A Biomechanical Study of a Novel Asymmetric 6-Strand Flexor Tendon Repair Using Porcine Tendons

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Abstract

Background: This study evaluated the biomechanical performance of a novel asymmetric 6-strand flexor tendon repair technique without locking loops. **Methods:** Twenty porcine flexor tendons were equally repaired by using the asymmetric technique and compared with the modified Lim-Tsai repair technique. The ultimate tensile strength, load to 1-mm gap force, stiffness, and mechanism of failure were measured. **Results:** The asymmetric repair technique had significantly higher tensile strength (63.3 ± 3.7 N) than the modified Lim-Tsai repairs (46.7 ± 8.3 N). **Conclusions:** A novel flexor tendon repair technique with improved biomechanical performance may be available for use in flexor tendon repairs.

Keywords: tendon repair, multistrand, ultimate tensile strength, biomechanics, asymmetric, symmetric

Introduction

Early active mobilization has been shown to be effective for tendon healing.^{2,14} Strickland¹⁸ laid down 6 requirements for an ideal flexor tendon repair: easy placement of sutures in the tendon, secure suture knots, smooth junction of tendon ends, minimal gapping at the repair site, minimal interference with tendon vascularity, and sufficient strength throughout healing to permit the application of early motion stress to prevent repair rupture. To provide sufficient repair strength for early active mobilization, the current state-of-the-art techniques are based on multistrand flexor tendon repairs.^{5,10,15}

Adhesions between the tendon and surrounding tissues are inevitable during healing. Early active mobilization minimizes the effect of these adhesions. As such, the focus on flexor tendon repair techniques has been biased toward better biomechanical performance to avoid ruptures during the early rehabilitation period. Current biomechanical studies had identified the major factors, such as the number of strands crossing the repair site, suture caliber, tendon purchase, and suture material, which could affect the repair strength. In particular, a study comparing the repair strengths of different numbers of strands crossing the repair site showed that more strands resulted in stronger repairs. As such, many flexor tendon repair techniques have been developed and are classified according to the number of strands in the repair: Kessler¹³ and Tsuge et al¹⁹ (2 strand); Cruciate,³ and Cao and Tang⁴ (4 strand); Savage¹⁶ and modified Lim-Tsai⁹ (6 strand); modified Kessler⁶ (8 strand).

Like other factors, such as larger suture caliber and the placement of knots outside the repair site, increasing the number of strands across the repair site is also associated with increased repair bulk. This increases gliding resistance which can inhibit mobilization and increase the risk of rupture. Increasing the number of suture strands crossing the repair site also reduces the amount of tendon interface available for healing.¹⁷ Furthermore, having numerous suture passes through the tendon ends increases the amount of handling of the tendon ends, and this could result in increased inflammation, fibrosis, and adhesions.¹

To have a successful repair with early active rehabilitation, it was suggested that a minimum repair strength of 75 N is required for early active motion of repaired finger flexor tendons.^{8,16} However, recent biomechanical studies of 6-strand modified Lim-Tsai tendon repair technique have shown that the repair strength was only 47 ± 8 N⁹ and 51.3 ± 6.3 N²¹ based on nylon suture (Supramid Extra II 4-0) which is still below what is required for early active mobilization.

In this pilot study, a novel 6-strand flexor tendon repair technique, based on an asymmetric design and without the use of locking loops, was tested. A biomechanical study of

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Figure 1. Repair configuration of novel asymmetric technique.

its performance was conducted and compared with the modified Lim-Tsai technique.

Materials and Methods

Flexor Tendon Specimens

Twenty defrosted porcine flexor digitorum profundus tendons harvested from the second digit of porcine forelimbs were used. The average diameter and length of each porcine tendon are 5 ± 1 mm and 60 ± 10 mm, respectively, which is similar to the flexor digitorum profundus tendons in human fingers.¹² A transverse cut across the middle of each porcine tendon was done to simulate a complete tendon injury. The lacerated tendons were then repaired alternately using the asymmetric and modified Lim-Tsai repair techniques.

