A 3-dimensional suture technique for flexor tendon repair: A biomechanical study

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A 3-Dimensional Suture Technique for Flexor Tendon Repair: A Biomechanical Study

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Purpose Flexor tendon injury continues to pose a number of challenges for hand surgeons. Improving mechanical properties of repairs should allow for earlier and unprotected rehabilitation. A 3-dimensional (3D) 4-strand suture technique has been proposed to combine high tensile strength and low gliding resistance without causing suture pullout due to tendon delamination. Our hypothesis is that the 3D technique can result in better mechanical properties than the Adelaide technique.

Methods Four groups of 10 porcine flexor tendons were sutured using the 3D or Adelaide technique with a 3-0 polypropylene or ultrahigh molecular weight polyethylene (UHMWPE) suture. The axial traction test to failure was performed on each tendon to measure 2-mm gap force and ultimate tensile strength.

Results The mean 2-mm gap force was 49 N for group A (3D + polypropylene), 145 N for group B (3D + UHMWPE), 47 N for group C (Adelaide + polypropylene), and 80 N for group D (Adelaide + UHMWPE). Failure mode was caused by suture breakage for group A (10/10) and mainly by suture pullout for the other groups (8/10 up to 10/10). With the UHMWPE suture, the mean ultimate tensile strength was 145 N for the 3D technique and 80 N for the Adelaide technique.

Conclusions Porcine flexor tendons repaired using the 3D technique and UHMWPE suture exceeded a 2-mm gap force and tensile strength of 140 N. The ultimate tensile strength was superior to that of the Adelaide technique, regardless of the suture material.

Clinical relevance This *in vitro* study on porcine flexor tendon suture highlights that the mechanical properties of 3D repair are better than those of 3D repair using the Adelaide technique when a UHMWPE suture is used. *(J Hand Surg Am. 2021;■(■):1.e1-e9.*

Key words 2-mm gap force, flexor tendon, hand injuries, suture techniques, tensile strength, UHMWPE.

Hand flexor tendon injuries are frequent, and their treatment can be challenging. Restoring satisfactory function after tendon repair requires sufficient tensile strength and low gliding resistance to allow for early active mobilization.[1–3] The tensile strength of the repair is affected by the number of strands, caliber of the core suture, suture material (braided or not), surface treatments, size and shape of the needle, knot configuration, loop configuration, and number of anchor points.[3–7] Improvements in suture materials and repair techniques have led to stronger repairs.[3,8–10] Despite these advances, most conventional tendon repair techniques do not provide sufficient tensile strength to immediately allow for unprotected mobilization.[1,3,4,8,11,12] Protected active rehabilitation implies wearing an orthosis during the 6 weeks of tendon healing. Even then, adhesions, stiffness, and repair-site gapping remain a frequent outcome.[8,12–14] There are 3 possible causes of tendon repair failure: suture breakage, knot failure, and suture pullout due to tendon delamination (longitudinal tear).[2]

The axial tensile force applied to a repaired flexor tendon during full extension of the finger and active flexion is unknown in the literature; however, based on findings by Savage,[15] we postulated that the strength of a flexor tendon repair, which is held only by a suture material, should be at least140 N to allow for unprotected rehabilitation.

In conventional suturing techniques, a nonabsorbable 3-0 or 4-0 suture is used, often reinforced with a peripheral epitendinous running suture with a 5-0 or 6-0 suture.[2,3] The common techniques are a modified 4-strand Kessler technique and the Becker, Adelaide, or Strickland technique, with several variants; their biomechanical properties have been studied using *in vitro* tensile tests (on cadaver or porcine tendons) and, more rarely, using *in vivo* tests.[2–4,8,16–18]

An extensive literature review conducted in 2000 defined 6 characteristics of the ideal suture technique.[2] The sutures should be easily placed in the tendon with secure suture knots, allowing for a smooth juncture of the tendon ends, minimal gapping at the repair site, and minimal interference with tendon vascularity, and have sufficient tensile strength throughout healing. Based on these criteria, Strickland[2] considered the Adelaide repair technique (also known as locked cruciate) as the gold standard, providing the highest tensile strength in *in vitro* studies, up to 120 N with ultrahigh molecular weight polyethylene (UHMWPE).[9]

We hypothesized that a 3-dimensional (3D) 4-strand repair technique would combine high tensile strength and low gliding resistance without causing suture pullout due to tendon delamination.

The objective of this study was to compare, *in vitro*, the biomechanical properties of 3D repair with those of the Adelaide repair technique. We hypothesized that the 3D repair technique can result in a 2-mm gap formation force and ultimate tensile strength of 140 N and, therefore, be able to withstand an immediate, active, unprotected rehabilitation protocol.

