EDITOR'S CHOICE

Biomechanical Properties of a Novel Mesh Suture in a Cadaveric Flexor Tendon Repair Model

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Purpose Conventional suture repairs, when stressed, fail by suture rupture, knot slippage, or suture pull-through, when the suture cuts through the intervening tissue. The purpose of this study was to compare the biomechanical properties of flexor tendon repairs using a novel mesh suture with traditional suture repairs.

Methods Sixty human cadaveric flexor digitorum profundus tendons were harvested and assigned to 1 of 3 suture repair groups: 3-0 and 4-0 braided poly-blend suture or 1-mm diameter mesh suture. All tendons were repaired using a 4-strand core cruciate suture configuration. Each tendon repair underwent linear loading or cyclic loading until failure. Outcome measures included yield strength, ultimate strength, the number of cycles and load required to achieve 1-mm and 2-mm gap formation, and failure.

Results Mesh suture repairs had significantly higher yield and ultimate force values when compared with 3-0 and 4-0 braided poly-blend suture repairs under linear testing. The average force required to produce repair gaps was significantly higher in mesh suture repairs than in conventional suture. Mesh suture repairs endured a significantly greater number of cycles and force applied before failure compared with both 3-0 and 4-0 conventional suture.

Conclusions This *ex vivo* biomechanical study of flexor tendon repairs using a novel mesh suture reveals significant increases in average yield strength, ultimate strength, and average force required for gap formation and repair failure with mesh suture repairs compared with conventional sutures.

Clinical relevance Mesh suture–based flexor tendon repairs could lead to improved healing at earlier time points. The findings could allow for earlier mobilization, decreased adhesion formation, and lower rupture rates after flexor tendon repairs. *(J Hand Surg Am. 2019;■(■):■–■. Copyright © 2018 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Flexor tendon repair, mesh suture, suture materials, ultimate tensile strength biomechanics.

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FLEXOR TENDON REPAIRS CAN BE complicated by adhesion formation, joint stiffness, and repair failure, leading to deficits in hand motion, grip, and pinch. Early motion rehabilitation protocols have been shown to reduce adhesion formation and joint stiffness.[1–4] Therefore, hand surgeons have been challenged to create a repair that is sufficiently durable to withstand motion in the initial postoperative period. Although many tendon repair techniques have been proposed, conventional sutures may have inherent limitations owing to their closed core configuration. Tendon repairs can fail by suture rupture and knot slippage, and the fascicular structure of tendons makes this tissue particularly susceptible to a phenomenon known as suture pull-through—when the suture cuts through the tissue being approximated.[5,6] To mitigate this occurrence, solid-core suture constructs for flexor tendon repair often involve sutures placed in various directions relative to the tendon fibers. However, suture pull-through following tendon repair remains a problem because it can result in gap formation, a known predictor of tendon repair failure.[5]

A novel mesh suture has recently been utilized for repair of abdominal wall defects with notable decreases in suture pull-through and subsequent hernia formation (Fig. 1).[7–9] Although not directly tested, the success of this mesh suture might be due to its larger surface area and macroporous design. The mesh suture is constructed from multiple polypropylene filaments woven into an open cylindrical cross-hatch configuration (Fig. 2). This open braid design allows for a larger suture diameter that collapses upon tying, creating a relatively smaller strand and knot profile. In addition to the large suture diameter, the mesh suture flattens perpendicular to the direction of force and interdigitates with the repaired tissue. This attribute theoretically increases the static friction between suture and tissue, enabling the suture material to resist pull-through by better distributing tensile forces across a greater surface area. Furthermore, preclinical biomaterial investigations have demonstrated that the macroporous structural design of mesh suture facilitates stronger and more biocompatible repairs through tissue ingrowth.[7] Although tendons and abdominal fascia differ in shape and movement, the material characteristics that make mesh suture well suited for approximation of abdominal wall fascia could be beneficial for flexor tendon repairs in the hand.[10]

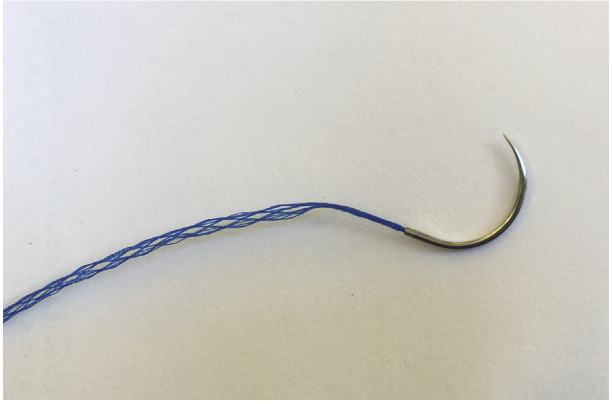


FIGURE 1: Mesh suture with multiple polypropylene filaments.

