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Original Research

Effects of Different Core Suture Lengths on Tensile Strength of Multiple-Strand Sutures for Flexor Tendon Repair

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Purpose: To compare 2 types of newly devised 8-strand quadruple-looped suture (QLS) techniques with a 6-strand triple-looped suture (TLS) technique; and to assess the effects of different core suture lengths (CSLs) (the length between 2 locking sites of a suture strand) within each suture row on tensile strength.
Methods: We repaired 24 flexor tendons from 12 rabbits using the TLS and QLS techniques, with equal CSL (QLS) or unequal CSL (unequal QLS) among each suture row. The QLS was composed of 4 looped sutures on the anterolateral and posterolateral aspects of the tendon. The cross-sectional area of the locking portion of each thread in the QLS was equal to that in the TLS. In the QLS technique, the CSL on each aspect of the tendon was 13 mm. In the unequal QLS technique, the CSL on each aspect of the tendon was 13 and 17 mm. The load at 1- and 2-mm gaps, the maximum load until the 3-mm gap, and the ultimate load were compared among the 3 techniques.
Results: The QLS was significantly stronger than the unequal QLS and the TLS for loads at 1-mm and 2-mm gaps, maximum load until 3-mm gap, and ultimate load. There was no significant difference between the unequal QLS and TLS techniques. The QLS technique showed an approximately 30% increase in gap resistance and ultimate strength compared with the TLS technique.
Conclusions: The QLS technique showed an estimated increase in tensile strength proportional to the number of suture strands compared with the TLS technique. Our study suggests that a consistent CSL in each suture row provides the highest strength in multistrand sutures consisting of the same configuration of suture rows.
Clinical relevance: The QLS technique may reduce the risk for tendon rupture associated with early active mobilization after flexor tendon repair.

Early postoperative passive and active mobilization protocols have improved the functional outcomes of digital flexor tendon repairs in zone II.[1–6] The current standard for managing flexor tendon lacerations consists of repairs with 4- or 6-strand suture techniques and early active mobilization.[7,8] Despite various modifications of suture techniques and rehabilitation protocols, tendon ruptures have not been eliminated.[2] The use of a 6-strand triple-looped suture (TLS) technique in zone II followed by early active mobilization showed satisfactory results.[1,9,10] In these studies, of 24 zone II repairs, 79% were excellent, 13% were good, and 8% were fair based on the original Strickland criteria, and there were no tendon ruptures. However, early active mobilization still has technical complexity and a risk for tendon rupture. Aiming to make early active mobilization safer, we devised an 8-strand quadruple-looped suture (QLS) technique with asymmetric core suture purchase lengths per suture strand to be able to apply 4 Tsuge sutures to digital flexor tendons with a limited circumference.

It was reported that in multistrand suture methods consisting of several suture rows, maintaining equal core suture purchase lengths of each suture row increases the gap resistance.[11] This study used the TLS technique and its modifications with symmetric core suture purchase lengths per suture strand.[11] In cases of suture

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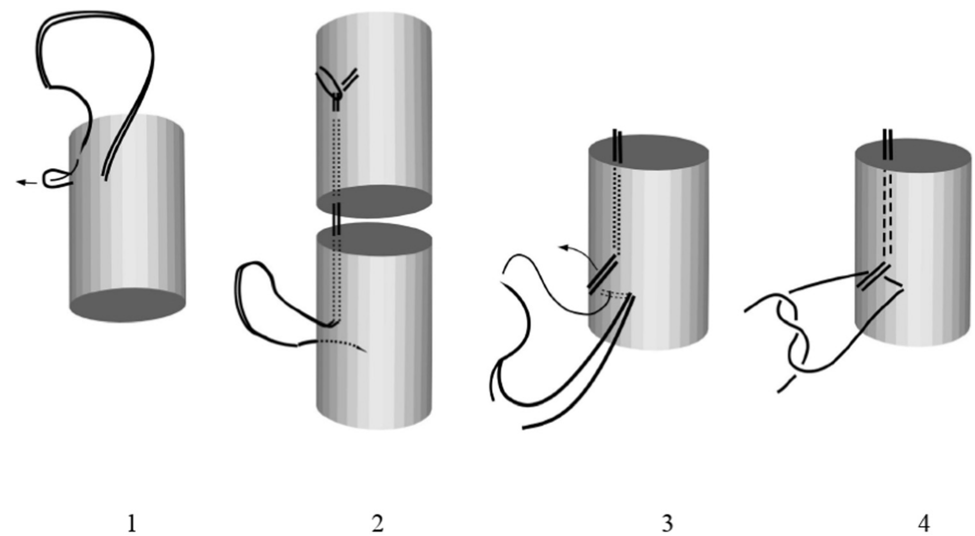

