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The Effect of Suture Preloading on the Force to Failure and Gap Formation After Flexor Tendon Repair

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Abstract

Purpose—Gap formation is a common and severe complication after flexor tendon repair that can affect the outcome and prolong tendon healing. The purpose of this study was to investigate the effect that a pretensional force applied to the suture during tendon repair has on the repair strength and force that causes gap formation.

Methods—We used a total of 48 flexor digitorum profundus tendons from 12 human cadaver hands. We employed a core tendon suture, using the modified Pennington technique, and a running suture for flexor tendon repair. Before tying the knots of the core suture, we preloaded the sutures in each tendon end 0, 5, 10, or 15 N for 10 seconds to compare the effect of loading magnitude on repaired tendon peak force to failure and force causing gap formation.

Results—The force to form a gap of 2 mm in the 15-N preload group was significantly increased compared with the 0-N and 5-N preload groups. At the 3-mm gap formation, the force of all preload groups was significantly higher than the nonpreload group. The peak force with a preload of 10 N and 15 N was significantly higher than 0-N preload.

Conclusions—These findings suggest that pretensioning with 10 to 15 N at the suture–tendon interface before tying the knot has a beneficial effect on both the tendon gap formation and the peak force to failure.

Clinical relevance—When the surgeons perform tendon repair, pretensioning at the suture–tendon conjunction will increase the repair strength.

Keywords

Gap formation; flexor tendon repair; biomechanics; human cadaver; suture preloading

FLEXOR TENDON INJURIES are particularly common among young, active people, can take several months to heal, and often result in loss of motion.¹ In past decades, much research has been performed attempting to optimize the outcome. This has led to the consensus of using nonabsorbable 3-0 or 4-0 core suture material for flexor tendon repairs and finishing with a running epitendinous repair.²⁻⁶ After flexor tendon repair, early mobilization leads to less adhesion formation and better clinical results.⁷⁻⁹

Increasing the number of suture strands crossing the repair site increases strength and resistance to gap formation.^{10,11} Also, using higher-strength suture techniques decreases the rate of tendon repair failure.¹¹⁻¹³ Despite these improvements in suture techniques, gap formation remains a common and severe complication after flexor tendon repair that can affect the outcome and complicate tendon healing and motion recovery.¹⁴⁻¹⁶ Several authors have stated that tendon gaps up to 10 mm after repair still lead to good results clinically.^{14,16} In contrast, Seradge¹⁷ found that the result of tenolysis after flexor tendon repair was correlated with the magnitude of gap formation, starting from 1 mm of gap. In an experimental canine model, Gelberman et al¹⁵ showed poor results after flexor tendon repair when the gap reached 3 mm. Zhao et al¹⁸ stated that the gliding resistance increased significantly starting from a 2-mm gap and that a gap of 3 mm can cause a repaired tendon to fail to glide or to rupture owing to catching on the pulley edge. The limitation of tendon motion could lead to adhesion formation, consistent with the observation¹⁷ that tenolysis was correlated with the magnitude of gap formation.

Based on our clinical and experimental experiences, the weakness of the suture–tendon interface could be strengthened by applying tension before completing the suture knots. Clinical advice for tendon suture includes tensioning sufficient to eliminate gapping, while avoiding tightening too much and causing the repair to bunch.^{19,20} Thus, we thought that some attempt to quantify a sufficient amount of tensioning would be clinically useful. Therefore, the purpose of this study was to investigate the effect of a pretension force applied to the suture during tendon repair on the repair strength and gap formation. We hypothesized that applying a preload before flexor tendon repair would reduce the gap formation postoperatively.

