Analysis of a Knotless Flexor Tendon Repair Using a Multifilament Stainless Steel Cable-Crimp System

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Purpose To compare the biomechanical and technical properties of flexor tendon repairs using a 4-strand cruciate FiberWire (FW) repair and a 2-strand multifilament stainless steel (MFSS) single cross-lock cable-crimp system.

Methods Eight tests were conducted for each type of repair using cadaver hand flexor digitorum profundus tendons. We measured the required surgical exposure, repair time, and force of flexion (friction) with a custom motor system with an inline load cell and measured ultimate tensile strength (UTS) and 2-mm gap force on a servo-hydraulic testing machine.

Results Repair time averaged less than 7 minutes for the 2-strand MFSS cable crimp repairs and 12 minutes for the FW repairs. The FW repair was performed with 2 cm of exposure and removal of the C-1 and A-3 pulleys. The C-1 and A-3 pulleys were retained in each of the MFSS cable crimp repairs with less than 1 cm of exposure. Following the FW repair, the average increase in friction was 89% compared with an average of 53% for the MFSS repairs. Six of the 8 MFSS specimens achieved the UTS before any gap had occurred, whereas all of the FW repairs had more than 2 mm of gap before the UTS, indicating that the MFSS was a stiffer repair. The average UTS appeared similar for both groups.

Conclusions We describe a 2-strand multifilament stainless steel single cross-lock cable crimp flexor repair system. In our studies of this cable crimp system, we found that surgical exposure, average repair times, and friction were reduced compared to the traditional 4-strand cruciate FW repair. While demonstrating these benefits, the crimp repair also produced a stiff construct and high UTS and 2-mm gap force.

Clinical relevance A cable crimp flexor tendon repair may offer an attractive alternative to current repair methods. The benefits may be important especially for flexor tendon repair in zone 2 or for the repair of multiple tendons. (J Hand Surg 2013;38A:677–683. Copyright © 2013 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Biomechanics, crimp, flexor tendon, stainless steel, suture.

Despite many recent improvements in the biomechanical parameters of repair technique and sutures, there are still challenges facing surgeons who perform flexor tendon repairs.\(^1\)–\(^10\) An optimal tendon repair should be simple to perform and provide accurate coaptation of the tendon ends. The repair should also provide strength for early active range of motion,\(^11\)–\(^16\) stiffness to resist gap formation during rehabilitation,\(^17\)–\(^20\) and compactness for smooth gliding through the pulley system. There has been little

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which is the strongest repair reported in the literature. The goal of this study was to analyze whether the cable crimp method would have technical advantages of reduced repair time, less surgical exposure, and low force of flexion (friction) while still producing a strong repair with high ultimate tensile strength (UTS) and 2-mm gap force.

**MATERIALS AND METHODS**

We compared the parameters of the MFSS cable-crimp repair with a 4-strand cruciate FW repair. We measured the force of flexion of the intact tendon and then measured the force of flexion following repair. The percent change in this force was then calculated. We also measured the ultimate load and load at 2-mm gap, which likely correlates with clinical performance. We measured the time for the tendon repair and measured the length of surgical exposure needed.

**Force of flexion (friction), ultimate tensile strength, and 2-mm gap force**

Flexor digitorum profundus tendons were used in the index, middle, and ring fingers of cadaver hands, with 8 samples in 2 groups. The force of flexion was determined by mounting the hands to plastic boards using Steinmann pins that were drilled through the radius and ulna. The skin was removed from the palmar surface of the finger and palm from the distal interphalangeal joint crease to the mid palmar crease, leaving the tendons and the entire pulley system intact. The flexor digitorum profundus tendons were then dissected and separated at the wrist. Each tendon was connected to a custom motor system that flexed the finger though a repeatable excursion 50 times. To measure and record the force needed for full excursion of the tendon, an inline load cell was connected between the tendon and the motor. We marked a point on the tendon 1 cm distal to the A2 pulley and initially measured the baseline force required for this point on the tendon to travel to a point proximal to the A1 pulley. To extend the finger, a suture was passed through the nail of each finger and connected to a 100-g weight that was hung over the end of the board.

Each tendon was transected 1 cm distal to the A2 pulley and then repaired.

Group 1 received a 4-strand, cruciate repair, using 3-0 FW with a knot consisting of 5 throws, and group 2 received a 2-strand, single cross-lock cable-crimp repair, using 4-0 MFSS (double suture).

For the MFSS cable-crimp repairs, we used MFSS with a specifically designed stainless steel crimp that we have previously described. For the MFSS crimp repairs, we used a single cross-locked repair configura-
tion attached to each side of the divided tendon. In preliminary testing on a servo-hydraulic testing machine (Mini-Bionix 858; MTS, Eden Prairie, MN), the strength of multiple repair configurations for tendon attachment was measured and the single cross-lock was found to be the strongest (Table 1).

