J Shoulder Elbow Surg (2025) 34, e890–e896

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Pectoralis major tendon tears: a biomechanical study to analyze the influence of intratendinous suture distance on repair stability

Christopher Wahlers, Dr Med[a,*], Kai Hoffeld, Dr Med[a], Jan Hockmann, Dr Med[a], Lars Peter Müller, Prof Dr Med[a], Tim Leschinger, PD Dr Med[a], Michael Hackl, Prof Dr Med[b]

[a]*Faculty of Medicine and University Hospital of Cologne, Department of Orthopaedic, Trauma, and Plastic Surgery, University of Cologne, Cologne, Germany*
[b]*Medical Faculty Mannheim, Department of Orthopaedic and Trauma Surgery, University Medical Centre, Mannheim, University of Heidelberg, Mannheim, Germany*

Background: Tendon tears of the pectoralis major (PM) are uncommon and can be challenging to manage. The lack of consensus on optimal repair methods for PM tendon tears prompts further investigation.
Methods: Twenty four fresh-frozen shoulder specimens were used for this biomechanical in-vitro investigation. After simulating complete tears of the PM at its insertion, repair was performed with 3 suture anchors using a locking whipstitch technique of the PM tendon over a length of 2 (group 2), 4 (group 4), or 6 cm (group 6), 8 specimens per group. Incremental cyclic loading of the specimens was performed from 10 to 200 N and the number of cycles and the force until failure (5-mm gap formation at the tendon-bone interface) occurred were analyzed.
Results: The mean number of cycles until failure was 89 for group 2, 81 for group 4, and 175 for group 6. Group 6 withstood significantly more loading cycles than groups 2 and 4 ($P = .019$). The mean force until failure was 63.8 N for group 2, 67.5 N for group 4, and 110.0 N for group 6. Group 6 reached significantly higher failure loads when compared to groups 2 and 4 ($P \leq .014$).
Conclusions: This study contributes valuable insights into the optimal suture technique for repair of PM tendon tears, highlighting the biomechanical stability associated with varying lengths of locking whipstitches. The results of this investigation show that a locking whipstitch of the PM tendon over a length of 6 cm provides superior biomechanical properties at time zero. Clinical data are necessary to evaluate its relevance on the functional patient outcome.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Pectoralis major tendon tear; repair technique; locking whipstitch; suture length; pectoralis major tendon; repair stability

Injuries to the pectoralis major (PM) tendon are relatively rare injuries.[8] Due to a lack of experience and knowledge in this area, they are often overlooked or improperly treated.[8] Most commonly, they are caused by an indirect mechanism, especially during strength-intensive

Ethical approval for this study was provided by the Institutional Review Board of the University of Cologne (approval no.: 24-1023).

*Reprint requests: Christopher Wahlers, Dr Med, Faculty of Medicine and University Hospital of Cologne, Department of Orthopaedic, Trauma, and Plastic Surgery, University of Cologne, Joseph-Stelzmann-Straße 24, Cologne 50937, Germany.

E-mail address: ch.wahlers@googlemail.com (C. Wahlers).

1058-2746/© 2025 The Author(s). This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
https://doi.org/10.1016/j.jse.2025.01.045

sports, typically during bench pressing, often associated with steroid abuse.[2,9] Clinically, they are typically characterized by a specific disruption of the anterior axillary fold and a hematoma. A loss of adduction and internal rotation strength is another clinical indicator of an existing rupture. After the swelling subsides, deformation with medial retraction of the muscle belly becomes apparent.

The PM is largely responsible for the adduction and internal rotation of the humerus. Depending on the arm position, the PM can assist in flexion from an extended or neutral position or in extension from a forward-bent position.[8] The PM is a multipennate muscle with a broad, 3-part origin that includes the clavicle (Pars clavicularis), the sternum (Pars sternocostalis), and the abdominal muscles (Pars abdominalis), and indirectly inserts into the humerus through a thin but expansive tendon attachment. From there, the tendon insertion diverges into 2 overlapping and interwoven but separate structures: the clavicular attachment, originating from the medial half to two-thirds of the collarbone, and the sternocostal attachment, originating from the upper two-thirds of the breastbone, ribs 2-4, and the abdominal muscles. Ultimately, the PM converges laterally and divides into 2 laminae (anterior and posterior) that run over the long head of the biceps tendon and attach to the lateroventral Crista tuberculi majoris of the humerus.

