1 **Flexor Tendon Repair: A Comparative Study between a Knotless Barbed Suture Repair and**
2 **a**
3 **Traditional Four-Strand Monofilament Suture Repair**

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ABSTRACT

We compared the tensile strength of a novel knotless barbed suture method with a traditional four-strand Adelaide technique for flexor tendon repairs. Forty fresh porcine flexor tendons were transected and randomly assigned to one of the repair groups before repair. Biomechanical testing demonstrated that the tensile strengths between both tendon groups were very similar. However, less force was required to create a 2 mm gap in the four-strand repair method compared with the knotless barbed technique. There was a significant reduction in the cross-sectional area in the barbed suture group after repair compared with the Adelaide group. This would create better gliding within the pulley system in vivo and could decrease gapping and tendon rupture.

INTRODUCTION

Strickland (1995; 2000) reported that the ideal flexor tendon repair includes safe, easily placed sutures to permit the stress of early post-operative motion, close approximation between the tendon sections with little gapping, congruity of the tendon ends, and a minimally compromised tendon blood supply.

Factors that affect the strength of a flexor tendon have been well researched and include the type and diameter of suture material used (Wada et al., 2001) the number of strands crossing the repair site (Barrie et al., 2000) the length of core suture purchase (Cao et al., 2006; Tang et al., 2005), the number of throws on the knot (Strick et al., 2004), the tension of the core suture (Wu and Tang, 2012) and the method of epitendinous repair (Moriya et al., 2010). Suture rupture as a cause of repair failure has almost been eliminated because of advances in suture materials and the refinement of multi-strand repair techniques (Parikh et al., 2009). Nowadays, the tensile strength of flexor tendon repairs is limited by inadequate suture-tendon interaction at the site of locking loops as well as failure of the suture knot (Tang et al., 2005; Trail et al., 1989; Xie and Tang, 2005)

1 Barbed sutures were first patented in 1964 and were first described in flexor tendon repairs
2 by McKenzie (1967) who used a unidirectional barbed suture to repair a lacerated tendon.
3 Despite having potential theoretical advantages over traditional repair techniques they have
4 been little used until recently. Currently used barbed sutures have major differences from
5 the barbed steel wires that McKenzie used. Modern barbed sutures can be absorbable or
6 non-absorbable and can be bi-directional, with barbs spiralling circumferentially around the
7 core of the suture. The theoretical advantages of barbed sutures over monofilament sutures
8 in flexor tendon repairs include improved tissue apposition as well as less foreign body
9 reaction (Peltz et al., 2013). Another recognized advantage of barbed sutures is their
10 unidirectional nature, which facilitates easy and unrestricted passage in the direction of the
11 barbs and tissue purchase, and firm resistance to passage against the direction of the barbs.
12 Barbed sutures tendon repairs do not require a knot and therefore eliminate the knot as a
13 potential “weak link” in repair (Parikh et al., 2009). Parikh et al. (2009) demonstrated that a
14 knotless barbed suture repair had a tensile strength that was equivalent to or stronger than
15 an unbarbed, locked cruciate repair.

16 We have compared the tensile strength and other features of a knotless tendon repair using
17 a barbed suture with a traditional four-strand Adelaide technique (Sandow and McMahon,
18 2011).

19

20 **MATERIALS AND METHODS**

21 Forty fresh porcine flexor digitorum profundus tendons were obtained for our study. These
22 were chosen as they have been used in many previous studies on the tensile strengths of
23 tendon repairs. They have similar biomechanical properties to the flexor tendon of the
24 middle finger in humans (Cao et al., 2006; Hausmann et al., 2009; Mao et al., 2011; Rigó et
25 al., 2012; Smith et al., 2005; Tang et al., 2005). We examined all the tendons for any

1 abnormalities and imperfections including synovitis, degeneration and trauma. Those that
2 had any defects were rejected.

