Comparing Biomechanical Properties, Repair Times, and Value of Common Core Flexor Tendon Repairs

HAND
2018, Vol. 13(3) 313–318
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DOI: 10.1177/1558944717701238
hand.sagepub.com

Aakash Chauhan¹, Patrick Schimoler^{1,2}, Mark C. Miller^{1,2}, Alexander Kharlamov¹, Gregory A. Merrell³, and Bradley A. Palmer¹

Abstract

Background: The aim of the study was to compare biomechanical strength, repair times, and repair values for zone II core flexor tendon repairs. **Methods:** A total of 75 fresh-frozen human cadaveric flexor tendons were harvested from the index through small finger and randomized into one of 5 repair groups: 4-stranded cross-stitch cruciate (4-0 polyester and 4-0 braided suture), 4-stranded double Pennington (2-0 knotless barbed suture), 4-stranded Pennington (4-0 double-stranded braided suture), and 6-stranded modified Lim-Tsai (4-0 looped braided suture). Repairs were measured in situ and their repair times were measured. Tendons were linearly loaded to failure and multiple biomechanical values were measured. The repair value was calculated based on operating room costs, repair times, and suture costs. Analysis of variance (ANOVA) and Tukey post hoc statistical analysis were used to compare repair data. **Results:** The braided cruciate was the strongest repair ($P > .05$) but the slowest ($P > .05$), and the 4-stranded Pennington using double-stranded suture was the fastest ($P > .05$) to perform. The total repair value was the highest for braided cruciate ($P > .05$) compared with all other repairs. Barbed suture did not outperform any repairs in any categories. **Conclusions:** The braided cruciate was the strongest of the tested flexor tendon repairs. The 2-mm gapping and maximum load to failure for this repair approached similar historical strength of other 6- and 8-stranded repairs. In this study, suture cost was negligible in the overall repair cost and should be not a determining factor in choosing a repair.

Keywords: flexor tendon repairs, biomechanical properties, repair times, value

Introduction

There is no consensus on the repair technique that fits Strickland's description as the "ideal" zone II flexor tendon repair.¹⁷ There are numerous repair configurations, simple and complex, that range from 2 to 8 core repair strands.^{2,16} Confusion over nomenclature, especially the erroneous usage of "modified Kessler" in both biomechanical and clinical studies, has also added a degree of complexity surrounding the historical context of these repairs.¹⁶

In terms of technical strategies, increasing the number of core strands, adding an epitendinous stitch, and using a strong synthetic suture material (eg, FiberWire) can optimize biomechanical properties (eg, overall strength and repair site gapping) of the repair construct. This knowledge has translated directly into rehabilitation protocols so that repair constructs can withstand early postoperative active range of motion exercises.

A minimum of 4 core strands is considered standard for early light active motion protocols. Increasing the number of core strands to 6 or 8 adds to the biomechanical strength but can also increase the technical difficulty of the repair. Biomechanical data on 4 core stranded repairs are extensive and consistently show further optimization with the addition of epitendinous stitches.² The 6 core stranded repairs usually use looped suture materials with multiple passes and cut down on knot usage to maximize strength and efficiency.

¹Department of Orthopaedic Surgery, Allegheny General Hospital, Pittsburgh, PA, USA

²University of Pittsburgh, PA, USA

³Indiana Hand to Shoulder Center, Indianapolis, USA

Corresponding Author:

Bradley A. Palmer, Division of Hand, Upper Extremity, and Microvascular Surgery, Department of Orthopaedic Surgery, Allegheny General Hospital, 320 E North Avenue, Pittsburgh, PA 15212, USA.
Email: bradley.palmer@ahn.org

Figure 1. Schematic and cadaveric drawings of different repair configurations.

Note. The repair configurations (A) are demonstrated as follows: (a) Cross-stitch cruciate (4-0 polyester [TiCron] and 4-0 braided [FiberWire]), (b) knotless barbed suture double Pennington (2-0 bidirectional polypropylene barbed suture [Quill]),⁹ (c) Pennington (4-0 double-stranded braided [FiberWire]), and (d) modified Lim-Tsai (4-0 looped braided [FiberLoop]). The repair configurations are also depicted in the cadaveric hand (B) as follows: (a) cross-stitch cruciate, (b) modified Lim-Tsai, and (c) barbed suture double Pennington.