Due to the substantial function of the muscle in daily life, surgical therapy is usually sought.[1] The goal of surgical treatment is the primary reattachment of the tendon to its humeral insertion to enable tendon healing in an anatomic position. Various techniques for repairing a PM tendon tear have been described, including different reattachment methods and systems with various stitching and knotting techniques.

The main challenge in repairing a PM tendon tear is achieving an adequate restoration of the anatomical length (from cranial to caudal) of the musculotendinous unit in a robust manner, approaching the natural anatomical structure and its complex insertion on the humerus.[1] There is no unified gold standard for the choice of diverse anchor systems or the tendon reinforcement technique.[3,5,7]

Various stitching techniques have already been evaluated,[4] but there have been no statements in the current literature regarding the required reattachment length of the tendon and the subsequent musculotendinous transition.

Hence, this study aimed to investigate the influence of intratendinous suture distance on primary stability of PM tendon repairs. We hypothesized that locking whipstitches over a longer distance of the PM result in higher stability of the repair.

Materials and methods

Ethical approval for this study was obtained by the Institutional Review Board of the University Cologne (approval number: 24-1023).

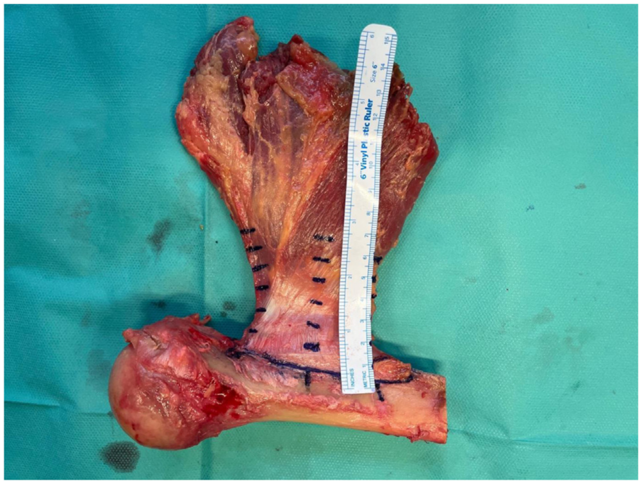

Figure 1 Specimen preparation. Pectoralis major muscle before release of the footprint with markings for the length of the locking whipstitch technique (6 cm suture length; 1 whipstitch per cm).

Specimen preparation

Twenty four fresh-frozen cadaveric shoulder specimens were available for this biomechanical in-vitro study (8 specimens per group). The specimens were stored at −20°C and thawed at room temperature 16-18 hours before dissection and biomechanical testing. Fluoroscopic and clinical examinations were performed to exclude specimens with osteoarthritis or signs of previous surgery and trauma. The scapula and clavicle as well as all soft tissues around the shoulder except the PM were removed and the humerus was shortened to a length of 15 cm.

The PM tendon was completely released of its footprint at the humerus to simulate a complete tear. Three titanium suture anchors (Corkscrew 6.5 mm, Arthrex Inc., Naples, FL, USA) were placed at a distance of 3 cm to each other at the footprint of the PM tendon. One anchor was placed at the cranial part of the tendon, 1 at the caudal part, and 1 in between. The tendon repairs were performed using a locking whipstitches at a distance of 1 cm, one locking whipstich where used per centimeter of intratendinous suture distance. As part of the standardized repair, repair lengths of 2 cm, 4 cm, and 6 cm were formed in 3 study groups (Fig. 1).

For subsequent photographic analysis during biomechanical testing, 3 beads were placed at the PM tendon adjacent to the insertion of the suture anchors and 3 1.4-mm K-wires were placed into the humerus immediately lateral to the PM tendon footprint.