MATERIALS AND METHODS

This study follows the design of published biomechanical evaluations of *in vitro* porcine flexor tendon repair techniques.[4,9,17,19] The sample size was estimated based on similar *in vitro* studies. A convenience sample of 10 tendons for each group was studied.

The use of animal tissues complied with the guidelines of the authors' institution, the National Institutes of Health, and the French law on the use of laboratory animals.

Fresh porcine forelimbs were used in the study. Both flexor tendons were harvested from each forelimb, with an average cross-sectional area of 20 mm^2 and a minimum length of 10 cm, allowing them to be installed in the clamps of a traction machine. A clean cross-tendon cut made using a scalpel simulated a traumatic laceration.

Forty tendons were randomly allocated to 4 groups of 10 tendons each (Fig. 1), repaired, and tested in axial traction. To ensure consistency of the technique, the section sites and points of entry of the core suture were premarked on the tendons, and all suturing procedures were performed by a single surgeon (M.C.). The core suturing procedure (3D or Adelaide) was performed using a 3-0 suture (polypropylene or UHMWPE) and reinforced with a peripheral epitendinous polypropylene 6-0 running suture 2 mm from the section site. Repaired tendons were stored in a freezer at −80 °C to preserve their mechanical properties before testing.[19,20]

Surgical technique: the 3D repair

The basic pattern of 3D repair is a 3D figure of 8 with 4 anchors in the 3 planes of space. This pattern is repeated using 2 sliding sutures on both ends of the tendon, forming a 4-strand repair. The loops are simply grasping (ie, still able to slide) once the passes are completed (Figs. 2, 3; Video 1). For optimal tensile strength, suture tensioning should result in an approximately 10% shortening of the tendon length at