MATERIALS AND METHODS

We used a total of 48 flexor digitorum profundus tendons from 12 human cadaver hands, including 9 male and 3 female, after we obtained institutional review board approval. The average age of the cadavers was 72 years (range, 40–98 y). We dissected the tendons and cut them 50 mm proximal to their insertion. We introduced a core tendon suture (coated, braided polyester, Ethibond 3-0; Ethicon, Somerville, NJ) into the proximal and distal tendon ends separately using the modified Pennington looping technique.^{21,22} We placed all core suture loops 1 cm from the ends of the tendons. The sutures in each tendon end were loaded by hanging a weight, calibrated in newtons, for 10 seconds, and then we connected the 2 tendon ends using a 2-strand overhand knot plus 2 square knots (2-strand overhand locking) to avoid knot unraveling. All core suture knots were located between the tendon ends.

Subsequently, we applied a circumferential running suture (monofilament polypropylene, Prolene 6-0; Ethicon) around the edge of the coaptation site (Fig. 1). The running suture throws were approximately 2 mm from the ends of the tendons. We tied the running suture knots with 4 square knots. The same surgeon performed all repairs to improve consistency of the repair technique.

In the first part of the pilot study, we progressively loaded the core suture, in a single tendon end, from 0 to 35 N, with steps of 5 N. The data showed that the core suture slippage mostly occurred between 0 and 15 N. This is why we selected 4 different loads, 0, 5, 10, and 15 N, to compare the effects of loading magnitude before tying the knots.

After repair, we mounted the tendon on a servohydraulic testing machine (MTS Systems, Eden Prairie, MN). The specimens were gripped 5 mm above and 5 mm below the core suture. We attached a displacement sensor (DVRT; Microstrain, Williston, VT) at the repair

site to measure gap formation during testing. The tendons were distracted at a rate of 20 mm/min until the repair site had completely ruptured. We collected force, actuator displacement, and DVRT displacement data at a sample rate of 20 Hz. Tendons were kept moist throughout testing with a saline mist. We compared the ultimate force to failure and measured gap formation for different amounts of tension load.

Statistics

We calculated sample size using an effect size approach. A sample size of 12 per group provided 80% power to detect an effect size of 0.9 or larger when comparing any 2 of the 4 preload groups, based on a paired *t*-test with an alpha of 0.05, 2-sided.

Outcomes analyzed included force at gaps of 1, 2, and 3 mm; the peak force to failure; and the gap at peak force. We performed separate analyses for each measure. Each of the 12 cadavers contributed 3 flexor digitorum profundus tendons and 1 flexor pollicis longus tendon to the experiment, with each digit being randomly allocated to 1 of the 4 different preload groups. The randomization was balanced in such a way that each preload group contained 3 specimens from each of the 5 digits, so as not to confound digit type with experimental preload group. Therefore, we analyzed each outcome using a 1-way repeated-measures analysis of variance to evaluate the association of the amount of suture preload with the outcome. We analyzed significant results further using the Ryan-Einot-Gabriel-Welsch multiple comparisons procedure. All statistical tests were 2-sided, and *P* values less than .050 were considered statistically significant.

RESULTS

We observed that in general, gap formation initiated before pullout or breakage of the running suture. In all the tendon repairs, failure occurred by breakage of the core suture. We observed no suture pullout in any of the repairs. Table 1 shows the results of tendon repair testing. There was no significant difference in force to form a 1-mm gap among preload groups ($P = .450$). The force at 2-mm gap in the 15-N preload group was significantly higher than that in 5- and 0-N preload groups ($P = .005$). There was no significant difference in the force to form a 2-mm gap between 15- and 10-N groups and between 0- and 5-N groups (Fig. 2). At 3-mm gap formation, the force in 15-, 10-, and 5-N preload groups was significantly higher than the force in the 0-N preload group ($P = .002$). However, there was no significant difference in force to form a 3-mm gap among 15-, 10-, and 5-N groups (Fig. 3).

The peak force to failure in the 15-N preload group was significantly higher than that in 5- and 0-N preload groups ($P < .001$). The peak force to failure in the 10-N preload group was significantly higher than the 0-N preload group ($P < .001$). There was no significant difference in peak force between 15- and 10-N preload groups and between 0- and 5-N preload groups (Fig. 4). For the gap formation at peak force, there was no significant difference between preload groups ($P = .410$).

