Original Article

A novel method for reducing gap formation in tendon repair

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ABSTRACT

Background: This study investigates gap formation in tendon repair using a novel tensioning method.**Hypothesis:** The novel stitch will demonstrate less gap formation than the other suture configurations tested.**Methods:** Porcine tendons stitched with classic Krackow stitch configurations were compared to a Krackow stitch modified with a proximal Tension-Assist Loop. Each group was cyclically loaded followed by analysis of the tendon-suture construct for gap formation.**Results:** The Tension-Assist Loop group produced significantly less gap formation than each of the other stitch groups.**Conclusion:** Decreasing early gap formation may be beneficial in allowing early rehabilitation and range of motion.

1. Introduction

Surgical repair of tendons is common practice in orthopaedics. Secure fixation between the tendon and bone is critical for clinical success of the tendon repair.^{1,2} In addition, early rehabilitation protocols, which allow early weight bearing and range of motion, are dependent on resistance to gap formation.^{1,2,3,4}

Various studies have been performed to identify the suture technique that provides the greatest resistance to gap formation. These studies compare new suture configurations as well as varying the number of throws in known suture configurations. These studies assess gap formation, load to failure, and failure mode.^{4,5,7} The Krackow stitch is recommended due to its greater resistance to gap formation.⁴

Mechanisms of gap formation include suture tear-out,⁴ suture material elasticity,⁸ knot failure⁹ and suture slack.^{10,11} Suture slack is the laxity that exists in a tendon suture construct. When a suture-tendon construct is tensioned, a decrease of tendon width occurs due to the constricting effects of the suture loops.⁴ As the constriction occurs, suture is extruded from the tendon end, resulting in gap formation between tendon and fixation site. Due to the compressible properties of tendon tissue, suture slack exists even with meticulous technique. This concept is demonstrated below (Fig. 1), with foam exaggerating the compressible nature of tendon.

The purpose of our study was to quantitate and subsequently reduce gap formation due to suture slack. Current methods to reduce suture slack are limited to distal tensioning of suture-tendon constructs by

hand before proceeding to final fixation. We describe a method which allows for simultaneous proximal and distal tensioning. We hypothesized this method would demonstrate less gap formation than the other suture configurations tested.

2. Materials and methods

2.1. Tendon preparation

A total of 32 equally sized fresh 6 mm porcine flexor digitorum tendons were obtained and randomly assigned into 4 groups, each with a sample size of 8 tendons (Fig. 2). The first 3 groups were prepared with the same stitch configuration, an 8-throw Krackow[K], each with different suture material: No. 2 FiberWire[FW], 2 mm FiberTape[FT], and 1.5 mm LabralTape[LT]. For each of these groups, the Krackow stitch was constructed in the classic Krackow fashion, starting 10 mm from the free end of the tendon. The pitch between the suture throws was 5 mm.^{12,13} Each stitch loop throughout the process was tensioned by hand to eliminate suture material and the finished construct was robustly tensioned by hand to a minimum of 25 N (confirmed by linear tensiometer), simulating operating room technique.

The fourth, experimental, group consisted of a modified 8-throw Krackow Tension-Assist Loop (TAL) Stitch using No. 2 FiberWire. The stitch was identical to the Krackow stitch described above with the following exception: a 15 cm loop of suture was left at the most proximal aspect of the configuration, between the 4th and 5th throw

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Fig. 1. This image depicts the concept of suture slack. As greater tension is applied, the foam (which represents tendon) is compressed. This results in movement of the suture with resultant gap formation. Movement is demonstrated by the black indicators advancing to the right.

(Fig. 3). This loop is able to be tensioned, effectively creating an anchor allowing for suture tensioning in the proximal direction.

The specimen was transferred to the Hughston Auburn Rotational Testing (HART) machine for “slack-removal.” The loop just constructed was placed on the actuation arm of our tensioning machine and the suture free ends were affixed to a rigid vice directly below the actuation arm (Fig. 4).

The machine then applied tension at 1 mm displacement per second until 250 N (56 lbs) was reached. This was repeated 5 times for each TAL Stitch tendon. 250 N was chosen as the pre-tensioning load as it was substantially lower than the ultimate strength of the suture material.⁴ It is important to note that once the suture pattern was complete, the tension was applied between the proximal suture loop and the distal suture free ends. This is in contrast to the other tested models, where tension is applied through the distal suture free ends alone (which mimic the clinical scenario).