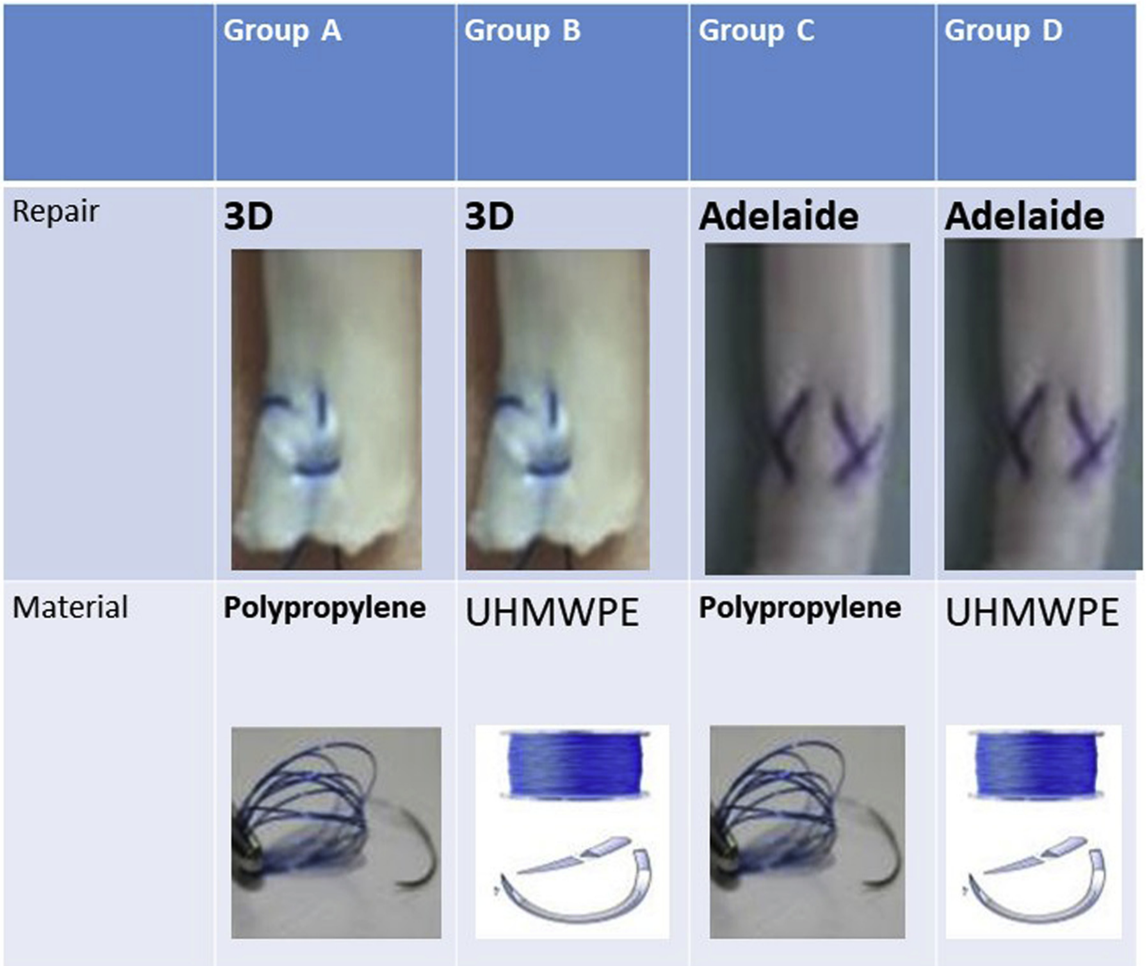

FIGURE 1: Study protocol. Allocation of each group of 10 tendons to a repair technique and a suture type.

the suture site.[20] The suture ends are knotted at the ends of the tendon stumps (Fig. 2B).

The gold standard repair technique chosen for comparison in this study was the Adelaide or 4-strand locked cruciate repair technique.[19]

Suture materials

Both the repair techniques were tested using a 3-0 polypropylene (Prolene, Ethicon) and a 0.25-mm UHMWPE suture. The polypropylene suture is a nonabsorbable, monofilament suture commonly used for flexor tendon repairs, premounted with a curved taper needle. During preliminary testing, tendons repair using the 3D technique and polypropylene suture failed because of suture breakage. This observation prompted us to use a stronger suture.

In the existing studies, repairs using the UHMWPE suture had the highest tensile strength.[9,10] The UHMWPE suture is a nonabsorbable fiber made from ultrahigh molecular weight polyethylene, a light-weight and high-strength material used in arthroplasties since the 1980s and, more recently, in sutures largely used for flexor tendons. Surgical UHMWPE sutures were unavailable to us at the time of the study. Therefore, we used a commercially available 100% UHMWPE (KastKing) fishing braid, with a 0.25-mm-diameter surgical 3-0 suture, mounted with a curved cutting-edge free needle.[21]

Outcomes and mechanical testing

The primary outcome was 2-mm gap formation force (N). The secondary outcomes were ultimate tensile strength (N), failure mode of the repair (knot failure, suture breakage, or suture pullout), stress (ultimate tensile strength divided by the tendon cross-section area, in N/mm^2), and stiffness (N/mm).

Mechanical testing was conducted on an Instron 5566A axial traction machine (Instron Corp) (Fig. E1A, available online on the Journal's website at www.jhandsurg.org). The tendons were thawed in saline-soaked gauze at 4 °C for 24 hours before testing. The dimensions of the tendon were recorded