Figure 1. Locking configuration of a modified Tsuge suture. (1, 2) Needles are inserted into the tendon perpendicular to the long axis of the tendon to hold tendon bundles. (3) The suture loop is cut near the needle after the suture is passed transversely to make the strand double throughout its length. (4) A 3-throw square knot is made.

techniques with asymmetric core suture purchase lengths per suture strand such as the QLS technique, it is appropriate to use core suture lengths (CSLs) that are the distance between 2 locking sites to analyze mechanical properties.

The purposes of this study were to compare the tensile strengths of the QLS and TLS techniques and to assess the effects of the different CSLs of each suture row on tensile strength. We hypothesized that the QLS technique would have higher tensile strength than the TLS technique and that the QLS technique with a consistent CSL would provide the highest strength.

Materials and Methods

Experimental design

We obtained ethical approval from the animal care committee of our institution. In this study, we used 24 flexor digitorum fibularis tendons harvested from 12 skeletally mature Japanese white rabbit hind paws (Kyudo Co Ltd, Japan SLC, Shizuoka, Japan), weighing 3.2 to 3.6 kg, because they are similar in size to human flexor tendons (4.5 mm compared with 5.0 mm in humans) and have been used in previous studies.[10,11] The tendons were stored at −25°C until they were ready for repair and testing. Before we cut the tendon, we marked lines using a custom-made marker described by Hirpara et al[12]: a transection site, grasping sites on either side of the transection level, and sites 20 mm from the transection level on the either side. The tendons were transected at the level of the flexor retinaculum and the centers of the tendon stumps were marked with a fine needle. The tendons were randomly divided into 3 groups with 8 tendons each and repaired with one of the 3 techniques described subsequently. The repairs were performed by the same surgeon under a surgical microscope. The specimens were kept moist using a saline spray during the procedures.

Suture techniques

Triple-looped suture technique

The TLS technique consisted of the 3 modified Tsuge sutures[13] (Fig. 1). Three 5-0 monofilament looped nylon threads were used for the core suture. A 3-throw square knot was made. Three looped threads were inserted: 2 on the posterolateral and one on the

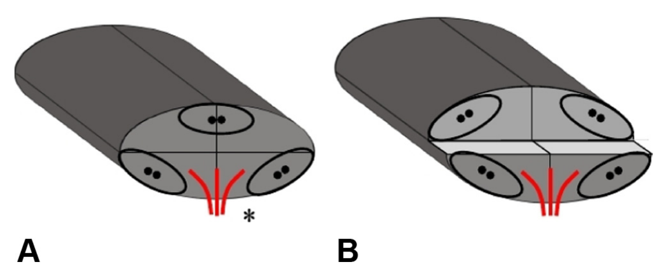

Figure 2. Locking sites in the axial plane. **A** A TLS. Each thread locks one-sixth of the tendon circumference. **B** A QLS. Two of the 4 locking sites are placed at different levels of the tendon. Each thread locks one-sixth of the tendon circumference, as in the TLS technique. Asterisks represent dorsal vessels.

anterior aspect of the tendon. Each thread locked one-sixth of the tendon circumference (Fig. 2A). All locking sites were 6 mm from the tendon laceration (Fig. 3A). The CSL of all locking sites was 12 mm. Four stitches of 6-0 monofilament nylon were used for the epitendinous suture.