Biomechanical testing

The specimens were mounted horizontally on a custom testing rig with the PM tendon footprint facing anterior. An interdigitating metal clamp was fixed to the PM muscle belly 8 cm medial to its tendon insertion. Cyclic, incremental loading was performed with a servohydraulic testing machine (Z010; Zwick & Roell, Germany) by upward movement of the mobile traverse (Fig. 2) from 10 to 200 N (10 N preload, 50 cycles 10-60 N, 50 cycles 10-80 N, 50 cycles 10-100 N, 50 cycles 10-120 N, 50 cycles 10-140 N, 50 cycles 10-160 N, 50 cycles 10-180 N, and 50 cycles 10-200 N,

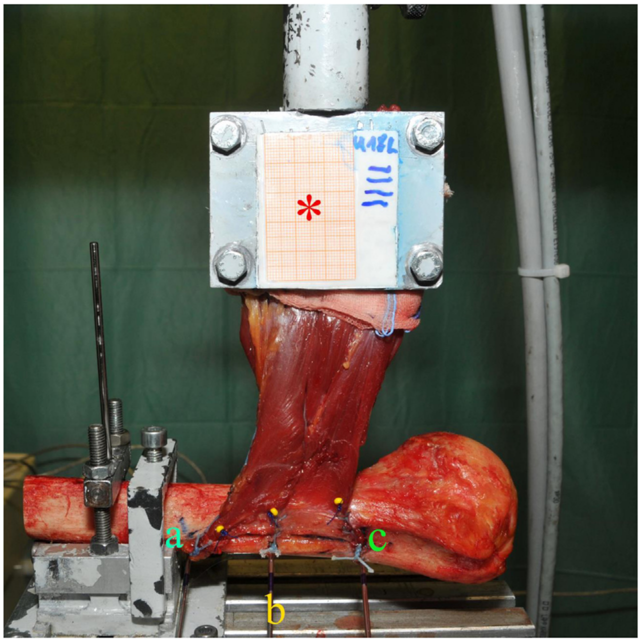

Figure 2 Experimental setup: Repaired pectoralis major tendon in the testing machine; scale pattern for image analysis (*). (a-c) Three K-wires were placed in the humerus lateral to the tendon footprint and the 3 *yellow* beads were positioned at the tendon close to its footprint. The distance between the K-wires and the beads was measured to evaluate gap formation at the tendon-bone interface. ≥5 mm gap formation was considered as failure of the repair.

with a final "load to failure" measurement). After each individual pulling cycle, photographic documentation of the experiment is carried out for subsequent analysis of the distance of the PM tendon (bead) to its footprint (K-wire). The distances at 10 N preload are set as the zero-point distances, all following distances after cyclic load are subtracted to achieve the real increasing distance after a tensile cycle (Fig. 3).

A mean gap formation of the PM tendon to its footprint of ≥5 mm was considered as failure of the repair. We orientated that failure point on previous studies.[6]

The cycles reached up to this failure point and the maximum tensile force form the basis of the statistical analysis.

To exclude a potential bias regarding bone quality of the specimens, the Deltoid Tuberosity Index (DTI) was evaluated for each specimen.

The analysis of the photo-documented (single-lens reflex camera Nikon D100, 10 Megapixels) data regarding the distance of the PM tendon to the bony PM footprint at the end of each pulling cycle was carried out using the analysis program ImageJ 1.54 g.

Statistical methods

This is a biomechanical in-vitro study analyzing the influence of intratendinous suture distance on repair stability.

Statistical analysis was performed using IBM SPSS Statistics (version 29.0.2.0 for Mac; IBM Corp., Armonk, NY, USA). Data are reported as median (range) and/or mean ± standard deviation. A P value < .05 was considered statistically significant.

Initially, we assessed the normal distribution of parameters through the Kolmogorov-Smirnov test, revealing that some parameters partially followed a normal distribution (age, DTI, and weight of the patient = Weightkg), while others did not (force until failure = MaxForce and number of cycles until failure = MaxCycles). An analysis of variance was conducted to determine significant differences between groups for normally distributed values (age, DTI, and Weightkg).

