

Mechanical Properties of the Flexor Digitorum Profundus Tendon Attachment

Jerrold J. Felder · Loredana M. Guseila ·
Archana Saranathan · Timothy J. Shary ·
Steven B. Lippitt · John J. Elias

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Abstract The current study was performed to determine the strength and rigidity of the intact flexor digitorum profundus (FDP) tendon attachment and compare the rigidity at the attachment site to the rigidity within a more proximal part of the tendon. Eight cadaveric index fingers were tested to failure of the FDP tendon. Lines were drawn on each tendon with India ink stain at the position of the attachment to bone and 5 mm and 10 mm proximally. Each test was recorded using a high resolution video camera. A minimum of six images per test were used for analysis of tissue deformation. The centroid of each line was computationally identified to characterize the deformation of the tendon between the lines. Force vs. deformation curves were generated for the 5 mm region representing the tendon attachment and the 5 mm region adjacent to the attachment. Stiffness measurements were generated for each curve, and normalized by the initial length to determine the rigidity. The failure strength ranged from 263 N to 548 N, with rigidity values ranging from 2201 N/(mm/mm) to 8714 N/(mm/mm) and from 3459 N/(mm/mm) to 6414 N/(mm/mm) for the attachment and the tendon proximal to the attachment, respectively. The rigidity did not vary significantly between the attachment and proximal tendon based on a Wilcoxon signed rank test ($p=0.2$). The measured strength and rigidity establish biomechanical properties for the FDP tendon attachment to bone.

Keywords Flexor digitorum profundus tendon · Tendon attachment · Stiffness · Strength

Introduction

Distal avulsions of the flexor digitorum profundus (FDP) tendon from the distal phalanx typically require surgical fixation of the tendon to bone to restore function. The goal of the repair is to provide sufficient strength to withstand the forces generated during postoperative rehabilitation without allowing excessive deformation [1] that can hinder tendon to bone healing [2] and contribute to reduced post-operative range of motion [3]. In vitro biomechanical testing studies have been performed to evaluate repairs using the pull-out suture technique and bone anchors, with average strength values ranging from approximately 30 to 100 N [1–9], compared to 400 N or larger for the intact tendon [10, 11]. Forces generated to induce flexion without resistance are on the order of 20 N but can exceed 100 N during pinching [12], indicating that passive motion should be emphasized during rehabilitation. Reported values of rigidity at the repaired attachment site, which is the stiffness normalized by the initial length, have ranged from approximately 100 to nearly 750 N/(mm/mm) [1, 2, 7–9, 13]. No comparative data on the rigidity at the intact attachment has been published previously.

The current study was performed to characterize the strength and rigidity of the intact FDP tendon attachment. At the direct tendon to bone insertion, the composition of the tissue changes from tendon to fibrocartilage, calcified fibrocartilage and bone [9, 14]. Because of the change in composition, rigidity was evaluated directly at the insertion site and more proximally in the tendon. Previous studies with small animal models have shown that the stiffness tends to be lower at the attachment than within the midsubstance of a tendon [15, 16].

Methods

The mechanical characteristics of the FDP tendon attachment were examined in a group of eight cadaveric index fingers of unpaired hands. Data from a ninth finger was

J. J. Felder · L. M. Guseila · A. Saranathan · T. J. Shary ·
S. B. Lippitt · J. J. Elias
Department of Orthopaedic Surgery, Akron General Medical
Center, Akron, OH, USA

J. J. Elias (✉)
Calhoun Research Laboratory, Akron General Medical Center,
400 Wabash Avenue, Akron, OH 44307, USA
e-mail: john.elias@akrongeneral.org

discarded after the tendon slipped from the fixation without failing. The age of the donors ranged from 35 to 92 years, with a mean of 77 years. Six of the donors were female. The specimens were stored frozen and thawed for dissection. All soft tissues surrounding the tendon were removed, including the pulleys, without disturbing the tendon insertion at the distal phalanx. The finger was disarticulated at the metacarpophalangeal joint.

Failure tests were performed using a loading protocol adapted from previous studies [1, 2, 8]. The fingers were secured to a testing stand on a material testing system (8511, Instron, Canton, MA), with the distal phalanx at the base (Fig. 1). The proximal and middle phalanges were secured to the stand with screws, with a zip tie distal to the tendon insertion providing nondestructive resistance to flexion. The tendon was fixed in a clamp coated with sandpaper and preconditioned to 5 N for 5 cycles, followed by loading to failure at 0.5 % strain/s. Applied force was recorded at 2 Hz using a load cell with a maximum capacity of 1000 N (Interface, Scottsdale, AZ). The force at failure was the largest force recorded by the actuator.