Quadruple-looped suture technique

Four 5-0 monofilament nylon looped threads were used for the core suture. A 3-throw square knot was made. Each thread locked one-sixth of the tendon circumference, as in the TLS technique (Fig. 2B). The 2 anterolateral locking sites were 7 mm proximal and 6 mm distal to the laceration site on each tendon segment, whereas the 2 posterolateral locking sites were 6 mm proximal and 7 mm distal to the laceration site on each tendon segment (Fig. 3B). Therefore, the CSL of all suture strands was 13 mm (Fig. 3B). Four stitches of 6-0 monofilament nylon were used for the epitendinous suture.

Unequal QLS technique

This was a modification of the QLS technique, with each CLS unequal in each suture row (Fig. 3C). Four 5-0 monofilament nylon looped threads were used for the core suture. A 3-throw square knot was made. Each thread locked one-sixth of the tendon circumference, as in the TLS technique (Fig. 2B). The 2 anterolateral locking sites were 7 mm proximal and 6 mm distal to the laceration site on each tendon segment, and the 2 posterolateral locking sites

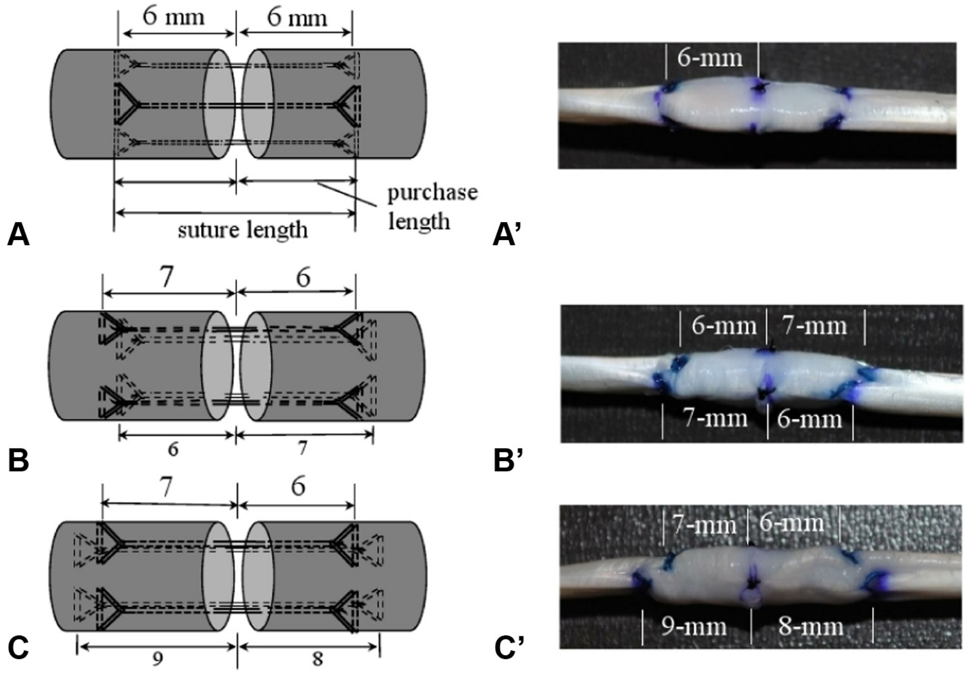

Figure 3. Repair techniques in this study. **A**–**C** Anterior views. **A′**–**C′** Lateral views. **A** and **A′** A TLS. All 3 sutures have a purchase length of 6 mm and a suture length of 12 mm. **B** and **B′** A QLS.. All 4 sutures have a purchase length of 7 or 6 mm and a suture length of 13 mm. **C** and **C′** An unequal QLS. The 2 anterolateral sutures have a purchase length of 7 or 6 mm and a suture length of 13 mm. The 2 posterolateral sutures have a purchase length of 8 or 9 mm and a suture length of 17 mm.