For non-normally distributed values (MaxForce and MaxCycles), Kruskal-Wallis tests were employed to assess significant differences between groups. These parameters were measured until failure occurred, defined by an averaged displacement of the tendon from its footprint of ≥5 mm. Asymptotic significance was used for the sample size under 30 to approximate the P value, acknowledging potential limitations in accuracy due to the small sample size.

Furthermore, a Pearson correlation test was performed to evaluate correlations among individual parameters.

Results

The biomechanical performance of Groups 2, 4, and 6 was analyzed based on the number of loading cycles until failure (MaxCycles) and the maximum tensile force until failure (MaxForce). In addition, age, weight, and DTI were evaluated to ensure comparability across groups.

The descriptive statistics presented in Table I indicated comparable distributions of age, weight, and DTI among the groups. Testing confirmed normal distribution for these parameters (Table II). No statistically significant differences were observed between the groups for age (analysis of variance: F = 0.791; P = .467), DTI (F = 1.648; P = .216), or Weightkg (F = 0.632; P = .541), ensuring that the specimens were evenly distributed across the study groups. Bone quality, as assessed by DTI, was found to be consistent across the groups, reducing the likelihood of bias due to specimen variability.

Significant differences were identified among the groups 2, 4, and 6 (MaxCycles asymptotic significance 0.02; MaxForce asymptotic significance 0.017).

Analysis of MaxCycles revealed mean values of 89 cycles (±83) for Group 2, 81 cycles (±37) for Group 4, and 175 cycles (±60) for Group 6 (Fig. 4).

The mean MaxForce values were 63.8 N (±15.3) for Group 2, 67.5 N (±12.1) for Group 4, and 110.0 N (±20.4) for Group 6 (Fig. 4).

Post hoc comparisons indicated no significant difference between Groups 2 and 4 (P = .89), while Group 6 demonstrated significantly higher loading cycles compared to Groups 2 (P = .013) and 4 (P = .019).