Once 5 cycles were reached, the construct was removed from the HART machine. The loop was then cut and tied with 5 square knots (Fig. 5).

This concluded the “slack-reduction” process. From a testing configuration, it now had the same construct pattern as the traditional

Fig. 3. The TAL Stitch configuration. The 15 cm loop allows for tensioning the suture from the proximal end.

Krackow of first three groups, yet by tensioning in this method, higher constricting effects led to greater slack reduction. This was made possible by the simultaneous proximal and distal force applied as well as the high magnitude of the force.

2.2. Biomechanical testing

Tests were performed by use of the validated Hughston Auburn Rotational Testing (HART) machine.⁶ This machine applies and measures torque via an actuation arm. For this loading application, torque was converted to tension by dividing the torque measurement by the radius of the actuation arm (Fig. 6). This conversion was verified by the use of a linear tension gauge prior to testing.

The free ends of prepared tendons were placed in a vice below the actuation arm. The vice was fixed and submerged in 0.15 M saline bath with temperatures maintained between 90 and 110 (mean 100) degrees Fahrenheit to approximate physiologic conditions.¹⁴ The free ends of the sutures were affixed around a post on the actuation arm and tied with 6 square knots. Prior to placing tendons in the testing machine setup, gap formation indicators were placed on each free suture end. These markers consisted of metal loops crimped on both suture leads directly adjacent to the midsubstance of the tendon, where the suture exited. One was placed on each side in the event that gap formed unevenly between the 2 suture ends. The placements of the indicators were marked with permanent marker to ensure that any slippage of the

Fig. 2. Groups 1–4 stitch configurations (Right to Left).

Fig. 4. The TAL stitch during slack-removal. The loop is above and free suture ends below. This allows for a simultaneous proximal and distal tensioning of the construct, as compared to distal hand tensioning alone.

Fig. 5. After slack-reduction, the loop end of the TAL Stitch was cut and tied with 5 square knots, concluding the TAL Stitch method.

crimps from their original location would be detected (Fig. 7).

Once placed in the testing machine as described above, each specimen was preloaded to 5 N followed by cyclic loading to 200 N, 200 times, consistent with the tendon loading protocol described by Hahn et al.⁴ At the 200th load, the testing machine was halted at 200 N. A photograph was then taken of the specimen from a fixed distance from the vice. The photo was uploaded and analyzed using Image-J software (National Institute of Health). Image-J works by reporting the number of pixels between 2 points within the photo. Pixels were converted to mm by scaling them against a known distance. Our scale was determined by photographing a micrometer set to 10 mm placed at the location of the tendons in the vice. Using this measurement method, the distance of each indicator from the tendon end was determined. The

Fig. 6. Torque to Force Conversion.

Fig. 7. Test specimen setup. Specimen A has not undergone loading, metal crimps are adjacent to tendon end. Specimen B has undergone cyclic loading, metal crimps are no longer adjacent to tendon end, thus gap formation has occurred. Arrows indicate metal crimps.

average of the 2 indicators was taken to be gap formation.

2.3. Data collection and analysis

Differences in total gap formation was assessed using independent samples *t*-tests with alpha set at 0.05.

3. Results

Gap formation at the end of 200 cycles is shown in Fig. 8. The TAL produced significantly less gap formation than each of the other stitch groups (Table 1), 75.4% less than the traditional Krackow with the same suture material. The TAL produced 69.4% less gap formation

Fig. 8. Comparison of mean gap formation between each stitch group. Error bars indicate SDs. TAL: Tension Assist Loop Stitch, KFT: Krackow Stitch with FiberTape, KFW: Krackow Stich with FiberWire, KLT: Krackow Stitch with LabralTape.

Table 1
Gap Comparison Between Stitch Types.

Comparison	P
TAL vs. KFT	< 0.00001
TAL vs. KFW	< 0.00001
TAL vs. KLT	< 0.00001
KFT vs. KFW	0.011
KFT vs. KLT	0.0002
KFW vs. KLT	0.226

compared to the Krackow with FiberTape ($P < 0.00001$), the closest in comparison.