Following the cable crimp repair, the C1 and A3 finger pulleys were removed to make the groups equal for measurement of the force of flexion. The hand was then returned to the testing machine, and the force of flexion test was repeated, using the same excursion as the baseline testing. The change in the force of flexion was compared to the baseline measurements for each group. The tendons were then removed from the hand so the ultimate load and load at 2-mm gap could be measured.

Each tendon repair was loaded in uniaxial tension using the standard protocol of our laboratory. Briefly, the repaired tendon was loaded onto a servo-hydraulic testing machine (Mini-Bionix 858; MTS) and subjected to 10 slow cycles from 5 to 10 N to pretension the tendon. The tendon was then loaded in uniaxial tension at 1 mm/sec until failure. Video of the test was analyzed frame by frame to determine the maximum force before 2 mm of gapping.

Surgical method

Standard 4-strand cruciate repairs using 3-0 FW and a running nonlocking epitendinous stitch using 5-0 monofilament nylon were performed on the 8 tendons in group 1. Removal of C1 and A3 provided the required exposure for the repair (Fig. 1).

The cable crimp repairs on the 8 tendons in group 2 were performed with a 3-0 MFSS suture (Fig. 2). Initially, the suture was attached to the tendon on each side of the laceration, using a single cross-lock stitch. The suture was first passed across the tendon at a right angle to the long axis 1.2 cm from the cut end. A second pass was made 0.6 cm from the cut end, also at right angles, to create a large single cross-lock attachment. The suture ends were then passed out the cut end with a simple gliding stitch. Each side was attached separately, and this required 1.2 cm of exposed tendon brought into the wound one at a time but not simultaneously. The distal tendon was presented by flexing the interphalangeal joints to expose this length of tendon. The cross-lock was then allowed to retract within the pulley on both the proximal and distal sides. Both ends of the cut tendon were not brought together until the time of crimping. The needles were cut off from the suture ends, and a crimp holder was used to bring a crimp into the repair site. The sutures were passed through the lumen of the crimp from each end (Fig. 3). The sutures were pulled tight to ensure a secure cross-lock attachment to the tendon. Traction from both sides was then applied to approximate the tendon ends to exactly the tension needed to provide optimal coaptation without overlap or gap. At this point, a single epitendinous stitch using 5-0 nylon was used on the radial or ulnar side of the repair to ensure exact rotation. A calibrated crimp tool was introduced from the side of the repair opposite to this stitch and used to compress the crimp, thereby fixing the sutures from each side together. Two additional simple interrupted epitendinous stitches of 5-0 monofilament nylon were placed on the palmar surface.
FIGURE 3: A Multifilament stainless steel sutures from each end of the divided tendon are brought through a crimp (held by a crimp holder). B The crimp is shown containing cables from each side of the divided tendon. C A calibrated crimp tool is used to compress the crimp and connect the sutures. D The completed crimp repair is covered with simple interrupted epitendinous stitches. The A2, C1, and A3 pulleys are intact, and the repair occurs in less than 1 cm between the C1 and A3 pulleys.

of the tendon to bury the crimp within the tendon repair site.

Repair time
Eight repairs each were completed for the FW repair and the MFSS single cross-lock cable crimp repair. We recorded the time for each of these 16 repairs. The tendon ends were prepared for repair, and time was measured from the start of the repair until the final epitendinous stitch was tied. The time for surgical exposure, preparation of the tendon, and skin closure was not included.

Surgical exposure
The distance needed to complete the repair in each group was recorded. The FW repair required removal of the C-1 and A-3 pulleys. Pulleys were left intact for the MFSS repair, and suture connection was completed between the pulleys.

Statistical analysis
Data for the UTS, maximum load before 2 mm of gapping, and percent change in friction from baseline were compared between the 2 groups using a Mann-Whitney U test with significance set at $P < .05$.

RESULTS

Repair time
The repair time for tendon repairs averaged 12 minutes for the 4-strand cruciate FW repair and less than 7 minutes for the 2-strand MFSS cable crimp repair.

Surgical exposure
The surgical exposure for the FW repair averaged 2.1 cm. The average exposure for the MFSS was 0.6 cm. All FW repairs required resection of C1 and A3 pulleys. Pulleys were retained in all 2-strand MFSS repairs.

Force of flexion, ultimate tensile strength, and 2-mm gap force
The force of flexion measured $89 \pm 35\%$ and $53 \pm 18\%$ for the 4-strand cruciate FW repair and 2-strand MFSS cable crimp repair, respectively ($P = .007$). In 6 of the 8 tests using the 2-strand MFSS cable crimp repair, the 2-mm gap occurred after core suture failure,
demonstrating the stiffness of the repair. The 2-strand MFSS cable crimp repairs were stiffer than the FW cruciate repairs. Six of the 8 MFSS specimens achieved the UTS before any gap had occurred, whereas all of the 4-strand cruciate FW specimens had more than 2 mm of gap before the UTS. This difference was statistically significant (Fisher’s exact test, \( P = .007 \)). With 8 specimens in each group, there were no statistically significant differences in the ultimate load between the 2 groups.