were 9 mm proximal and 8 mm distal to the laceration site on each tendon segment (Fig. 3C). Therefore, the CSLs of the anterolateral and posterolateral suture strands were 13 mm and 17 mm, respectively (Fig. 3C). Four stitches of 6-0 monofilament nylon were used for the epitendinous suture.

Methods of evaluation

The repaired tendons were mounted into the upper and lower clamps of a tensile strength testing machine (Autograph AGS-H, Shimazu Co Ltd, Kyoto, Japan). They were then subjected to a linear noncyclic load-to-failure test. The specimens were kept moist with a saline spray during the test. A light-emitting diode in the testing field was triggered to provide a visual signal indicating the start of the test (Fig. 4). A ruler with 1-mm graduated markings was placed in the video field, parallel to the tendon, to serve as a length reference. A mirror was placed behind the repaired tendons to view all 3 or 4 threads and knots (Fig. 4). A 1.0-N preload was applied and the tendons were stretched at a constant rate of 17-mm/min. We recorded the strength versus displacement data using a computerized data acquisition system. All tests were recorded using a 30-Hz video system (HDR-FX 1000, Sony Co Ltd, Tokyo, Japan) to analyze gap formation. The development of the repair site was analyzed using frame-by-frame playback on the video recorder. We measured the tensile load required to create a 1-mm and 2-mm gap and to cause overall failure of the repair (ultimate load). We defined a gap as the distance between both tendon ends in the center. We also measured the maximum tensile load until a 3-mm gap was created. The rationale behind stopping at 3 mm was based on evidence from clinical and experimental studies, which indicated that the quality of a flexor tendon repair deteriorates when a gap of 3 mm or more develops between tendon ends.[14,15]

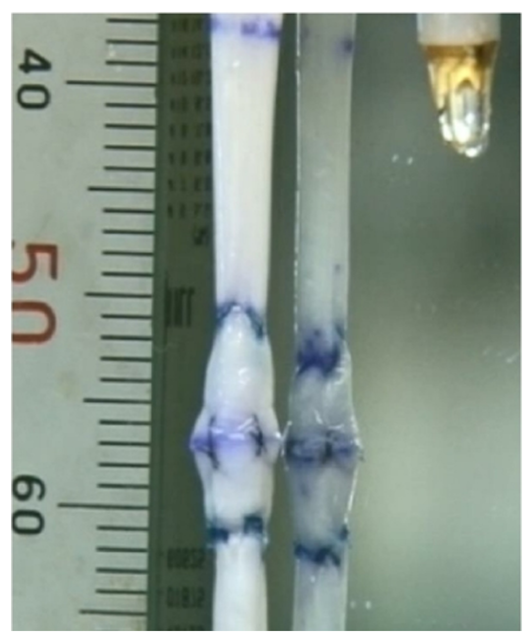

Figure 4. A ruler and a light-emitting diode were placed parallel to the repaired tendon. A mirror was placed behind the repaired tendon.

The failure mode of the core suture was recorded for each thread as suture breakage, suture pullout, or knot failure using frame-by-frame playback.