However, when directly comparing overall strength of 6-stranded with 4 core stranded repairs, there are surprisingly little data.² The most well-studied 8 core repair at this time is the Winters-Gelberman repair, which has robust biomechanical strength.^{12,13,18} However, there may be technical challenges in performing this repair in smaller tendons, as well as difficulty with multiple suture passes if the surgeon is unfamiliar with the technique.

Finally, advances in suture materials have provided alternative suture options, including barbed suture, which at this point has demonstrated mixed results,^{1,4-8,11,14,19} and

stainless steel which has shown promising biomechanical strength in limited studies.^{3,9}

At this time, no research has studied the association of strength, time, and cost of repairs. Specifically, in a health care environment where all expenses matter, it is important to evaluate the value of the products we use in repairs. Also, significant variability remains across studies comparing the same constructs/suture, with few studies presenting comprehensive biomechanical data across multiple commonly used configurations, including barbed suture.

Therefore, the purpose of this study was to determine the optimal repair configuration in terms of biomechanical strength, repair time, and repair value for popular zone II flexor tendon repairs. Our hypothesis was there would be no significant difference in the biomechanical strength, time, and between any of the chosen repairs.

Materials and Methods

After institutional approval for human cadaver use, we repaired 75 fresh-frozen flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) tendons. The index, middle, ring, and small finger tendons were used for biomechanical analysis. Tendons were randomized into one of 5 repair groups (15 tendons/group): 4-stranded cross-stitch cruciate (4-0 polyester [TiCron]; 4-0 braided [FiberWire]), 4-stranded knotless double Pennington (2-0 polypropylene barbed suture [Quill]),⁷ 4-stranded Pennington (4-0 double-stranded FiberWire), and 6-stranded modified Lim-Tsai (4-0 looped braided [FiberLoop]) (Figure 1). Repair constructs were chosen based on familiarity with repair configurations, similarity of suture caliber, historical strength, and technical difficulty. No epitendinous stitch was placed to assess the true core repair strength. Some technical repair details include suture purchase 1 cm from the injury site, and using 5 throws of a surgeon's square knot except the barbed suture which was knotless.

Repair site cross-sectional area was measured before and after repair using calipers. The ratio of the repaired to unrepaired areas was then computed. Next, repair time was measured for each repair group. The tendons were lacerated in zone II and repaired in situ for each repair group by a hand fellowship-trained surgeon. The repair configurations were done in a random order, and different fingers were randomly allocated to undergo different repairs to create variability in flexor tendon. These repairs were harvested and used for further biomechanical testing. The repair time was defined by the time from laceration to final repair. An average of the repair times was calculated for each repair group. Tendons were then tested immediately after the repair. Spherical markers of diameter 1 mm were attached to the tendon with cyanoacrylate adhesive. The tendon was then

Figure 2. Gapping and maximum load to failure.

Note. The 2-mm gapping and maximum load to failure are shown. P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington.

*Denotes a statistically significant difference ($P < .05$) of B-XC compared with all other repairs except B-MLT for 2-mm gapping.

**Denotes statistical significance ($P < .05$) of B-XC compared with all other repairs for maximum load to failure.

loaded to failure at 30 mm/min in a uniaxial tensile testing machine (828 Bionix; MTS, Eden Prairie, Minnesota) and the tension recorded at 10 Hz while 3-dimensional marker position during loading was tracked using a camera system also recording at 10 Hz (Spicatek, Kihei, Hawaii). Saline solution was sprayed on the tendons throughout the experiment to minimize deterioration.

The maximum load to failure and 2-mm gapping loads for each tendon were extracted from the load data, and repair stiffness was calculated as the slope of the linear portion of the force-displacement curve. The measured load-displacement data were used to compute the energy (joules = force $\times$ distance) absorbed in opening the gap and in extending the tendon. Basic averages were computed for all measurements. Statistical comparisons were performed with an analysis of variance (ANOVA) in Minitab (Minitab Inc, State College, Pennsylvania) with post hoc comparisons using the Tukey method if the primary independent variable proved to be statistically significant. Statistical significance was deemed as a P value $< .05$ for all comparative measurements. In addition, the suture and fixed outpatient operating room costs were obtained to assist with determining the value of the repair.

Results

2-mm Gapping Loads and Maximum Load to Failure

The braided cross-stitch cruciate repair was statistically stronger than all other repairs except the braided modified Lim-Tsai for 2-mm gapping and statistically higher compared with all other repairs for maximum load to failure (Figure 2).