The Krackow with FiberTape produced less gap formation than the Krackow with FiberWire ($P = 0.011$) and the Krackow with LabralTape ($P = 0.0002$).

There was no difference in gap formation between the Krackow with FiberWire and the Krackow with LabralTape ($P = 0.226$).

4. Discussion

This study demonstrated, in a validated model,⁴ that traditional Krackow suture constructs all had greater than 9 mm of gap formation. These would all be deemed clinical failure as a gap greater than 5 mm may represent a failure.⁵ Varying the type of suture material did not change the gap formation enough to eliminate “clinical failure.” The ability to reduce slack in the suture-tendon construct using the TAL method substantially decreased gap formation, reducing it to less than 3 mm, thus supporting suture slack as a significant mechanism of gap formation.

Slack formation as a mechanism of gap formation has been suggested by previous studies.⁴ One study found that increasing the number of throws in a suture construct increased gap formation and postulated the mechanism was due to increased suture material allowing for more suture slippage. This is consistent with our theory given that additional knots introduce additional area in the construct for constriction and compression of tendon.

Further support for suture slack is evidenced in animal and human studies using radiopaque markers for gap measurement.^{10,11} These studies found that gap formation occurs spontaneously within 10 days in an immobilized tendon repair. They proposed that the resolution of the edematous nature of the tissue during the time of repair led to the “slackening” of the suture construct. This is consistent with the idea that although suture constructs are tightened by hand diligently by surgeons, once the tissue becomes more compressible in vivo, slackening will result.

The degree of gap formation (9 mm) is alarming at first, and suggests a possible methodical flaw. Despite methodical repair, purposeful tensioning of suture constructs in the operating room by surgeons may not produce enough tension to allow for significant suture slack reduction. All conventional Krackow repaired specimens had clinical failures (gap formation greater than 5 mm) when compared to the TAL method. This same degree of gap formation in Krackow stitched constructs was confirmed by McKeon¹⁵ (12.9–21.2 mm) and Hahn⁴ (13.9–16.3) in each of their studies on tendon repair which validates our results. Nonetheless, this degree of gap formation seems alarmingly high for a well-established suture technique.

The TAL Stitch showing significantly less gap formation may be a result of two factors. The first being the ability to apply tension from a proximal direction and distal direction simultaneously. Because the conventional Krackow is a locking stitch, it is designed to resist suture slippage under unilateral tension. By applying tension from both directions with the TAL Stitch, it was possible to overcome the locking nature of the Krackow leading to greater slack removal throughout all loops of the suture construct.

The second factor may be the high magnitude of tension applied to

the TAL Stitch during the slack removal process. This level of tension may have allowed for greater constricting effects than a conventional Krackow tensioned by hand. While a conventional Krackow can be tensioned to this magnitude in the lab, without a tensiometer, it may be impractical to apply 250 N (56 lbs) to the distal end of a tendon in the OR as the force would be directly transferred to the patient's anatomy. In contrast, because the TAL Stitch relies on suture to suture tensioning, all additional stress on the anatomy is eliminated.

A potential limitation to the TAL Stitch involves the tying of the proximal loop with 5 square knots after slack-reduction tensioning has occurred. The protrusion of the knot may have negative effects on gliding tendon repairs. In contrast, the reduction of width by the constricting effects of the suture loops may assist tendon gliding.⁴

FiberTape had less gap formation than both FiberWire and LabralTape. This may also support the suture slack theory of gap formation. FiberTape has greater surface area per length as well as a coarser surface than the other materials which may lead to less suture slippage when tensioned.

There are limitations to this study. First, the study was based on porcine flexor tendons instead of human tissue. The biomechanical properties of porcine tissue, although similar, are not identical to human tissue.¹⁶ Second, this was an in vitro study, which does not reproduce the in vivo healing process.

5. Conclusion

The results of this study suggest that gap formation in tendon repair is in part due to suture slack in suture-tendon constructs. This can be significantly reduced if constructs can be tensioned with simultaneous proximal and distal tension, as well as with a substantial magnitude of force, prior to final fixation. Understanding the mechanism behind gap formation in tendon repair may help facilitate innovation in tendon repair rehabilitation and technology.

Conflicts of interest

None.

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