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Looped Versus Single-Stranded Flexor Tendon Repairs: A Cadaveric Mechanical Study

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Abstract

Purpose—To compare the tensile properties of 4-strand modified Kessler flexor tendon repairs using a looped or single-stranded suture.

Methods—We evaluated the mechanical properties of 4-strand Kessler zone II core suture repairs using either looped or single-stranded suture in human flexor digitorum profundus and flexor pollicis longus tendons. Forty repairs were performed on tendons from bilateral cadaveric hands: 20 matched tendons were divided into equal groups of 3-0 looped and 3-0 single-strand repairs and 20 additional matched tendons were divided into equal groups of 4-0 looped and 4-0 single-strand repairs. Repaired tendons were tested in uniaxial tension to failure to determine mechanical properties and failure modes. Data were analyzed to determine the effect of repair type (ie, looped vs single-stranded) for each suture caliber (ie, 3-0 and 4-0).

Results—Single-strand repairs with 3-0 suture demonstrated a significantly greater maximum load to failure and a significantly higher force at 2-mm gap compared with repairs with looped 3-0 suture. All 8 looped repairs with 3-0 suture failed by suture pullout whereas 7 of 8 repairs with 3-0 single-stranded suture failed by suture breakage. The mechanical properties of looped versus single-stranded repairs with 4-0 caliber suture were not statistically different. Repairs with 4-0 caliber suture failed by suture breakage in 8 of 10 single-strand repairs and failed by suture pullout in 6 of 10 repairs with looped suture.

Conclusions—In a time-0 *ex vivo* human cadaveric core suture model, the mechanical properties of a 4-strand repair using 3-0 single-stranded suture were significantly better than the same 4-strand repair performed with looped suture.

Clinical relevance—Four-strand flexor tendon repairs with 3-0 suture are mechanically superior when performed with single-strand suture versus looped suture.

Keywords

Flexor tendon; looped; repair; zone II

Debate regarding the ideal method of zone II flexor tendon repair has continued for over 5 decades, with advocates for numerous repair methods and materials aiming to optimize repair strength. To this end, prior investigations tested the mechanical properties of alternative core suture and epitenon suture placement,^{1–6} core suture size,^{7–11} core suture strand number,^{2,10–13} and core suture material.^{14,15} As a result, both higher-caliber suture^{7,8,11} and a greater number of core suture strands^{8,11,13} are known to increase repair site strength.

Although an increased number of core suture strands across the repair site increases repair strength, additional needle passes increase technical complexity and length of surgery. With the advent of looped suture, hand surgeons have been able to increase the number of core suture strands while decreasing in half the number of needle passes needed. However, it is unclear how the tendon—suture interaction is affected when looped suture is used. The ease of performing multistrand repairs using looped sutures may compromise the grasping capacity of a suture within a tendon repair construct.

The purpose of this study was to evaluate the time-0 mechanical properties of 4-strand flexor tendon repairs with looped versus single-stranded sutures. It is possible that a looped suture is preferable because the collagen fibers are better preserved with fewer suture passes and tension on each strand is more evenly distributed owing to simultaneous placement. Alternatively, single-strand repairs may be preferable because the higher number of passes through the tendon would increase tendon—suture interaction, thereby increasing tendon pullout strength. We tested the hypothesis that a single-strand suture repair would have superior mechanical properties compared with a looped suture repair.

