Barbed Suture Tenorrhaphy: An Ex Vivo Biomechanical Analysis

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Background: Using barbed suture for flexor tenorrhaphy could permit knotless repair with tendon-barb adherence along the suture’s entire length. The purpose of this study was to evaluate the tensile strength and repair-site profile of a technique of barbed suture tenorrhaphy.

Methods: Thirty-eight cadaveric flexor digitorum profundus tendons were randomized to polypropylene barbed suture repair in a knotless three-strand or six-strand configuration, or to unbarbed four-strand cruciate repair. For each repair, the authors recorded the repair site cross-sectional area before and after tenorrhaphy. Tendons were distracted to failure, and data regarding load at failure and mode of failure were recorded.

Results: The mean cross-sectional area ratio of control repairs was 1.5 ± 0.3, whereas that of three-strand and six-strand barbed repairs was 1.2 ± 0.2 (p = 0.009) and 1.2 ± 0.1 (p = 0.005), respectively. Mean load to failure of control repairs was 29 ± 7 N, whereas that of three-strand and six-strand barbed repairs was 36 ± 7 N (p = 0.32) and 88 ± 4 N (p < 0.001), respectively. All cruciate repairs failed by knot rupture or suture pullout, whereas barbed repairs failed by suture breakage in 13 of 14 repairs (p < 0.001).

Conclusions: In an ex vivo model of flexor tenorrhaphy, a three-strand barbed suture technique achieved tensile strength comparable to that of four-strand cruciate repairs and demonstrated significantly less repair-site bunching. A six-strand barbed suture technique demonstrated increased tensile strength compared with four-strand cruciate controls and significantly less repair-site bunching. Barbed suture repair may offer several advantages in flexor tenorrhaphy, and further in vivo testing is warranted. (Plast. Reconstr. Surg. 124: 1551, 2009.)

Achiving sufficient repair tensile strength to allow early passive and active motion is essential to functional rehabilitation and favorable outcomes following flexor tendon injury and repair. Refinements in suture material and the use of multistrand repair techniques have nearly eliminated suture rupture as a cause of repair failure. Instead, inadequate suture-tendon interaction at the site of grasping or locking loops, and suture knot failure limit the tensile strength of current repairs.

The notion of barbed suture tenorrhaphy was first conceived by McKenzie in 1967. His original report demonstrated that repair with custom-fabricated, barbed 3-0 nylon suture could achieve a tensile strength of 17.8 to 26.7 N, equivalent to that of a two-strand Bunnell repair with G40 stainless steel wire. This repair allowed for excellent healing in canine flexor tendons after 5 weeks of immobilization. Since McKenzie’s original report, no additional work has been published on this promising concept to address the potential role of barbed suture tenorrhaphy in the era of multi-strand repairs and early active motion rehabilitation protocols demanding higher repair-site tensile strength. In 2006, the application of barbed loops, and suture knot failure limit the tensile strength of current repairs.

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suture to expedite and more evenly distribute tension in skin closure was described by Murtha et al.23 Their technique used modern, commercially available sutures, and allowed for knotless repair, with strength and wound healing equivalent to traditional suture technique.

To date, no current literature exists regarding the tensile strength of tenorrhaphy with modern barbed sutures. We hypothesize that such a suture could allow for knotless tendon repair with barb-tendon adherence along the entire suture length. In addition to improving tensile strength by eliminating knots and loops, such a technique may allow for decreased repair-site bunching. The purpose of this study was to evaluate the tensile strength and repair-site characteristics of a multi-strand technique for flexor tenorrhaphy using barbed suture.

MATERIALS AND METHODS

Tendon Harvest and Preparation

Flexor digitorum profundus tendons from the index, long, and ring fingers of thawed fresh cadavers were harvested immediately before repair. The section of each tendon corresponding to zone II was identified and the center point of this area was marked. The cross-sectional area of the tendon was measured by a single observer at this point using an area micrometer. Tendons were then lacerated at this point with a scalpel, and desiccation was prevented during tendon harvest, preparation, repair, and testing with application of normal saline mist.