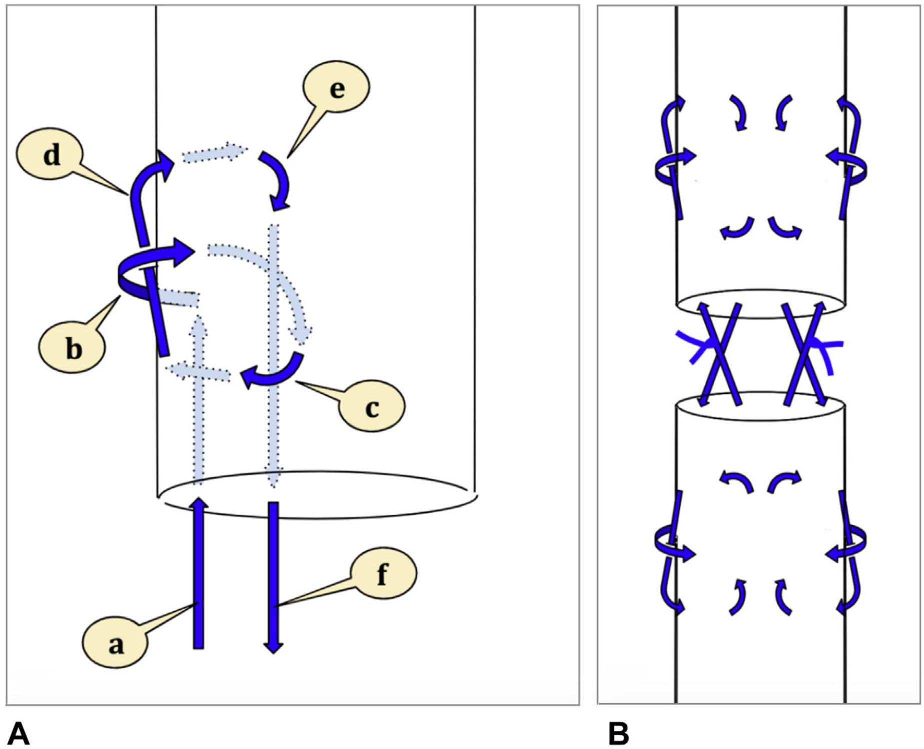

FIGURE 2: 3D repair technique. **A** Illustration of the basic pattern of 3D repair following passages of the suture in the order of execution. The suture is shown in dark blue while outside the tendon and light blue while inside the tendon. Pass a: entry through the rupture; Pass b: transverse pass from posterior to anterior, diving deep; Pass c: transverse anterior pass; Pass d: lateral vertical pass under Pass b; Pass e: anterior vertical pass, crossing superficial to Pass b; Pass f: exit through the rupture and over to the other tendon side. **B** Illustration of the completed 3D repair using 2 sutures tied with 2 intratendinous knots at the repair site.

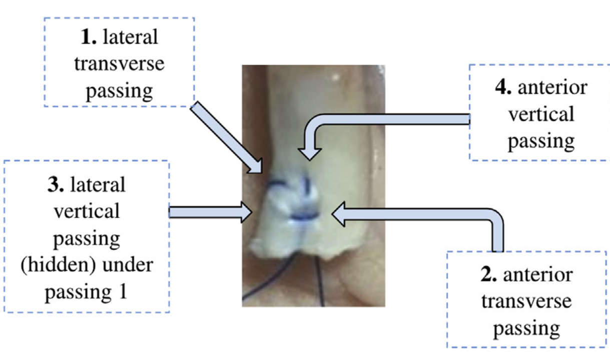

FIGURE 3: Basic configuration of 3D repair with the polypropylene 3-0 suture on the distal end of a porcine flexor tendon.

at the suture site and at a healthy site 30 mm distally. Estimations of the cross-section areas were then calculated using the following formula for the area of an ellipse: (small diameter 2) $\times$ (large diameter 2) $\times$ π. Both ends of the repaired tendon were mounted onto standard clamps. The initial distance between the clamps was set at 40 mm for all the tendons. The repaired tendons were subjected to a load-to-failure test. After application of a 1-N preload, the tendons were pulled at a constant speed of 10 mm/min. Data were recorded at a rate of 10 Hz. Bluehill Universal Software (Instron Corp) was used to create a load displacement curve, from which the ultimate tensile strength was determined (peak of the curve). Stiffness was calculated as the slope of the initial linear section of the curve. A ruler was attached to the upper clamp next to the tendon, and the test was monitored using a high-definition camera to determine the 2-mm gap formation force (Fig. E1B). The 2-mm landmark was considered reached as soon as a 2-mm gap formed on either part of the repair site (Fig. E1C). Failure mode was determined by visual examination of the tendons, photographed after testing.

Statistical analysis

The Shapiro-Wilk test was used to ensure that the cross-sectional areas of the tendons were normally distributed. The nonparametric Mann-Whitney test was used to compare the numeric outcomes (mechanical testing results and cross-section areas) between each group. The Fisher exact test was used to compare the failure mode between each group.

Using the Bonferroni correction for multiple group comparisons (A vs B, C vs D, A vs D, B vs C, A vs

TABLE 1. Mechanical Testing in Axial Traction

Parameters*	Group A	Group B	Group C	Group D
	3D + Polypropylene	3D + UHMWPE	Adelaide + Polypropylene	Adelaide + UHMWPE
2-mm gap force (N)	49.1; 48.0 (43.9−54.3)	145.0; 136.5 (119.2−170.8)	47.0; 47.5 (40.6−53.3)	79.6; 79.0 (71.8−87.4)
Ultimate tensile strength (N)	64.6; 63.6 (59.6−69.5)	145.0; 145.5 (131.0−179.0)	52.8; 52.2 (46.8−58.8)	80.4; 79.8 (72.6−88.3)
Stiffness (N/mm)	6.0; 5.9 (5.3−6.7)	15.0; 14.9 (12.7−17.4)	4.4; 4.5 (4.0−4.8)	10.4; 10.1 (9.3−11.6)
Stress (N/mm^2)	3.2; 3.0 (2.6−3.8)	8.3; 8.7 (7.2−9.5)	2.4; 2.2 (2.1−2.7)	5.0; 4.8 (4.3−5.6)
Cross-section area at healthy site (mm^2)	20.4; 19.9 (17.4−25.0)	18.9; 19.0 (16.4−21.4)	22.5; 22.5 (20.5−24.5)	16.6; 15.6 (14.1−19.2)
Cross-section area at suture site (mm^2)	33.0; 30.3 (25.7−40.4)	43.8; 40.7 (38.9−48.6)	36.7; 37.2 (33.4−40.7)	43.4; 42.0 (37.2−49.6)
Failure Mode	n = 10	n = 10	n = 10	n = 10
Suture breakage	10/10	0	1/10	0
Knot failure	0	0	0	2/10
Suture pullout	0	10/10	9/10	8/10

*The results are presented for each numeric outcome as mean value; median value (95% confidence interval). Failure mode is expressed as number of tendons / 10.