DISCUSSION

Strong flexor tendon repair has always been considered seriously by hand surgeons because the repair rupture or gap formation may lead to a repair failure. The strategies to improve repair strength have been well studied in many aspects, including multiple strands repair techniques, tendon-suture locking configurations, and suture size and material.^{10-13,21,23-25} The purpose of the current study was to investigate the effects of pretension at the suture-tendon interface on the repair mechanical properties. Surgeons are aware that knots should be tied snugly, of course. However, especially with tendon suture, there is a fine line

between too much slack, which leads to gapping, and too little, which leads to bunching of the repair. Until now, surgeons have not had quantitative guidelines as to how snugly to pull on the sutures to take up the slack and equalize the tension on the strands of the repair. Here, we quantify an amount of tension that is sufficient to take up the slack while not being as tight as possible. Our results demonstrated that the pretension should be over 10 N to achieve the optimal effect on repair failure strength and resistance to gap formation. In contrast, less than 5 N pretension was not effective. The reported strength to failure and force to form a gap for the 0-N preload tendons was similar to findings in previous published articles using the same repair technique²³⁻²⁵ and materials.²³

The mechanism by which preloading improves peak force to failure is unclear. We do not believe that preloading increases the underlying strength of the suture material. Instead, we believe that it is most likely that preloading helps to even the load on the suture strands, so that they share the applied load more evenly.

A surgical device could be developed consisting of a clamp connected to a load cell, similar in concept to a fish scale. This device would make it possible to preload the core sutures in each tendon end precisely before knotting.

We chose coated, braided polyester suture (Ethibond) instead of braided polyester–monofilament polyethylene composite suture (FiberWire; Arthrex, Naples, FL) because the coated, braided polyester suture showed less slippage compared with the braided polyester–monofilament polyethylene composite suture in a pilot study. Miller²⁶ stated that the braided polyester–monofilament polyethylene composite suture was significantly stronger than the coated, braided polyester suture when used in a locked flexor tendon suture repair technique, but Silva et al²³ could not confirm the superior effect of the braided polyester–monofilament polyethylene composite suture.

We repaired all tendons using a modified Pennington core suture technique.^{21,22} The reason for choosing the Pennington repair was based on previous publications showing that this repair has relatively high strength and lower frictional force.^{24,27} This locking technique consists of 2 longitudinal components, 2 vertical components, and 1 transverse component. A portion of the longitudinal component passes outside the tendon to make sure that the vertical components are placed behind the transverse component, which consistently ensures a locking loop. We do not believe that the knotting technique we used influenced the test results, because we repaired the tendons in both preload and no-load groups with the same knot.

There are several limitations to this study that are inherent in most cadaveric biomechanical studies. First, we did not conduct cyclic stress testing. Repairs would be subjected to cyclic loading *in vivo*, and the linear load to failure may not mimic physiologic conditions as closely as a cyclic loading protocol.²⁸⁻³⁰ We did not cyclically precondition the tendons before testing because we thought that the cyclic preconditioning might add an effect similar to the preload in the control tendons. Also, we did not consider the effects of tendon healing and adhesion formation over time in this biomechanical study. Second, aside from the effect of the pretension on repair strength, we did not test whether the pretension altered the repaired tendon gliding capability. We tested only 1 repair technique with 1 suture material. It is possible that different repair techniques or suture materials might have had different responses to the pretension mechanism. We also pretensioned up to 15 N. Therefore, we do not know whether pretension loads larger than 15 N would have had an even greater effect. Finally, although we attempted to make the core suture knots with similar tension in every repair, ultimately the core suture knots were handmade and may

have varied slightly from tendon to tendon. However, we believe that these effects should be random and not affect one repair type more than another.

