The American Journal of Sports Medicine

http://ajs.sagepub.com/

Biomechanical Analysis of the Pectoralis Major Tendon and Comparison of Techniques for Tendo-osseous Repair

Seth L. Sherman, Emery C. Lin, Nikhil N. Verma, Richard C. Mather, James M. Gregory, Justin Dishkin, Daniel P. Harwood, Vincent M. Wang, Elizabeth F. Shewman, Brian J. Cole and Anthony A. Romeo

Am J Sports Med 2012 40: 1887 originally published online July 9, 2012
DOI: 10.1177/0363546512452849

The online version of this article can be found at:
http://ajs.sagepub.com/content/40/8/1887

Published by:
SAGE
http://www.sagepublications.com

On behalf of:
American Orthopaedic Society for Sports Medicine
AOSSM

Biomechanical Analysis of the Pectoralis Major Tendon and Comparison of Techniques for Tendo-osseous Repair

Seth L. Sherman,* MD, Emery C. Lin,† BA, Nikhil N. Verma,†‡ MD, Richard C. Mather,§ MD, James M. Gregory,† MD, Justin Dishkin,† MS, Daniel P. Harwood,† MS, Vincent M. Wang,† PhD, Elizabeth F. Shewman,† MS, Brian J. Cole,† MD, MBA, and Anthony A. Romeo,† MD
Investigation performed at the Division of Sports Medicine, Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, Illinois

Background: Various described surgical techniques exist for the repair of pectoralis major ruptures at the tendo-osseous junction. It is unclear how these techniques restore the native properties of the pectoralis major tendon because its biomechanical properties have not been described.

Hypothesis: All repairs will have lower initial biomechanical profiles than the native attachment, and transosseous sutures will demonstrate improved initial biomechanical performance compared with anchors or buttons.

Study Design: Controlled laboratory study.

Methods: Twenty-four fresh-frozen cadaveric shoulders were randomized to 4 equal groups, including 3 experimental repair groups and 1 control group of intact pectoralis major tendons. The characteristics of the native anatomic footprint were recorded, and the experimental groups underwent pectoralis detachment, followed by subsequent repair. The restoration of the anatomic footprint was recorded. All specimens were tested with cyclic loading and load-to-failure protocols with load, displacement, and optical marker data simultaneously collected.

Results: Under cyclic loading, the intact specimens demonstrated a significantly higher secant stiffness (74.8 ± 1.6 N/mm) than the repair groups (endosteal Pec Button [PB], 46.2 ± 6.4 N/mm; suture anchor [SA], 45.9 ± 8.7 N/mm; transosseous [TO], 44.2 ± 5.5 N/mm). Measured as a percentage change, the PB and SA groups showed a significantly higher initial excursion than the intact group (PB, 24.0% ± 11.7%; SA, 17.5% ± 6.9%; intact, 2.2% ± 1.0%), and the PB group demonstrated a significantly higher cyclic elongation than the intact group (PB, 7.5% ± 2.9%; intact, 1.5% ± 1.5%). Under load-to-failure testing, the intact group showed a significantly greater maximum load (1454.8 ± 795.7 N) and linear stiffness (221.0 ± 111.7 N/mm) than the 3 repair groups (PB, 353.5 ± 88.3 N and 63.5 ± 6.9 N/mm; SA, 292.0 ± 73.3 N and 77.0 ± 7.8 N/mm; TO, 359.2 ± 110.4 N and 64.5 ± 14.1 N/mm, respectively). All repair constructs failed via suture pulling through the tendon.

Conclusion: The biomechanical characteristics of the transosseous repair, suture anchors, or Pec Button repair were inferior to those of the native pectoralis tendon. There was no significant difference in any of the biomechanical outcomes among the repair groups. Further refinement and evaluation of suture technique and configuration in pectoralis major repair should be considered.

Clinical Relevance: Transosseous repair, suture anchors, and endosteal Pec Buttons appear to confer similar biomechanical integrity for pectoralis major repair. Restricting early activities to thresholds below the identified failure loads seems prudent until soft tissue healing to bone is reliably achieved.

Keywords: pectoralis major; tendon rupture; biomechanical; tendon repair

The pectoralis major is a powerful adductor and internal rotator of the arm.[7,10] Rupture of the pectoralis major is a relatively rare occurrence, with the majority of these cases occurring in athletes (in particular, weight lifters) and heavy laborers.[10] While low-demand patients may have no difficulty with activities of daily life after nonoperative treatment, the inability to attain full strength without surgical repair necessitates operative treatment for the majority of athletes and laborers.[3,10] There are only a number of small case series describing techniques and outcomes of pectoralis major repair.[2,5,8-10,14] A recent meta-analysis reported excellent results in 88% of patients treated operatively.[2] However, results of individual small case series vary from 46% to 100% excellent results.[5,8,9,14] Despite a multitude of described repair techniques, there is no definitive gold-standard surgical procedure to repair the pectoralis major.