C, B vs D, n = 6), the α risk was set at 0.05/6 = 0.0083.[22] Therefore, having the α risk set at 0.0083, the *post hoc* power (1−β) was calculated for each comparison.

RESULTS

The mean 2-mm gap force was 49 N for group A (3D + polypropylene), 145 N for group B (3D + UHMWPE), 47 N for group C (Adelaide + polypropylene), and 80 N for group D (Adelaide + UHMWPE).

Failure mode was caused by suture breakage for group A (10/10) and mainly by suture pullout for the other groups (8/10 up to 10/10).

With the UHMWPE suture, the mean ultimate tensile strength with the 3D technique was 145 N. The individual results ranged from 122.6 to 237.5 N, with the ultimate tensile strength of 6 of the 10 repairs exceeding 140 N. Tendons repaired using the 3D technique were 1.8 times stronger than those repaired using the Adelaide technique with the UHMWPE suture and 1.2 times stronger with the polypropylene suture.

The gross mechanical testing results are presented in Table 1 and compared for each group in Tables 2 and 3.

DISCUSSION

The 2-mm gap formation force with 3D repairs was significantly higher than that with Adelaide repairs with the UHMWPE suture but similar with the polypropylene suture. As with the ultimate tensile strength, lower resistance of the polypropylene suture may explain this outcome. Gap formation (1−3 mm) has been shown to be associated with adhesions and poorer clinical results, but the exact limit for tendon healing remains unknown.[9,23,24]

Tendons repaired using the 3D technique had a significantly higher ultimate tensile strength than tendons repaired with the Adelaide technique, regardless of the suture used (polypropylene or UHMWPE). The mean ultimate tensile strength with the 3D technique and UHMWPE suture exceeded 140 N, which is the tensile strength required to allow for immediate unprotected active rehabilitation. The lower value of the confidence interval was 130 N. To our knowledge, that is the highest ultimate tensile

TABLE 2. Statistical Comparison of Tendons Sutured with Polypropylene Suture: 3D Versus Adelaide Technique (Group A vs C)

Parameters	Group A 3D + Polypropylene	Group C Adelaide + Polypropylene	*P* Value	Power (%)
2-mm gap force (N)	49.1; 48.0; Min 36, Max 60 (43.9−54.3)	47.0; 47.5; Min 34, Max 64 (40.6−53.3)	.51	3
Ultimate tensile strength (N)	64.6; 63.6; Min 53.9; Max 75.4 (59.6−69.5)	52.8; 52.2; Min 39.4; Max 69.9 (46.8−58.8)	.0015*	89
Stiffness (N/mm)	6.0; 5.9 (5.3−6.7)	4.4; 4.5 (4.0−4.8)	.0004*	99
Stress (N/mm^2)	3.2; 3.0 (2.6−3.8)	2.4; 2.2 (2.1−2.7)	.015	83
Cross-section area at healthy site (mm^2)	20.4; 19.9 (17.4−25.0)	22.5; 22.5 (20.5−24.5)	.21	24
Cross-section area at suture site (mm^2)	33.0; 30.3 (25.7−40.4)	36.7; 37.2 (33.4−40.7)	.34	5
Failure Mode	n = 10	n = 10		
Suture breakage	10/10	1/10	E-7*	100
Knot failure	0	0		
Suture pullout	0	9/10		

Max, maximum; Min, minimum.
*Significant *P* value.

strength reported with the 4-strand technique and 3-0 suture. It is also superior to the reported results of 6- and 8-strand techniques.[2,4,8,10,16,18,19,25−28] However, the tensile strength of 140 N was not achieved with the polypropylene suture. Indeed, 3D repairs with the polypropylene suture exceeded the tensile strength of Adelaide repair by only 11 N and failed because of suture breakage in all the cases, implying that the resistance of the suture material was the limiting factor. Conversely, tendons repaired using the 3D technique with the UHMWPE suture gained 82 N of ultimate tensile strength compared with those repaired using the 3D technique with the polypropylene suture. In a previous study by Lawrence and Davis,[4] repairs using the Adelaide technique reached a mean ultimate tensile strength of 63 N with a 4-0 polypropylene suture; all their repairs reportedly failed because of suture rupture. In our study, the repair of tendons using the Adelaide technique failed because of suture pullout in 9 of the 10 cases with the polypropylene suture and 8 of the 10 cases with the UHMWPE suture.