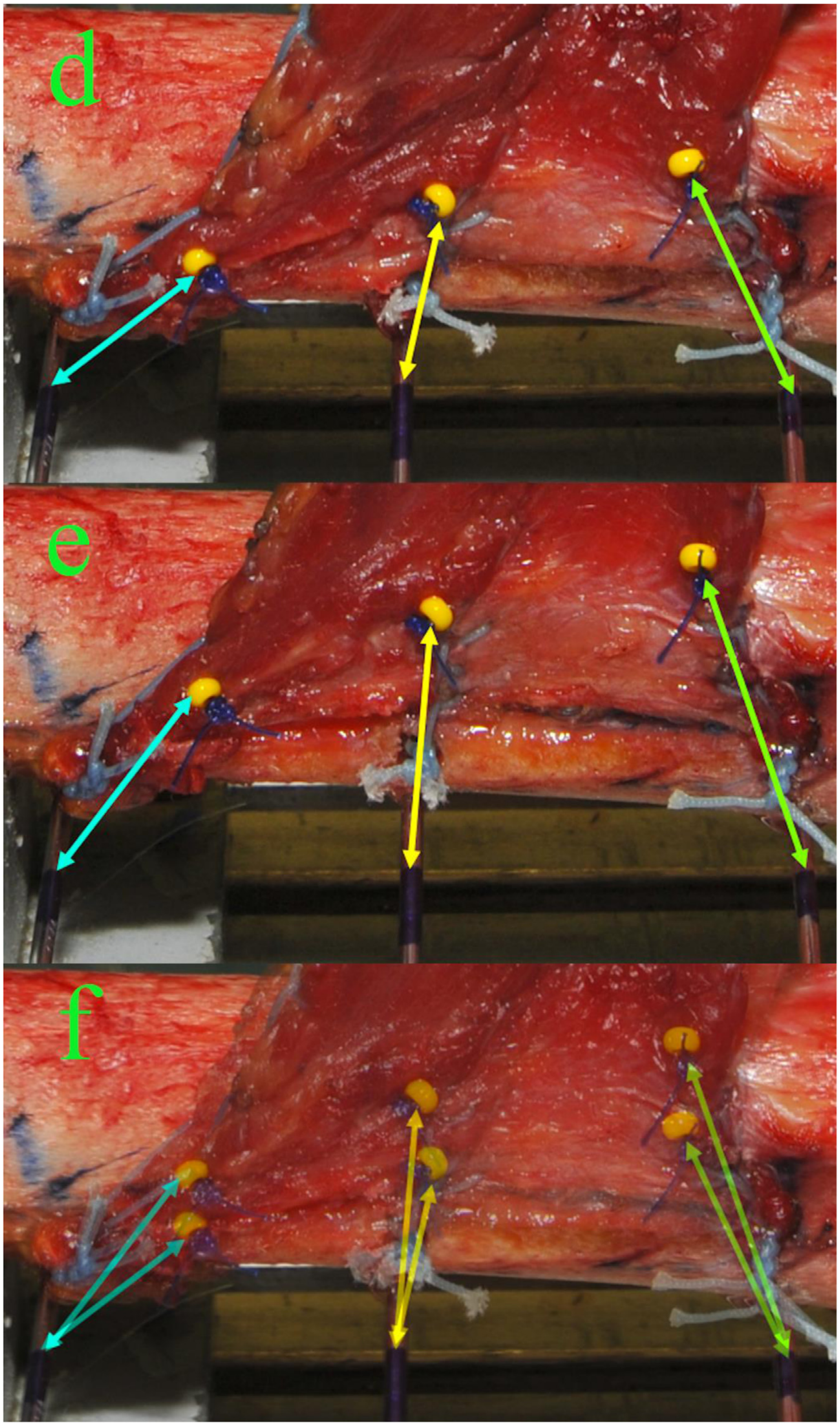

Figure 3 Measurement of the muscle removal from the reinsertion (↕: distance measuring; *green* d: distances at 10 N prestress before start of cyclic loading; *green* e: distances of the same specimen after 200 cycles of loading; *green* f: layover of both to demonstrate the continuously increasing distancing of the muscle from the footprint at cyclic loading). To achieve the actual increase in distance, preloading distances are subtracted from the distance after cyclic loading.

Furthermore, testing confirmed significant differences among the groups (asymptotic significance = 0.017). Post hoc analysis showed no significant difference between Groups 2 and 4 (P = .98), whereas Group 6 exhibited significantly higher failure forces compared to both Group 2 (P = .014) and Group 4 (P = .013).

Table I Descriptive statistics

Group	Age	Weightkg	Deltoid tuberosity index	MaxCycles	MaxForce
Group 2					
Mean	82	66.4	1.42	89	63.8 N
Standard deviation	9	22.2	0.09	83	47.8 N
Median	81	58.7	1.45	80	70.0 N
Range				250	140.0 N
Group 4					
Mean	75	78.6	1.48	81	67.5 N
Standard deviation	16	20.7	0.28	37	28.2 N
Median	77	79.6	1.34	100	80.0 N
Range				100	80.0 N
Group 6					
Mean	81	73.9	1.60	175	110.0 N
Standard deviation	9	23.0	0.16	60	23.9 N
Median	81	73.2	1.64	200	120.0 N
Range				200	80.0 N
Overall					
Mean	79	73.0	1.50	115	80.4 N
N	24	24	24	24	24
Standard deviation	12	21.6	0.20		
Median	79	70.5	1.49	100	80.0 N
Range				2500	140.0 N

Table II Kolmogorov-Smirnov test for normal distribution

	Kolmogorov-Smirnov		
	Statistic	N	Significance
MaxCycles	0.205	24	0.010
MaxForce	0.204	24	0.011
Gender	0.358	24	<0.001
Age	0.115	24	0.200
Weightkg	0.149	24	0.177
Side	0.358	24	<0.001
Deltoid tuberosity index	0.133	24	0.200

In summary, differences in biomechanical performance were observed based on suture length. Group 6 (with a suture length of 6 cm) displayed higher loading cycles and tensile forces until failure compared to Groups 2 and 4. No significant differences were observed between Groups 2 and 4 for these parameters.