MATERIALS AND METHODS

Tendon repairs

Matched fresh human upper limbs (4 pairs) were obtained and all flexor digitorum profundus tendons and flexor pollicis longus tendons were harvested from both hands. The tendons ($n = 40$) were transected using a scalpel in zone II, 40 to 55 mm proximal to the insertion on the distal phalanx. All tendons from a given cadaver remained matched, right versus left. We randomly assigned tendons from the right side to repair by looped or single-stranded suture type. Each matching left-sided tendon was repaired by the alternative suture type to allow for paired statistical comparison. Twenty repairs were completed on matched tendons with 3-0 suture, with 10 repairs for each suture type (looped and single-stranded) and 20 repairs were completed on matched tendons with 4-0 suture caliber (divided between looped and single-stranded suture types). All repairs were 4-strand core suture repairs completed with either single-stranded or looped polyfilament caprolactam (Supramid, S Jackson, Alexandria, VA). Repairs with looped suture used the non-locking modified Kessler technique and repairs with single-stranded suture used the non-locking modified double Kessler technique (Fig. 1). Tendons repaired with looped suture were performed with a core purchase of 10 mm, and single-stranded suture repairs were performed with core purchases of 8 and 12 mm for the 2 Kessler passes (mean, 10 mm). We determined suture purchase depth using calipers (Hayden Medical, Inc, Santa Clarita, CA). To minimize the number of variables affecting the mechanical properties of the repairs, no epitenon repair

was performed. All repairs were performed with the same size tapered needle. All repairs were performed by 2 hand fellowship—trained attending surgeons (R.P.C. and M.I.B.).

Mechanical analysis

Mechanical analysis was performed as described previously.^{10,11} Tendon width and thickness were determined 3 to 8 mm distal to the repair grasping loops using calibrated images and a laser micrometer, respectively. Tendon cross-sectional area was determined assuming an elliptical cross-section. For mechanical testing, we grasped repaired tendons with a custom grip holding the distal phalanx and a triangular-toothed grip holding the proximal stump. Tendons were then tested in uniaxial tension at a strain rate of 0.005/s until failure. Tensile properties and failure mode were recorded for all tendons. We excluded 2 tendons owing to preparation errors. These 2 outliers, both in the 3-0 single-stranded group, and their pairs in the 3-0 looped group were removed from statistical analysis.

Statistical analysis

We used historical data from our laboratory to estimate the sample size required for analysis of tendon repair methods. This power analysis showed that $n = 8/\text{group}$ was required to detect a clinically relevant change in maximum load (30%) between repair groups ($\alpha = .05$; $\beta = .20$). Descriptive statistics were produced to characterize the tendons' cross-sectional areas and mean mechanical properties. Two-sided paired Student t tests were used to determine differences in tendon cross-sectional area and mechanical properties according to suture type (looped vs single-stranded). McNemar exact test was used to analyze for differences in the method of repair failure. No statistical comparisons were made according to suture caliber (3-0 vs 4-0) because these repairs were not performed on matching limbs and thus differences in tendon properties between cadavers could introduce systematic error. Statistical significance was defined as $P < .05$.

RESULTS

Tendon geometry

There was no significant difference in cross-sectional area between tendons repaired with 3-0 looped suture (8.9 ± 2.2 mm) and 3-0 single-stranded suture (8.8 ± 2.1 mm) ($P = .97$) or 4-0 looped suture (8.3 ± 1.6 mm) and 4-0 single-stranded suture (8.8 ± 2.3 mm) ($P = .22$).

3-0 suture comparison: 4-strand looped and single-stranded repairs

The 3-0 looped repairs demonstrated inferior mechanical properties compared with the 3-0 single-stranded repairs: load required to produce a clinically relevant 2-mm gap¹⁶ was decreased ($P = .02$), rigidity (the slope of the load—strain plot) was decreased ($P = .01$), and maximal load to failure was decreased ($P = .04$) (Appendix A [available on the *Journal's* Web site at www.jhandsurg.org], Fig. 2). Failure modes were significantly different between 3-0 looped and 3-0 single-stranded suture, with looped suture failing predominantly by suture pullout compared with single-stranded repairs, which failed by suture breakage ($P = .02$) (Fig. 3).

4-0 suture flexor tendon repair comparison: 4-strand looped and single-stranded repairs

Mechanical properties were not statistically different when comparing looped versus single-stranded repairs with 4-0 caliber suture (Appendix A, available on the *Journal's* Web site at www.jhandsurg.org). Failure modes did not reach significance for 4-0 looped and single-stranded repairs although most looped suture repairs failed by suture pullout and most single-stranded repairs failed by suture breakage (Fig. 3).