The principles of pectoralis major repair are the same regardless of the technique chosen. The goal is to utilize

The American Journal of Sports Medicine, Vol. 40, No. 8
DOI: 10.1177/0363546512452849

TABLE 1
Summary of the Demographics of the Cadaveric Shoulders[a]

Study Group	Age, Mean ± SD, y	Sex, n		Shoulder Side, n		Bone Density, Mean ± SD
		Male	Female	Right	Left	
Pec Button	69.8 ± 10.2	4	2	4	2	607.2 ± 116.7
Suture anchor	72.0 ± 12.6	4	2	3	3	625.0 ± 98.8
Transosseous suture	72.7 ± 9.1	4	2	3	3	607.1 ± 130.4
Intact	77.8 ± 11.3	4	2	3	3	571.7 ± 157.1

[a]The groups did not differ significantly in age, bone density, sex, or shoulder side. SD, standard deviation.

sutures to obtain an anatomic reduction of the tendon footprint while avoiding injury to the adjacent long head of the biceps. A number of methods have been described to reattach the avulsed tendon to its normal humeral insertion. The majority of techniques involve suture repair using either transosseous tunnels and bone troughs or, more recently, suture anchors.[10] In the largest series of surgical repairs (n = 33), Aarimaa et al[1] found no difference between those treated with suture anchors and those with transosseous suture repairs. Additionally, a recent biomechanical study by Hart et al[6] found no statistically significant difference in ultimate failure load and stiffness between suture anchors and transosseous sutures for pectoralis repair.

Our current methods of repair involve either a transosseous repair with 6 sutures through four 2.0-mm bone tunnels, a suture anchor repair utilizing 3 double-loaded 5.0- to 6.0-mm suture anchors, or an endosteal Pec Button (Arthrex, Naples, Florida) repair utilizing 3 double-loaded buttons. The biomechanical properties of using an endosteal Pec Button for pectoralis major repair have not been examined. Additionally, the biomechanical properties and strength of the native intact pectoralis have never been described. It is unknown how well these 3 repair techniques are able to restore the native properties of the intact pectoralis.

The goal of the current investigation is to critically evaluate the biomechanical profiles of these 3 repairs and compare the results with those of the native pectoralis to make evidence-based treatment recommendations for pectoralis major repair. Our hypothesis is that all repairs will have lower initial biomechanical profiles compared with the native attachment and that transosseous sutures will demonstrate improved initial biomechanical performance compared with anchors or buttons.

MATERIALS AND METHODS

Twenty-four fresh-frozen, human cadaveric shoulders were thawed at room temperature before dissection, repair, and testing. Quantitative computed tomography was used to determine the bone density of the intertubercular groove before testing to distribute the specimens into 4 groups of 6 specimens each, with similar mean values of bone mineral density per group (Table 1). The pectoralis major tendon was identified through a deltopectoral approach. The humerus and rotator cuff muscles were dissected free of skin and any underlying soft tissues. The insertion was carefully marked, and the length and midportion width of the footprint were measured with a digital caliper. In all but the intact tendon group, the entire length of the tendon, including both the clavicular and sternal heads, was incised at the insertion and removed completely. The tear was repaired with the transosseous tunnel, suture anchor, or Pec Button technique (Figure 1).

For the transosseous tunnel technique, four 2-mm bone tunnels were made with a 2-mm drill bit along the insertion. Two tunnels were 5 mm from the proximal and distal edges of the insertion, and 2 tunnels were placed equidistant between the other 2 tunnels. Two rows of holes were made, one along the insertion and one just inside the bicipital groove with care taken to protect the biceps tendon. The bone bridge left between the holes was approximately 1 cm. Two strands of No. 2 Orthocord (DePuy Mitek, Raynham, Massachusetts) were placed through the 3 most proximal tunnels, and one shuttle suture was placed through each of the 3 most distal holes. The pectoralis tendon was sutured utilizing a modified Mason-Allen stitch configuration. Once the sutures were passed through the tendon, they were shuttled to the next most distal tunnel so that

‡Address correspondence to Nikhil N. Verma, MD, Rush University Medical Center, Department of Orthopaedic Surgery, Division of Sports Medicine, 1611 West Harrison Street, Suite 300, Chicago, IL 60612 (e-mail: nikhil.verma@rushortho.com).

