Original Article
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Biomechanical Characterization of a New Locking Loop Stitch for Graft Fixation versus Krackow Stitch

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Background: The purpose of this study was to quantify and compare the biomechanical characteristics of a new locking loop stitch (LLS), developed utilizing the concepts of both running locking stitch and needleless stitch, to the traditional Krackow stitch.

Methods: The Krackow stitch with No.2 braided suture and the LLS with 1.3-mm augmented polyblend suture tape were compared biomechanically. The LLS was performed with single strand locking loops and wrapping suture around the tendon, resulting in half the needle penetrations through the graft compared to the Krackow stitch. Twenty bovine extensor tendons were divided randomly into two groups. The tendons were prepared to match equal thickness and cross-sectional area. Each suture-tendon was stitched and preloaded to 5 N for 60 seconds, cyclically loaded to 20 N, 40 N, and 60 N for 10 cycles each, and then loaded to failure. The deformation of the suture-tendon construct, stiffness, yield load, and ultimate load were measured.

Results: The LLS had significantly less deformation of the suture-tendon construct at 100 N, 200 N, 300 N, and at ultimate load compared to the Krackow stitch (Krackow stitch and LLS at 100 N: 1.3 ± 0.1 mm and 1.0 ± 0.2 mm, $p < 0.001$; 200 N: 3.0 ± 0.3 mm and 1.9 ± 0.2 mm, $p < 0.001$; 300 N: 5.1 ± 0.6 mm and 2.9 ± 0.4 mm, $p < 0.001$; ultimate load: 12.8 ± 2.8 mm and 5.0 ± 1.2 mm, $p < 0.001$). The LLS had significantly greater stiffness (Krackow stitch and LLS: 97.5 ± 6.9 N/mm and 117.2 ± 13.9 N/mm, $p < 0.001$) and yield load (Krackow stitch and LLS: 66.2 ± 15.9 N and 237.9 ± 93.6 N, $p < 0.001$) compared to the Krackow stitch. There was no significant difference in ultimate load (Krackow stitch: 450.2 ± 49.4 N; LLS: 472.6 ± 59.8 N; $p = 0.290$).

Conclusions: The LLS had significantly smaller deformation of the suture-tendon construct compared to the Krackow stitch. The LLS may be a viable surgical alternative to the Krackow stitch for graft fixation when secure fixation is necessary.

Keywords: *Locking loop, Krackow, Graft, Biomechanics*

Ligament reconstruction using tendon grafts is commonly employed for the treatment of ligamentous insufficiency. Running stitches that penetrate the tendon with a needle, such as locking Krackow stitch and non-locking whip stitch, have been widely used for graft preparation.[1-3] Since tendon penetration with a needle is time-consuming and risks tendon damage,[4] some surgeons have advocated needleless stitches.[4-6] Needleless stitches such as a

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modified finger-trap suture, modified rolling-hitch suture, modified Prusik knot, and Wittstein suture loop are performed by wrapping the suture around the tendon to increase the contact area between the suture-tendon interface, resulting in increased grip strength and resistance against tensile force.[5-9]

Secure primary fixation of the graft-bone construct is crucial to achieve biological healing.[10] There are several risk factors for postoperative laxity due to loosening of the graft fixation including deformation of the suture-tendon construct, knot slippage, suture breakage, and fracture at the fixation site.[11-14] Needleless stitches have a risk of the suture unraveling at low tensile load,[6,7] resulting in postoperative laxity. Consequently, surgeons tend to use needleless stitches for handling the graft and running stitches for graft fixation. In previous studies comparing running locking loops (Krackow stitch) and running non-locking loops (whip stitch), the Krackow stitch showed less deformation of the suture-tendon construct than the whip stitch.[3,15-17] However, even with the Krackow stitch, more than 3-mm deformation of the suture-tendon construct, which is one of the criteria of postoperative laxity after anterior cruciate ligament reconstruction,[18,19] was found after cyclic loading to 200 N.[20]

Recently, a wide high-tensile strength polyblend suture tape has been gaining popularity as an alternative to the conventional high-tensile round suture that potentially achieves a secure suture-tendon construct. As for the inherent mechanical properties of suture materials, a 1.3-mm-wide suture tape had greater tensile stiffness than a No.2 round suture.[21] When porcine tendons were sutured with Krakow stitch, however, the stiffness of the 1.3-mm-wide was less than that of the No.2 round suture.[22] Hong et al.[22] inferred that larger diameter tendon holes owing to wider suture penetrations compromised the suture-tendon construct. Simple, quick, and secure tendon grasping techniques are desired for ligament reconstruction using tendon grafts. Here, a new suture technique called the locking loop stitch (LLS), was developed. It incorporated principles of both the running locking stitch and needleless stitch using a suture tape that reinforces the weak link between the tendon holes and sutures.