Deformation at the attachment site was characterized using a video-analysis system [15–17]. Horizontal reference lines were drawn on the tendon with India ink stain at the approximate bone-tendon interface and at 5 mm intervals along the tendon. Tests to failure were recorded at 30 frames/s with a resolution of 1920×1080p (HDC-TM90

video camera, Panasonic). Six to ten images from the onset of loading to the frame before failure were captured from each video. A ruler fixed to the testing stand provided a scale for the recorded images. The analysis focused on two 5 mm regions defined by the lines. One region included the tendon within 5 mm of the attachment site, with the second adjacent and proximal to the first (Fig. 1). Final determination of the line on the tendon closest to the attachment site was based on post-testing analysis of the video and the specimen. The horizontal lines on each image were traced and darkened, and the background was filtered, leaving just the lines (ImageJ, National Institutes of Health). The position of the centroid was quantified for each line. The vertical distance between the centroids was quantified to determine the initial length and the deformation as the load increased. A sharp drop in the applied force was synchronized with an image of a clean break at the attachment site to set the time scale for the applied force and tissue deformation. The rigidity was determined from a linear regression including all points on the force vs. displacement curve, with the displacement normalized by the initial distance between the lines on the tendon. The square of the correlation coefficient (r^2) was quantified to determine the strength of each linear relationship. Rigidity was compared between the interface and the tendon just proximal to the interface using a non-parametric Wilcoxon signed rank test (SPSS Statistics, IBM).

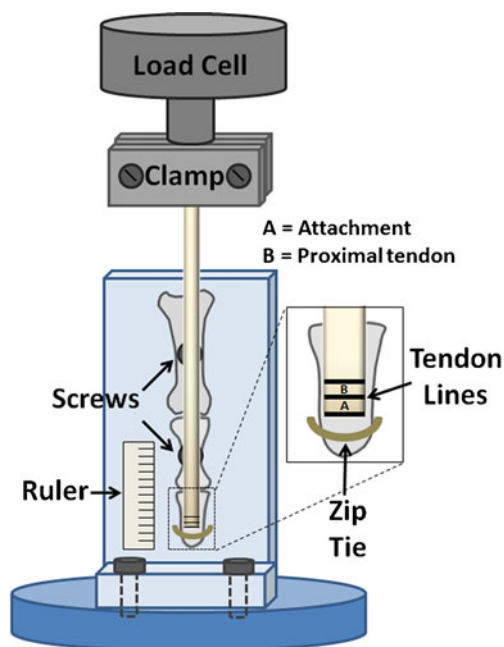


Fig. 1 Schematic diagram of the experimental set-up. The finger is oriented with the distal phalanx closest to the base of the testing frame. Screws constrain the middle and proximal phalanges, while flexion of the distal phalanx is prevented with a zip tie. The lines drawn on the tendon are used to characterize deformation at the attachment site and within a region just proximal to the attachment from a high resolution video recording of the test to failure

Results

Seven of the tendons failed through an avulsion fracture, while one failed within the tendon. For the avulsion fractures, the tendon pulled a piece of bone from the distal phalanx. The failure through the tendon occurred within 5 mm of the attachment point. The failure strength ranged from 263 N to 548 N for the specimens, with a strength of 404 N for the specimen that failed within the tendon (Table 1).

The rigidity was similar for the attachment site and the proximal tendon. The rigidity values were within a range from 2201 N/(mm/mm) to 8714 N/(mm/mm) and from 3459 N/(mm/mm) to 6414 N/(mm/mm) for the attachment and the tendon proximal to the attachment, respectively. The values were not significantly different ($p=0.2$). For both regions, the applied force increased approximately linearly with deformation (Fig. 2). The value of r^2 for both regression lines was greater than 0.87 for all specimens.

Discussion

The strength and rigidity of the intact FDP tendon attachment are substantially larger than values reported following repair. The average strength for the intact attachment was

Table 1 Properties of the intact FDP tendon attachment for each specimen tested, with rigidity quantified within 5 mm of the attachment and 5 mm more proximally within the tendon

Age/Gender	Failure Mode	Failure Strength	Attachment Rigidity	Tendon Rigidity
72/Female	Avulsion	263 N	3405 N/(mm/mm)	3459 N/(mm/mm)
87/Female	Avulsion	294 N	2201 N/(mm/mm)	5197 N/(mm/mm)
92/Female	Avulsion	297 N	2760 N/(mm/mm)	4293 N/(mm/mm)
86/Female	Tendon	404 N	8714 N/(mm/mm)	5883 N/(mm/mm)
80/Male	Avulsion	447 N	4362 N/(mm/mm)	4218 N/(mm/mm)
82/Male	Avulsion	473 N	4220 N/(mm/mm)	6169 N/(mm/mm)
82/Female	Avulsion	474 N	3585 N/(mm/mm)	4574 N/(mm/mm)
35/Female	Avulsion	548 N	6013 N/(mm/mm)	6414 N/(mm/mm)