*Department of Orthopedic Surgery, Missouri Orthopaedic Institute, University of Missouri Health System, Columbia, Missouri.

†Division of Sports Medicine, Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, Illinois.

§Department of Orthopaedics, Duke University Medical Center, Durham, North Carolina.

Presented at the 38th annual meeting of the AOSSM, Baltimore, Maryland, July 2012.

One or more of the authors has declared the following potential conflict of interest or source of funding: Dr Romeo has received grants and speaker fees from Arthrex. Dr Cole receives research funds from Arthrex, Zimmer, DePuy, DonJoy Ortho, Smith & Nephew, and Omeros. Dr Verma is a consultant to Smith & Nephew and Vindico Medical, owns stock in Smith & Nephew, and receives research support from Arthrex, Smith & Nephew, Ossur, and Linvatec. Sutures and suture anchors for this study were donated by DePuy Mitek. Pec Buttons were donated by Arthrex.

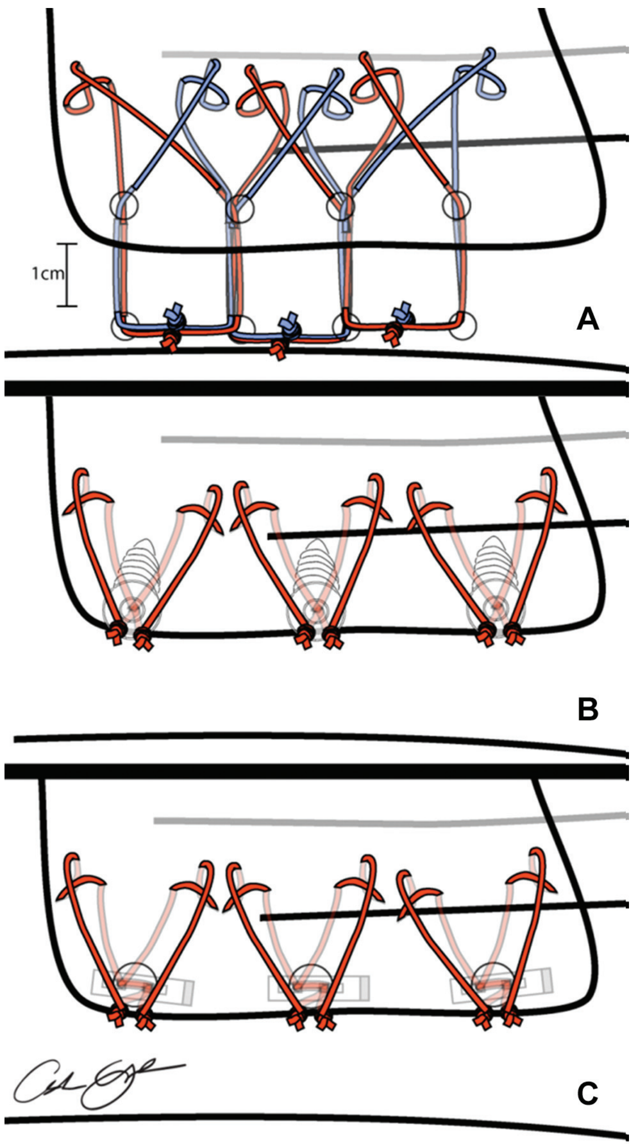

Figure 1. Transosseous repair construct (A), suture anchor repair construct (B), and endosteal Pec Button (Arthrex, Naples, Florida) repair construct (C). All repairs utilize a modified Mason-Allen stitch configuration.

the construct could be tied down as a classic transosseous tendon repair, using standard alternating half-hitch knots.

For the suture anchor technique, three 5.5-mm Super QuickAnchors (DePuy Mitek) double loaded with No. 2 Orthocord were placed. One anchor each was placed 5 mm from the proximal and distal edges of the footprint. The third anchor was placed equidistant between the other 2 anchors. One arm of each suture was passed through the tendon using the same modified Mason-Allen stitch configuration described above. The second arm was tensioned to bring the tendon to the suture anchor and then tied using the same technique of standard alternating half-hitch knots.