The objective of this study was to evaluate the biomechanical properties of the new suture-tendon construct, the LLS, and compare it to the widely used Krakow stitch. The hypothesis was that deformation of the suture-tendon construct of the LLS would be less than that of the Krackow stitch.

METHODS

Institutional Review Board or Institutional Animal Care and Use Committee approval was waived by our institution for this basic science study.

A total of 20 pre-cut fresh-frozen bovine extensor tendons from the forelimbs were used in this controlled laboratory study. The tendons were trimmed and prepared to size match them across the two groups. The mean tendon thickness and mean cross-sectional area of the tendon in the two groups were as follows: Krackow, 3.0 ± 0.1 mm and 22.6 ± 0.56 mm^2, respectively; LLS, 3.0 ± 0.1 mm and 22.6 ± 0.42 mm^2, respectively ($p = 0.55$). After thawing at room temperature, all tendons were prepared and kept moist throughout testing with 0.9% saline solution. Tendon thickness and cross-sectional area were measured using an area micrometer.[23,24]

Two tendon-grasping techniques were investigated: the Krackow stitch and the LLS (Fig. 1). Each tendon was randomly divided into two groups (10 tendons per group). For each suture configuration, 3 locking loops were performed. The Krackow stitch required 6 needle penetrations through the graft, while 3 penetrations were required for the LLS. Each locking loop was sutured at 5-mm intervals. The most distal suture throw was set at a 7-mm distance from the free end of the tendon. A single orthopedic surgeon (YI) performed all tendon grasping sutures.

Krackow Stitch

The Krackow stitch was carried out by locking loops along

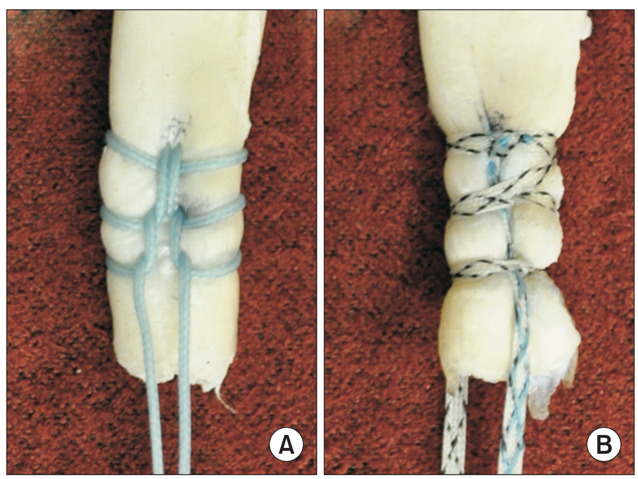

Fig. 1. Photograph showing the prepared suture-tendon constructs of the Krackow stitch (A) and locking loop stitch (B).

each side of the tendon with No. 2 FiberWire (Arthrex, Naples, FL, USA). The pitch between suture throws was set at 5 mm,[1,3] and the distance between the two symmetric strands was 1 mm. Locking loop slack was removed using hand tension (Fig. 1A).

Locking Loop Stitch

The LLS was performed with a 1.3-mm-wide SutureTape reinforced with a 4-0 suture (Arthrex). The LLS was started by wrapping the suture around the tendon, followed by penetration of the center of both the reinforced SutureTape and tendon to make a locking loop at the proximal starting point. For each subsequent throw, a simple wrapping suture was performed and followed by needle penetration of wrapping suture, the reinforced suture tape, and tendon together. Each wrapping throw and locking loop was performed at 5-mm intervals with hand tension to eliminate excess suture material within the loops (Figs. 1B, 2, and 3).

