The Effect of Varying Throws in Three Suture Techniques for Tendon Graft Fixation- A Biomechanical Study

Abstract

Purpose: Biomechanically evaluate the optimal number of throws for achieving graft-holding capacity of currently used suture techniques. Methods: Porcine flexor profundus tendons randomly divided into 9 groups of 11 specimens were used. Three stitch configurations, namely the Krachow stitch, locking SpeedWhip (LSW) stitch and modified finger trap (MFT) suture, were assessed with 3, 5 and 7 throws. The Krackow stitch and MFT suture were completed with a No. 2 FiberWire suture (Arthrex), while the LSW stitches were completed with a loop of No. 2 FiberWire suture (Arthrex). Each tendon was pre-tensioned to 100 N for three cycles and then cyclically loaded to 200 N for 200 cycles. Finally, each tendon was loaded to failure. Percent elongation, load to failure, and mode of failure for each suture-tendon construct were measured. Results: After being pre-tensioned, there were no significant differences in the elongation between different suture throws in the LSW and MFT suture groups (p= 0.38 and 0.34). The elongation of the 7-throw group in the Krackow suture group was significantly larger than the 5-throw group (p= 0.01) and 3-throw group (p= 0.03). After cyclic loading, there was no significant difference
in the elongation of each suture technique, with respect to different suture throws. The elongation after 200 loading cycles of the MFT sutures was significantly less than the Krackow sutures and LSW sutures for the 3, 5, and 7-throw. The load to failure and cross-sectional area were not significantly different across all suture groups.

**Conclusion:** This study showed that there are no significant differences in the elongation after cyclic loading and loads to failure among the various suture throws in any of the tested suture configurations. **Clinical Relevance:** The 3-suture throw configuration may provide sufficient fixation of the tendon graft with regard to biomechanical characteristics of elongation and load to failure.
**Introduction**

The increased use of autologous tendon grafts and allograft tendon tissue for ligament reconstruction has motivated surgeons to create a reliable and efficient method of soft tissue fixation within a bone tunnel for free tendon-end grafts.\(^{(1)}\) Elongation of the graft construct under loading that may lead to clinical failure has been of significant concern. Many factors may affect the elongation of the graft construct, including tissue quality, stitch technique, suture strength and number of suture throws.\(^{(2-8)}\) Biomechanical characteristics of the construct elongation may be affected by a number of variables, such as slippage of the suture material from the tendon tissue, viscoelastic elongation of the tendon graft and creep elongation of the suture material.\(^{(9)}\) Increasing the number of suture throws across the tendon graft may provide more contact area between the thread surface and the tendon to ensure security of the construct. However, each additional suture throw may represent more nonlinear material within the tendon and increase the risk of the suture eventually lengthening by pulling through the tendon graft when tensile forces are applied. It is speculated that an optimal number of throws probably exists that allows for sufficient fixation while minimizing the potential for elongation. Some previous reports have studied the effect of the number of throws on the holding strength of the Krackow stitch. Results indicated that there were no significant differences in the
elongation of the construct and maximum failure load with various suture throws. In addition to the Krackow stitch, a variety of other suture techniques exists for grasping and holding soft tissues. The locked Speedwhip (LSW) stitch, which requires fewer needle passes than the Krackow stitch, is popular for its quick application and is often used in anterior cruciate ligament (ACL) reconstruction. In this regard, Su et al. also reported a newly devised suture technique (the modified finger-trap, MFT). This cost-effective technique reduces both the exposure to needles as well as the amount of time necessary for suture placement, and has been commonly adopted in ACL reconstruction by the authors. These locking loop stitches and needleless suture loop techniques could be associated with a difference in the mechanics of the overall construct when compared to the Krackow stitch. Although the aforementioned suture techniques have been widely used for most ligament reconstruction surgeries, there have been no systematic studies of the optimal numbers of throws in these currently used suture configurations that will provide the maximum graft-holding capacity. The purpose of this study was to evaluate the optimal number of throws for achieving graft-holding capacity of three currently used suture configurations (namely, the Krachow stitch, locking SpeedWhip stitch, and MFT suture). We hypothesized that various numbers of suture throws would affect elongation of the fixation construct after pretension and
cyclic loading.