Asymmetric Repair Technique

The design of the repair is as shown in Figure 1. Nylon (Supramid Extra II 4-0) double-stranded suture was used. A surgical marker and a ruler were used to ensure the position of suture placement. The first stitch was made superficially on the proximal tendon, 10 mm from the edge. The suture was then passed through the repair site to the distal tendon, and exited 10 mm from the tendon edge. A stitch was made again, by grasping a width of approximately 2 mm of tendon fibers. The suture was then routed back to the proximal tendon by crossing through the repair site, and the needle exited the tendon 12 mm proximally from the tendon edge. The suture crossed the repair site a third time, before exiting via the distal tendon, and surrounded the previously constructed 2-mm suture stitch. To end the repair, a surgical knot with 3 throws (in a double-single-single configuration)

was tied on the surface of the tendon. The surgical knot, commonly used by surgeons, is able to provide more friction and reduce loosening. No epitendinous repair was done for the purposes of this study.

Modified Lim-Tsai Repairs

As shown in Figure 2, the same double-stranded nylon suture was used to cross the repair site 3 times, hence forming a 6-strand repair. Two Lim-Tsai locking loops were incorporated on each side of the laceration in order to place the suture on the tendon. To complete the repair, the same type of surgical knot was made on the tendon surface. No epitendinous repair was done for the purpose of this study.

Mechanical Testing

An Instron 3343 (Instron Corp, Canton, Massachusetts) was used for mechanical testing. As shown in Figure 3, the ends of the repaired tendons were grasped by the upper and lower pneumatic grippers with blasted clamping surfaces. The vertical distance between the 2 grippers was fixed at 25 mm at the start of each trial. A 2 N preload was applied to exercise the repaired tendons for 5 cycles, before they were pulled to failure. The pulling rate of the mechanical tester was set at 20 mm/min. The measured tensile forces were recorded in load displacement curves, from which the ultimate tensile strength and stiffness could be determined. The 1-mm gap formation was determined by using a concurrent video recorder and documenting the instantaneous force at 1-mm gap. The mechanism of failure for each tendon repair was also recorded by visual inspection, and classified into 1 of 2 groups according to the way the repair fails during the tensile test. Rupture of core sutures in the middle of the repair

Figure 2. Six-strand modified Lim-Tsai repair.

Figure 3. Experimental setup for biomechanical testing of repaired tendons.

site was classified as “suture rupture,” while displacement of the intact repair knot or locking loop from the tendon without any rupture along the suture was classified as “suture pullout.”

Statistical Analysis

Mean and standard deviation of the ultimate tensile strength and stiffness were calculated for the asymmetric and modified Lim-Tsai repairs. Two-tailed Student *t* test was adopted to compute the statistical difference between the mean values of the repairs for each variable. A *P* value of less than .05 was considered to be statistically significant.

Results

Ultimate Tensile Strength

The mean ultimate tensile strength of asymmetric repair was 63.3 ± 3.7 N, which is significantly higher when compared with the modified Lim-Tsai repair ($P < .0001$). The tendons repaired by the modified Lim-Tsai technique achieved a mean ultimate tensile strength of 46.7 ± 8.3 N. This represents a 35.5% and 55.4% improvement in mean ultimate tensile strength and standard deviation, respectively.

Load at 1-mm Gap Formation

Tendons repaired by asymmetric repair had mean load to 1-mm gap force of 13.9 ± 2 N. The modified Lim-Tsai repairs had mean load to 1-mm gap force of 16.7 ± 6 N. This difference was not statistically significant ($P = .165$).

Stiffness

The mean stiffness was 4.97 ± 0.73 N/mm for the asymmetric repairs and 4.96 ± 2.5 N/mm for the modified

Figure 4. Anchor points for (a) asymmetric repair and (b) modified Lim-Tsai repair.

Note. Anchor points are the suture bite on the surface of tendon.

Lim-Tsai repairs. This difference was not statistically significant ($P = .987$).

Mechanism of Failure

Eighty percent of the asymmetric repairs failed by suture breakage and the remaining 20% by suture pullout. There was no knot unraveling. For the modified Lim-Tsai repairs, all failed by suture breakage.