Biomechanical Testing

A material testing machine (Instron, Canton, MA, USA) was used to perform biomechanical testing. The clamp for the non-sutured side of the tendon graft was mounted on an X-Y translator. A hook loading device was attached to the crosshead and load cell. The suture construct was adjusted so that the direction of loading was perpendicular to the tendon. Suture strands were tied with 10 square knots after wrapping around the hook loading device. The initial distance between the lower clamp and the bottom of the hook was set at 50 mm (Fig. 4).

Each tendon was preloaded with 5 N for 60 seconds, and then cyclic loading was performed from 5 N to 20 N for 10 cycles, from 5 N to 40 N for 10 cycles, and from 5 N

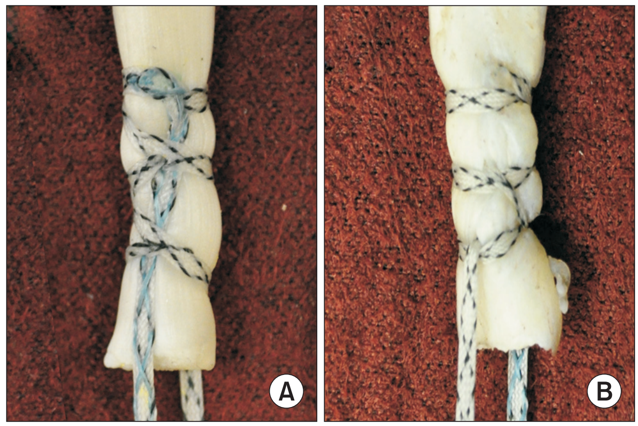

Fig. 3. Photographs of the final suture-tendon construct of the locking loop stitch. (A) Front side view. (B) Back side view.

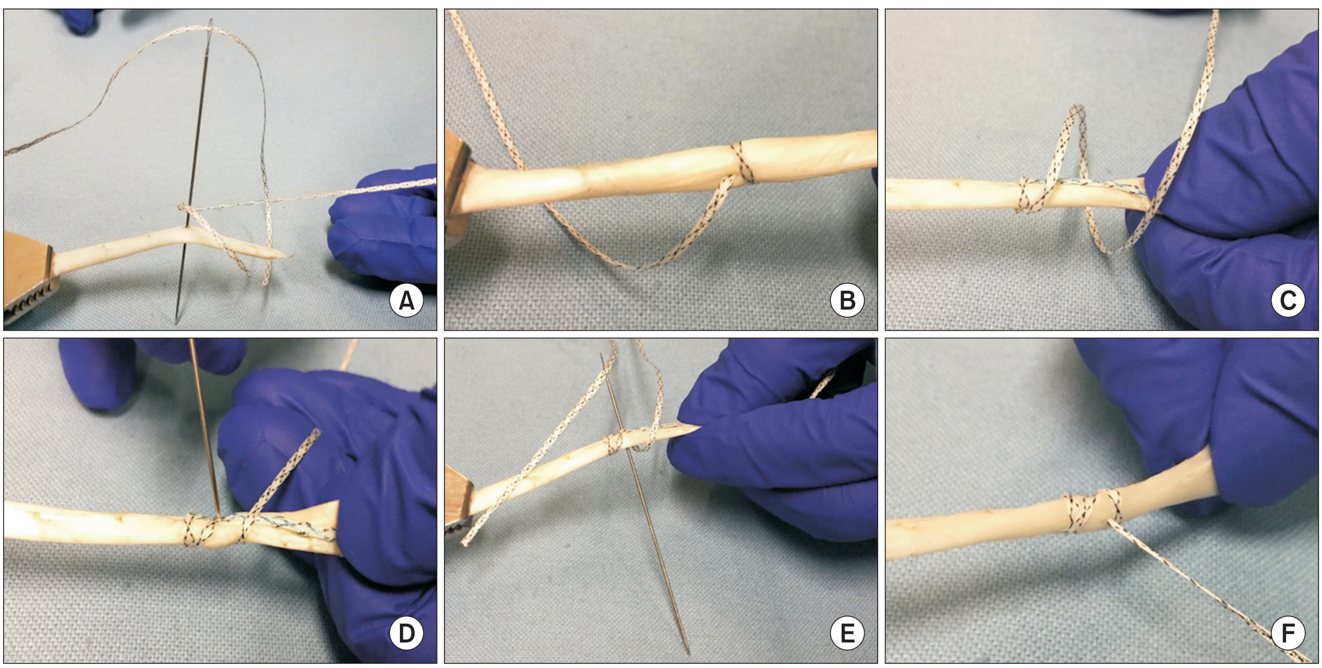

Fig. 2. Procedure for the locking loop stitch. (A) The center of both the reinforced polyblend tape and tendon is penetrated by an initial wrapping throw to make a locking loop. (B) Slack of the locking loop is removed by hand tension (back side view). (C) The next simple wrapping suture is performed distally. (D) The wrapped suture is pinned 5 mm distal to the first throw. (E) The wrapped suture, reinforced by the polyblend tape, and tendon are penetrated together to make a second locking loop. (F) Locking loop slack is removed again (back side view).