All MFSS repairs failed by suture breakage, with the cross-lock remaining secure in the tendon at the point of failure. Five of the FW repairs failed by suture pullout from the tendon and 3 by knot failure.

**DISCUSSION**

Despite advances in flexor tendon repair and identification of factors that affect the outcome of these repairs, there remains a need for a repair that is simple and fast and results in a strong, stiff construct. In this study, we report on a 2-strand cable crimp repair with a 3-0 MFSS cable that satisfies these criteria. This repair uses a single cross-lock stitch, requires minimal surgical exposure, and requires approximately half the surgical time to complete the repair when compared to a 4-strand cruciate FW repair.

Use of a crimp in tendon repair has several benefits. Each end of the tendon can have the suture inserted independently and then brought together for the tendon repair. This means that both sides of the repair do not need to be exposed simultaneously, and therefore the need for surgical exposure is reduced, usually to less than 1 cm. This decreases exposure to a mini-incision that we have described previously. Using a crimp enables tensioning of the tendon ends as they are approximated, avoiding excessive bunching, yet with exact tendon contact. The repair described requires only 2 strands and 1 cross-lock with limited tendon handling. This may be beneficial for situations in which multiple tendons need to be repaired.

Previous reports have investigated the suitability of stainless steel as a material for tendon repairs. Monofilament stainless steel was widely used at one time. Despite its strength, it lost favor because it is stiff. Monofilament stainless steel kinks readily, which makes it difficult to handle. The MFSS cable used in the present study is pliable and handles easily, like a polymer suture. Crimping has previously been described in other areas of orthopedic surgery, but with much larger constructs such as the greater trochanter with the Dall-Miles cable grip system (Stryker, Kalamazoo, MI). We have previously reported on MFSS cable, which has an ultimate tensile strength more than twice that of FW, with half the elongation at the point of failure. We have also previously reported on the use of a crimp to connect sutures that we found to be stiffer and stronger than a knot. We have combined this cable and crimp with a firm attachment of suture to the tendon that we developed in preliminary testing. With this combination, we were able to produce a strong and stiff tendon repair with both a high UTS and a high 2-mm gap force. This gap formation of 2 to 3 mm after tendon repair has been shown to decrease mechanical performance and may indicate that the tendon repair has been loaded beyond its ultimate failure point. Stronger suture material with a higher caliber has been shown to decrease gap formation. The extra strength from a higher-caliber suture and increased number of strands is reported to increase the UTS and 2-mm gap force, but this must be balanced with the additional bulk and resistance to gliding that it brings to the repair. The increased friction in the FW cruciate repairs compared with the cable crimp repair may result from the epitenodinous stitching or the bulk of the knot, considering that FW requires 5 throws to resist untwisting. The stiffness of the repair, and therefore the ability to resist 2-mm gap, was demonstrated by the finding that in 6 of 8 of the repairs using the 2-strand cable crimp with 3-0 MFSS, the core suture broke before the 2-mm gap was reached.

Stronger and higher-caliber suture materials may increase repair strength, but they also increase the possibility that the repair will fail by suture pullout from the tendon. Earlier tests investigated strength and friction in configurations of suture attachment to tendon. We ultimately selected the single cross-lock, which provided the optimal combination of high strength and low force of flexion. For the control repair, we chose a 4-strand cruciate FW suture repair, as this is reported to be the strongest repair in several studies.

The knot has been identified as the area of the suture that is weakest. If the suture attachment to the tendon is stronger than the suture and knot complex, the repair will fail by suture breakage at the knot. In the repairs using FW, we found that repair failure occurred by suture pullout or by breakage at the knot. Even though the crimp is stronger than a knot, all of the cable crimp repairs failed at the crimp. This raises the potential for further strength of the repair with added engineering of the crimp, such as smoother edges to avoid suture breakage.

Epitenodinous sutures have been used to increase UTS in other repairs, but we found this unnecessary, as we achieved sufficient strength and excellent
coaptation with the core stitch. We used 2 or 3 interrupted epitenon stitches on the palmar surface of the tendon to bury the crimp within the repair site. No epitenon stitches were needed on the dorsal surface, as this was found to be well aligned, thereby reducing interference with the vincular system and simplifying the repair.

Damage to the tendon and interference with vascularity is difficult to assess. The primary vascular supply to the tendon in zone 2 enters from the vinculae, which approach the dorsal aspect of the tendon. Other nutritional contributions come from surface vessels and bone attachments, as well as the synovial fluid. A repair placed in the dorsal part of the tendon may have greater tensile strength when locking sutures are used but may interfere with the vincular supply. Although the repair method described placed the cross-lock in the palmar half of the tendon as not to interfere with the dorsal circulation, it achieved good UTS and 2-mm gap force.

Additional studies concerning healing and use of MFSS cable crimp systems in the clinical setting are needed to further define their role in tendon repair.

REFERENCES