Figure 3. Cross-sectional area ratio.

Note. P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington.

*Denotes a statistically significant difference ($P < .05$) compared with P-XC and DB-P only.

Table 1. Modes of Failure.

Repair	Most common mode of failure
P-XC	67% suture rupture
B-MLT	60% suture pullout
BS-DP	100% suture rupture
B-XC	80% knot failure
DB-P	60% suture pullout

Note. P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington.

Cross-Sectional Area and Mode of Failure

The cross-stitch cruciate demonstrated the highest cross-sectional repair ratio (repaired/native) compared with all other repairs (Figure 3).

The majority of the polyester cross-stitch cruciate repairs failed by suture rupture, whereas the majority of the braided cross-stitch cruciate repairs failed by knot failure. The barbed suture repairs all failed by suture failure within the substance of the suture itself, and both the braided modified Lim-Tsai and double-stranded Pennington failed commonly by suture pullout with an intact knot. There were no statistically significant differences in modes of failure (Table 1).

Stiffness and Energy

There were no statistically significant differences in the stiffness of the repairs (Figure 4). The braided cross-stitch cruciate had a significantly higher energy to reach a 2-mm gap during loading compared with all other repairs (Figure 5).

Repair Time and Value

The braided cross-stitch cruciate was significantly longer to repair compared with all other repairs at an average of 4

Figure 4. Stiffness.

Note. There was no statistically significant difference between any of the repairs. P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington.

Figure 5. Energy to 2-mm gap.

Note. P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington. The single asterisk (*) denotes a statistically significant difference ($P < .05$) between B-XC and all other repairs for energy required to cause 2-mm gapping.

minutes 12 seconds. The double-stranded braided Pennington (“modified Kessler”) was statistically the quickest repair to perform compared with all other repairs at an average of 2 minutes 20 seconds (Table 2).

Discussion

There is an abundance of flexor tendon repair configurations available to hand surgeons with no consensus on the “ideal” configuration or construct. The addition of epitendinous stitches can augment the total strength and gapping characteristics of repairs, but a strong core suture configuration is necessary to tolerate the demands of active motion which places approximately 27 N on the repair.¹⁵

This study confirmed that a 4-0 braided cross-stitch cruciate repair was stronger but bulkier and slower to perform

Table 2. Repair Times and Value.

Repair	Repair time (min)	Average total repair value (\$)
P-XC	3.7	423.66
B-MLT	2.9	387.08
BS-DP	3.4	415.12
B-XC	4.2*	501.00*
DB-P	2.3**	324.76**

Note. Average total repair value = (suture cost) + (repair time × institutional cost/minute of operating room time). P-XC = polyester cross-stitch cruciate; B-MLT = braided modified Lim-Tsai; BS-DP = barbed suture double Pennington; B-XC = braided cross-stitch cruciate; DB-P = double-stranded braided Pennington.

*Denotes that it is statistically higher compared with all other repairs.

**Denotes that it is statistically lower compared with all other repairs.

than all other repairs, including a 6-stranded modified Lim-Tsai. The true size of barbed suture is estimated to be one size smaller than described, and the 4-0 braided cross-stitch cruciate was stronger than the 2-0 polypropylene barbed suture (equivalent to an unbarbed 3-0 polypropylene) in a double Pennington configuration for all biomechanical tests. The 4-0 TiCron suture was used in a cross-stitch cruciate configuration as a comparative control, because the suture is much less expensive than braided suture. It was also significantly weaker in 2-mm gapping and load to failure compared with the braided version.

Few studies to date have evaluated repair times. McLaren et al evaluated repair times for a 4-strand nonlocking cruciate, 2-strand Pennington “modified Kessler,” 4-strand Indiana (Strickland) repair technique, and 6 stranded Savage repair techniques.¹⁰ The nonlocking cruciate was similar in repair time to the 2-strand Pennington “modified Kessler” (~4 and 3 minutes, respectively) and statistically faster than the Indiana (~6 minutes) or Savage (~14 minutes) repairs.¹⁰ Gordon et al compared repair times of a 4-0 braided cross-stitch cruciate plus an epitendinous suture with a 2-strand 3-0 monofilament stainless steel suture plus an epitendinous suture.³ They found average repair times to be 12 minutes for the cross-stitch cruciate with a running epitendinous suture and 7 minutes for the stainless steel repairs with only dorsal epitendinous interrupted stitches.³ In our study, the cross-stitch cruciate repairs had a significantly longer repair time (average 4.2 minutes) compared with all other repairs (Figure 3). Clinically, we do not feel that the differences in our study between repair times would point toward a clear preference for a single tendon or double zone II tendon lacerations, given that most of the repair times were within minutes of each other. However, repair times do matter in situations where there are multiple tendon lacerations with other associated injuries (eg, neurovascular bundle injuries or fractures) where expedient repairs can collectively save the surgeon time and decrease time in the operating room thereby reducing costs.