to 60 N for 10 cycles. After cyclic testing, each specimen was loaded to failure. The crosshead speed was set at 60 mm/min for both cyclic testing and load to failure testing.

Measurements

The width and thickness of the suture-tendon constructs at the second locking loop were measured before and after cyclic testing three times with a digital caliper. Permanent dots were marked on the tendon 3 mm proximal to the most proximal throw and on the suture 7 mm distal to the most distal throw, which corresponded to the end of the free tendon. Deformation of the suture-tendon construct was defined as the change in length from the dot on the tendon to the dot on the sutures (Fig. 4).[17,20] A video digitizing system and WINanalyze motion software (Mikromak Service) were used to analyze the data. A standard ruler was placed adjacent and parallel to the tendon to provide a calibration scale.[25,26]

For cyclic loading, stiffness, hysteresis at the 10th cycle of each loading condition, and total deformation of the suture-tendon construct at the end of each loading condition were measured. In failure testing, yield load, ultimate load, energy absorbed, and deformation at both yield and ultimate load as well as failure mode were measured. Also, the load at 1, 2, 3 mm of deformation of the suture-tendon construct, and deformation of the suture-tendon construct at 100 N, 200 N, and 300 N were evaluated. From the load-displacement curve, the yield point was defined as the point where the slope deviated from linear, and ultimate point was defined as the peak of the load displacement curve.

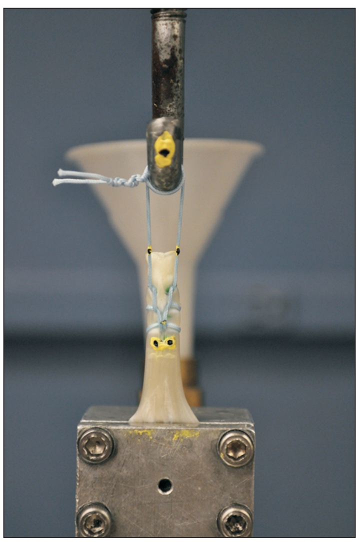

Fig. 4. Photograph of the suture-tendon construct mounted on the Instron material testing machine and knotted around the loading hook.

Statistical Analysis

Tendon dimensions before and after cyclic testing were compared with the Wilcoxon signed-rank test. Comparisons of loading properties between the Krackow stitch and the LLS were performed with the Wilcoxon rank sum test. A sample size calculation was performed using the difference in ultimate load. Based on the mean and standard deviation of the first four specimens in each group (mean difference, 40.2; mean standard deviation, 54.3), a total of 18 specimens (9 specimens in each group) were determined as needed to reach $\alpha = 0.05$ and power $(1-\beta)$ of 0.80. All statistical analyses were performed using JMP software package (ver. 11; SAS Institute). A $p < 0.05$ was considered statistically significant.

RESULTS

Cyclic Testing

The width of the Krackow suture-tendon constructs became wider after cyclic loading ($p = 0.002$). There was no significant difference in Krackow suture-tendon construct thickness after cyclic loading ($p = 0.23$). There were no significant differences in the LLS suture-tendon construct width or thickness before and after cyclic loading ($p = 0.92$ and $p = 0.19$, respectively) (Table 1).

The stiffness of the LLS at cycle 10 of 5–60 N was significantly greater than that of the Krackow stitch ($p = 0.016$). Hysteresis in the LLS during cycle 10 was significantly smaller than that in the Krackow stitch at each loading condition ($p = 0.028$). Deformation of the suture-tendon construct in the LLS group was significantly smaller than that in the Krackow stitch group with each loading condition ($p = 0.041$) (Table 2).