Statistical analysis

We performed a power analysis to estimate the required sample size to detect a significant difference of 30% in gap resistant forces

Table 1
Tensile Load, N

Suture Techniques	1-mm Gap	2-mm Gap	Maximum Load Until 3-mm Gap	Ultimate
TLS	44.8 ± 8.8	41.9 ± 5.6	48.5 ± 6.2	50.4 ± 4.8
Unequal QLS	48.9 ± 4.3	48.8 ± 7.5	54.1 ± 5.5	55.6 ± 3.8
QLS	56.5 ± 3.3*	58.0 ± 8.3*	63.5 ± 5.5*	63.5 ± 5.5*

* $P < .05$ versus TLS and unequal QLS.

between repair groups ($\alpha = 0.05$; $\beta = 0.20$). Eight tendons per group were included in the current study. Groups were compared using analysis of variance followed by Tukey-Kramer multiple comparison test for pairwise comparisons when appropriate. With regard to the mode of failure, we performed statistical analysis using Pearson chi-square test. $P < .05$ was accepted as statistically significant.

Results

Load at 1-mm gap

The QLS was significantly stronger than the TLS ($P < .01$) and the unequal QLS ($P < .05$). The tensile load to create a 1-mm gap with the QLS was 26% greater than that with the TLS and 16% greater than that with the unequal QLS. There was no significant difference between the TLS and the unequal QLS ($P = .38$) (Table 1).

Load at 2-mm gap

The QLS was significantly stronger than the TLS ($P < .01$) and the unequal QLS ($P < .05$). The tensile load to create a 2-mm gap with the QLS was 38% greater than that with the TLS and 19% greater than that with the unequal QLS. There was no significant difference between the TLS and the unequal QLS ($P = .16$) (Table 1).

Maximum load until 3-mm gap

The QLS was significantly stronger than the TLS ($P < .01$) and the unequal QLS ($P = .01$). The maximum load until the 3-mm gap with QLS was 31% greater than that with the TLS and 17% greater than that with the unequal QLS. There was no significant difference between the TLS and the unequal QLS ($P = .15$) (Table 1).

Ultimate load

The QLS allowed greater tensile load than the TLS ($P < .01$) and the unequal QLS ($P < .01$). The ultimate load with QLS was 26% greater than that with the TLS and 14% greater than that with the unequal QLS. There was no significant difference between the TLS and the unequal QLS ($P = .09$) (Table 1).

Mode of failure

There was no statistical difference among the 3 suture types in terms of the failure mode. The failure mode was mainly suture breakage; all 3 techniques showed this mode of failure with over 80% frequency (Table 2). The percentage of suture pullout and knot failure was less than 12% for all techniques.

Discussion

With regard to multistrand locking suture techniques, several factors affect the gap strength and ultimate strength of the repair, such as the number of suture strands crossing the repair site,[10,16–19] the cross-sectional area of locking loops,[20] and the different lengths of core suture purchase in each suture row.[11]

Table 2
Failure Mode (%)

Suture Techniques	Suture Breakage	Suture Pullout	Knot Failure
TLS	83.3 (20 of 24)	12.5 (3 of 24)	4.2 (1 of 24)
Unequal QLS	90.6 (29 of 32)	6.3 (2 of 32)	3.1 (1 of 32)
QLS	84.4 (27 of 32)	12.5 (4 of 32)	3.1 (1 of 32)

Our study showed that the QLS was significantly stronger than the TLS in terms of both gap resistance and ultimate strength. Theoretically, 8-strand sutures are 33% stronger than 6-strand sutures. However, if there are 4 locking areas placed on the same horizontal plane of the tendon, the area of the locking must be reduced because of the limited tendon circumference. Hatanaka and Manske[20] showed that increasing the cross-sectional area of the locking loops from 10% to 50% resulted in a proportionate increase in the ultimate tensile strength. Therefore, in this study, 2 of 4 locking sites were longitudinally shifted to a different level of the tendon from the other 2 to make each locking area equal. In this study, the QLS technique, in which the core suture purchase for each suture is equal, showed the expected increase in tensile strength.