Tendon Repair

Each tendon was randomized to one of five repair groups. All repairs were performed immediately after laceration by a single surgeon (P.M.P.) under 2.5× loupe magnification. Tendons in the three control groups were repaired with the four-strand locked cruciate technique24 using either 4-0 monofilament polypropylene suture (Prolene; Ethicon, Inc., Somerville, N.J.), 4-0 braided polyester suture (Ethibond; Ethicon), or 4-0 composite polyethylene and braided polyester suture (Fiberwire; Arthrex, Inc., Naples, Fla.). To evaluate the repair strength using core sutures alone, peripheral epitendinous repair was not performed.

All barbed suture repairs were performed using 2-0 bidirectional barbed polypropylene suture (Quill; Surgical Specialties Corp., Reading, Pa.) (Fig. 1), which has been demonstrated to have a tensile strength that most closely resembles that of

Fig. 1. (Above) 2-0 polypropylene barbed suture, double armed with 7-cm antiparallel barbed segments flanking 1-cm unbarbed segment at the midpoint. (Below) Close-up view of the barbed segment demonstrating barb orientation.
4-0 unbarbed suture.25,26 Each barbed suture has a 1-cm segment of unbarbed monofilament at its midpoint, flanked by two 7-cm antiparallel barbed segments swaged onto 18-mm, 3/8 circle cutting needles.

The following technique was used for all barbed suture repairs (Fig. 2). One needle was passed anterograde into the distal tendon stump, and the other needle was passed retrograde into the proximal tendon stump. Each needle was advanced through the tendon, parallel to the direction of the fibrils, for a distance of 0.5 cm before exiting the tendon surface. Each end of the suture was then advanced to secure the unbarbed central 1 cm of suture in the repair site and approximate the tendon ends. Next, each needle was used to make two transverse passes at each tendon end, perpendicular to the direction of the tendon fibrils. Each needle was then reintroduced into the tendon and advanced parallel to the fibrils to traverse the injury site and enter the opposite end of the tendon. Again, two transverse passes were made to anchor the suture, and following the second pass, the excess suture and needles were cut off. This process resulted in a knotless repair with three strands crossing the injury site and four transverse passes at each end of the tenorrhaphy.

For six-strand barbed repairs, the three-strand technique described above was performed and then repeated with a second bidirectional barbed suture (Fig. 3). The cross-sectional area of each tendon at the repair site was measured and the ratio of the postrepair and prerepair cross-sectional areas was calculated.
Biomechanical Testing

Repaired tendons were placed on a Mini-Bionix load cell (MTS Systems Corp., Eden Prairie, Minn.) with grasping clamps (pretested to ensure no tendon slippage with loads up to 500 N), preloaded to 2 N, and then linearly distracted at a rate of 50 mm/minute. Distraction parameters were chosen to exceed the forces experienced by the repair site during early active motion rehabilitation protocols. Distraction continued until mechanical failure of the repair occurred, as defined by an abrupt drop in tensile strength or a visible gap of 3 mm. The load at failure was recorded. The failed repairs were then inspected under 4.0× loupe magnification to determine the mode of failure. Failures were categorized as suture breakage, knot rupture, or pullout when the suture and knot remained intact.

Statistical Analysis

Within-group and between-group comparisons were performed for load to failure and cross-sectional area data using one-way analysis of variance and the Tukey honestly significant difference test to perform comparisons between multiple groups. Individual group comparisons were performed using an independent sample, heteroscedastic, two-tailed t test. A chi-square test was used to test for significance in mode of failure data. Differences at the \( p \leq 0.05 \) level were considered significant.

RESULTS

Repair and testing were completed for 38 tendons. Testing was completed for eight tendons in each control cruciate repair group and in the three-strand barbed repair group. Testing was completed for six tendons in the six-strand barbed repair group.

