In Vitro Comparison of Two Barbed Suture Configurations for Flexor Tendon Repair

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J Hand Microsurg 2017;9:126–130.

Abstract

Purpose The current study compares the strength of a previously studied technique for flexor tendon repair with barbed sutures to an experimental approach that aligns all the barbs to oppose distraction.

Methods Twelve flexor tendons from cadaveric specimens were mechanically tested following repair of simulated zone II tendon injuries. Two repair techniques utilizing barbed sutures were studied: the Marrero-Amadeo four-core barbed suture approach and the experimental configuration with all barbs on four cores opposing distraction. Maximum applied load at failure, that is, ultimate load, and 2-mm gap force were compared between the two repair techniques, both as raw values and after normalization to cross-sectional area of the intact tendon. Statistical testing was performed using *t*-tests and Mann-Whitney *U*-tests, where appropriate, with a significance level of 0.05.

Results The ultimate loads, raw (58.2 N) and normalized (4.8 N/mm²), were significantly larger for the Marrero-Amadeo repair than the proposed experimental approach (35.6 N and 2.7 N/mm²; *p* < 0.05). No significant differences were identified for 2-mm gap force.

Conclusion The innovation of suturing to align all barbs to oppose distraction does not improve strength of the repaired tendon. The Marrero-Amadeo technique was found to have superior strength for use in traumatic zone II flexor tendon injuries.

Keywords

- ▶ flexor tendon repair
- ▶ barbed suture
- ▶ strength
- ▶ mechanical testing

Introduction

Flexor tendon lacerations are traumatic injuries with the potential to devastate functionality of the hand; particularly challenging are zone II flexor tendon injuries.^{1,2} For decades, primary suture repair has been the gold standard treatment, but postoperative adhesion formation and increased glide resistance through the pulley system, related to the addition of suture and knots, have been problematic.³ Early active motion has been shown to promote greater restoration of function than immobilization or passive motion protocols.⁴ The ideal suture technique should create a repair site with minimal bulk and low friction while maintaining adequate

strength across the repair site to allow motion without risking failure, for example tendon gapping ≥ 2 mm.⁵ Current literature recommends use of a four-strand repair for zone II flexor tendon injuries using 3–0 or 4–0, braided, nonabsorbable sutures.⁶ The strength of traditional knotted suture repairs is enhanced by increasing the number of strands crossing the repair as well as the suture caliber.^{7–9} However, this strength increase results in an increased knot size and tendon bulk, making it more difficult for the repaired tendon to pass through the pulley system.^{10,11}

Repair techniques utilizing barbed sutures have been introduced to improve grip of the tendon by the sutures and eliminate suture knots, thus reducing the bulk of the repaired

received

July 14, 2017

accepted after revision

August 11, 2017

published online

November 6, 2017

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DOI <https://doi.org/10.1055/s-0037-1606628>.
ISSN 0974-3227.

tendon. Passing bidirectional barbed suture through the tendon to maximize passes with one suture aligns portions of the barbs to resist tendon distraction, that is, separation of the repaired tendon with tensioning, with other suture portions not providing resistance to distraction.¹²⁻¹⁶ The previous biomechanical studies investigating barbed suture have shown that the ultimate load and 2-mm gap force were comparable but not superior to standard knotted sutures,^{12,13} possibly due to underutilization of the barbs to prevent distraction.

A novel repair technique is proposed that engages all suture barbs against tendon distraction at the repair site. Bidirectional, barbed suture is passed through the tendon such that all barbs are active to limit distraction at the repair site in response to applied tension, in contrast to current approaches that align only a portion of the barbs at the repair site to resist tension. The current study was performed to compare the strength of the proposed technique to a previously studied barbed suture technique, Marrero-Amadeo, which was found to be comparable in strength to a standard, four-core, knotted repair.¹² The hypothesis is that the proposed technique will provide superior failure strength and resistance to gap formation than the barbed suture technique that does not take full advantage of the bidirectional nature of the barbed suture against tendon distraction.

Methods

Flexor digitorum profundus tendons of the index, long, and ring fingers were harvested from nine hands of fresh frozen cadaveric specimens, for a total of 14 tendons. Only 14 out of 27 possible tendons were used due to specimen availability as the remaining tendons were used for purposes outside of this study. Eight of the hands were pairs from the same cadavers. The hands came from three male and two female cadavers with an age range of 67 to 79 years. These tendons were all examined for and found to be absent of abnormalities, tumors, and degenerative areas.