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REFERENCES

1. Kelsey, JL. Injuries. In: Praemer, A., editor. *Upper Extremity Disorders: Frequency, Impact, and Cost*. Churchill Livingstone; New York, NY: 1997. p. 9-16.
2. Cetin A, Dincer F, Kecik A, Cetin M. Rehabilitation of flexor tendon injuries by use of a combined regimen of modified Kleinert and modified Duran techniques. *Am J Phys Med Rehabil*. 2001; 80(10):721–728. [PubMed: 11562553]
3. Elliot D. Primary flexor tendon repair—operative repair, pulley management and rehabilitation. *J Hand Surg Br*. 2002; 27(6):507–513. [PubMed: 12475505]
4. Golash A, Kay A, Warner JG, Peck F, Watson JS, Lees VC. Efficacy of ADCON-T/N after primary flexor tendon repair in Zone II: a controlled clinical trial. *J Hand Surg Br*. 2003; 28(2):113–115. [PubMed: 12631480]
5. Miller B, Dodds SD, deMars A, Zagoreas N, Waitayawinyu T, Trumble TE. Flexor tendon repairs: the impact of fiberwire on grasping and locking core sutures. *J Hand Surg Am*. 2007; 32(5):591–596. [PubMed: 17481994]
6. Helm R. The management of flexor tendon injuries in zone II. *Curr Orthop*. 2002; 16(6):434–444.
7. Lister GD, Kleinert HE, Kutz JE, Atasoy E. Primary flexor tendon repair followed by immediate controlled mobilization. *J Hand Surg Am*. 1977; 2(6):441–451. [PubMed: 336675]
8. Silfverskiöld KL, May EJ. Flexor tendon repair in zone II with a new suture technique and an early mobilization program combining passive and active flexion. *J Hand Surg Am*. 1994; 19(1):53–60. [PubMed: 8169369]
9. Strickland JW. Flexor tendon surgery, part 1: primary flexor tendon repair. *J Hand Surg Br*. 1989; 14(3):261–272. [PubMed: 2677186]
10. Viinikainen A, Goransson H, Huovinen K, Kellomäki M, Rokkanen P. A comparative analysis of the biomechanical behaviour of five flexor tendon core sutures. *J Hand Surg Br*. 2004; 29(6):536–543. [PubMed: 15542212]
11. Winters SC, Gelberman RH, Woo SL, Chan SS, Grewal R, Seiler JG III. The effects of multiple-strand suture methods on the strength and excursion of repaired intrasynovial flexor tendons: a biomechanical study in dogs. *J Hand Surg Am*. 1998; 23(1):97–104. [PubMed: 9523962]
12. Lee H. Double loop locking suture: a technique of tendon repair for early active mobilization, part II: clinical experience. *J Hand Surg Am*. 1990; 15(6):953–958. [PubMed: 2269790]
13. McLarney E, Hoffman H, Wolfe SW. Biomechanical analysis of the cruciate four-strand flexor tendon repair. *J Hand Surg Am*. 1999; 24(2):295–301. [PubMed: 10194013]
14. Ejekkar A, Irstam L. Elongation in profundus tendon repair: a clinical and radiological study. *Scand J Plast Reconstr Surg*. 1981; 15(1):61–68. [PubMed: 7022619]
15. 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 Joint Surg Am*. 1999; 81(7):975–982. [PubMed: 10428129]
16. Silfverskiöld KL, May EJ, Tornvall AH. Gap formation during controlled motion after flexor tendon repair in zone II: a prospective clinical study. *J Hand Surg Am*. 1992; 17(3):539–546. [PubMed: 1613237]
17. Seradge H. Elongation of the repair configuration following flexor tendon repair. *J Hand Surg Am*. 1983; 8(2):182–185. [PubMed: 6339603]
18. Zhao C, Amadio PC, Tanaka T, Kutsumi K, Tsubone T, Zobitz ME, et al. Effect of gap size on gliding resistance after flexor tendon repair. *J Bone Joint Surg Am*. 2004; 86(11):2482–2488. [PubMed: 15523022]