Load to Failure

Load-to-failure data are listed in Table 1. There were no statistically significant differences in mean load to failure between any of the three control groups. Knotless three-strand barbed repair achieved mean load to failure that did not differ significantly from control cruciate repairs, despite having one less core suture. Knotless six-strand repair demonstrated a significantly increased mean load to failure when compared with each of the other groups (\( p < 0.001 \)).

Mode of Failure

The proportion of repairs failing by suture pullout and by suture breakage in each group is shown in Table 2. All tendons in cruciate repair groups failed by knot rupture or suture pullout, whereas the majority of tendons in barbed repair groups failed by suture breakage. This difference in mode of failure was significant (\( p < 0.001 \)).

Repair-Site Distortion

Repair sites are shown in Figure 4, and cross-sectional area data are shown in Table 3. A significant decrease in repair-site bunching (as measured by the ratio of the cross-sectional area of repaired tendon to that of uninjured tendon) was observed between both barbed repair groups and all control cruciate groups (\( p < 0.01 \)). No significant difference was observed between barbed suture groups.

DISCUSSION

The ideal suture for tendon repair should be strong, inelastic, nonreactive, and easy to handle and should knot securely. The ideal suture technique has been described by Momose et al. as easy to perform, strong enough to allow early active motion, and resulting in a smooth external junction without increasing bulk at the repair site. Numerous authors have suggested that the cruciate repair of McLarney et al. and its modifications approach the characteristics of the ideal tendon suture technique. However, the absolute need for a knot and the reliance on locking suture loops to grip the tendon substance ultimately limit the tensile strength of repairs performed with current suture technology and techniques.

Although the potential benefits of barbed sutures in tendon surgery were recognized as early

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Table 1. Load to Failure of Unbarbed Cruciate Repair versus Barbed Suture Repair*

<table>
<thead>
<tr>
<th>Repair Group</th>
<th>No. of Tendons in Group</th>
<th>Load to Failure (N)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbarbed cruciate repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monofilament polypropylene</td>
<td>8</td>
<td>29 ± 7</td>
</tr>
<tr>
<td>Braided polyester</td>
<td>8</td>
<td>30 ± 8</td>
</tr>
<tr>
<td>Fiberwire</td>
<td>8</td>
<td>40 ± 11</td>
</tr>
<tr>
<td>All cruciate repairs</td>
<td>24</td>
<td>33 ± 10</td>
</tr>
<tr>
<td>Barbed suture repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-strand</td>
<td>8</td>
<td>36 ± 7</td>
</tr>
<tr>
<td>Six-strand</td>
<td>6</td>
<td>88 ± 4</td>
</tr>
</tbody>
</table>

*Cruciate repairs: No significant differences observed between groups. Three-strand barbed vs. unbarbed cruciate, \( p = 0.32 \); six-strand barbed vs. unbarbed cruciate, \( p < 0.001 \); three-strand barbed vs. six-strand barbed, \( p < 0.001 \).

†Values are mean ± SD.
as the 1950s by Mansberger et al.\textsuperscript{32} and Bunnell,\textsuperscript{33} and the application of this concept was first studied by McKenzie in 1967, these early attempts were limited by the materials of the era and never gained widespread popularity.\textsuperscript{22} The recent introduction and U.S. Food and Drug Administration approval of barbed nylon, polydioxanone, and polypropylene sutures has reopened investigation into the potential benefits of these sutures in overcoming limitations to flexor tendon repair.

The principal advantage of barbed suture is its unidirectional nature, allowing for smooth, unrestrained passage in the direction of the barbs and tissue purchase and firm resistance to passage against the direction of the barbs. This directionality eliminates the need for a knot and therefore eliminates the knot as a potential “weak link” in repair failure. A second theoretical advantage of barbed suture is the more even distribution of load throughout the repair offered by the greater number of points for barb-tendon interaction along the length of the suture. As a result, slippage of locking loops is also eliminated as a potential point of repair failure.