The height and width of each tendon was measured at the anticipated transection site with a caliper. The cross-sectional area of each tendon was calculated, assuming an elliptical geometry. The tendon was transected at the level of the A2 pulley using a scalpel, representing a traumatic injury.

Each tendon was repaired with one of two suturing techniques utilizing barbed sutures: the Marrero-Amadeo approach¹² (► Fig. 1A) or the proposed experimental approach (► Fig. 1B). For each set of two specimens harvested, the repair technique was randomized with one for each tendon. Six tendons were tested for each approach. The additional two tendons were tested but discarded from analysis due to the applied preconditioning force exceeding the prescribed magnitude for one tendon and an error in the video recording of the test for another tendon. The repairs were performed using a 2-0 barbed polypropylene suture (Quill, Surgical Specialties Corporation, Wyomissing, Pennsylvania, United States). A core suture purchase of 1 cm was used on all repairs. A single surgeon performed each repair using 2.5x loupe magnification. Though a running, epitendinous suture, that is, circumferential suture, is utilized as reinforcement in standard flexor tendon repairs, this additional suture was not included for either repair to focus on the strength provided by the suture cores.

For the experimental approach, one end of the suture was introduced through the transected end of the tendon and brought out 1 cm. The same suture was passed diagonally across the tendon twice with an epitendon bite at each pass. The opposite end of the suture was brought through the other end of the tendon in the same fashion, leaving the transition point for directionality of the barbs at the transection site (► Fig. 1B), aligning all barbs around the repair site to engage the tendon to resist distraction. The approach was repeated with three additional sutures for a total of four core suture passes. Both the repairs had an equal number of suture passes, that is, a total of four cores, as studies have shown that tendon repair strength is correlated with the number of cores used in the repair.^{7,8}

Fig. 1 Schematic diagrams of the barbed suture techniques utilized: (A) Marrero-Amadeo technique that uses a single suture and (B) experimental, knotless technique that uses four sutures. For the experimental approach, different line breaks represent separate sutures used. In each schematic, black dots represent the transition site for the direction of the suture barbs on each suture.

Fig. 2 Experimental setup used for ramp to failure testing of the repaired flexor tendons showing the repair site, marker beads used for calculating 2-mm gap force, and compression clamps.

Mechanical Testing

Prior to testing, black, spherical markers were glued into place on both sides of the repair site (► **Fig. 2**). Each tendon was secured to a material testing machine (Acumen, MTS, Eden Prairie, Minnesota, United States) for mechanical testing to failure. Compression clamps, with sandpaper in the grips, secured the ends of each tendon. The length of each tendon between the clamps was approximately 4 cm. The tendons were preconditioned by cycling from 0 to 3 N 10 times in a sinusoidal motion. A preload of 1 N was then applied for 1 minute, followed by a ramp to failure at a rate of 20 mm/min.^{12,17–20} The peak load (i.e., ultimate load) was recorded for each test and was normalized by the cross-sectional area of the intact tendon. The mode of failure for each repair was recorded as either suture pullout or rupture.

Data Analysis

The 2-mm gap force, that is, force at which the repair gaps by 2 mm, was recorded for each test. A video-based motion analysis system (MaxTRAQ, Innovision Systems Inc., Columbiaville, Michigan, United States) captured the position of each black marker during the 1 N preload and the ramp to failure. Calibration with a reference frame allowed quantification of the position of each marker in three dimensions. Evaluation of the system for repeatability of distance measurement between markers gave a precision less than 0.1 mm.²¹ Motion of the markers was processed with a custom-written algorithm (Matlab, Mathworks, Natick, Massachusetts, United States). A Gaussian filter was applied to

the marker position data. The distance between the markers secured to the tendon on both sides of the repair in the direction of the applied load was quantified. A moving average filter was applied to the distance data. The 2-mm gap force during the ramp to failure phase was determined as the recorded force when the distance between the markers on each side of the repair increased by 2 mm from the respective distance when the tendon was preloaded at 1 N. The 2-mm gap force was also normalized to the tendon cross-sectional area.