400 N for the current study, compared to values less than 100 N reported for repairs [1, 2, 4, 7–9, 13]. Previous studies have secured the distal phalanx within a fixture to characterize the strength of the intact attachment, with average strength values of 387 N and 558 N [10, 11]. The current set-up retained the articulation at the distal interphalangeal joint and constrained flexion with an external resistance to represent the loading condition that produces injury through forced hyperextension as the finger is flexing [18]. Failure occurred at the tendon attachment, primarily with avulsion of bone, similar to the injury commonly noted clinically [18]. The current data confirms the weakened state of the repaired flexor tendon attachment, and the necessity of limiting tendon loading during rehabilitation. Forces generated to induce flexion without resistance are on the order of 20 N, but can exceed 100 N during pinching [12]. The average rigidity for the intact attachment was 4,400 N/(mm/mm) for the current study, compared to

previously reported values of less than 750 N/(mm/mm) following repair [1, 2, 4, 7–9, 13]. The previous studies that characterized the strength of the intact tendon attachment did not measure rigidity. The current results reinforce the belief that insufficient rigidity of the repaired flexor tendon attachment can hinder healing and post-operative function [8].

The study did not identify a difference in rigidity between the attachment and the tendon just proximal to the attachment. At the attachment, the composition of the tissue transitions from tendon to fibrocartilage, calcified fibrocartilage and bone [14]. Previous studies have reported more disorganized collagen fibers and lower stiffness values at the attachment site compared to tendon midsubstance in small animal models [15, 16]. Based on a power analysis of the current data, for a power of 0.9, approximately 90 specimens would be needed to identify a significantly lower rigidity at the attachment than within the proximal tendon. Not finding a difference for the current study may be related to evaluating two adjacent regions rather than evaluating a more proximal region within the tendon. The force vs. deformation curves for both regions showed slightly reduced stiffness at the onset of testing (Fig. 2). The reduced stiffness at the onset of testing may be due to uncrimping of collagen fibers [15].

Limitations of the current study include the loading rate, the age of the specimens and testing only index fingers. A higher loading rate more representative of in vivo injury would be expected to produce a larger strength and stiffness for the FDP tendon attachment based on previous studies focused on bone [19], ligaments that fail through bone avulsion [20], and repaired tendons [21]. Based on previous data focused on the anterior cruciate ligament [22, 23], testing specimens from younger donors would likely have also increased the measured strength and rigidity. Previous studies focused on the strength of repairs have used index, middle and ring fingers [1, 2, 4–7] to compare between techniques. Differences in properties between the three fingers are currently unknown, but are assumed to be small compared to the difference between the intact attachment site and the various methods of repair.

The current data characterizes the strength and rigidity of the intact flexor tendon attachment. The properties greatly exceed those produced by techniques used to repair the

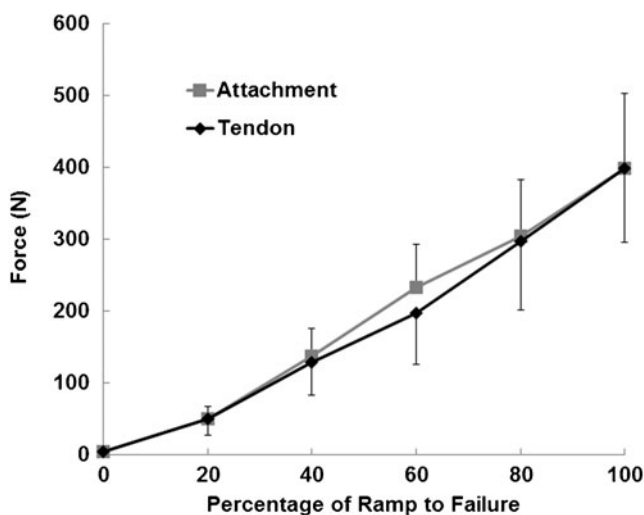


Fig. 2 Average (\pm standard deviation) applied force vs. deformation of the tendon within 5 mm of the attachment site and 5 mm more proximally within the tendon during the ramp to failure. To allow averaging over the length of the test, the deformation is expressed as the percentage of the deformation at failure, and the loads are interpolated to 20 % intervals along the ramp. The force increases approximately linearly with tissue deformation from the onset of loading until failure

attachment following an avulsion injury. The lack of strength leaves the repaired tendon at risk for post-operative failure, while the lack of rigidity can hinder tendon to bone healing and contribute to reduced post-operative range of motion. Efforts to further improve techniques for repair of the FDP tendon attachment seem warranted.