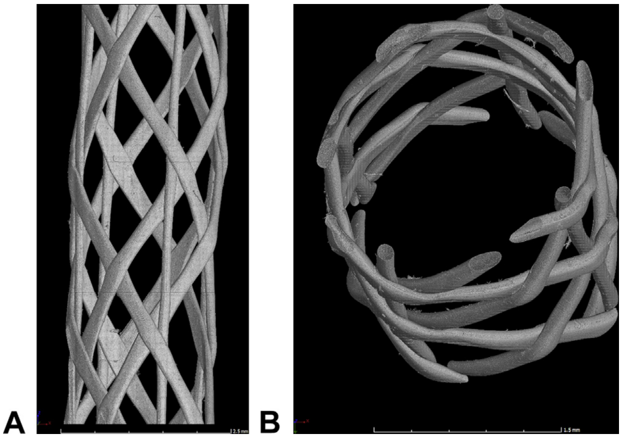


FIGURE 2: A, B Micro computed tomography demonstrates the cross-hatch design and increased surface area of the mesh suture.

The purpose of this study was to compare the biomechanical properties of flexor tendon repairs using a novel mesh suture with repairs performed with common suture material and sizes. We hypothesized that mesh suture will have improved biomechanical properties compared with 3-0 and 4-0 braided poly-blend suture.

MATERIALS AND METHODS

The study utilized a novel mesh suture (2-0 Tetramesh Suture; Mesh Suture Inc., Dorado, Puerto Rico; currently not commercially available) for analysis. The diameter assigned to the mesh suture is based on the diameter of the mandrel on which it is woven and sealed. The suture is cylindrical in shape consisting of 12 polypropylene filaments, each measuring 0.10 mm in diameter. Four filaments are oriented linearly along the suture axis and 8 additional filaments are braided to the 4 longitudinal sutures to create a mesh pattern. Each filament is bonded to the others at every contact point.

Sixty fresh-frozen human cadaveric flexor digitorum profundus tendons of the index, middle, and ring fingers were harvested for this study. These

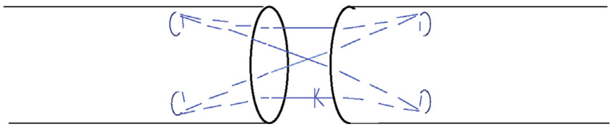


FIGURE 3: Diagram of the 4-strand core cruciate tendon repair technique.

specimens were randomized into equal groups (30 specimens each) for separate linear testing and cyclic testing. Within each test group, 10 tendons were randomly assigned to 1 of 3 separate suture repair groups using mesh suture or a braided poly-blend suture (3-0 or 4-0 FiberWire; Arthrex, Inc, Naples, FL).[11,12] The first 10 tendons removed from the specimen bag were assigned to mesh suture, after which the next set of 10 was assigned to 3-0 braided poly-blend suture, and the remaining 10 were allocated for 4-0 braided poly-blend suture. With the specimens frozen at the time of assignment, inspection for tendon quality and size was not performed.

Sample size determination

Sample size was determined based on pilot testing. Three tendon repairs per experimental group were included in preliminary testing. Average load required for repair gapping to 1 mm was 33% higher for mesh suture repairs than for 3-0 braided poly-blend suture—the stronger of the 2 most common sutures currently used for tendon repairs at our institutions. A sample size estimate of 5 tendons per group was made using an alpha of 0.05 and power of 0.80.

Specimen preparation

Each specimen was thawed for 30 minutes prior to preparation and kept moist in saline-soaked gauze. Tendons were trimmed to a standardized length of 10 cm and transected using a scalpel to create a complete, transverse laceration at the tendon midpoint. All tendons were repaired with 1 of the 3 suture materials using a 4-strand core cruciate configuration (Figs. 3, 4).[13] A total of 3 square knots, with the first 1 being a surgeon's knot, were placed for each repair. A digital caliper was used to measure the width and thickness of each tendon at the midpoint before division and after repair, allowing for pre- and postrepair cross-sectional area calculations. Biomechanical testing was performed immediately after tendon repair.