In our study, with the UHMWPE suture, the tendons repaired using the Adelaide technique reached 79 N, a similar tensile strength to those repaired using the Adelaide technique with a 4-0 fiberwire in the study by Lawrence and Davis,[4] whereas the maximum tensile strength reported for the Adelaide technique was 119 N with a 3-0 fiberwire in the study by Croog et al.[9] Scherman et al[21] measured the cross-section area of several sutures, finding that the 3-0 fiberwire corresponded to the standard 2-0 size and the 3-0 polypropylene suture was between 2-0 and 3-0. In comparison, the cross-section area of the 0.25-mm UHMWPE suture corresponds to a 3-0 size. This difference in suture caliber between the 3-0 fiberwire and 0.25-mm UHMWPE suture may explain the higher tensile strength for tendons repaired using the Adelaide technique in the study by Croog et al[9] compared with that in our study.

Ultrahigh molecular weight polyethylene is the main component of the strongest current braided sutures, in addition to fishing lines and climbing and boat ropes. We selected the strongest available suture to test the repair technique itself and the knot without limitations related to the intrinsic resistance of the material. While using a polypropylene suture for the 3D repair, failure occurred at 63 N because of suture breakage. With the stronger UHMWPE suture, 3D repair in the tendons failed because of suture pullout.

TABLE 3. **Statistical Analysis of Tendons Sutured with UHMWPE Suture: 3D Versus Adelaide Technique (Group B vs D)**

Parameters	Group B 3D + UHMWPE	Group D Adelaide + UHMWPE	*P* Value	Power (%)
2-mm gap force (N)	145.0; 136.5; Min 109; Max 237 (119.2−170.8)	79.6; 79.0; Min 59; Max 94 (71.8−87.4)	.0002*	99
Ultimate tensile strength (N)	145.0; 145.5; Min 122.6; Max 237.5 (131.0−179.0)	80.4; 79.8; Min 59.8; Max 94.8 (72.6−88.3)	E-5*	100
Stiffness (N/mm)	15.0; 14.9 (12.7−17.4)	10.4; 10.1 (9.3−11.6)	.0016*	91
Stress (N/mm^2)	8.3; 8.7 (7.2−9.5)	5.0; 4.8 (4.3−5.6)	E-5*	99
Cross-section area at healthy site (mm^2)	18.9; 19.0 (16.4−21.4)	16.6; 15.6 (14.1−19.2)	.16	12
Cross-section area at suture site (mm^2)	43.8; 40.7 (38.9−48.6)	43.4; 42.0 (37.2−49.6)	.91	1
Failure Mode	n = 10	n = 10		
Suture breakage	0	0	*P* = .5	11
Knot failure	0	2/10		
Suture pullout	10/10	8/10		

Max, maximum; Min, minimum.
*Significant *P* value.

In tendons repaired using the Adelaide technique with the polypropylene suture, suture pullout occurred in all but 1 case before reaching the maximum resistance of the suture or knot. Suture pullout was also the main failure mode with the UHMWPE suture, but this result might have been due to the use of a cutting needle of a higher cross-section area. Indeed, the UHMWPE suture was used with a free cutting needle, whereas the polypropylene suture had a mounted thinner taper needle. We hypothesized that 3D repair with a surgical UHMWPE suture and mounted taper needle, such as a fiberwire, would result in few suture pullouts, which may increase the ultimate tensile strength of the repair. Fiberwire is constructed from a multistrand, long-chain UHMWPE core with a braided jacket of polyester and UHMWP to increase its tensile strength.[29]

The main limitation of this study is the use of a nonsurgical UHMWPE unmounted braid, instead of a surgical UHMWPE suture, which was unavailable at the time of the study. The core resistance of the UHMWPE suture that we used should have been identical to that of a surgical suture, but surface treatments and threading techniques might have increased or decreased its biomechanical properties. Moreover, the use of a separate cutting needle, different in shape and size from that of the premounted needle of a surgical suture, might have increased tissue damage during the repair and favored suture pullout. Therefore, these outcomes require further confirmation with a surgical UHMWPE suture.