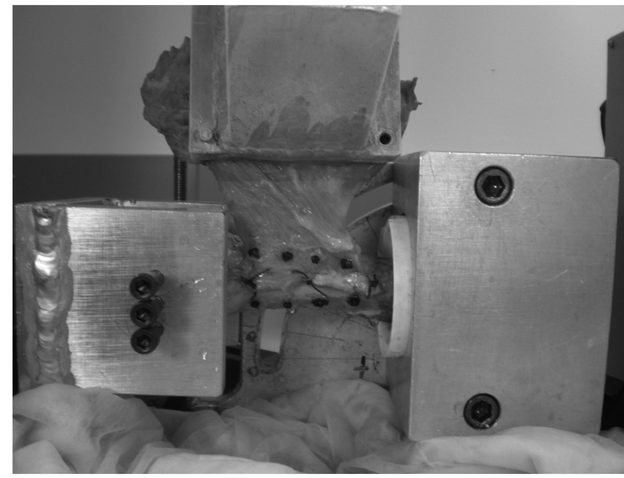

Figure 2. Pectoralis major tendon secured with custom test fixtures and freezer clamp attached to a materials testing system actuator (MTS Inc, Eden Prairie, Minnesota). Markers placed on the tendon surface were used for optical measurements of regional tissue deformation. The dashed line represents the muscle-tendon junction.

For the Pec Button technique, a 3.2-mm drill was used to create 3 unicortical holes in the same placement as described above for the suture anchors. The Pec Button is a 2.6 × 10.9–mm titanium button that can be loaded with a suture. It has a 45° angle on each end of the button, so that it rotates upon striking the far cortex of the bone, allowing endosteal engagement. Three Pec Buttons were double loaded with No. 2 Orthocord and inserted so that they engaged the endosteal cortex. Appropriate engagement of the button can be confirmed by removing the inserter handle and toggling the suture limbs. The pectoralis tendon was attached, tensioned, and tied utilizing the same stitch configuration and methods as described above.

After the repairs were completed, the footprint length and midportion width were remeasured. The humerus was then cut transversely 4 inches distal to the pectoralis insertion and potted in a 3-inch-long by 3-inch-diameter polyvinyl chloride (PVC) pipe using acrylic cement (Isocryl, Lang Dental, Wheeling, Illinois). The specimen was oriented such that the predominant fibers of the pectoralis tendon were aligned with the axis of applied tensile loading, and the potted distal humerus was secured using an adjustable fixture (Figure 2) rigidly attached to the base of an Insight 5 materials testing system (MTS Inc, Eden Prairie, Minnesota). A separate fixture was used to stabilize the proximal humerus (Figure 2) via 3 screws drilled into the humeral head. Following the approach we have used in prior studies in our laboratory,[12,13] a custom-designed cryogenic clamp was used to securely grasp the muscle to minimize muscle slippage during tensile loading of the repair constructs. Nearly the entire length of the muscle was placed within the clamp, with the lower end of the clamp positioned 3 to 4 mm proximal to the muscle-tendon junction. Throughout testing, musculotendinous junction and proximal tendon temperatures were maintained at 19°C

TABLE 2
Footprint Length and Width[a]

	Native Tendon, mm		Repaired Tendon, mm		Percentage of Native Footprint Restored	
Study Group	Length	Width	Length	Width	Length	Width
Pec Button	72.6 ± 10.2	6.2 ± 1.4	62.2 ± 9.8	5.4 ± 1.3	85.5 ± 3.1	91.1 ± 35.6
Suture anchor	62.2 ± 13.5	6.3 ± 1.5	53.5 ± 10.8	5.8 ± 1.5	86.8 ± 9.6	96.6 ± 34.9
Transosseous suture	61.1 ± 11.1	6.1 ± 0.8	47.8 ± 11.8	6.8 ± 1.4	77.4 ± 6.3	114.2 ± 29.8
Intact	64.4 ± 5.6	5.6 ± 0.5	—	—	—	—

[a]Values are expressed as mean ± standard deviation.

Figure 3. Native footprint and the restored footprint after each repair. PB, Pec Button; SA, suture anchor; TO, transosseous.

(as verified using an infrared thermometer) by using a warm saline spray.

Two rows of 4 markers each were placed for optical tracking: one row was placed along the humeral shaft, and parallel to this, one row was placed on the tendon 20 mm from the footprint (Figure 2). A digital motion analysis system composed of a 1-megapixel digital video camera (IPX-1M48-L, Imperx, Boca Raton, Florida) and motion analysis software (Spica Technology Corp, Kihei, Maui, Hawaii) were used to optically measure displacements of each set of markers affixed to the repairs.[12] After a 10-N preload, which was held for 2 minutes, each tendon was cycled from 10 N to 125 N for 150 cycles at 90 N/s, followed by a load-to-failure test at 1 mm/s. Construct failure mode was visually classified as occurring within the tendon, suture, bone, or anchor. Suture failure included breakage of the sutures or the knots coming undone.