This study also showed that the QLS technique was significantly stronger in gap resistance and ultimate loads than the unequal QLS technique. A possible explanation for the reduction in gap resistance of the unequal QLS technique is uneven load sharing among suture strands.[11] The suture strand is an elastic body that follows Hooke's law represented, by $F = kx$, in which F is force, k is a constant, and x is the extension distance). Because the spring constant of a spring is inversely proportional to the length of the spring, the spring constant is lower in a longer suture. Therefore, tensile load applied to a suture at each gap distance is lower in a longer suture. Gap resistance in techniques with multiple suture rows is affected by the sum of tensile load applied to each suture. Therefore, the unequal QLS technique provides less gap resistance than the QLS technique. On the other hand, the reduction in the ultimate load of the unequal QLS technique cannot be explained using Hooke's low because the ultimate load in load–displacement curves is not in the range of the elastic portion. One possible explanation is that the tensile load on each suture row was not equal when the tensile load on the repaired tendon was applied to result in ultimate failure of the repair. However, it is possible that the tensile load on each suture row was equal owing to the slippage of suture strands on the tendon fiber bundles.

Okubo et al[11] reported that an equal core suture purchase length in each suture row provides the highest strength in the TLS technique. Whereas the TLS technique and its modifications in the previous study had symmetric core suture purchase, the QLS technique in the current study had asymmetric core suture purchase. Therefore, the current study showed that equal CSL in each suture row provides the highest strength in the TLS technique. Furthermore, this study suggests that the results may be applicable to other multistrand sutures consisting of the same configuration of suture rows, such as the modified Becker suture with 2 or 3 rows, double-looped suture, TLS, and asymmetric Pennington suture.[21–23]

It was reported that asymmetric core suture purchase may improve gap resistance and fatigue strength.[22,23] The QLS technique also has an asymmetric configuration; however, we consider longitudinal shifting by 1 mm to be insufficient to enhance the tensile properties. In our study, the QLS technique showed an increase in both gap resistance and ultimate strength that was proportional to the number of suture strands. Taken together, our study provided no apparent data to support the concept that asymmetric core suture purchase improves gap resistance.

The current standard for digital flexor tendon repair is 4- or 6-strand sutures.[7,8] Clinical outcomes using 6-strand sutures have been reported[1,4,9,16,24,25] and showed that 6-strand sutures provide sufficient strength for early active mobilization exercises in the clinical setting. In 1998, Winters et al[26] reported in an *in vivo* study that the 8-strand technique has significantly greater strength than the 2- and 4-strand techniques. Therefore, other 8-strand tendon repair techniques were introduced, such as the new half-hitch loop suture,[27] surface locking Kessler techniques,[28] and 8-strand cross-locked cruciate repair using a double-stranded suture.[29] Despite several biomechanical studies, there are no reports that detail clinical outcomes using 8-strand sutures and early active mobilization. These techniques have relatively complex configurations. Conversely, the QLS technique consists of the commonly used modified Tsuge suture, which is widely accepted because of its simpler configuration. Therefore, the QLS technique is relatively easy to use in clinical practice for 8-strand sutures.

In this study, we used a 5-0 thread that was smaller than the 3-0 or 4-0 thread usually used in the clinical setting. However, we believe that our rabbit model using a 5-0 thread is clinically relevant because mechanical studies using our model similarly showed in clinically relevant model that the repair strengths of 2-, 4-, 6-, and 8-strand sutures were proportional to the numbers of suture strands.[10,18,26,30] In addition, according to the report that compared the repair strengths of an 8-strand suture using a 4-0 thread with those of a 4-strand suture using a 3-0 or 4-0 thread,[31] the QLS technique using a 4-0 strand may have 1.4 times or 1.7 times greater repair strengths compared with a 4-strand suture using a 3-0 or 4-0 thread, respectively. Therefore, it is suggested that the QLS technique using a 4-0 thread have mechanical advantages compared with 4-strand suture techniques using a 3-0 or 4-0 thread.