The other limitations are those of *in vitro* biomechanical studies for flexor tendon repair and their extrapolation to *in vivo* conditions. The unique axial tensile test fails to account for different speeds and angles of elongation stress, fatigue after multiple cycles, and work of flexion. The use of porcine flexor tendons instead of human cadaver tendons is also a limitation, although most studies about flexor repair have used porcine tendons because of their similarities to human tendons and the ease of access to well-preserved tissue.

REFERENCES

1. Sandow MJ, McMahon M. Active mobilisation following single cross grasp four-strand flexor tenorrhaphy (Adelaide repair). *J Hand Surg Eur* Vol. 2011;36(6):467−475.

2. Strickland JW. Development of flexor tendon surgery: twenty-five years of progress. *J Hand Surg*. 2000;25(2):214−235.
3. Ayhan E, Tuna Z, Oksuz C. Getting better results in flexor tendon surgery and therapy. *Plast Reconstr Surg Glob Open*. 2021;18(9): e3432.
4. Lawrence TM, Davis TR. A biomechanical analysis of suture materials and their influence on a four-strand flexor tendon repair. *J Hand Surg*. 2005;30(4):836−841.
5. Taras JS, Raphael JS, Marczyk SC, Bauerle WB. Evaluation of suture caliber in flexor tendon repair. *J Hand Surg*. 2001;26(6):1100−1104.
6. Trail IA, Powell ES, Noble J. An evaluation of suture materials used in tendon surgery. *J Hand Surg Edinb Scotl*. 1989;14(4):422−427.
7. Vizesi F, Jones C, Lotz N, Gianoutsos M, Walsh WR. Stress relaxation and creep: viscoelastic properties of common suture materials used for flexor tendon repair. *J Hand Surg*. 2008;33(2):241−246.
8. Chauhan A, Palmer BA, Merrell GA. Flexor tendon repairs: techniques, eponyms, and evidence. *J Hand Surg*. 2014;39(9): 1846−1853.
9. Croog A, Goldstein R, Nasser P, Lee SK. Comparative biomechanic performances of locked cruciate four-strand flexor tendon repairs in an ex vivo porcine model. *J Hand Surg*. 2007;32(2):225−232.
10. Waitayawinyu T, Martineau P, Luria S, Hanel D, Trumble T. Comparative biomechanic study of flexor tendon repair using fiberwire. *J Hand Surg*. 2008;33(5):701−708.
11. Woythal L, Hølmer P, Brorson S. Splints, with or without wrist immobilization, following surgical repair of flexor tendon lesions of the hand: a systematic review. *Hand Surg Rehabil*. 2019;38(4): 217−222.
12. Klifto CS, Bookman J, Paksima N. Postsurgical rehabilitation of flexor tendon injuries. *J Hand Surg*. 2019;44(8):680−686.
13. Moriya K, Yoshizu T, Tsubokawa N, Narisawa H, Maki Y. Incidence of tenolysis and features of adhesions in the digital flexor tendons after multi-strand repair and early active motion. *J Hand Surg Eur Vol*. 2019;44(4):354−360.
14. Pan ZJ, Pan L, Xu YF, Ma T, Yao LH. Outcomes of 200 digital flexor tendon repairs using updated protocols and 30 repairs using an old protocol: experience over 7 years. *J Hand Surg Eur Vol*. 2020;45(1):56−63.
15. Savage R. In vitro studies of a new method of flexor tendon repair. *J Hand Surg Br Eur Vol*. 1985;10(2):135−141.
16. Vigler M, Palti R, Goldstein R, Patel VP, Nasser P, Lee SK. Biomechanical study of cross-locked cruciate versus strickland flexor tendon repair. *J Hand Surg*. 2008;33(10):1826−1833.
17. Hirpara KM, Sullivan PJ, Raheem O, O'Sullivan ME. A biomechanical analysis of multistrand repairs with the Silfverskiöld peripheral cross-stitch. *Bone Jt J*. 2007;89(10):1396−1401.
18. McLarney E, Hoffman H, Wolfe SW. Biomechanical analysis of the cruciate four-strand flexor tendon repair. *J Hand Surg*. 1999;24(2): 295−301.
19. Jordan MC, Schmitt V, Jansen H, Meffert RH, Hoelscher-Doht S. Biomechanical analysis of the modified Kessler, Lahey, Adelaide, and Becker sutures for flexor tendon repair. *J Hand Surg*. 2015;40(9): 1812−1817.
20. Wu YF, Tang JB. Effects of tension across the tendon repair site on tendon gap and ultimate strength. *J Hand Surg*. 2012;37(5): 906−912.
21. Scherman P, Haddad R, Scougall P, Walsh WR. Cross-sectional area and strength differences of fiberwire, polypropylene, and ticron sutures. *J Hand Surg*. 2010;35(5):780−784.
22. Solla F, Tran A, Bertoncelli D, Musoff C, Bertoncelli CM. Why a P-value is not enough. *Clin Spine Surg*. 2018;31(9):385−388.
23. Seradge H. Elongation of the repair configuration following flexor tendon repair. *J Hand Surg*. 1983;8(2):182−185.
24. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons. An experimental study on the early stages of tendon-healing in dogs. *J Bone Jt Surg Am*. 1999;81(7): 975−982.
25. Torres Fuentes CE, Carvajal Flechas FS, Hernández JA, et al. Helical 6-strand cruciate tenorrhaphy: description of a new technique and biomechanical comparative analysis with 2 standard techniques. *Hand (N Y)*. Published online January 23, 2020. https://doi.org/10.1177/1558944719897132
26. Çolak Ö, Kankaya Y, Sungur N, et al. Barbed sutures versus conventional tenorrhaphy in flexor tendon repair: an ex vivo biomechanical analysis. *Arch Plast Surg*. 2019;46(3):228−234.
27. Lee JS, Wong YR, Tay SC. Asymmetric 6-strand flexor tendon repair—biomechanical analysis using barbed suture. *J Hand Surg Asian-Pac Vol*. 2019;24(3):297−302.
28. Angeles JG, Heminger H, Mass DP. Comparative biomechanical performances of 4-strand core suture repairs for zone II flexor tendon lacerations. *J Hand Surg*. 2002;27(3):508−517.
29. Silva JM, Zhao C, An KN, Zobitz ME, Amadio PC. Gliding resistance and strength of composite sutures in human flexor digitorum profundus tendon repair: an in vitro biomechanical study. *J Hand Surg Am*. 2009;34(1):87−92.