Also of interest to us were the results of the barbed suture repair. There has been a plethora of recent in vivo and ex vivo research evaluating the efficacy of barbed suture for flexor tendon repairs.^{4-8,11,14,19} Noted reasons to use barbed suture are the lack of knots which can reduce points of weakness in the repair, decreased bulkiness at the repair site which may obviate the need of an epitendinous suture, the ability for barbs to capture and lock tissue, and the ease of suture passage.^{7,8,14,19} However, in our study, barbed suture did not reveal any of these characteristics. The repair did not have the smallest cross-sectional area, was not the fastest repair, and was similar to all other repairs except the braided cross-stitch cruciate in terms of biomechanical strength. Recently, the addition of a barbed PDO epitendinous suture to a core barbed suture repair was evaluated.⁴ As expected, the addition of a barbed epitendinous stitch increased the biomechanical strength.⁴ However, the proposed advantages are lost with an epitendinous suture, especially made of barbed suture. The repair time would certainly be longer and, more importantly, add to the amount of exposed barbed suture which would theoretically increase gliding friction. Based on recent literature and our study, barbed suture has failed to demonstrate an advantage compared with other repair materials and repair configurations. Therefore, our enthusiasm for its use is limited.

In this study, we also attempted to define a value for each repair based on different variables: an institutionally based fixed cost per minute for a half hour of operating room time, institutional cost of suture, and measured repair times. Based on this analysis, the braided cross-stitch cruciate repair had a significantly higher cost and the double-stranded braided Pennington had a significantly lower cost compared with all repairs. Given the variability in flexor tendon injuries (isolated to multiple tendons), our approach was used to evaluate the value of just 1 repair of 1 tendon in an isolated injury. This is not representative of all clinical scenarios, of course, and the calculations of values are based on our institution's costs. Clinically, this cost difference, which is driven by the variable cost of the suture and repair times, may be deemed negligible; however, we wanted to highlight an important concept that may be applicable to any institution.

The limitations of this study include that it is an ex vivo biomechanical study on human fresh-frozen cadaveric tendons. This study is also not representative of all repair techniques but incorporated common methods as represented in the literature. The repair time was not reflective of the exposure, soft tissue dissection, expected placement of an epitendinous stitch, and wound closure representative of a complete case. In regard to the omission of an epitendinous suture, many biomechanical studies in the literature report values for repairs that include an epitendinous stitch. However, the specific purpose of this project was to report on a series of repairs on their "true" core strength. Especially in the setting of barbed suture, where the proposed advantage is a

knotless, epitendinous free repair configuration, our data clearly prove that even a 4-stranded braided suture configuration such as a double-stranded Pennington without an epitendinous stitch is similar in strength, less bulky, faster, and cheaper than a barbed suture repair of similar configuration. The financial value of the repairs is based on factors that may be variable for different institutions. Also, the fixed cost of operating room time was representative for a half hour; more time would certainly increase the cost, and may be necessary in many circumstances. Other associated operating room variable costs were also not included. A single hand fellowship-trained surgeon did the timed repairs to decrease variability; however, this may be faster or slower than times seen at other institutions.

In summary, our study demonstrates that a cross-stitch cruciate repair using 4-0 braided suture was statistically the strongest but was bulkier and slower to perform than the other repairs. The performance of barbed suture was similar to other techniques except the braided cross-stitch cruciate and did not stand out in any way. Finally, repair times and value are important factors to consider when choosing a repair technique. In simple injuries with isolated 1 or 2 tendon lacerations, repair time and value may not be as strong a factor in choosing a repair technique. However, in cases with multiple digit lacerations with other significant associated injuries (eg, digital nerve or artery, fractures, etc.), a repair that exhibits properties of strength while also being expedient and economical to perform may be an important factor to consider.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

This article does not contain any studies with live human or animal subjects.

Statement of Informed Consent

There were no live human subjects in this study, and therefore, there was no need for informed consent.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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