**Methods**

Three different tendon-grasping techniques were investigated: the Krackow stitch, locking SpeedWhip (LSW) stitch and MFT suture. The suture configurations of the Krackow stitch and MFT suture were completed with a No. 2 FiberWire suture (Arthrex), while the locking SpeedWhip stitch was completed with a loop of No. 2 FiberWire suture and a FiberLoop needle (Arthrex).

All three types of suture fixation techniques were performed by the same experienced orthopedic surgeon for each specimen. Fresh porcine hind-leg trotters were stored at -20°C and thawed to room temperature before testing. The flexor profundus tendon was dissected at its insertion site in the feet and kept moist by spraying with 0.9% saline solution during preparation and testing. A total of 99 tendons of equal length and free of any apparent degenerative or pathologic changes were obtained, and randomly divided into 9 groups of 11 specimens each. Each group was randomly assigned to receive 3, 5, or 7 suture throws for one of the three suture configurations (Figure 1 A-C). The elongation test assignment was also randomly ordered.
Biomechanical Testing

Before testing, a transverse section was taken from the distal end of the tendon and photographed alongside a calibration scale with a 6.2-megapixel digital camera (D50; Nikon, Tokyo, Japan) mounted on a tripod. Image analysis software (SigmaScan Pro 5.0; SPSS, Chicago, IL) was employed to calculate the cross-sectional area of the tendon section. During testing, the tendons and sutures were kept moist with normal saline solution maintained at 23°C. After completion of all suture placements, each specimen was mounted on the universal materials testing machine (AG-X; Shimadzu, Tokyo, Japan). The proximal end of the tendon was fixed by means of a clamp to allow an equal length of free tendon for testing. In all three suture configurations, both ends of the suture were knotted with a square knot and looped over a bar on the adapter of the materials testing machine (Figure 2). The initial distance between the clamp end and the center point of the pulley was 200 mm. This setup was used to maintain the same force on both suture limbs, thereby allowing tensioning of the suture within the tendon and ensuring an optimal and repeatable working condition for the tested tendon. This arrangement has been widely used by other authors in biomechanical studies. (7, 10-12)
The suture-tendon construct was pre-tensioned to 100 N at a rate of 200 mm/min for three cycles to simulate the surgical practice of removing slack from the suture-tendon construct before tying the suture. Each tendon was preloaded to 50 N to simulate the tension of sutures tied over a cortical bone bridge in ligament reconstruction. Strength of the fixation was measured by suture loop elongation under a 200-N cyclic loading for 200 cycles, which are considered typical research parameters. A black dot was marked on each suture strand at the point where it exited the tendon; further, a black line was marked on the tendon 5 cm proximal to the initial stitch of the suture construct. Elongation of the suture-tendon construct for the pre-tension test was calculated by measuring the change of the marked dot on the suture strand relative to the marked line on the tendon from its original location to final location after being pre-tensioned. Elongation of both sides of the suture strand was summed to obtain total elongation. The change in elongation of the suture-tendon construct for the cyclic loading test was determined by measuring the total elongation of each suture strand after cyclic loading and subtracting the amount of total elongation in the pre-tension test. The percent elongation used to normalize the result was calculated as the change in total elongation divided by the baseline measurement. A video (DCR-DVD 803 digital video camera; Sony, Tokyo, Japan) recorded the markers during the course of tensile pull force and failure mode,
and was used for later evaluation. Markers were digitized and distances calculated with image analysis software (SigmaScan Pro 5.0) so that precise measurements of elongations could be obtained. All measures were performed by an independent observer blinded to the application of the suture fixation techniques. After cyclic loading for 200 cycles, each sample was loaded to failure in the displacement control, the extensile rate of which was set to 200 mm/min. During testing, the load and displacement were recorded at a sampling rate of 1 kHz. Ultimate load and mode of failure (e.g., suture breakage, suture slippage, or tendon breakage) were recorded.

**Statistical Analysis**

Sample size was calculated according to the elongations after being pre-tensioned in a pilot study, in which there were a total of 27 specimens randomly assigned to 9 subgroups (n=3 each). \( \alpha = .05 \) and a power \((1 - \beta)\) of 0.80 were given for this priori model of power analysis, while effect sizes in the Krackow stitch, LSW stitch and MFT suture calculated from the pilot study were 0.57, 0.62, and 0.57. Sample sizes of 11 specimens in each subgroup were determined with the use of G*Power Version 3.1.3.