DISCUSSION

Our data indicate superior mechanical properties of single-stranded suture repairs compared with looped suture repairs using 3-0 caliber suture at time 0 in human flexor digitorum profundus and flexor pollicis longus tendons. The 3-0 single-stranded repairs failed by suture breakage, whereas 3-0 looped repairs failed predominately by suture pullout. This suggests that looped repairs had weaker tendon—suture interactions than single-strand repairs. This can be explained by noting that each pass with looped suture places 2 strands within the same needle track, thereby creating a smaller interaction area between suture and tendon than 2 single strands passed individually. These data indicate that single-strand repairs may prove mechanically advantageous because the increased number of passes through the tendon increases tendon—suture interaction and increases tendon pullout strength. In this investigation, the diminished tendon—suture interaction inherent in the looped suture outweighed any mechanical benefit of having core suture strands with more evenly distributed tension than those placed with single-strand suture. Thus, if a tendon will accept 3-0 suture, the additional time to complete a 4-strand repair with single-stranded suture is mechanically beneficial at time 0.

The mechanical benefit of using single-strand suture for 3-0 caliber suture repairs was lost when 4-0 caliber suture repairs were performed. The 4-0 looped repairs failed by suture rupture in 40% of instances. The force required for pullout was not significantly different from that required to rupture 4-0 suture. Therefore, the difference in the method of repair failure that was evident in 3-0 caliber repair according to suture type was obscured in 4-0 caliber repairs.

Brockardt et al¹⁷ suggested the mechanical superiority of single-stranded repairs with 3-0 caliber suture. Using porcine tendons, they tested the *ex vivo* mechanical properties of a 4-strand Kessler repair using looped suture versus a 4-strand repair using single-stranded suture in a double Kessler fashion. They found that looped suture repairs with 3-0 polyfilament caprolactam and with 4-0 FiberWire (Arthrex, Naples, FL) were each significantly weaker at force to 2-mm gap compared with corresponding repairs with single-stranded suture. However, maximum load at failure was not significantly different between the looped and single-stranded repairs with polyfilament caprolactam. They did not report the mode of repair failure (suture pullout vs suture breakage). This discrepancy with our load to failure results may be attributed to the use by Brockardt et al use of locking loops, or to differences in porcine versus human tendons.

Cao and Tang¹⁸ also studied porcine tendon repairs to analyze the mechanical properties of 4-strand repairs using a double Kessler with 4-0 nylon, modified Tang repair with

polyfilament caprolactam, and looped repair with polyfilament caprolactam. They found superior force to 2-mm gap and superior force to ultimate failure gap for each of their looped suture repairs compared with the double Kessler repairs, which was not consistent with our data or those of Brockardt et al.¹⁷ They therefore recommended 4-stranded repairs using a looped suture over single-stranded repairs. They did not discuss the mode of failure and the core suture purchase distance. We suspect that locking passes using the looped suture and a non-locking configuration for their single-strand repairs may explain the discrepancy between their data and ours.

Netscher et al¹⁹ investigated the knot strength of looped versus single-strand suture. They found that looped suture knots were weaker than knots in single-strand suture for both 3-0 and 4-0 suture. They postulated that the difference was related to the knot bulk and variable compression of suture within the knots. In their experimental model, single knots, as opposed to double knots, would optimize strength in a simulated repair. Their data raise another concern regarding the use of looped suture at 4-strand strength. Our data indicate that when tendons are repaired, weakened tendon—suture interaction produced by looped suture may compromise repair strength before knot strength is fully tested.