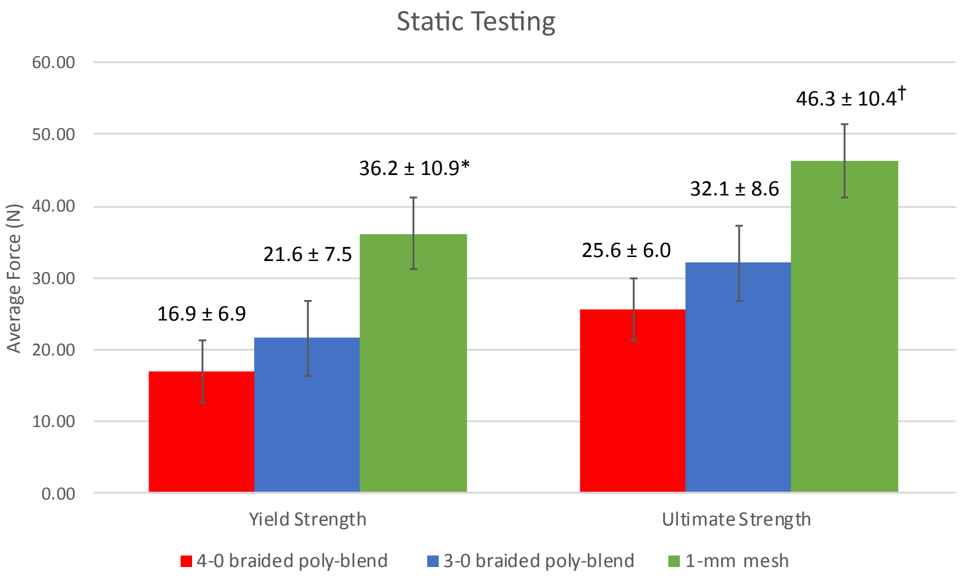
Biomechanical testing: linear protocol

Thirty tendons were subject to a linear testing protocol that was based on previously published protocols.[14,15] Each tendon was attached to a tensile testing machine (MTS Insight, Eden Prairie, MN), using custom grasping clamps reinforced with sandpaper then preconditioned to 5 N for 10 cycles before applying a constant displacement rate of 0.1 mm/s. Force (N) and cross-head elongation (mm) were recorded as well as mode of failure. Failure of repair was characterized as suture breakage, suture pull-through, or knot slippage. Testing was terminated when the tensile force decreased below 1 N.

FIGURE 4: A human flexor digitorum profundus tendon status post 4-strand core cruciate repair with the novel mesh suture. The core strands and internal knot are covered by tendon collagen fibers. A piece of the 1-mm novel mesh suture rests beside the repaired tendon for comparison.

Biomechanical testing: cyclic protocol

Thirty tendons underwent testing using an incremental cyclic loading similar to prior protocols.[16–18] Specimen testing began as each tendon was preloaded to 11.5 N then cycled from 3 N to 20 N force



* mesh suture had significantly higher average yield strength than both 4-0 and 3-0 braided poly-blend suture, $P < .05$.
† mesh suture had a significantly higher average ultimate strength than both 4-0 and 3-0 braided poly-blend suture, $P < .05$.

FIGURE 5: The average yield strength and ultimate strength for each repair type.

for 20 cycles at 0.2 Hz. Maximum force applied was successively increased by 5 N increments, maintaining a constant force amplitude of 17 N. Each new loading magnitude was repeated for 20 cycles until an 80 N peak load was reached or the repair failed.

Isolated suture material tensiometry

Isolated tensiometry testing of each suture type was performed using a single-column tabletop testing system (Instron, Norwood, MA). Force was applied at 1000 N/min until suture failure, as indicated by suture breakage. Three runs for each suture type were performed, and the force needed for failure (N) was averaged.