19. Strickland JW. Flexor tendon injuries, I: foundations of treatment. *J Am Acad Orthop Surg.* 1995; 3(1):44–54. [PubMed: 10790652]
20. Boyer M, Strickland JW, Engles D, Sachar K, Leversedge F. Flexor tendon repair and rehabilitation: state of the art in 2002. *Instr Course Lect.* 2003; (52):137–161. [PubMed: 12690845]
21. Hatanaka H, Manske PR. Effect of suture size on locking and grasping flexor tendon repair techniques. *Clin Orthop Relat Res.* 2000; (375):267–274. [PubMed: 10853178]
22. Hatanaka H, Zhang J, Manske PR. An in vivo study of locking and grasping techniques using a passive mobilization protocol in experimental animals. *J Hand Surg Am.* 2000; 25(2):260–269. [PubMed: 10722817]
23. 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. [PubMed: 19121735]
24. Tanaka T, Amadio PC, Zhao C, Zobitz ME, Yang C, An KN. Gliding characteristics and gap formation for locking and grasping tendon repairs: a biomechanical study in a human cadaver model. *J Hand Surg Am.* 2004; 29(1):6–14. [PubMed: 14751096]
25. Waitayawinyu T, Martineau PA, Luria S, Hanel DP, Trumble TE. Comparative biomechanic study of flexor tendon repair using FiberWire. *J Hand Surg Am.* 2008; 33(5):701–708. [PubMed: 18590853]
26. Miller RC. Flexor tendon repair over the proximal phalanx. *Am J Surg.* 1971; 122(3):319–324. [PubMed: 4255105]
27. Zhao C, Sun YL, Kirk RL, Thoreson AR, Jay GD, Moran SL, et al. Effects of a lubricin-containing compound on the results of flexor tendon repair in a canine model in vivo. *J Bone Joint Surg Am.* 2010; 92(6):1453–1461. [PubMed: 20516321]
28. Barrie KA, Tomak SL, Cholewicki J, Wolfe SW. The role of multiple strands and locking sutures on gap formation of flexor tendon repairs during cyclical loading. *J Hand Surg Am.* 2000; 25(4): 714–720. [PubMed: 10913213]
29. Choueka J, Heminger H, Mass DP. Cyclical testing of zone II flexor tendon repairs. *J Hand Surg Am.* 2000; 25(4):1127–1134. [PubMed: 11119674]
30. Pruitt DL, Manske PR, Fink B. Cyclic stress analysis of flexor tendon repair. *J Hand Surg Am.* 1991; 16(4):701–707. [PubMed: 1880369]

FIGURE 1.

Different steps of tendon repair: (1) placing core suture; (2) preloading the core suture with a dead weight; (3) connecting the 2 tendon ends by tying the suture; and (4) applying a circumferential running suture.

FIGURE 2.

Comparison of force at 2-mm tendon gap among different preload groups. X-axis, different preload groups. Y-axis, force at 2-mm tendon gap. Horizontal lines represent significant differences among preload groups.

FIGURE 3.

Comparison of force at 3-mm tendon gap among different preload groups. X-axis, different preload groups. Y-axis, force at 3-mm tendon gap. Horizontal lines represent significant differences among preload groups.

FIGURE 4.

Comparison of peak force among different preload groups. X-axis, different preload groups. Y-axis, peak force. Horizontal lines represent significant differences among preload groups.

TABLE 1

Means of Force and Gap by Suture Preload

	0 N Preload	5 N Preload	10 N Preload	15 N Preload
Force at 1 mm	36.8 N (SD, 11.7)	30.5 N (SD, 16.2)	36.1 N (SD, 11.2)	40.0 N (SD, 16.6)
Force at 2 mm	44.3 N (SD, 14.6)	46.9 N (SD, 8.0)	53.5 N (SD, 13.5)	58.0 N (SD, 14.5)
Force at 3 mm	35.1 N (SD, 14.5)	44.4 N (SD, 14.6)	49.0 N (SD, 15.7)	47.7 N (SD, 13.0)
Peak force	52.6 N (SD, 11.2)	55.2 N (SD, 12.9)	61.0 N (SD, 14.2)	65.9 N (SD, 12.2)
Gap at peak force	1.7 mm (SD, 0.6)	2.1 mm (SD, 0.6)	2.0 mm (SD, 0.8)	2.1 mm (SD, 0.9)