Statistical Analysis

The raw and normalized ultimate loads and 2-mm gap forces were compared between the repair techniques (Marrero-Amadeo and Experimental) using *t*-tests. Testing for outliers and normality was performed using a box-and-whisker technique and Shapiro-Wilks test, respectively. If normality testing failed or outliers were present, Mann-Whitney *U*-tests were used to compare repair techniques. The significance level for all tests was set at $p < 0.05$. A pre-study power analysis for *t*-tests with 80% power revealed that 11 tendons per group were needed assuming an effect size of 1.13, 20% greater than reported for 2-mm gap force in Marrero-Amadeo et al. (2011) for comparing the Marrero-Amadeo technique to a traditional four-core Tajima technique.

Results

The ultimate load tended to be largest for the Marrero-Amadeo repair. The raw ultimate force was significantly larger for the Marrero-Amadeo repair technique than the experimental technique ($p = 0.01$, ► **Table 1**). For the normalized ultimate load, the Marrero-Amadeo technique was also significantly larger than the experimental technique ($p = 0.018$).

The force producing a 2-mm gap tended to be largest for the Marrero-Amadeo repair. Without cross-sectional area normalization, the 2-mm gap force was not significantly different among repair techniques ($p = 0.2$, ► **Table 1**). The 2-mm gap force normalized by cross-sectional area data failed normality testing, and the Mann-Whitney *U*-tests revealed that there was no significant difference among repair techniques ($p = 0.13$).

Table 1 Mean ($\pm$ standard deviation) results from ramp to failure tests

	Experimental	Marrero-Amadeo	<i>p</i> -value
Ultimate load (N)	35.6 $\pm$ 13.8	58.2 $\pm$ 10.6	0.010 ^a
Normalized ultimate load (N/mm ²)	2.7 $\pm$ 1.5	4.8 $\pm$ 1.0	0.018 ^a
2-mm gap force (N)	27.1 $\pm$ 10.1	35.6 $\pm$ 11.6	0.205
Normalized 2-mm gap force (N/mm ²)	2.0 $\pm$ 0.9	2.9 $\pm$ 0.8	0.132

^aSignificantly different.

Five of the six repairs performed using the experimental knotless suture technique failed by suture pullout, with the other failing due to suture breakage. For the Marrero-Amadeo repaired tendons, five out of the six failed by suture breakage with the remaining repair failing by suture pullout.

Discussion

This study results do not support the hypothesis that the proposed four-core barbed suture approach, with all barbs aligned to resist distraction, provides more strength than the Marrero-Amadeo method of tendon repair. Biomechanical studies have shown that tendon repair strength is directly proportional to the number of cores used within the repair.^{7,8} Therefore, the experimental repair was designed to have an equal number of suture cores, that is, four, to the Marrero-Amadeo approach. Barbed suture tendon repair techniques have been proposed as a potential method to reduce bulk of a repaired tendon by eliminating the use of suture knots due to the tendon grip provided by the barbs. Previous biomechanical studies have demonstrated that barbed suture techniques, for example Marrero-Amadeo approach,¹² were similar but not superior to standard knotted sutures.^{12,13,15,16,22} The Marrero-Amadeo repair is a four-core barbed suture approach in which the suture is passed such that the barbs oppose applied tension, that is, engage against tendon distraction, for only half of the suture cores on each side of the repair.¹²

The experimental bidirectional barbed suture approach was designed to include four suture cores with all of the barbs opposing tendon distraction on both halves of the repaired tendon. The technique failed to exceed the strength measures of the Marrero-Amadeo technique and actually provided a significantly lower ultimate load, both raw and normalized, than the Marrero-Amadeo technique with power ≥ 0.73 . There was no significant difference between the repairs for the 2-mm gap force; however, it should be noted that the statistical tests were underpowered (power = 0.23 and 0.36 for raw and normalized 2-mm gap force, respectively). The authors expect that with additional specimens, the Marrero-Amadeo technique would have a significantly larger 2-mm gap force. Sample size analyses revealed that the authors would have needed to test at least 16 specimens per technique to achieve 80% power for the normalized 2-mm gap force variable and 27 specimens per technique for the raw 2-mm gap force. Testing was halted because it was apparent that the experimental approach would not be superior to the Marrero-Amadeo approach with additional testing.