Data Analysis

For optical data analysis, segment length was measured between all 4 pairs of medial and lateral markers for each tendon specimen (Figure 2). For consistency, segment length was defined as the vertical distance between a pair of markers.[12] The change (increase) in segment length relative to the preloaded state was computed for each anatomic region to describe local construct deformation throughout testing. From the cyclic test, 3 primary parameters were quantified: (1) cyclic elongation, defined as the increase in segment length from the peak load of the first cycle to the peak load of the last cycle of testing; (2) initial excursion, defined as the increase in segment length from the preloaded state to the peak of the first cycle; and (3) mean secant stiffness of the first as well as last 5 cycles, with secant stiffness defined as the slope of the line joining minimum and maximum points of the loading phase of the force-deformation curve.[4] From the pull-to-failure test, 3 parameters were quantified: (1) maximum load, (2) segment elongation at maximum load relative to the initial segment length at the start of the failure test, and (3) linear stiffness, calculated as the maximum slope of the load-displacement curve spanning 40% of the data points collected between initiation of the failure test and the maximum load. A repeated-measures (within-group) analysis of variance (ANOVA) with a Tukey post hoc test was used for comparison of tendon regions, while a between-group ANOVA with a Tukey post hoc test was utilized to compare properties of the repair techniques. Failure modes were statistically compared using a χ^2 test. Results were considered statistically significant at $P < .05$.

RESULTS

There was no significant difference ($P > .05$) among groups with regard to age, bone density, sex, or shoulder side (Table 1). Table 2 summarizes the footprint length and midportion width of the specimens before and after repair as well as the percentage change of footprint dimension. All repair groups demonstrated adequate footprint restoration with no significant differences detected between the repair types (Figure 3). The restored footprint length of

TABLE 3
Cyclic Testing Results

Study Group	Initial Excursion, % Change	Cyclic Elongation, % Change	Secant Stiffness, N/mm	
			Initial 5 Cycles	Final 5 Cycles
Pec Button	24.0 ± 11.7[a]	7.5 ± 2.9[a]	31.4 ± 4.2	46.2 ± 6.4
Suture anchor	17.5 ± 6.9[a]	5.2 ± 2.0	35.0 ± 4.2	45.9 ± 8.7
Transosseous suture	15.6 ± 9.1	4.8 ± 4.1	33.9 ± 4.9	44.2 ± 5.5
Intact	2.2 ± 1.0	1.5 ± 1.5	73.9 ± 10.3[b]	74.8 ± 1.6[b]

[a]Significantly different from the intact group.
[b]Significantly different from all other groups.

TABLE 4
Load-to-Failure Testing Results

Study Group	Maximum Load, N	Elongation, % Change	Linear Stiffness, N/mm
Pec Button	353.5 ± 88.3	33.9 ± 13.8	63.5 ± 6.9
Suture anchor	292.0 ± 73.3	36.3 ± 23.8[a]	77.0 ± 7.8
Transosseous suture	359.2 ± 110.4	22.6 ± 8.0	64.5 ± 14.1
Intact	1454.8 ± 795.7[b]	8.2 ± 4.8	221.0 ± 111.7[b]

[a]Significantly different from the intact group.
[b]Significantly different from all other groups.

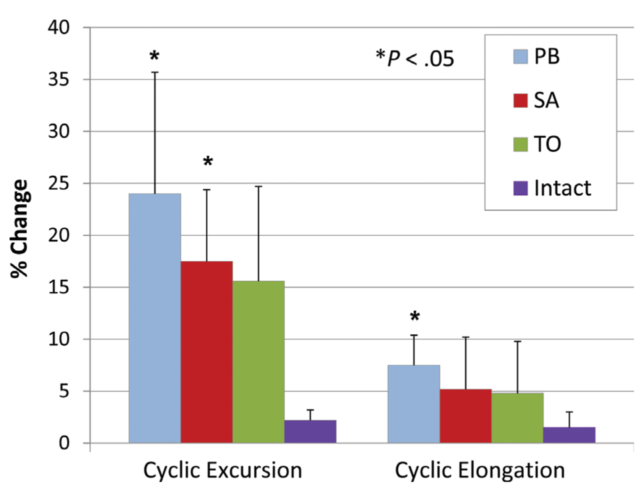

Figure 4. Cyclic excursion and cyclic elongation of the repair groups and intact specimens. *Significantly different from the intact group. PB, Pec Button; SA, suture anchor; TO, transosseous.