There were several limitations to this study. First, we employed only the noncyclic linear load-to-failure test model. Therefore, the influence of cyclic loading conditions could not be addressed. Second, this was an *in vitro* study that did not investigate the *in vivo* healing process. However, a previous report of the 8-strand method showed no decrease in tensile strength during the early phase of healing, when early mobilization was selected for postoperative rehabilitation in canines.[32] We believe the QLS technique to be no more traumatic to the tendon than the 8-strand method, with no postoperative decline in tensile strength. Third, 4 interrupted sutures (which are rarely used in clinical practice) were used for the epitendinous sutures in this study. We used this simple technique to focus on the mechanical properties of core sutures. However, the contribution of the peripheral epitendinous sutures to additional strength is limited when 6- or 8-strand core sutures with high tensile strength are used.[33]

The QLS technique with consistent CSLs in each suture strand showed the expected increase in tensile strength proportional to the number of suture strands crossing the repair site. Our results suggest that consistent CSLs among multiple-strand sutures comprising the same configuration of suture rows provides the highest gap-resistant strength.

References

1. Osada D, Fujita S, Tamai K, Yamaguchi T, Iwamoto A, Saotome K. Flexor tendon repair in zone II with 6-strand techniques and early active mobilization. *J Hand Surg Am*. 2006;31(6):987–992.
2. Vögelin E, Elliot E, Amadio PC. IFSSH Scientific Committee on Flexor Tendon Repair. *ezine IFSSH*. 2015;5(4):21–34.
3. Chai SC, Wong CW. Dynamic traction and passive mobilization for the rehabilitation of zone II flexor tendon injuries: modified regime. *Med J Malaysia*. 2005;60(Suppl C):59–65.
4. Hoffmann GL, Büchler U, Vögelin E. Clinical results of flexor tendon repair in zone II using a six-strand double-loop technique compared with a two-strand technique. *J Hand Surg Br*. 2008;33(4):418–423.
5. Früeh FS, Kunz VS, Gravestock IJ, et al. Primary flexor tendon repair in zones I and II: early passive mobilization versus controlled active motion. *J Hand Surg Am*. 2014;39(7):1344–1350.
6. Silfverskiöld KL, May EJ. Flexor tendon repair in zone II with a new suture technique and an early mobilization program combining passive and active flexion. *J Hand Surg Am*. 1994;19(1):53–60.
7. Wu YF, Tang JB. Recent developments in flexor tendon repair techniques and factors influencing strength of the tendon repair. *J Hand Surg Eur Vol*. 2014;39(1):6–19.
8. Tang JB. Outcomes and evaluation of flexor tendon repair. *Hand Clin*. 2013;29(2):251–259.
9. Kusano N, Shirase S, Koizumi H. Outcomes of flexor tendon repairs in zones 1 and 2 [in Japanese]. *J Jpn Soc Surg Hand*. 2020;36(4):464–468.
10. Kusano N, Yoshizu T, Maki Y. Experimental study of two new flexor tendon suture techniques for postoperative early active flexion exercises. *J Hand Surg Br*. 1999;24(2):152–156.
11. Okubo H, Kusano N, Kinjyo M, Kanaya F. Influence of different length of core suture purchase among suture row on the strength of 6-strand tendon repairs. *Hand Surg*. 2015;20(1):19–24.
12. Hirpara KM, Sullivan PJ, O'Neill B, O'Sullivan M. The optimum length of the Silfeverskiöld circumferential cross stitch. *J Hand Surg Eur Vol*. 2009;34(5):651–655.
13. Hayashi J, Ikuta Y, Umeda S, Kojima S, Kanaujia R, Tsuge K. Experimental study regarding tensile strength of tendon suturing methods [in Japanese]. *J Jpn Soc Surg Hand*. 1984;1(1):58–61.
14. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendon: an experimental study on the early stages of tendon-heeling in dogs. *J Bone Joint Surg Am*. 1999;81(7):975–982.
15. Seradge H. Elongation of the repair configuration following flexor tendon repair. *J Hand Surg Am*. 1983;8(2):182–185.
16. Savage R. In vitro studies of a new method of flexor tendon repair. *J Hand Surg Br*. 1985;10(2):135–141.
17. Aoki M, Pruitt DL, Kubota H, Manske PR. Effect of suture knots on tensile strength of repaired canine flexor tendons. *J Hand Surg Br*. 1995;20(1):72–75.
18. Thurman RT, Trumble TE, Hanel DP, Tencer AF, Kiser PK. Two-, four-, and six-strand zone II flexor tendon repairs: an in situ biomechanical comparison using a cadaver model. *J Hand Surg Am*. 1998;23(2):261–265.
19. Shaieb MD, Singer DI. Tensile strengths of various suture techniques. *J Hand Surg Br*. 1997;22(6):764–767.
20. Hatanaka H, Manske PR. Effect of the cross-sectional area of locking loops in flexor tendon repair. *J Hand Surg Am*. 1999;24(4):751–760.
21. Greenwald DP, Hong HZ, May JW Jr. Mechanical analysis of tendon suture techniques. *J Hand Surg Am*. 1994;19(4):641–647.
22. Wu YF, Tang JB. The effect of asymmetric core suture purchase on gap resistance of tendon repair in linear cyclic loading. *J Hand Surg Am*. 2014;39(5):910–918.
23. Kozono N, Okada T, Takeuchi N, Shimoto T, Higaki H, Nakashima Y. A biomechanical comparison between asymmetric Pennington technique and conventional core suture techniques: 6-strand flexor tendon repair. *J Hand Surg Am*. 2018;43(1):79.e1–79.e8.
24. Tang JB, Shi D, Gu YQ, Chen JC, Zhou B. Double and multiple looped suture tendon repair. *J Hand Surg Br*. 1994;19(6):699–703.
25. Savage R, Ristano G. Flexor tendon repair using a "six strand" method of repair and early active mobilisation. *J Hand Surg Br*. 1989;14(4):396–399.
26. Winters SC, Gelberman RH, Woo SL, Chan SS, Grewal R, Seiler JG III. The effects of multiple-strand suture methods on the strength and excursion of repaired intrasynovial flexor tendons: a biomechanical study in dogs. *J Hand Surg Am*. 1998;23(1):97–104.
27. Kormpakis L, Linderman SW, Thomopoulos S, Gelberman RH. Enhanced zone II flexor tendon repair through a new half hitch loop suture configuration. *PLoS One*. 2016;11(4):e0153822.

