuff repair: a retrospective review with minimum 2-year follow-up. *Arthroscopy*. 2006;22:587-594.
- White CD, Bunker TD, Hooper RM. The strength of suture configurations in arthroscopic rotator cuff repair. *Arthroscopy*. 2006;22:837-841.
- Wright PB, Budoff JE, Yeh ML, Kelm ZS, Luo ZP. Strength of damaged suture: an in vitro study. *Arthroscopy*. 2006;22:1270-1275.e3.
- Wust DM, Meyer DC, Favre P, Gerber C. Mechanical and handling properties of braided polyblend polyethylene sutures in comparison to braided polyester and monofilament polydioxanone sutures. *Arthroscopy*. 2006;22:1146-1153.
- Yamagami N, Mori R, Yotsumoto T, Hatanaka H, Takao M, Uchio Y. Biomechanical differences resulting from the combination of suture materials and repair techniques. *J Orthop Sci*. 2006;11:614-619.