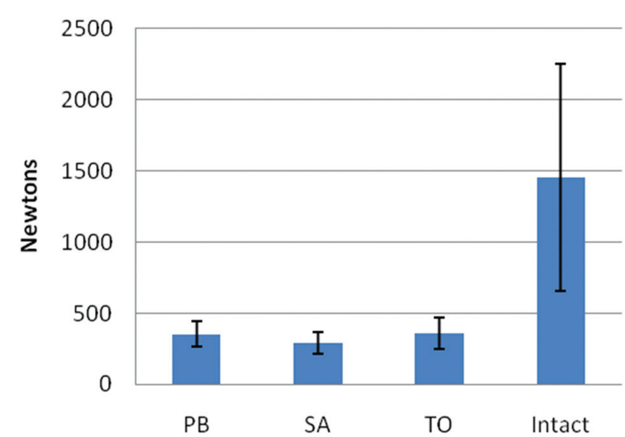

Figure 5. Maximum load to failure of the repair groups and intact specimens. The intact group had significantly higher load to failure than the Pec Button (Arthrex, Naples, Florida) group. PB, Pec Button; SA, suture anchor; TO, transosseous.

all 3 repair groups was significantly shorter than the intact footprint; however, the restored footprint thickness of all 3 repair groups was not significantly different from the intact footprint.

Cyclic Testing

One specimen in the suture anchor group failed during cyclic loading and was excluded from the data analysis for cyclic testing. The Pec Button and suture anchor groups showed a significantly higher initial excursion than the intact group. The Pec Button group demonstrated a significantly higher cyclic elongation than the intact group (Figure 4). The intact group exhibited a significantly higher secant stiffness of both the first 5 and last 5 cycles compared with the 3 repair groups (Table 3). There were no significant biomechanical differences among the repair groups.

Failure Properties

The single specimen in the suture anchor group that failed during cyclic loading was considered to have failed at

TABLE 5
Mode of Failure

Study Group	Musculotendinous Junction, n	Bone-Tendon Junction, n	Suture Pullout, n	Bone Fracture, n
Pec Button	0	—	6	0
Suture anchor	0	—	6	0
Transosseous suture	0	—	6	0
Intact	3	1	—	2

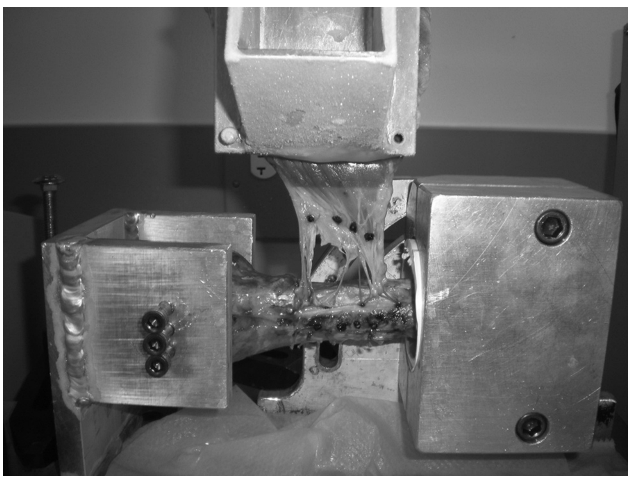

Figure 6. Failure of the repaired pectoralis major tendon via suture pulling through the tendon.

a maximum load of 125 N but was excluded from the analysis for elongation and linear stiffness. The intact group showed a significantly higher maximum load to failure (Figure 5) compared with the 3 repair groups, but there was no significant difference in load to failure among the 3 repair groups (Table 4). The suture anchor group exhibited a significantly higher elongation at maximum load than the intact group but was not significantly higher than the other repair groups. The intact group also showed a significantly higher linear stiffness compared with the 3 repair groups, but there was no significant difference in stiffness among the 3 repair groups.

All specimens in the 3 repair groups failed via suture pulling through the tendon (Figure 6 and Table 5). In the intact group, 3 specimens failed at the musculotendinous junction at 561 N, 824 N, and 988 N; 1 specimen failed via an avulsion at the bone-tendon junction at 1651 N; and 2 specimens failed via bone fracture at 2130 N and 2576 N.

Our results revealed no differences in cyclic and failure properties or modes of failure among the 3 repair procedures examined. Analysis of the superior tissue markers' displacement and the inferior tissue markers' displacement revealed no significant differences between the 2 regions. The study was powered using a sample size of 6 specimens per group, which is comparable with other similar studies in the literature.[6]

DISCUSSION

This study demonstrates that the initial biomechanical characteristics of pectoralis repair with transosseous sutures, suture anchors, and endosteal-fixed Pec Buttons are similar. We noted no significant difference between fixation devices with regard to cyclic loading or load-to-failure properties. All 3 techniques re-created the native footprint similarly. No instances of hardware failure were noted. However, we did note that all repair constructs failed at the suture-tendon interface. This suggests that suture configuration is the limiting factor in overall repair strength in this model. Additionally, to our knowledge, the present study is the first report of biomechanical properties of the intact human pectoralis major tendon, thereby providing a valuable control group against which to measure the biomechanical integrity of surgical intervention. In addition, these values help to provide a surrogate to compare the forces inherent in early postoperative activities in an effort to better define safe-zone activities that can be implemented prior to definitive tendon-bone healing.