Table 1. Prepared Suture-Tendon Construct Dimensions before and after Cyclic Loading

Variable	Before cyclic loading	After cyclic loading	*p*-value
Krackow stitch			
Thickness (mm)	3.9 ± 0.3	3.8 ± 0.3	0.23
Width (mm)	7.7 ± 0.4	8.1 ± 0.4	0.002
Locking loop stitch			
Thickness (mm)	4.4 ± 0.3	4.5 ± 0.3	0.19
Width (mm)	5.4 ± 0.2	5.5 ± 0.2	0.92

Values are presented as mean ± standard deviation.

Load to Failure Testing

The LLS had significantly less deformation of the suture-tendon construct at 100 N, 200 N, and 300 N, compared to the Krackow stitch (Krackow stitch and LLS at 100 N: 1.3 ± 0.1 mm and 1.0 ± 0.2 mm, $p < 0.001$; 200 N: 3.0 ± 0.3 mm and 1.9 ± 0.2 mm, $p < 0.001$; 300 N: 5.1 ± 0.6 mm and 2.9 ± 0.4 mm, $p < 0.001$). The load of the suture-tendon construct of the LLS was significantly higher than that of the Krackow stitch at 1-, 2-, and 3-mm displacement (Krackow stitch and LLS at 1 mm: 81.7 ± 6.7 N and 107.4 ± 18.2 N, $p < 0.001$, 2 mm: 143.4 ± 12.9 N and 219.1 ± 26.2 N, $p < 0.001$, 3 mm: 201.1 ± 16.7 N and 318.1 ± 39.6 N, $p < 0.001$).

The LLS showed significantly higher stiffness ($p < 0.001$), yield load ($p < 0.001$), deformation at yield ($p = 0.002$), and energy absorbed to yield load ($p < 0.001$) than the Krackow stitch (Table 3). The LLS had significantly lower deformation at ultimate load ($p < 0.001$) and energy absorbed to ultimate load ($p < 0.001$) than the Krackow stitch. There were no significant differences in ultimate load between the Krackow stitch and the LLS ($p = 0.290$). All LLS constructs failed by suture breakage. The Krackow stitches sequentially failed from the distal loop to the proximal loop. For the Krackow stitch, 4 of 10 (40%) failed by tendon cut through and 6 of 10 (60%) failed by suture breakage in the process of sequential failure.

Table 2. Biomechanical Parameters during Cyclic Testing

Variable	Krackow stitch	Locking loop stitch	*p*-value
Stiffness in cycle 10 (N/mm)			
5–20 N	80.1 ± 21.4	86.2 ± 36.5	0.880
5–40 N	100.3 ± 22.9	123.3 ± 42.8	0.174
5–60 N	113.2 ± 23.6	151.6 ± 32.5	0.016
Hysteresis in cycle 10 (N/mm)			
5–20 N	0.2 ± 0.1	0.1 ± 0.1	0.028
5–40 N	1.4 ± 0.3	1.0 ± 0.3	0.004
5–60 N	3.3 ± 0.6	2.2 ± 0.5	< 0.001
Deformation of the suture-tendon construct at the end of cycle 10 (mm)			
5–20 N	0.4 ± 0.2	0.3 ± 0.1	0.041
5–40 N	1.0 ± 0.2	0.6 ± 0.2	< 0.001
5–60 N	1.7 ± 0.3	0.9 ± 0.2	< 0.001

Values are presented as mean ± standard deviation.

DISCUSSION

This study demonstrated that the LLS, a new suture technique developed with the concept of both running locking stitch and needleless stitch using a suture tape that reinforced the weak link between tendon holes and suture tapes, had significantly greater stiffness, yield load, and smaller deformation of the suture-tendon construct at 100 N, 200 N, 300 N, and at ultimate load compared to the Krackow stitch. The loads at 1, 2, and 3 mm of defor-

Table 3. Biomechanical Comparison of Load to Failure Characteristics between the Krackow Stitch and the Locking Loop Stitch

Characteristic	Krackow stitch	Locking loop stitch	*p*-value
Stiffness (N/mm)	97.5 ± 6.9	117.2 ± 13.9	< 0.001
Yield load (N)	66.2 ± 15.9	237.9 ± 93.6	< 0.001
Energy absorbed to yield load (N/mm)	24.5 ± 14.9	276.2 ± 195.0	< 0.001
Deformation at yield load (mm)	0.8 ± 0.2	2.1 ± 0.9	0.002
Ultimate load (N)	450.2 ± 49.4	472.6 ± 59.8	0.290
Energy absorbed to ultimate load (N/mm)	3,578.5 ± 870.1	1,273.1 ± 453.1	< 0.001
Deformation at ultimate load (mm)	12.8 ± 2.8	5.0 ± 1.2	< 0.001
Failure mode			-
Suture breakage	6*	10	
Tendon cut through	4	0	