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References

1. Silva MJ, Hollstien SB, Brodt MD, Boyer MI, Tetro AM, Gelberman RH (1998) Flexor digitorum profundus tendon-to-bone repair: An ex vivo biomechanical analysis of 3 pullout suture techniques. *J Hand Surg Am* 23:120–6
2. Dovan TT, Gelberman RH, Kusano N, Calcaterra M, Silva MJ (2005) Zone I flexor digitorum profundus repair: An ex vivo biomechanical analysis of tendon to bone repair in cadavera. *J Hand Surg Am* 30:258–66
3. Moiemens NS, Elliot D (2000) Primary flexor tendon repair in zone 1. *J Hand Surg Br* 25:78–84
4. Kusano N, Zaegel MA, Placzek JD, Gelberman RH, Silva MJ (2005) Supplementary core sutures increase resistance to gapping for flexor digitorum profundus tendon to bone surface repair - an in vitro biomechanical analysis. *J Hand Surg Br* 30:288–93
5. Brustein M, Pellegrini J, Choueka J, Heminger H, Mass D (2001) Bone suture anchors versus the pullout button for repair of distal profundus tendon injuries: A comparison of strength in human cadaveric hands. *J Hand Surg Am* 26:489–496
6. Latendresse K, Dona E, Scougall PJ, Schreuder FB, Puchert E, Walsh WR (2005) Cyclic testing of pullout sutures and micro-mitek suture anchors in flexor digitorum profundus tendon distal fixation. *J Hand Surg Am* 30:471–8
7. Matsuzaki H, Zaegel MA, Gelberman RH, Silva MJ (2008) Effect of suture material and bone quality on the mechanical properties of zone I flexor tendon-bone reattachment with bone anchors. *J Hand Surg Am* 33:709–17
8. Silva MJ, Hollstien SB, Fayazi AH, Adler P, Gelberman RH, Boyer MI (1998) The effects of multiple-strand suture techniques on the tensile properties of repair of the flexor digitorum profundus tendon to bone. *J Bone Joint Surg Am* 80:1507–14
9. Silva MJ, Thomopoulos S, Kusano N, Zaegel MA, Harwood FL, Matsuzaki H, Havlioglu N, Dovan TT, Amiel D, Gelberman RH (2006) Early healing of flexor tendon insertion site injuries: Tunnel repair is mechanically and histologically inferior to surface repair in a canine model. *J Orthop Res* 24:990–1000
10. Holden CE, Northmore-Ball MD (1975) The strength of the profundus tendon insertion. *Hand* 7:238–40
11. Pring DJ, Amis AA, Coombs RR (1985) The mechanical properties of human flexor tendons in relation to artificial tendons. *J Hand Surg Br* 10:331–6
12. Schuind F, Garcia-Elias M, Cooney WP, An KN (1992) Flexor tendon forces: In vivo measurements. *J Hand Surg Am* 17:291–298
13. Thomopoulos S, Zampiakis E, Das R, Silva MJ, Gelberman RH (2008) The effect of muscle loading on flexor tendon-to-bone healing in a canine model. *J Orthop Res* 26:1611–7
14. Cooper RR, Misol S (1970) Tendon and ligament insertion. A light and electron microscopic study. *J Bone Joint Surg Am* 52:1–20
15. Miller KS, Connizzo BK, Feeney E, Soslowky LJ (2012) Characterizing local collagen fiber re-alignment and crimp behavior throughout mechanical testing in a mature mouse supraspinatus tendon model. *J Biomech* 45:2061–5
16. Thomas SJ, Miller KS, Soslowky LJ (2012) The upper band of the subscapularis tendon in the rat has altered mechanical and histologic properties. *J Shoulder Elbow Surg* 21:1687–93
17. Derwin KA, Soslowky LJ, Green WD, Elder SH (1994) A new optical system for the determination of deformations and strains: Calibration characteristics and experimental results. *J Biomech* 27:1277–85
18. Tuttle HG, Olvey SP, Stern PJ (2006) Tendon avulsion injuries of the distal phalanx. *Clin Orthop Relat Res* 445:157–68
19. Wright TM, Hayes WC (1976) Tensile testing of bone over a wide range of strain rates: Effects of strain rate, microstructure and density. *Med Biol Eng* 14:671–80
20. Woo SL, Peterson RH, Ohland KJ, Sites TJ, Danto MI (1990) The effects of strain rate on the properties of the medial collateral ligament in skeletally immature and mature rabbits: A biomechanical and histological study. *J Orthop Res* 8:712–21
21. Parimi M, Zhao C, Thoreson AR, An KN, Amadio PC (2012) Does loading velocity affect failure strength after tendon repair? *J Biomech* 45:2939–42
22. Hashemi J, Mansouri H, Chandrashekar N, Slauterbeck JR, Hardy DM, Beynon BD (2011) Age, sex, body anthropometry, and ACL size predict the structural properties of the human anterior cruciate ligament. *J Orthop Res* 29:993–1001
23. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S (1991) Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med* 19:217–25