28. Yoneda S, Okubo H, Linderman SW, et al. The effect of modified locking methods and suture materials on zone II flexor tendon repair—An ex vivo study. *PLoS One*. 2018;13(19):e0205121.
29. Watanabe K, Ota H, Sasaki H. Eight-strand cross-locked cruciate flexor tendon repair using double-stranded suture: a description of the surgical technique. *Plast Reconstr Surg*. 2016;4(11):e1048.
30. Gill RS, Lim BH, Shatford RA, Toth E, Voor MJ, Tsai TM. A comparative analysis of the six-strand double-loop flexor tendon repair and three other techniques: a human cadaveric study. *J Hand Surg Am*. 1999;24(6):1315–1322.
31. Osei DA, Stepan JG, Calfee RP, et al. The effect of suture caliber and number of core suture strands on zone II flexor tendon repair; a study in human cadavers. *J Hand Surg Am*. 2014;39(2):262–268.
32. Boyer MI, Gelberman RH, Burns ME, Dinopoulos H, Hofem R, Silva MJ. Intrasynovial flexor tendon repair: an experimental study comparing low and high levels of in vivo force during rehabilitation in canines. *J Bone Joint Surg Am*. 2001;83(6):891–899.
33. Giesen T, Calcagni M, Elliot D. Primary flexor tendon repair with early active motion: experience in Europe. *Hand Clin*. 2017;33(3):465–472.