Our study had several limitations. We elected not to perform circumferential epitendinous suturing of the repair because non-identical placement of the additional suture could influence results. This study was an *ex vivo* investigation and only provided time-0 data. Mechanical differences between repair techniques in this study did not account for the changes at the repair sites during the healing process. In addition, repairs in cadaveric tendons that have been removed from the fibroosseous pulley system repairs are not subject to the surface friction imparted by the intact sheath encountered during clinical rehabilitation. Two surgeons performed all tendon repairs and no measurement of surgeon effect was evaluated. Both surgeons (R.P.C. and M.I.B.) were experienced in flexor tendon repair, were hand fellowship—trained, and fixed equal numbers of tendons in each group. We could not predict the mechanical impact of looped versus single-stranded repairs using alternative suture configurations or with increased number of core suture strands. Alternative core suture configurations and locking suture passes may mitigate the weaker tendon—suture interaction associated with the use of looped suture. Finally, the study design, which used paired tendons to compare single and looped repairs, was not appropriate to directly compare the mechanical properties of 3-0 and 4-0 repairs because of potential inter-cadaveric differences.

Not every flexor tendon laceration is amenable to the same core repair technique. Tendon quality, size, and associated injuries all affect the surgeon's approach to the placement of core suture. The use of looped suture enables tendon repairs with fewer knots and half the number of needle passes to achieve the same core repair compared with single-strand suture. With some multistrand repair techniques, such as an 8-strand repair, a looped suture is necessary to make the repair feasible. However, a 4-strand repair can be accomplished with either looped or single-stranded suture. Based on time-0 *ex vivo* biomechanical data of the current study, we postulate that if an injured tendon can accommodate a 3-0 suture, the strength of 4-strand repairs at time 0 is optimized when using single-stranded suture as opposed to looped suture.

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APPENDIX A. Mechanical Properties of Single-Stranded Versus Looped Repairs

	Gap at 20 N, mm	Gap at Maximum Load, mm	Stiffness (N/mm)	Load at 2-mm Gap, N	Maximum Load, N	Rigidity, N
3-0 single-stranded mean	3.2 ± 0.7	7.5 ± 1.4	7.8 ± 2.5	16 ± 4	48 ± 13	1.2 ± 0.4
3-0 looped mean	6.2 ± 1.4	14 ± 4.2	5.1 ± 1.6	9 ± 4	34 ± 9	0.8 ± 0.2
3-0 suture-paired means difference*	-3.0 ± 1.8 (<i>P</i> < .01)	-6.2 ± 4.1 (<i>P</i> < .01)	2.7 ± 2.3 (<i>P</i> = .14)	7 ± 7 (<i>P</i> = .02)	14 ± 16 (<i>P</i> = .04)	0.4 ± 3.5 (<i>P</i> = .01)
4-0 single-stranded mean	3.6 ± 0.9	8.8 ± 3.6	8.5 ± 8.1	15 ± 4	42 ± 17	1.3 ± 1.2
4-0 looped mean	4.4 ± 1.3	8.6 ± 2.6	5.5 ± 1.2	17 ± 8	31 ± 7	1.0 ± 0.2
4-0 suture-paired means difference*	-0.8 ± 2.0 (<i>P</i> = .25)	0.3 ± 4.3 (<i>P</i> = .86)	2.9 ± 8.5 (<i>P</i> = .30)	-3 ± 11 (<i>P</i> = .42)	11 ± 20 (<i>P</i> = .13)	0.3 ± 1.2 (<i>P</i> = .39)

* Means differences shown are single-stranded minus looped. Standard deviations of means are unpaired SDs. Standard deviations of means difference are SDs of the difference within pairs.

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FIGURE 1.

Repair techniques used in the study. **A** Single-stranded repair with the nonlocking modified double Kessler. **B** Looped repair with the nonlocking modified Kessler.

FIGURE 2.

Load at 2-mm gap, maximum load, and rigidity were significantly increased in the 3-0 single-stranded repairs compared with the 3-0 looped repairs.

FIGURE 3.

The failure mode was significantly different between 3-0 single-stranded repairs and 3-0 looped repairs. There was no significant difference in failure mode between 4-0 single-stranded repairs and 4-0 looped repairs.