Values are presented as mean ± standard deviation.
*Suture breakage in the process of sequential failure.

mation of the suture-tendon construct in the LLS group was significantly greater than those in the Krackow stitch group, although there was no significant difference in ultimate load between the two techniques. All LLS constructs failed by suture breakage, but 4 of 10 in the Krackow stitch failed by tendon cut through. As the LLS has half the needle penetrations through the tendon, which could potentially lead to reduced surgical time,[4] resulting in a more secure suture-tendon construct compared with the Krackow stitch, our findings suggest that the LLS could be a viable alternative to the conventional stitches, such as the Krackow stitch, whip stitch, and needleless stitches.

The Krackow stitch has been proven to be a secure tendon-grasping technique.[1-3,15-17,20] Although the Krackow stitch provides secure fixation at the suture-tendon construct,[3,15-17] the placement of two strands of locking loops is time-consuming and causes tendon damage due to multiple needle penetrations.[4] Conversely, needleless stitches have the advantages of decreasing the risk of tendon damage and reducing time for suture placement,[4-6] but there is risk of unraveling at low tensile loads.[6,7] The LLS is a hybrid technique of the running locking stitch and needleless stitches, compensating for the disadvantages of each suture technique. With half of the needle penetrations compared to the Krackow stitch and no risk of unraveling, the LLS may reduce surgical time and provide secure fixation of the suture-tendon construct for small tendons, such as semitendinosus tendon, gracilis tendon, palmaris longus tendon, and long head of the biceps tendon.

In the current study, deformation of the suture-tendon constructs in the LLS was significantly less than that of the Krackow stitch. A 3-mm postoperative laxity for anterior cruciate ligament reconstruction is thought to be one of the criteria of clinical failure.[18,19] Although Hong et al.[20] reported that even the Krackow stitch had 3.4-mm deformation of the suture-tendon construct after cyclic loading 200 N for 200 cycles, the Krackow stitch has been widely utilized for secure tendon fixation.[1-3,15-17] Our findings suggest that the LLS could be a viable option for graft fixation when secure fixation is necessary, such as suture-post fixation, pull-out button fixation, or docking fixation.

The LLS had a significantly smaller deformation of the suture-tendon construct compared with the Krackow stitch. All LLS constructs failed by suture breakage. For the Krakow stitch, 6 of 10 failed by suture breakage and 4 of 10 failed by tendon cut through in a sequential manner as previously reported.[1] The most distal locking loop tightened, then cut through the distal tendon, followed by the next most distal locking loop, which then failed in the same manner. As deformation of the suture-tendon construct is accompanied by suture cut through the tendon, the LLS may decrease tendon damage and fail in a more predictable manner compared to the Krackow stitch.

In this study, there was no significant difference in ultimate load between the LLS and the Krackow stitch. As needle penetrations through the suture have a risk of compromising the ultimate load of the suture-tendon construct, reinforced polyblend suture tape was utilized for the LLS, which has a wider area for needle penetration. Our findings suggest that the LLS with reinforced polyblend suture tape would provide an equivalent ultimate load to the Krackow stitch with No. 2 FiberWire.

With the LLS, there were no significant differences in tendon width and thickness before and after the cyclic testing. As the tendon width becomes narrower, the contact area between tendon and bone becomes smaller, which stunts biologic healing.[10] Significant narrowing of the tendon width was not observed in the LLS, and therefore it is unlikely that the LLS would compromise biologic healing.

In the Krackow stitch, cyclic loading significantly increased tendon width, but not tendon thickness. For the Krackow stitch, locking loops with needle penetrations are performed on both sides of tendon, while no wrapping loops are placed on the center of tendon.[2] Our findings suggest that loading on the double-strand loops may cause widening of the needle holes and suture cutting through the tendon into three bundles, whereas the center of tendon remains intact.