4 **Cross-sectional area measurements**

5 To ensure all tendons were of a similar size, the height and width of each tendon was
6 measured using a caliper (Digi-Max™ Slide Caliper, Bel-Art, N.J., USA). Measurements were
7 taken at the repair site and also 1 cm proximal and 1 cm distal to the repair site. To calculate
8 the cross-sectional area (CSA) of each tendon we used the mathematical formula for
9 calculating an ellipse ($CSA = \pi ab$), where a is equal to half the long axis of the tendon cross-
10 section and b is equal one-half of the short axis of the tendon cross-section. Each
11 measurement was taken three times at all sites, and the mean value of each was used in the
12 formula. Measurements were taken at all three of these sites before and after tendon
13 repair to ensure consistency.

15 **Repair**

16 Tendons were randomly assigned to either the barbed suture repair group or the Adelaide
17 repair group. The tendons were then carefully transected using a scalpel and the repairs
18 were carried out. To ensure maximum effectiveness, all knots in the traditional tendon
19 repair group received six throws (Le et al., 2012; Viinikainen et al., 2006).

20 On all repairs, a core suture purchase of 1 cm was used. A hand surgeon (KEW) carried out
21 all the flexor tendon repairs under 3.5 x loupe magnification. The four-strand Adelaide
22 repair (Figure 1) was made using a 3-0 nonabsorbable monofilament polypropylene suture
23 (Prolene; Ethicon Inc, Somerville, N.J.). The diameter of the 3-0 polypropylene suture ranged
24 from 0.200 to 0.249mm. The knotless barbed suture repair was carried out using a non-
25 absorbable polymer 2-0 barbed V-Loc PBT (Polybutester, Covidien, MA, USA) (Figure 2).
26 Polybutester is a copolymer of butylene terephthalate and polytetramethylene ether glycol.

1 The barbed suture diameter ranged from 0.300 to 0.339 mm. Due to its decreased effective
2 diameter as a result of the process of creating barbs, a barbed suture is typically rated as
3 equivalent to one United States Pharmacopoeia (USP) suture size greater than its
4 conventional equivalent (Greenberg and Clark, 2009). For this reason we chose a 2-0 barbed
5 suture. As we wanted to analyse only the core strength of the repair, a running epitendinous
6 suture was not carried in either group.

7 The 2-0 barbed V-Loc™ PBT is a single-ended suture with a welded loop at one end. It has
8 unidirectional barbs with circumferential distribution. The V-Loc™ PBT suture has 26 barbs
9 per centimetre of suture material and each barb is 0.38 mm in length. The V-Loc™ suture
10 has unidirectional barbs cut circumferentially around the strand of suture at 120° rotations.
11 We used elements of the Adelaide four-strand repair (Figure 1) to create this novel knotless
12 four-strand repair (Figure 2).

13 An initial small bite was made in the tendon and the needle was then passed through the
14 loop, thereby locking it down snugly to the outer part of the tendon. The remainder of the
15 repair was similar to that of the traditional Adelaide repair technique. Instead of tying a
16 knot at the end, the suture was passed back through the tendon at the site of transection
17 and cut flush with the tendon. A core suture purchase of 1 cm was used in the barbed
18 suture technique.

19

20 **Biomechanical testing**

21 After the tendon repair, we examined the tensile strength of each repair using a tensiometer
22 (Zwick™ GmbH, Ulm, Germany). We set the upper clamp of the tensiometer to a pre-load
23 of 1.5 N and used an advancement rate of 20 mm/min. These were chosen as they have
24 been shown to best represent forces acting on an immobilized tendon during active flexion
25 (Cao et al., 2006; McClellan et al., 2011; Tang et al., 2001; Xie et al., 2005) and have been
26 used in previous studies of the tensile strengths of flexor tendon repairs (McClellan et al.,

2011). The clamps had a large surface area lined with sandpaper for gripping and the tendon ends were clamped securely to prevent any slippage. All biomechanical testing was filmed using a video camera and results were analysed using the software package Zwick™ testXpert® (Ulm, Germany).