In this study, we found that in our ex vivo model of tendon injury and repair, knotless flexor tendon repair with polypropylene barbed sutures can achieve tensile strength that is equivalent to or stronger than that of unbarbed, locked cruciate repairs. Knotless three-strand repairs provided adequate tensile strength to withstand the forces anticipated during early protected-motion protocols, whereas six-strand repairs exceeded the 40 to 50 N suggested by Amadio et al. as sufficient to initiate early active motion.\textsuperscript{34}

In addition, we observed that all unbarbed control repairs failed by knot rupture or suture pullout, whereas 13 of 14 barbed suture repairs failed by suture breakage. We interpret this significant difference in mode of failure to suggest that suture knot strength and inadequate suture tendon interaction were the limiting factors to achieving high tensile strength with the cruciate

### Table 2. Mode of Repair Failure\textsuperscript{\textdagger}$

<table>
<thead>
<tr>
<th>Repair Group</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suture Breakage</td>
</tr>
<tr>
<td>Unbarred cruciate repair</td>
<td>0/8</td>
</tr>
<tr>
<td>Monofilament polypropylene</td>
<td>0/8</td>
</tr>
<tr>
<td>Braided polyester</td>
<td>0/8</td>
</tr>
<tr>
<td>Fiberwire</td>
<td></td>
</tr>
<tr>
<td>Barbed suture repair</td>
<td></td>
</tr>
<tr>
<td>Three-strand</td>
<td>7/8</td>
</tr>
<tr>
<td>Six-strand</td>
<td>6/6</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Values are number of tendons failing by each mode/total in group.

\textsuperscript{\textdagger}Unbarred cruciate repairs vs. barbed knotless repairs, \( p < 0.001. \)

\textsuperscript{\dagger}As there is no knot to rupture in barbed groups, \( \chi^2 \) analysis was performed by comparing the frequency of suture breakage vs. knot rupture or pullout between barbed and unbarbed groups.

### Table 3. Cross-Sectional Area Ratio at Repair Site

<table>
<thead>
<tr>
<th>Repair Group</th>
<th>No. of Tendons in Group</th>
<th>Cross-Sectional Area Ratio\textsuperscript{\dagger}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbarred cruciate repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monofilament polypropylene</td>
<td>8</td>
<td>1.6 $\pm$ 0.2</td>
</tr>
<tr>
<td>Braided polyester</td>
<td>8</td>
<td>1.3 $\pm$ 0.3</td>
</tr>
<tr>
<td>Fiberwire</td>
<td>8</td>
<td>1.2 $\pm$ 0.2</td>
</tr>
<tr>
<td>All cruciate repairs</td>
<td>24</td>
<td>1.5 $\pm$ 0.3</td>
</tr>
<tr>
<td>Barbed suture repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-strand</td>
<td>8</td>
<td>1.2 $\pm$ 0.2</td>
</tr>
<tr>
<td>Six-strand</td>
<td>6</td>
<td>1.2 $\pm$ 0.1</td>
</tr>
</tbody>
</table>

\textsuperscript{\dagger}Cruciate repairs: No significant differences observed between groups. Three-strand barbed vs. unbarbed cruciate, \( p = 0.099; \) six-strand barbed vs. unbarbed cruciate, \( p = 0.005; \) three-strand barbed vs. six-strand barbed, \( p = 0.62. \)

\textsuperscript{\dagger}Values are mean $\pm$ SD.
technique, whereas barbed repairs were limited by the native strength of the suture rather than by slippage. By increasing the suture’s diameter or by applying barbs into materials with higher tensile strengths than polypropylene, the potential exists to further increase repair-site tensile strength using this technique.