Statistical comparisons were conducted with SPSS 16 for Windows (SPSS, Inc.).
Descriptive statistics, including means and standard deviations, were performed for each group. Further, one-way ANOVA with LSD post hoc tests were used to compare the suture percent elongation with the pre-tension, cyclic loading, and load to failure among the different suture throws in the same suture configuration as well as different suture configurations with the same suture throws. Statistical significance was set at $p \leq .05$.

**Results**

After being pre-tensioned, there were no significant differences in elongation between different suture throws ($p= 0.38$ and 0.34) for the LSW and MFT sutures groups. On the other hand, elongation of the 7-throw group of the Krackow-suture groups was significantly larger than the 5- ($p= 0.01$) and 3-throw groups ($p= 0.03$). Elongation of the MFT sutures was significantly less than those of Krackow and LSW sutures in the 3, 5, and 7-throw groups ($p= 0.013$, 0.047 and <0.001). Of the 7-throw groups, elongation of LSW sutures ($5.5\% \pm 1.4\%$) was significantly less than the Krackow sutures ($8.3\% \pm 2.7\%$) ($p=0.002$).

After cyclic loading, there was no significant difference in the elongation of each suture technique with respect to different suture throws (Krackow sutures:}
26.5% ± 3.9%, 25.9% ± 6.1% and 27.6% ± 5.6%, p= 0.70; LSW sutures: 28.6% ± 5.3%, 29.2% ± 4.1% and 27.4% ± 4.0%, p= 0.56; MFT sutures: 19.1% ± 4.4%, 21.0% ± 3.8% and 21.3% ± 5.3%, p= 0.37). Elongation after 200 loading cycles for the MFT sutures was significantly less than those of Krackow and LSW sutures in the 3, 5, and 7-throw groups. There were no significant differences in elongation after 200 loading cycles between the Krachow and LSW sutures groups for 3, 5, and 7 throws (p= 0.35, 0.14 and 0.83).

Similarly, the failure loads were not significantly different among the 3, 5, or 7-throw groups for any of the tested suture techniques (p= 0.84, 0.71 and 0.72); further, there was also no significant difference among different suture methods for any of the suture throw numbers tested (p= 0.36, 0.34 and 0.20).

**Discussion**

This study investigated the biomechanical properties of different suture throws for the Krackow stitch, LSW stitch and MFT suture. The purpose of this study was not to advocate which suture technique was the best for fixation of the tendon graft, but rather to demonstrate the optimal number of suture throws in each configuration that provide the maximum fixation and the least potential for elongation. Results of
this study indicate that the effect of increasing suture throws on pretensioned suture elongation varied among the different suture configurations examined, depending on the various sewing processes and suture placements in each configuration. No significant differences in elongation were found after cyclic loading and loads to failure among the various suture throws in any of the tested suture configurations.

Pre-tensioning simulated the surgeon’s effort to remove slack from the original suture-tendon construct during preparation of the tendon graft. Failure to pre-tension the suture adequately would lead to subsequent elongation after the tendon graft was secured. In the Krackow stitch, there was no significant elongation difference observed after pretensioning in the 3 and 5-throw groups, which accords with Sakaguchi et al.(13) They investigated the Krachow stitch with 3, 5-paired locking loops, and demonstrated that no significant difference in elongation occurred after a preload of 50 N was applied for 10 minutes. However, elongation of 7 throws after pretensioning was significantly larger than for 3 and 5 throws in the present study. The Krackow stitch employs multiple locking loops along each side of the tendon. Sustained tensioning on each strand is needed while deploying the stitches to minimize suture slack during placement of each locking loop; however, this is difficult to achieve in practice. Therefore, excess suture slack can inevitably be
expected within each locking loop during the suturing procedure. It is possible that more than 5 throws would provide greater potential for elongation caused by increasing the slack or nonlinear suture with each sequentially added suture throw. In the LSW stitch and MFT suture, elongations in various throw groups showed no difference after being pre-tensioned. The LSW stitch, using a double arm suture, requires half as many needle passes through the tendon as compared with the Krackow stitch. By contrast, the MFT suture is a grasping suture, and consists of initial interlacing loops that provide a secure hold on the tendon. We found that it is relatively easier to apply sustained tension during the deployment of loop sutures for the LSW stitch and MFT suture than for the Krackow stitch, thus minimizing the slack of each loop suture. Comparing the pretension elongation among these three suture configurations, the elongations of the MFT suture were significant less than the elongations of both of Krackow and LSW stitches for any number of throws in our study. This finding is in agreement with a previous study(7) employing the same model, which found less pretension elongation with the MFT suture than with the other two stitch configurations with 5 suture throws.