The 2 mm-gap formation force was recorded as the force that produced a 2 mm gap in the repair site by linear distraction. The caliper was set at 2 mm and positioned below the tensiometer at the repair site. The 2 mm gap formation force was recorded by a tester when a gap occurred at the repair site that matched the 2 mm reading on the caliper. The ultimate strength was recorded as the greatest force occurring immediately before failure of the repair, which was defined as either pull-out or rupture. Pull-out occurred if the suture strands pulled through the tendon without breaking. Rupture occurred if the suture strands or knot broke.

Statistical analysis

The sample size required within each group was determined by a power analysis. Based on data from an initial pilot study, a minimum of 15 tendons was needed in each group for 0.80 power in the study to detect a significant difference of $p < 0.05$.

The Kolmogorov-Smirnov method was used to determine the normality or otherwise of the distributions of data. The maximum force and the 2 mm gap force between the two groups were compared using Student's *t*-test with Welch correction. The Mann-Whitney test was used to compare the difference in cross-sectional area between the two groups. Log transformations of the maximum force, the 2 mm gap force and the percentage change in cross-sectional area were carried out before analysis. A *p*-value of < 0.05 was considered statistically significant.

RESULTS

1 **Maximum force**

2 The maximum force that each repair technique could withstand before failure is shown in
3 Table 1. No significant difference was found between these two techniques (*t*-test, $p>0.05$).
4 All tendon repair failures were due to ruptures.

5

6 **2 mm gap force**

7 A 2 mm gap at the tendon ends is interpreted as clinical failure. Therefore, the force
8 required to produce a 2 mm gap at the repair site was compared between the groups (Table
9 1). The difference between the two techniques was statistically significant (*t*-test, $p<0.05$).

10

11 **Change In cross-sectional area**

12 The pre-repair and post-repair cross-sectional areas are shown in Table 1. There was no
13 statistical difference in the pre-repair cross-sectional areas. The difference in the cross-
14 sectional areas after the tendon repairs was statistically significant ($p<0.001$, Mann-Whitney
15 test).

16

17 **DISCUSSION**

18 Many different techniques of flexor tendon repair have been described, using a variety of
19 suture materials, but there is no established consensus amongst hand surgeons as to which
20 is the best method. There is still controversy about how best to decrease the formation of
21 adhesions and improve the overall outcome of flexor tendon repairs (Tang, 2007). Although
22 the ideal suture method for flexor tendon repair has not been established, it is agreed that it
23 should be strong, easy to insert, and have no deleterious effect on tendon gliding (Elliot,
24 2002).

25 Some surgeons advocate at least five throws in order to create a robust knot (Trail et al.,
26 1989). The resultant added bulk at the repair site has been shown to increase the cross-

1 sectional area of the tendon, which in turn increases gliding resistance through the pulley
2 system when active flexion occurs (Aoki et al., 1995; Coert et al., 1995; Momose et al., 2000;
3 Strick et al., 2004). Tendon gapping and rupture is known to occur because of the resulting
4 increase in load at the repair site (Barrie et al., 2000; Smith et al., 2012; Tang et al., 2001). It
5 has been reported that the knot is the weak point of the tendon repair because of decreased
6 tensile strength of the suture (Kim et al., 2007; Trail et al., 1989). The presence of a knot
7 decreases tendon apposition as it lies between the tendon ends (Pruitt et al., 1996). Knots
8 can also impede the vascular supply to the tendon and therefore interfere with healing as
9 optimum tendon nourishment is not obtained; this has been shown to lead to adhesion
10 formation (Datillo et al., 2002; Manske et al., 1984; Seiler et al., 1997). To avoid these
11 problems, techniques to bury both knots in the proximal and distal tendon parts have been
12 used (Kamath and Bhardwaj, 2006).