In addition to maintaining tensile strength, a repaired flexor tendon must be able to pass through the flexor sheath smoothly. Increased bulk caused by fraying, excess suture material, and bunching during repair can inhibit passage through the sheath. Traditionally, this issue has been addressed by the addition of an epitendinous peripheral suture to the strand suture repair, which smooths the repair site, and has been shown to add substantially to the repair strength.\(^3\)\(^5\) In this study, we found that barbed suture repairs resulted in a significantly less bulky repair compared with cruciate repairs. This finding may have implications not only for improving tendon gliding through the sheath but also in limiting or eliminating the need for peripheral tendon suturing.

As the properties of barbed suture in tendon are largely unknown, several significant technical issues warrant further consideration. To maximize the purchase of the barbs of the suture against the tendon fibrils, we designed the repair to traverse the tendon several times perpendicular to the direction of the collagen fibers, creating a “grasping zone” similar to the classic technique described by Bunnell. To minimize the potential for barbed material to sit proud on the gliding surface of the tendon, each time the needle exited the tendon, it was reinserted precisely into the same hole to “bury” the suture loop. Another concern is a potential inability to extract the suture from the tendon if removal were to become necessary. Should intraoperative removal be necessary because of technical error during repair, the suture can be cut at its unbarbed central segment in the tendon injury site, and the needle and suture can be advanced out of the tendon without difficulty.

Another potential concern with this study is the difference in suture diameter and number of strands between control and experimental groups. With regard to suture diameter, inscription of barbs into monofilament suture creates multiple stress risers that decrease its native tensile strength such that a 2-0 barbed suture has tensile strength approximating that of unbarbed 4-0 suture.\(^2\)\(^5\)\(^,\)\(^2\)\(^6\) For this reason, 2-0 barbed sutures were selected for use in this study to compare with conventional suture techniques using 4-0 unbarbed sutures. With regard to number of strands, the bidirectional orientation of the barbs and the knotless nature of the repair result in a technique that necessarily produces a repair with three strands crossing the repair site. As it is not possible to produce a symmetric, three-strand cruciate repair with unbarbed sutures, there is a discrepancy in the number of strands used in control groups (four) and in the experimental groups (three or six). Consequently, the results of this study are not intended to demonstrate a difference between repairs using barbed suture and unbarbed suture per se. Rather, the results of this study are intended to compare a technique using barbed suture against a well-studied, widely accepted standard in flexor tendon repair. Additional work would be necessary to determine the safety and efficacy of this technique before its clinical application.

In interpreting the results of this study, we acknowledge several important limitations that should be considered before clinical application of this technique. As repairs were not performed in situ, we cannot assess the ease of this technique in a clinical setting under the constraints of limited exposure, tendon retraction, and tension. However, as the need for grasping or locking loops and knot tying was eliminated, suture placement was technically straightforward and reproducible, and produced consistent results. Because of the ex vivo nature of our study, we cannot assess factors such as tendon ischemia and healing after repair, edema, adhesion formation, tendon gliding, or the mechanical properties of the repair over time. Such information would be necessary before applying this technique in a clinical setting. To address these concerns, this technique could easily be applied to tendon repair in an in situ cadaver model or in vivo animal models such as chicken and rabbit tendons. The biomechanical testing of our repairs used a linear load to failure as the primary outcome, which may not reflect physiologic conditions as well as cyclic loading models. In addition, as our mechanical testing of load to failure included only a qualitative assessment of gap formation, we cannot quantify and adequately compare resistance to gap formation with other techniques. All of these issues present opportunities to further define the potential role for barbed sutures in tendon repair.
CONCLUSIONS

The present study introduces the idea of using barbed suture in flexor tenorrhaphy. In our ex vivo model of flexor tendon repair, a three-strand barbed suture technique achieved tensile strength comparable to that of traditional four-strand cruciate repairs despite having one less core suture, and demonstrated significantly less repair-site bunching. A six-strand barbed suture technique demonstrated markedly increased tensile strength compared with four-strand cruciate controls, and significantly less repair-site bunching. Our data suggest that knotless barbed suture repair may offer several advantages in flexor tenorrhaphy and that further ex vivo and in vivo testing are warranted to evaluate the clinical applicability of this concept.

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