Statistical analysis

Linear and cyclic testing data was acquired with TestWorks software (MTS Insight, Eden Prairie, MN) and recorded with a high-resolution video camera. Data collected included yield strength, ultimate strength, and stiffness for linear testing and number of cycles and load required to achieve 1-mm and 2-mm gap formation and failure, as well as mode of repair failure, for cyclic testing. Stiffness (N/mm) was defined as the midportion slope of the elastic stage on the force-elongation curve. Using a ruler for calibration, gap formation at 1 mm and 2 mm was measured on the video and correlated with the number of cycles and instantaneous load at each time point. Total Newton-cycles were calculated as the sum of the incremental products of the applied load multiplied by the number of cycles that the force was applied to each tendon at 1-mm and 2-mm gaps and at failure (ie, fatigue strength). The number of cycles, force, and total Newton-cycles at 1-mm and 2-mm gaps and at repair failure were compared between suture types using a Student *t* test with a level of significance of P of .05 or less.

RESULTS

Linear testing

Yield strength and ultimate strength are summarized in Figure 5. Failure was by suture pull-through except in 3 specimens in which failure occurred by knot slippage—1 in each repair group. The mesh suture repair had a significantly higher average yield strength and ultimate strength compared with 4-0 and 3-0 braided poly-blend suture repairs. There was no significant difference of either yield strength or ultimate strength comparing 3-0 and 4-0 braided poly-blend suture groups.

Construct stiffness was significantly different between mesh repair and 3-0 braided poly-blend suture (5.2 ± 1.3 N/mm vs 3.8 ± 1.0 N/mm). Stiffness was not significantly different between mesh and 4-0 braided poly-blend suture ($P = .20$) or between 3-0 braided poly-blend suture and 4-0 braided poly-blend suture (4.4 ± 1.2 N/mm; $P = .36$).

Cyclic testing

Twenty-nine of 30 repairs failed by suture pull-through, with 1 mesh suture repair failing by suture rupture (after 170 cycles at a final load of 60 N). No repairs reached a maximum load greater than 80-N force.

Mesh suture repairs endured a significantly greater average number of cycles, force applied, and total Newton-cycles before 1-mm and 2-mm gapping compared with both 4-0 and 3-0 braided poly-blend suture (Table 1; $P < .05$). There was no significant difference in these parameters between 4-0 and 3-0 braided poly-blend suture. The minimum force to produce a 1-mm gap was 45 N (average 58 ± 7 N) in the mesh suture group compared with 20 N and 35 N for 4-0 braided poly-blend suture and 3-0 braided poly-blend suture repairs, respectively ($P < .05$).

Mesh suture repairs withstood a significantly greater number of cycles, force applied, and total Newton-cycles before catastrophic failure than both 4-0 braided poly-blend suture ($P < .05$) and 3-0 braided poly-blend suture (Fig. 6; $P < .05$). Repairs performed with 3-0 braided poly-blend suture sustained a significantly greater number of cycles, force applied, and Newton-cycles than 4-0 braided poly-blend suture before failure.

Cross-sectional area analysis

The repair site cross-sectional area increased by an average of 158% in both mesh suture and 3-0 braided poly-blend suture after repair (from 14.8 mm^2 to 37.9 mm^2 and from 10.6 mm^2 to 26.8 mm^2, respectively). There was a 141% increase in cross-sectional area following 4-0 braided poly-blend suture repairs (11.9 mm^2 to 28.9 mm^2), similar to both 3-0 braided poly-blend suture repairs and mesh suture–based repairs.

Isolated suture material tensiometry

The 1-mm mesh suture had the lowest average elastic modulus at 19.4 ± 2.6 MPa compared with both 3-0 braided poly-blend suture (38.1 ± 2.8 MPa) and 4-0 braided poly-blend suture (30.3 ± 1.0 MPa) suture (Table 2). The mesh suture also had the lowest average mechanical strength (defined as the load required for suture failure) at 36.4 ± 1.5 N compared with 73.2 ± 3.3 N with 3-0 braided poly-blend suture and 53.8 ± 1.5 N with 4-0 braided poly-blend suture.

TABLE 1. Gap Formation and Fatigue Strength of Tendon Repairs

	1-mm Gap			2-mm Gap			Failure		
Suture Type	Average Cycles	Average Force (N)	Total Newton-Cycles	Average Cycles	Average Force (N)	Total Newton-Cycles	Average Cycles	Average Force (N)	Total Newton-Cycles
4-0 braided poly-blend	75 ± 38	37 ± 10	2,176 ± 1,437	76 ± 36	38 ± 9	2,213 ± 1,402	77 ± 36*	38 ± 9*	2,243 ± 1,405*
3-0 braided poly-blend	94 ± 31	42 ± 7	2,872 ± 1,365	101 ± 33	44 ± 9	3,163 ± 1,500	120 ± 37*	49 ± 8*	4,041 ± 1,899*
1-mm mesh†	160 ± 26	58 ± 7	6,096 ± 1,466	167 ± 30	59 ± 7	6,517 ± 1,744	174 ± 36	61 ± 9	6,989 ± 2,199

*3-0 braided poly-blend sustained significantly larger Number of Cycles, Force, and Total Newton-Cycles compared with 4-0 braided poly-blend at Failure only ($P \leq .05$).