13 The results obtained from our study show that there was no significant difference in the
14 strength of repair between our four-strand knotless technique and the traditional four-
15 strand Adelaide technique. We found that the four-strand knotless method had a
16 significantly reduced cross-sectional area at the repair site compared with the Adelaide
17 repair method. This may theoretically decrease the amount of gliding resistance at the
18 repair site and therefore lower the rate of gap formation and tendon rupture. We also
19 found that the knotless barbed technique was able to withstand more force than the
20 Adelaide technique before a 2 mm gap was formed. The 2 mm gap formation force is
21 considered by some authors to be of more clinical significance than ultimate force as it
22 occurs at much lower loads (McDonald et al., 2012; Rigó et al., 2012). A 2 mm or larger gap
23 that forms during repaired flexor tendon mobilization significantly increases the gliding
24 resistance and catching at the pulleys (Zhao et al., 2004). However, the epitendinous suture
25 that is normally used in the repair of flexor tendons may make a significant contribution to
26 the prevention of gapping (Fufa et al., 2012).

1 We found the V-Loc™ barbed suture was easy to handle and quite robust for flexor tendon
2 repair. Care must be taken with each pass of the needle, as a misplaced pass through the
3 tendon cannot be corrected by pulling back on the suture owing to the barbs. We did find
4 that the barbed suture repair was quicker to carry out than the Adelaide repair as no knot
5 was required.

6 A theoretical problem with our knotless barbed repair is the presence of four cross grasps of
7 barbed suture material on the tendon surface. The exposed barbs on the tendon surface
8 could potentially damage the pulley system during mobilization. This might be overcome by
9 using the barbed suture in a modified Bunnell repair technique or any method where there
10 is less suture material on the tendon surface.

11 We acknowledge that there are several limitations to this study. We compared a 2-0
12 barbed suture with a 3-0 monofilament suture. It may be worth repeating the
13 biomechanical testing using a 3-0 barbed suture to compare it directly against the 3-0
14 monofilament suture. However, several studies have demonstrated that a 2-0 barbed
15 suture has tensile strength approximating that of an unbarbed 2-0 suture [Rashid et al.,
16 2007; Villa et al., 2008]. Furthermore, we compared a PBT barbed suture with a
17 polypropylene monofilament suture. It would have been preferable to make a direct
18 comparison between identical suture materials. Further work could be carried out to assess
19 the influence of an epitendinous repair on our two methods
20 The change in cross-sectional area pre- and post-repair was measured without a uniform
21 load on the tendon. It would have been ideal to carry out these cross-sectional
22 measurements with a uniform load to improve accuracy.

23

24 Recent studies looking at tendon repairs have focused carefully on the tension added to the
25 core suture when making the actual repair [Fufa et al., 2012; Wu and Tang, 2011 and 2012;
26 Wu et al., 2010] We did not formally measure this tension on our repairs, although we

1 attempted to make our repairs as uniform as possible. This was achieved in part by not
2 overshortening the tendon segment encompassed within the core sutures. Shortening this
3 tendon segment by as little as 10% by tensioning the core suture has been shown to
4 increase the gap resistance at the repair site [Wu and Tang, 2012].

5

6

7 **CONFLICT OF INTERESTS**

8 None declared

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16 **Figure 1. The four-strand Adelaide repair**

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18 **Figure 2. Diagram and photograph of the four-strand knotless barbed suture**
19 **repair.**

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Table 1. Data from biomechanical testing of flexor tendon repairs.

Table 1. Data from biomechanical testing of flexor tendon repairs; values are mean (SD).

Repair method	Maximum force, N	2 mm gap force, N	CSA, mm ²	Change in CSA, %
Knotless	55.5 (4.7)	46.5 (5.5)	85.7 (17)	2.8 (0.4)
Adelaide	52.0 (11.3)	41.5 (10.9)	87.8 (20)	7.7 (6.7)

CSA = cross-sectional area
2mm gap force

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