In the only other biomechanical study on pectoralis major repair, Hart et al[6] compared transosseous sutures and suture anchors and noted that ultimate failure load and stiffness were similar between the 2 groups. Their mean load to failure was >600 N, and the constructs failed either from suture breakage or bone breakage. No failures were noted at the suture-tendon interface in that study. Our mean load to failure was approximately 350 N, and all constructs failed at the suture-tendon interface. By means of comparison, our study varied from that of Hart et al[6] with regard to the strength, configuration, and overall number of sutures utilized. Their repair construct utilized a total of 8 No. 2 Orthocord sutures, of which 4 were initially placed as Krackow stitches, followed by 4 overlapping Bunnell stitches.[6] Even though the construct by Hart et al[6] utilized more sutures and a more complex repair technique, the ultimate load to failure did not come close to the ultimate failure load of the intact pectoralis tendon as measured by our study.

Furthermore, the Hart et al[6] study utilized only a load-to-failure test at 4 mm/s. In contrast, our approach consisted of tests under both load-controlled cycling from 10 N to 125 N and displacement-controlled failure testing at 1 mm/s. This yields relevant biomechanical parameters derived from both subfailure and load-to-failure testing. In addition, the potentially negative ramifications of such robust suture placement on tissue vascularity and tendon-to-bone healing are not known, nor are the soft tissue implications of having a bulky repair in near proximity to the bicipital groove. Further research is necessary to clarify these issues.

In clinical studies, repair techniques using Krackow and Bunnell stitches[6] or modified Kessler sutures[11] have been described, with a total of 8 strands of suture crossing the repair. The modified Mason-Allen stitches employed in our model included a total of 6 strands crossing the repair site. We believe that the suture configuration in our model contributed to the limitation in our overall repair strength. Further study is needed to determine whether variation in suture configuration or number will significantly increase the overall load to failure while respecting the biology of the tendon healing process.

Furthermore, we demonstrate that both the cyclic and failure biomechanical characteristics of the native intact pectoralis tendon are superior to those of the 3 repair techniques currently studied or those repair techniques analyzed previously.[6] Similarly, existing techniques of pectoralis repair demonstrate good results with low rates of hardware failure. A recent meta-analysis of all reported pectoralis ruptures showed 88% good or excellent results in surgically repaired patients compared to only 27% in those treated nonoperatively.[2] Additionally, isokinetic strength measurements confirm that the surgically repaired patient can obtain full strength if the repair is performed acutely.[11] The overall good results with acute pectoralis major repair suggest that despite the significantly weaker biomechanical profile of all repair constructs at time zero, biological healing strengthens the repair over time. This is somewhat expected but serves to reinforce the importance of early immobilization of these repairs. Phase I of our postoperative rehabilitation regimen utilizes strict sling immobilization and focuses on protection of the healing tendon, taking care not to increase loads above the threshold of the suture repair. As the repair is carried out in an extra-articular setting, we have not found significant issues with glenohumeral stiffness, even after prolonged immobilization of 6 weeks' duration.

Despite similar biomechanical profiles, there are several important distinctions to be made between repair techniques. Each repair technique has various advantages and disadvantages. Both Pec Buttons and suture anchors demonstrated a significantly greater initial excursion under cyclic loading than the intact tendon. The Pec Button group also showed significantly increased cyclic elongation compared with the intact tendon. Substantial variation existed among the specimens under cyclic testing, however, as evidenced by the large standard deviation within these groups. It is unclear whether the differences in cyclic loading characteristics are clinically meaningful because the amount of elongation or excursion that becomes a risk factor to failure remains unknown. Transosseous suture repairs have proven successful over time, but disadvantages may include increased operative time, greater dissection to expose the lateral cortex, and the possibility of creating a stress riser while creating a bone trough to dock the pectoralis tendon. In this study and in clinical practice, we choose to perform the transosseous repair without creating a large bone trough to avoid this stress riser. Suture anchors and endosteal buttons both have proposed advantages of shorter operative time and less surgical dissection. In our experience performing open repairs during this study, the endosteal buttons and suture anchors had similar ease of use and speed of repair, with both techniques much easier to use and faster than the transosseous technique. Any remaining tendon can be incorporated into the repair. However, disadvantages include cost, potential for local host reaction with bioactive materials, or interference with subsequent advanced imaging studies (primarily for metal implants).