APPENDIX A

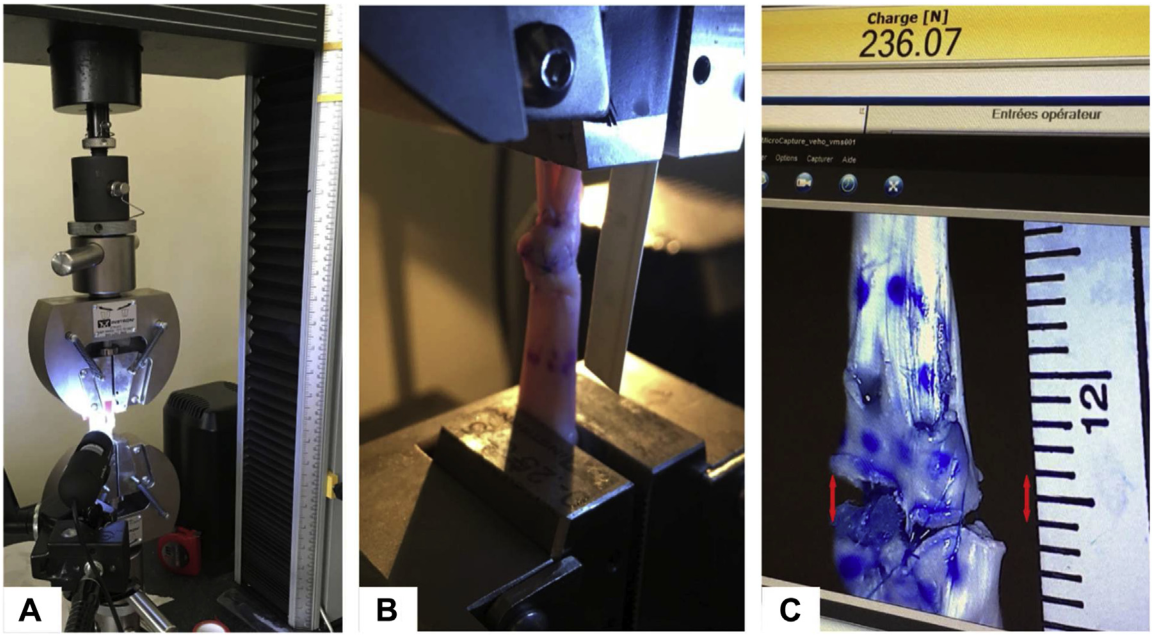

FIGURE E1: Mechanical testing machine. **A** Instron 3360 traction machine. **B** High-definition camera and ruler for the 2-mm gap force. **C** Example of a tendon sutured using the 3D technique. Simultaneous display of the applied load (236 N) and video image of the tendon and ruler measuring 2-mm gap.