In the current study, a 1.3-mm-wide polyblend suture tape with 4-0 suture was used for the LLS, whereas a conventional No.2 round suture was used for the Krackow stitch. In recent studies evaluating biomechanical properties of the Krackow stitch, a 1.3-mm-wide polyblend suture tape demonstrated less stiffness and more deformation of the suture tendon construct compared with a conventional No.2 high-tensile round suture.[22,27] Hong et al.[22] inferred that larger diameter tendon holes owing to wider suture penetrations compromised the stiffness and deformation of the suture-tendon construct. To reinforce the weak-link between the tendon holes and sutures in the running locking stitch, the LLS, polyblend tape, and tendon were penetrated together in the LLS. As needle penetrations through a No.2 conventional high-tensile round suture were technically demanding, the 1.3-mm-wide polyblend suture tape with 4-0 suture was used for the LLS.

There were several limitations in this study. First, we used bovine tendons instead of human tendons. However, a previous study reported that bovine extensor tendons had similar biomechanical properties to human tendons.[28] Second, this biomechanical study did not consider biologic healing, but secure fixation at time zero is considered to be an important factor for graft healing. Third, two different suture materials were used for the comparison between Krackow stitch and LLS. As needle penetrations through a No.2 conventional high-tensile round suture were technically demanding, a 1.3-mm-wide polyblend suture tape with 4-0 suture was used for the LLS. Fourth, we only evaluated 3 suture throw locking loop configurations, because three suture throws for the Krackow stitch has been shown to provide sufficient fixation strength of the suture-tendon construct.[3,20] Future studies may consider evaluating the effect of the number of loops in the LLS on the biomechanical characteristics of the suture-tendon construct.

The LLS had significantly smaller deformation of the suture-tendon construct compared to the Krackow stitch. The LLS may be a viable surgical alternative to the Krackow stitch for graft fixation when secure fixation is necessary.

CONFLICT OF INTEREST

This study was partially funded by Arthrex, Inc., which provided the specimens and surgical implants for this study. The funding sources did not play any role in the design of the study or the evaluation or reporting of data.

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REFERENCES

1. Jassem M, Rose AT, Meister K, Indelicato PA, Wheeler D. Biomechanical analysis of the effect of varying suture pitch in tendon graft fixation. Am J Sports Med. 2001;29(6):734-7.
2. Krackow KA, Thomas SC, Jones LC. A new stitch for ligament-tendon fixation. Brief note. J Bone Joint Surg Am. 1986;68(5):764-6.
3. Hahn JM, Inceoglu S, Wongworawat MD. Biomechanical comparison of Krackow locking stitch versus nonlocking loop stitch with varying number of throws. Am J Sports Med. 2014;42(12):3003-8.
4. Camarda L, Giambartino S, Lauria M, Saporito M, Triolo V, D'Arienzo M. Surgical time for graft preparation using different suture techniques. Muscles Ligaments Tendons J. 2016;6(2):236-40.
5. Hong CK, Yeh ML, Jou IM, Lin CL, Chang CH, Su WR. Evaluation of 3 needleless grasping suture techniques for soft-tissue graft fixation: a porcine biomechanical study. Arthroscopy. 2015;31(6):1151-5.
6. Hong CK, Kuo TH, Yeh ML, Jou IM, Lin CL, Su WR. Do needleless knots have similar strength as the Krackow suture?: an in vitro porcine tendon study. Clin Orthop Relat Res. 2017;475(2):552-7.
7. da Assuncao RE, Haddad R, Bruce WJ, Walker P, Walsh WR. Whip stitch versus grasping suture for tendon autograft. Eur J Orthop Surg Traumatol. 2013;23(1):105-9.
8. Hong CK, Chang CH, Chiang CH, Jou IM, Su WR. Hamstring graft preparation using a modified rolling hitch technique. Arthrosc Tech. 2014;3(3):e321-4.
9. Camarda L, Pitarresi G, Fazzari F, Tumino D, D'Arienzo M. Biomechanical comparison between the modified rolling-hitch and the modified finger-trap suture techniques. Arch Orthop Trauma Surg. 2016;136(11):1595-600.
10. Cole BJ, Sayegh ET, Yanke AB, Chalmers PN, Frank RM. Fixation of soft tissue to bone: techniques and fundamentals. J Am Acad Orthop Surg. 2016;24(2):83-95.
11. Latendresse K, Dona E, Scougall PJ, Schreuder FB, Puchert E, Walsh WR. Cyclic testing of pullout sutures and micromitek suture anchors in flexor digitorum profundus tendon distal fixation. J Hand Surg Am. 2005;30(3):471-8.
12. Schliemann B, Lenschow S, Schurmann P, et al. Biomechanics of a new technique for minimal-invasive coracoclavicular ligament reconstruction. Knee Surg Sports Traumatol

Arthrosc. 2013;21(5):1176-82.