Discussion

This study aimed to determine the influence of intratendinous suture distance on the primary stability of PM tendon repairs. Our findings show that longer locking whipstitches (6 cm) provide superior biomechanical stability compared to shorter ones (2 cm and 4 cm), as evidenced by significantly higher numbers of loading cycles and greater forces until failure. These results may suggest

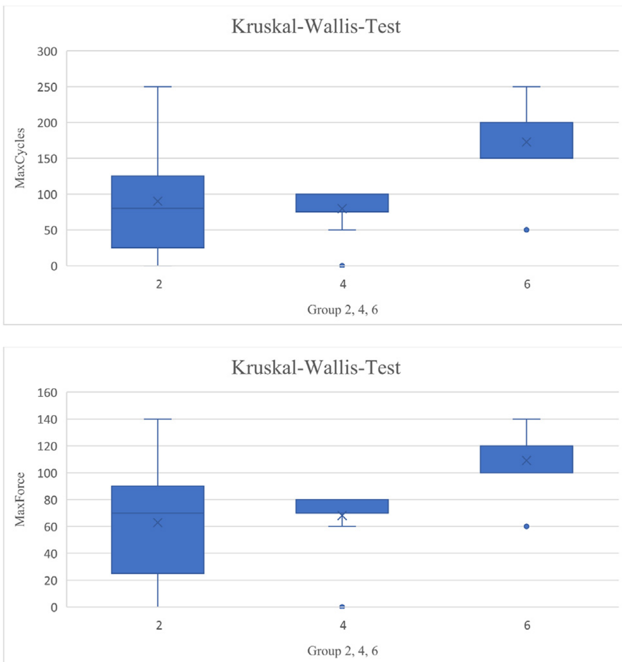

Figure 4 Kruskal-Wallis test for MaxCycles and MaxForce, significant differences between the groups.

that employing a 6-cm intratendinous suture distance can significantly reduce the risk of retears at point zero after operation. However, longer intratendinous suture distance may not always be feasible due to the nature of PM tears.

Edgar et al (2017)[3] conducted a comprehensive biomechanical analysis of modern repair configurations for PM tendon tears. They found that a U-shaped bone fixation with suture tape provided significantly greater peak load strength and lower displacement after cyclic loading compared to traditional techniques. Our study builds on these findings by demonstrating that the length of the suture further enhances the stability of the repair, particularly by providing greater resistance to cyclic loading and higher maximum tensile forces.

Gregory et al (2015)[4] explored the impact of different suture techniques on the biomechanical integrity of PM tendon repairs. While they observed no significant differences under cyclic loading, the polyethylene tape group withstood a significantly greater maximum load. Our results complement these findings, emphasizing that not only the technique but also the intratendinous suture distance is critical for repair stability, particularly under load-to-failure conditions.

Hart et al (2011)[7] provided a biomechanical analysis of various repair techniques for PM tendon ruptures. Our study adds to this by focusing on intratendinous suture distance, demonstrating that longer sutures significantly improve resistance to both cyclic loading and maximal tensile force, suggesting a new strategy for enhancing tendon repair stability.

Bodendorfer et al (2020) conducted a systematic review and meta-analysis on the timing and fixation methods for PM tendon repairs, concluding that early surgical intervention and robust fixation methods are critical for optimal recovery. Our findings suggest that optimizing intratendinous suture distance is an additional refinement that can further improve repair stability, facilitating safer early mobilization.[1]

The impact of biomechanical stability concerning postoperative treatment is crucial. Our data indicate that longer locking whipstitches (2 cm, 4 cm, and 6 cm) provide significant advantages in cyclic strength and maximum force, potentially allowing for a more restrictive yet safer postoperative regimen. Despite the rare occurrence of PM ruptures, the transferability of these findings to other tendon repairs should not be overlooked. Further biomechanical studies are needed to optimize repair lengths and compare different suture types and techniques.