Suture elongation of the graft construct under cyclic loading, which may lead to clinical failure, remains a significant concern. After cyclic loading, elongation did
not change according to the number of suture throws in the Krackow stitch, which is consistent with previous studies that have evaluated the biomechanical properties of graft fixation with various throws of the Krackow stitch. Sakaguchi et al. (13) showed that elongations of the Krackow stitch in 3, 5-paired locking loops were insignificant after 1500 loading cycles between 50 N and 200 N. McKeon et al. (11) tested the Krackow stitch in 2, 4, and 6-paired locking loops, using porcine Achilles tendons, and concluded that the number of paired locking loops (2, 4, or 6) did not affect the amount of elongation at failure. Further, Hapa et al. (14) examined the biomechanical characteristics of different Krackow stitch configurations using high strength sutures (Fiberwire). Their results revealed that elongations of the suture loop after cyclic loading (0 to 200 N, 200 cycles) were not significantly different between the 2 or 4 paired locking loops. Our results suggest that the initial 3 throws at each side provide sufficient fixation of the tendon graft, and that adding further suture stitches does not decrease elongation after cyclic loading. For the MFT suture, no significant differences in elongation after cyclic loading in the 3, 5 and 7-throw groups were found. The MFT suture is based on multiple interlacing loop suture throws and a final rolling-hitch suture, which provides a secure hold on the graft by constricting the graft when tension is imparted on the sutures. Our results suggest that the rolling-hitch suture plays an important role in holding the graft, thereby allowing a
reduction in the number of suture throws to 3 throws while simultaneously not increasing elongation after cyclic loading. These findings are compatible with those of da Assuncao et al. (15), who employed a similar grasping suture configuration with 5 suture throws, but lacked the final rolling-hitch suture. The failure behavior in their study revealed that the suture unraveled after slipping off the tendon and snapped at the final throw during tensile loading. In the LSW stitch, elongations in the various throw groups were not different after cyclic loadings. The LSW stitch was performed with continuous suture loops and additional locking stitches. There was 1 locking stitch in the 3-throw group, 2 in the 5-throw group, and 3 in the 7-throw group. Our results suggest the possibility that 3 suture throws with 1 locking stitch in the LSW suture provides sufficient fixation, meaning that adding more suture throws or locking stitches might not offer superior outcomes. Comparisons of elongation after cyclic loading among the three suture configurations illustrate that elongations of the MFT suture were significantly less than those of the Krackow and LSW stitches for all numbers of throws tested. These results are compatible with those of the previous study employing the same model (7), which found that the MFT suture group had less elongation after cyclic loading than the other two stitch configurations with 5 suture throws. The biomechanical property of suture elongation after cyclic loading represents the slippage of the suture material within the tendon graft by compressing
the graft fibers within the locking loops to decrease the radius of the locking loop when tensile forces are applied. Results of our present study demonstrate that the effect of adding more suture throws on suture elongation after cyclic loading does not significantly affect the construct. As such, using 3 throws would be an optimal choice since it could save time in harvesting the tendon graft and decrease the potential damage of the tissue being constricted by the suture loops. Furthermore, it is reasonable to assume that fewer suture throws may provide a larger area of tendon-bone interface with less suture material, thus likely improving tendon-to-bone healing.

The results of the failure load of the suture-tendon constructs in each subgroup are shown in Table 1. We found that the number of suture throws (3, 5, or 7) and the different kinds of suture techniques did not affect the load to failure, and rupture of the sutures was most commonly found during failure. These results were expected since several studies have reported similar findings. Deramo et al.(10) compared the biomechanical properties between the Krackow suture and non-locking SpeedWhip suture, the loads to failure of which were not different between the two groups. Jassem et al.(1) compared the effect of varying suture pitch over a standardized length of Achilles tendon. Their results showed that failure loads were not significantly different
between the two groups. In the study of Su et al. (7) employing the same model, no difference in failure loads were found between different suture techniques with 5 suture throws. Sakaguchi et al. (13) compared the Krackow stitch, baseball stitch and whipstitch with 6 throws and 10 throws each. They showed that the failure loads in the Krackow stitch with 6 and 10 throws were higher than the other groups; however, most specimens in the Krackow stitch group failed by suture rupture, while suture pullout was more common in the other groups. McKeon et al. (11) also found that the number of paired locking loops (2, 4 or 6) did not affect the failure loads, but that adding a second interlocking suture at 90° to the first nearly doubles the loads to failure. The test configuration in the present study was adapted from that of Su et al. (7), where securing sutures over the bar with 5-throw square knots probably contributed to stress risers in the knot while friction of the suture under the bar resulted in suture breakage at the knot level, which is similar to previous studies. Therefore, it can be assumed that the peak load to failure of the suture-tendon construct may actually exceed the breaking strain of the suture since suture breakage was the mode of failure.