13. Lee GH, Limpisvasti O, Park MC, McGarry MH, Yocum LA, Lee TQ. Revision ulnar collateral ligament reconstruction using a suspension button fixation technique. Am J Sports Med. 2010;38(3):575-80.

14. Tetsumura S, Fujita A, Nakajima M, Abe M. Biomechanical comparison of different fixation methods on the tibial side in anterior cruciate ligament reconstruction: a biomechanical study in porcine tibial bone. J Orthop Sci. 2006;11(3):278-82.

15. Deramo DM, White KL, Parks BG, Hinton RY. Krackow locking stitch versus nonlocking premanufactured loop stitch for soft-tissue fixation: a biomechanical study. Arthroscopy. 2008;24(5):599-603.

16. Sakaguchi K, Tachibana Y, Oda H. Biomechanical properties of porcine flexor tendon fixation with varying throws and stitch methods. Am J Sports Med. 2012;40(7):1641-5.

17. Su WR, Chu CH, Lin CL, Lin CJ, Jou IM, Chang CW. The modified finger-trap suture technique: a biomechanical comparison of a novel suture technique for graft fixation. Arthroscopy. 2012;28(5):702-10.

18. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR Jr. Arthroscopic anterior cruciate ligament reconstruction: a metaanalysis comparing patellar tendon and hamstring tendon autografts. Am J Sports Med. 2003;31(1):2-11.

19. Foster TE, Wolfe BL, Ryan S, Silvestri L, Kaye EK. Does the graft source really matter in the outcome of patients undergoing anterior cruciate ligament reconstruction?: an evaluation of autograft versus allograft reconstruction results: a systematic review. Am J Sports Med. 2010;38(1):189-99.

20. Hong CK, Lin CL, Chang CH, Jou IM, Su WR. Effect of the number of suture throws on the biomechanical characteristics of the suture-tendon construct. Arthroscopy. 2014;30(12):1609-15.

21. Leishman DJ, Chudik SC. Suture tape with broad full-width core versus traditional round suture with round core: a mechanical comparison. Arthroscopy. 2019;35(8):2461-6.

22. Hong CK, Su WR, Kuan FC, Chen Y, Chiang CH, Hsu KL. High-tensile strength tapes show greater ultimate failure load and less stiffness than high-tensile strength sutures in a subpectoral biceps tenodesis porcine model. Arthrosc Sports Med Rehabil. 2020;2(6):e795-801.

23. Ellis DG. Cross-sectional area measurements for tendon specimens: a comparison of several methods. J Biomech. 1969;2(2):175-86.

24. Hammond GW, Armstrong KL, McGarry MH, Lee TQ. Hybrid fixation improves structural properties of a free tendon anterior cruciate ligament reconstruction. Arthroscopy. 2006;22(7):781-6.

25. Park MC, Peterson A, Patton J, McGarry MH, Park CJ, Lee TQ. Biomechanical effects of a 2 suture-pass medial inter-implant mattress on transosseous-equivalent rotator cuff repair and considerations for a "technical efficiency ratio". J Shoulder Elbow Surg. 2014;23(3):361-8.

26. Tamboli M, Hwang J, McGarry MH, Kang Y, Lee TQ, Mihata T. Biomechanical characteristics of the horizontal mattress stitch: implication for double-row and suture-bridge rotator cuff repair. J Orthop Sci. 2014;19(2):235-41.

27. Borbas P, Fischer L, Ernstbrunner L, et al. High-strength suture tapes are biomechanically stronger than high-strength sutures used in rotator cuff repair. Arthrosc Sports Med Rehabil. 2021;3(3):e873-80.

28. Domnick C, Wieskotter B, Raschke MJ, et al. Evaluation of biomechanical properties: are porcine flexor tendons and bovine extensor tendons eligible surrogates for human tendons in in vitro studies? Arch Orthop Trauma Surg. 2016;136(10):1465-71.