Limitations

Overall, the presented study has some limitations inherent to biomechanical in-vitro studies.

Sample size and type: The study uses a limited number of 24 cadaveric shoulder specimens.

Exclusion criteria: The study excludes samples showing signs of osteoarthritis or prior surgeries and traumas. This could potentially introduce a bias in the sample, as these features might be present in patients with PM injuries.

Limited generalizability: Due to the rare nature of PM ruptures and the use of cadaveric specimens, the transferability of the results to the broader population might be limited. An additional limitation is that the findings of this study cannot be extrapolated to other fixation techniques, such as button fixation or bone tunnel techniques, which may differ significantly in their biomechanical properties.

These limitations should be considered in the interpretation of the study results and may indicate the need for further clinical research to strengthen the validity and applicability of the findings.

Conclusion

This study demonstrates that sutures placed 6 cm into the repaired tissue provide superior biomechanical stability compared to sutures placed 2 cm or 4 cm. While longer fixation lengths offer clear advantages, their feasibility in clinical scenarios requires careful consideration. Specimens repaired with longer intratendinous sutures withstood significantly more loading cycles and achieved higher maximum failure forces. These findings suggest that a locking whipstitch technique over a 6 cm distance is advantageous in reducing the risk of repair failure. Further clinical research is necessary to evaluate the relevance of these biomechanical results to patient outcomes.

Disclaimers:

Funding: No funding was disclosed by the authors.
Conflicts of interest: Michael Hackl is a consultant for Arthrex, Medartis, PrehApp, and Sporlastic; he received research support from IBRA and OTC. The other authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

1. Bodendorfer BM, Wang DX, McCormick BP, Looney AM, Conroy CM, Fryar CM, et al. Treatment of pectoralis major tendon tears: a systematic review and meta-analysis of repair timing and fixation methods. Am J Sports Med 2020;48:3376-85. https://doi.org/10.1177/0363546520904402
2. Butt U, Mehta S, Funk L, Monga P. Pectoralis major ruptures: a review of current management. J Shoulder Elbow Surg 2015;24:655-62. https://doi.org/10.1016/j.jse.2014.10.024
3. Edgar CM, Singh H, Obopilwe E, Voss A, Divenere J, Tassavor M, et al. Pectoralis major repair: a biomechanical analysis of modern repair configurations versus traditional repair configuration. Am J Sports Med 2017;45:2858-63. https://doi.org/10.1177/0363546517716175

4. Gregory JM, Klosterman EL, Thomas JM, Hammond J, Shewman EF, Wang VM, et al. Suture technique influences the biomechanical integrity of pectoralis major repairs. Orthopedics 2015;38:e746-52. https://doi.org/10.3928/01477447-20150902-50
5. Gupton M, Johnson JE. Surgical treatment of pectoralis major muscle ruptures: a systematic review and meta-analysis. Orthop J Sports Med 2019;7:2325967118824551. https://doi.org/10.1177/2325967118824551
6. Hackl M, Buess E, Kammerlohr S, Nacov J, Staat M, Leschinger T, et al. A "comma sign"-directed subscapularis repair in anterosuperior rotator cuff tears yields biomechanical advantages in a cadaveric model. Am J Sports Med 2021;49:3212-7. https://doi.org/10.1177/03635465211031506
7. Hart ND, Lindsey DP, McAdams TR. Pectoralis major tendon rupture: a biomechanical analysis of repair techniques. J Orthop Res 2011;29: 1783-7. https://doi.org/10.1002/jor.21438
8. Provencher CMT, Handfield K, Boniquit NT, Reiff SN, Sekiya JK, Romeo AA. Injuries to the pectoralis major muscle: diagnosis and management. Am J Sports Med 2010;38:1693-705. https://doi.org/10.1177/0363546509348051
9. Thompson K, Kwon Y, Flatow E, Jazrawi L, Strauss E, Alaia M. Everything pectoralis major: from repair to transfer. Phys Sportsmed 2020;48:33-45. https://doi.org/10.1080/00913847.2019.1637301