†1-mm mesh suture sustained significantly larger Number of Cycles, Force, and Total Newton-Cycles compared with both 4-0 braided poly-blend and 3-0 braided poly-blend at 1-mm Gap and 2-mm Gap Formation and at Failure ($P \leq .05$).

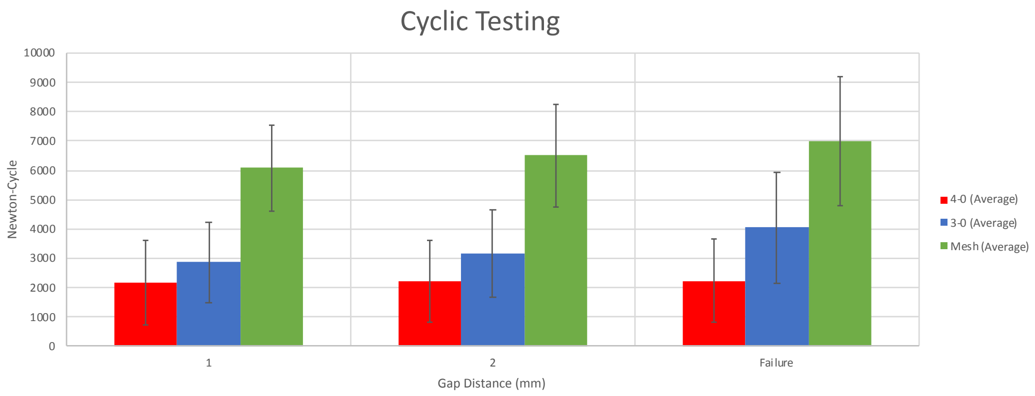


FIGURE 6: The average Newton-cycles needed for 1-mm gap formation (far left), 2-mm gap formation (center), and failure (far right) for each repair type.

TABLE 2. Biomechanical Properties of Isolated Suture Testing

Suture Type	Elastic Modulus (MPa)	Yield Strength (N)	Mechanical Strength (N)
4-0 braided poly-blend	30.3 ± 1.0	44. ± 1.8	53.8 ± 1.5
3-0 braided poly-blend	38.1 ± 2.8	62.8 ± 1.7	73.2 ± 3.3
1-mm mesh	19.4 ± 2.6*	27.6 ± 24†	35.4 ± 1.5‡

*Mesh suture had a significantly lower elastic modulus compared with 4-0 and 3-0 braided poly-blend, $P < .05$.

†Mesh suture had a lower average yield strength compared with both 4-0 and 3-0 braided poly-blend, $P < .05$.

‡Mesh suture had a lower average mechanical strength compared with both 4-0 and 3-0 braided poly-blend, $P < .05$.

DISCUSSION

The primary goal of flexor tendon repair is to create a strong suture-tendon construct that allows for early active motion while withstanding rupture. Early mobilization has been shown to reduce peritendinous adhesion formation and stimulate intrinsic tendon healing.[1–4] However, early active motion protocols should be used with caution because forces across the repair site increase the risk for gap formation and repair failure. Repair failure can be attributed to the pull-through phenomenon observed with typical suture materials.[5,6] Numerous tendon repair techniques have been proposed to overcome this challenge, employing varying tendon repair patterns, suture material, and size.[19–28]

This study analyzed the biomechanical properties of tendon repairs performed with a 1-mm-diameter mesh suture to those performed with 3-0 and 4-0 braided poly-blend suture in human cadaveric flexor digitorum profundus tendons under cyclic and linear testing protocols. Selection of the 1-mm-diameter mesh suture was based on the fact that it is the smallest diameter suture available of its kind. The use of 3-0 and 4-0 braided poly-blend sutures for comparison was selected because they are the most commonly used sutures for flexor tendon repairs at our institutions. Linear tensiometry provided simplified force results and cyclic tensiometry testing was employed as a more clinically relevant model, mimicking physiological postoperative conditions under an active rehabilitation protocol.[29]