The weaknesses in our study included the limited number of specimens and the age of the specimens. The mean age of the specimens was 73.1 years, and most patients with pectoralis ruptures are much younger. Consequently, it remains unknown whether the biomechanical values and footprint characteristics accurately represent those of the typical patient with pectoralis major rupture. Footprint dimensions varied substantially among specimens, and further study is needed to more accurately define the footprint and its variability. Additionally, Bak et al[2] reported that 65% of pectoralis major ruptures occur as a muscle tendon avulsion and that 27% occur at the musculotendinous junction, which differs from our testing results of intact specimens. Furthermore, as with any time zero study, only initial strength is represented; any healing response has not been accounted for.

In conclusion, we demonstrate no biomechanical differences between transosseous sutures, suture anchors, and endosteal buttons for pectoralis major repair. At present, the choice of surgical repair technique should rely heavily on surgeon comfort and experience. All 3 techniques demonstrate statistically lower failure loads and stiffness than the intact pectoralis tendon, providing a sound rationale for postoperative immobilization and thoughtful implementation of early-phase activities during tendon healing. All repair constructs failed at the suture-tendon interface, suggesting that changes in the configuration or number of sutures may improve overall performance. We are currently in the process of evaluating this. Future research is necessary to determine the best way to increase construct strength while respecting the biology of tendon healing.

ACKNOWLEDGMENT

Artwork courtesy of Adam B. Yanke.

REFERENCES

1. Aarimaa V, Rantanen J, Heikkila J, Helttula I, Orava S. Rupture of the pectoralis major muscle. *Am J Sports Med*. 2004;32(5):1256-1262.
2. Bak K, Cameron EA, Henderson IJ. Rupture of the pectoralis major: a meta-analysis of 112 cases. *Knee Surg Sports Traumatol Arthrosc*. 2000;8(2):113-119.
3. Carek PJ, Hawkins A. Rupture of pectoralis major during parallel bar dips: case report and review. *Med Sci Sports Exerc*. 1998;30(3): 335-338.
4. Gupta A, Lattermann C, Busam M, et al. Biomechanical evaluation of bioabsorbable versus metallic screws for posterior cruciate ligament inlay graft fixation: a comparative study. *Am J Sports Med*. 2009;37(4):748-753.

5. Hanna CM, Glenny AB, Stanley SN, Caughey MA. Pectoralis major tears: comparison of surgical and conservative treatment. *Br J Sports Med*. 2001;35(3):202-206.
6. Hart ND, Lindsey DP, McAdams TR. Pectoralis major tendon rupture: a biomechanical analysis of repair techniques. *J Orthop Res*. 2011;29(11):1783-1787.
7. Iannotti JP, Williams GR. Traumatic muscle ruptures. In: Iannotti JP, Williams GR, eds. *Disorders of the Shoulder: Diagnosis and Management*. Singapore: Lippincott Williams & Wilkins; 1999:191-197.
8. Kakwani RG, Matthews JJ, Kumar KM, Pimpalnerkar A, Mohtadi N. Rupture of the pectoralis major muscle: surgical treatment in athletes. *Int Orthop*. 2007;31(2):159-163.
9. Kretzler HH Jr, Richardson AB. Rupture of the pectoralis major muscle. *Am J Sports Med*. 1989;17(4):453-458.
10. Provencher MT, Handfield K, Boniquit NT, et al. Injuries to the pectoralis major muscle: diagnosis and management. *Am J Sports Med*. 2010;38(8):1693-1705.
11. Schepsis AA, Grafe MW, Jones HP, Lemos MJ. Rupture of the pectoralis major muscle: outcome after repair of acute and chronic injuries. *Am J Sports Med*. 2000;28(1):9-15.
12. Van Thiel GS, Wang VM, Wang FC, et al. Biomechanical similarities among subscapularis repairs after shoulder arthroplasty. *J Shoulder Elbow Surg*. 2010;19(5):657-663.
13. Wang VM, Wang FC, McNickle AG, et al. Medial versus lateral supraspinatus tendon properties: implications for double-row rotator cuff repair. *Am J Sports Med*. 2010;38(12):2456-2463.
14. Zeman SC, Rosenfeld RT, Lipscomb PR. Tears of the pectoralis major muscle. *Am J Sports Med*. 1979;7(6):343-347.