As with most other studies, some limitations in this investigation exist. First, we used porcine flexor profundus tendons instead of human cadaveric tendons. Although previous studies have validated the use of porcine tendons (7, 13), there still may be
different properties of a porcine and human tendon which could bias this study. Consequently, it would be advisable to repeat this study with fresh human cadaveric hamstring tendons. Despite this limitation, there was consistency among the tendons and they were randomly allocated for use. Second, this study was focused on suture elongation in the suture-tendon construct without considering the physiological healing process that could contribute to the success of tendon graft reconstruction surgery. Therefore, these findings only offer relative results and cannot be directly extrapolated to clinical settings. Third, this study assessed tensile properties using a cyclic loading test in a single axial direction, which do not represent physiologic conditions. Tendon grafts in joints are often subject to compressive and shear forces in addition to tensile loads; however, this is complex to simulate with an in vitro setup. Finally, the intent of this study was to determine the optimal number of suture throws that allow for maximal fixation and the least potential for suture elongation. Although some investigations have reported that increasing the number of suture throws might constrict more of the intratendinous vessels and reduce tendon vascularization, the clinical relevance of excess suture material on the tendon graft is unknown. Consequently, further clinical histological studies are needed to substantiate that excess suture material in the tendon-bone interface may interfere with the tendon-to-bone healing.
Conclusion

This study showed that there are no significant differences in elongation after cyclic loading and loads to failure among the various suture throws for the three kinds of suture configuration investigated. Elongation of 7 throws after pretension was significantly larger than 3 and 5 throws in the Krackow stitch configuration.
Reference


7. Su WR, Chu CH, Lin CL, Lin CJ, Jou IM, Chang CW. The modified


2013;52:448-450.


Figure 1. Three stitch configurations: (A) the Krachow stitch, (B) locking SpeedWhip (LSW) stitch, and (C) modified finger trap (MFT) suture were assessed with varying suture throws (3, 5 and 7 throws).

Figure 2. Test specimen setup in the MTS materials testing system.
Table 1. Biomechanical Properties among the various suture throws for the three kinds of suture configuration investigated

<table>
<thead>
<tr>
<th></th>
<th>Krackow Sutures (throws)</th>
<th>LSW Sutures (throws)</th>
<th>MFT Sutures (throws)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Elongation after</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-tension, mm (%)</td>
<td>0.8 ± 0.1</td>
<td>0.7 ± 0.3</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>(6.2 ±0.9)\textsuperscript{a}</td>
<td>(5.8±2.5)\textsuperscript{a}</td>
<td>(6.9 ±2.3)\textsuperscript{a}</td>
</tr>
<tr>
<td>Elongation after</td>
<td>3.4 ± 0.7</td>
<td>3.4 ± 0.6</td>
<td>3.5 ± 0.6</td>
</tr>
<tr>
<td>cyclic loading, mm (%)</td>
<td>3.4 ± 0.7</td>
<td>3.4 ± 0.6</td>
<td>3.5 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>(26.5 ±3.9)\textsuperscript{b}</td>
<td>(25.9 ±6.1)\textsuperscript{b}</td>
<td>(27.6 ±5.6)\textsuperscript{b}</td>
</tr>
<tr>
<td>Load to failure, N</td>
<td>318 ± 33</td>
<td>330 ± 36</td>
<td>322 ± 36</td>
</tr>
</tbody>
</table>

\*Significantly different elongation after pre-tension between different suture techniques with same suture throws in LSD post-hoc test: $P < 0.05$

\textsuperscript{a}Significantly different elongation after pre-tension between different suture throws within the same suture technique in LSD post-hoc test: $P < 0.05$

\textsuperscript{b}Significantly different elongation after cyclic loading between different suture techniques with same suture throws in LSD post-hoc test: $P < 0.05$