Linear testing results showed significantly higher average yield strength and ultimate strength values in mesh suture–based repairs than both 3-0 and 4-0 braided poly-blend suture repairs. Mesh suture repairs had double the average yield strength and 80% greater average ultimate strength than 4-0 braided poly-blend suture repairs and 67% greater average yield strength and 45% greater average ultimate strength than 3-0 braided poly-blend suture–based repairs. The yield strength is often regarded as the maximum strength of the intact repair composite because it represents the upper limit of force prior to permanent deformation of the construct.[30] Cyclic tensiometry results showed that repairs using the 1-mm-diameter mesh suture have a statistically significant greater tensile strength. Specifically, compared with 4-0 braided poly-blend suture tendon repairs, the mesh suture repairs required over double the number of cycles and 50% more load (in Newtons) on average to develop a 1-mm gap, a 2-mm gap, or failure. Compared with 3-0 braided poly-blend suture repairs, the novel mesh suture repairs required at least 50 more cycles and 25% more force on average to develop a 1-mm gap, a 2-mm gap, or failure.

It is difficult to directly compare our results with those of other *ex vivo* studies because biomechanical testing protocols, tensiometry setup, and tendon repair methods, vary greatly. Studies by Lawrence and Davis[14] and Wong et al[15] most closely approximated our tendon repair and linear tensiometry methodology. However, these studies tested porcine tendons and employed a locking 4-strand core cruciate repair configuration, which has been shown to contribute to repair site strength.[16] Other studies by Xie et al[31] and Angeles et al[32] utilized similar tendon models but used different tensiometry protocols and repair techniques.

Numerous *in vivo* studies have quantified the forces exerted across intact human flexor tendons during passive and active motion.[33–37] A study by Powell and Trail[33] noted forces ranging from 0.2 N to 50 N during active and passive movement and movement against resistance up to 500 g (∼ 5 N). The wide range in force measurements was common across studies, with forces varying by up to 50%.[33–37] Such variation is likely a combination of intrinsic patient variability and technical difficulties in accurately capturing these forces. Whereas mesh suture repairs achieved higher average forces before gapping and failure than both 3-0 and 4-0 braided poly-blend suture in this study, *in vivo* data are needed to see whether mesh suture better resists force across the repair site during early active motion rehabilitation protocols.

Linear tensiometry testing of each isolated suture material to failure revealed that the 1-mm mesh suture had a lower average elastic modulus (MPa) than both 3-0 and 4-0 braided poly-blend suture (Table 2). Although this finding conflicts with our tensiometry tendon repair results, it may explain how mesh suture repairs could be more resilient to cyclic forces than braided poly-blend suture repairs. Specifically, the woven, cylindrical construct of the mesh suture accounts for its elastic properties and allows the suture to flatten perpendicular to the direction of force, thereby better distributing forces across a greater surface area. The mesh suture is able to stretch and recoil when dynamic forces are exerted across the repair site. The 1-mm mesh suture had a lower average mechanical strength (N) on linear tensiometry of the isolated suture, yet significantly higher average fatigue strength seen on linear and cyclic testing of tendon repairs than 3-0 and 4-0 braided poly-blend sutures. Although not proven, we suspect the increase in fatigue strength seen when the mesh suture is incorporated into a tendon repair is due to tissue-suture interaction and potential friction created through the open woven design.

The mesh suture material used in this study was engineered to mitigate the shortcomings of currently available sutures that can cut through soft fascicular planes or contribute to excessive synthetic suture bulk. We acknowledge that all surgical materials carry certain disadvantages. Because mesh suture is not in clinical use for tendon repairs currently, some of the potential disadvantages associated with this material include increased repair site bulk, increased gliding resistance, early suture degradation, and decreased flexion of the affected digit. We did measure the percent change in cross-sectional area before and after tenorrhaphy for each specimen for insight into repair site bulk. All repair groups produced similar increases in cross-sectional area postrepair, but *in vivo* studies are the standard way to assess for these drawbacks. We hypothesize that enhanced tissue ingrowth, seen as soon as 8 days postrepair in preclinical studies of mesh suture,[7] will improve the strength of the mesh suture tendon repairs at earlier time points, thereby allowing for early, possibly immediate, motion protocols after flexor tendon repair.

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