The proposed experimental approach did not achieve the anticipated gains in strength from having all barbs oriented to resist tendon distraction.^{14,23} A potential explanation for the reduced strength of the experimental approach is that this repair may have provided less initial compression, or gap closure, along the repair site than the Marrero-Amadeo approach. For the experimental approach, each suture strand was passed across the repair site one time while the Marrero-Amadeo technique loops the suture to cross the repair site twice with locking loops. Achieving initial gap closure was much more difficult for the experimental repair without the

locking loop to tighten against. Though no data were collected to assess initial compression at the repair site, the observation was made that the two transected ends of the tendon were compressed together after tightening the Marrero-Amadeo repair. In addition, the initial gap closure and locking loop may have also contributed to the difference in failure mode for each suture configuration. The Marrero-Amadeo approach primarily failed by suture breakage whereas the experimental repair primarily failed by suture pullout.

The current results indicate that the Marrero-Amadeo suture provides a significant strength advantage over the proposed technique. The raw 2-mm gap force and ultimate load results of the presented study agree within 1 standard deviation (SD) to those of Marrero-Amadeo et al (ultimate load = 50 N and 2-mm gap force = 32 N).¹² The previous study found that the Marrero-Amadeo technique was comparable in strength but not superior to the Tajima technique, a traditional four-core technique, with epitendinous suture repair.¹² Specifically, the previous study found that the Tajima technique had an ultimate load of 48 N and a 2-mm gap force of 42 N. Therefore, the authors can conclude that the proposed experimental repair would not be superior to the traditional, Tajima knotted technique. Flexor tendons are subject to physiologic forces as high as 9 N during passive finger motion and 35 N during active finger motion without resistance.²⁴ Both the Marrero-Amadeo repair and the experimental repair provide a sufficient strength repair to allow for early active and passive range of motion therapy, which is important to prevent post-repair adhesion formation.³ However, increased resistance of the repaired tendon within its sheath, for example from tendon bulking and inflammation, leads to higher physiologic forces than a normal, intact tendon.³ The goal of a tendon repair is to achieve repair strengths higher than normal physiologic loads while also minimizing tendon bulk, that is, an advantage of knotless techniques with barbed sutures.

Limitations of the study should be noted. The study utilized cadaveric tendons from relatively old donors (all aged > 65), whereas most flexor tendon injuries and repairs occur in a younger patient population. The limitation was addressed by examining the tendons for gross degenerative changes, but there may still have been degeneration on a microscopic level. An additional limitation was the use of tendons from nine hands and no matching between testing groups. This resulted from specimen availability; some tendons from each hand were used for purposes outside of this study. Variations in properties of the intact tendon between groups are likely. This limitation was addressed by normalizing the strength data by the cross-sectional area at the repair site prior to transection to control for tendon size. Another limitation is the small sample size for each testing group. The goal of the study was to see whether the experimental approach improved the strength of a repaired tendon compared with the Marrero-Amadeo approach. Testing was halted after it had become apparent that the proposed repair technique would not be superior to the Marrero-Amadeo approach. Further testing would only further demonstrate that the Marrero-Amadeo approach was superior to the proposed experimental approach.

In conclusion, the Marrero-Amadeo approach was shown to have superior strength compared with the proposed experimental approach. Though further studies should be performed to assess gliding resistance and in vivo use of the Marrero-Amadeo technique, this study shows promise for use in traumatic zone II flexor tendon injuries. The experimental barbed suture approach did not improve strength compared with the Marrero-Amadeo approach despite aligning all barbs to resist distraction. Additional attempts to improve suture configuration to reduce the risk of failure from re-rupture, poor healing, or loss of flexion are warranted.

Conflict of Interest

Dr. Elias reports nonfinancial support from Surgical Specialties Corporation, during the conduct of the study; grants from MedShape, grants from NIH, grants from Arthroscopy Association of North America, grants from Pediatric Orthopaedic Society of North America, outside the submitted work. All the other authors report no conflict of interest.

Acknowledgments

The authors would like to thank Surgical Specialties Corporation (Wyomissing, Pennsylvania) for donating Quill barbed sutures used for this study. Funding was provided by a Buel Smith Research Grant from Cleveland Clinic Akron General.

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