Discussion

We were aware that increasing the number of core suture strands could improve repair strength, but the repair bulk would have to be compromised. In addition, we postulated that the ideal strength of the repair technique was not optimized due to an uneven load-bearing problem existing in current repair techniques.²⁰ As such, we believed that there was an unmet need to develop stronger repair techniques without increasing the number of core suture strands.

In cadaveric and ex vivo studies of the 6-strand modified Lim-Tsai flexor tendon repair, technique have shown that it had comparable repair strengths among other flexor tendon repairs currently in use.^{9,10} As such, the asymmetric repair technique was compared with the modified Lim-Tsai technique in order to establish its biomechanical performance.

In comparing the asymmetric repairs with modified Lim-Tsai repairs, the repair strength increased significantly from 46.7 N to 63.3 N, corresponding to a 35.5% increment without increasing the number of strands crossing the repair site. The standard deviation of the repair strength of the asymmetric technique was also better, at 3.7 N compared with the modified Lim-Tsai's 8.3 N, representing a 55.4% reduction. This could be due to the fact that the Lim-Tsai lock is more technically demanding, thus making it more difficult to achieve a consistent locking loop. Because the asymmetric repair does not involve any complicated locking loop, we expect the biomechanical performance to be more consistent and promising, as less technical skill is needed. To understand the factors underlying the higher and more consistent repair strength of the new repair technique, the design of the repair technique is discussed.

The asymmetric configuration of the asymmetric repair technique is very unique as compared with the traditional repair techniques, such as the modified Lim-Tsai, which are based on a symmetric configuration. To aid in understanding the difference between these repair configurations, the anchor point, also known as the purchase point, is defined as the site where the suture exits onto the surface of the tendon, not counting the start and the end. Based on the given definition, the modified Lim-Tsai technique consists of 1 anchor point on each side of the tendon laceration in a symmetrical manner as shown in Figure 2. This is in contrast to the new repair technique, as shown in Figure 1, where there are 3 anchor points on 1 side of the tendon laceration, and 2 anchor points on the other side (see Figures 4a and 4b). Therefore, there are 5 anchor points in the asymmetric repair, which is more than double that of the modified Lim-Tsai repair. We believed that the reason for the improved repair strength of the asymmetrical design was the increase in the number of anchor points, which allowed the tensile load to be distributed to a wider area on the tendon surface.

Our results also contradicted that of another study, which showed that an increased number of anchor points resulted in no significant effect on the repair strength.⁷ This could be attributed to the fact that 4 anchor points were placed rotationally symmetric about the laceration site, and the transverse stitches lie superficial to the longitudinal components. Thus, we believed that when increasing the number of anchor points, our proposed asymmetric configuration is crucial to improving the repair strength, as compared with the symmetrical configuration found in other repair techniques.

We also believe that the higher repair strength achieved by the asymmetric repair is due to its novel repair configuration, which does not utilize any locking loop as an anchor point. Literature reviews of multistrand flexor tendon repairs have shown that a locking loop as an anchor point causes uneven load bearing in the 2 adjacent strands, as the locking loops interrupt the transmission of tensile force.^{11,20} In addition, the Lim-Tsai locking loop is different from the other types of locking loops, such as the cross stitch variant, because the Lim-Tsai locking loop requires suture reentry into the loop. Thus, this leads to premature suture breakage of the strand bearing the highest tensile load. However, the

design of the asymmetric repair technique allows smooth transmission of tensile forces within the strands, such that the tensile load can be evenly distributed to each strand. As such, maximum repair strength can theoretically be obtained when the tensile load is more equally distributed.

The modified Lim-Tsai repair technique resulted in 100% of repairs failing by suture rupture, whereas the asymmetric repair technique resulted in 80% of repairs failing by suture rupture and the remaining 20% by suture pullout. Theoretically, the mode of failure depends on which load is achieved first—the repair strength, which leads to suture breakage, or the pullout strength, which leads to suture pullout. This is because suture breakage occurs when tensile loads reach the ultimate tensile strength of the suture used, while suture pullout occurs when the holding force of the anchor point is reached. For the asymmetric repair technique, an increased number of anchor points and the lack of locking loops may help to distribute the tensile load evenly among the strands, which ensures that its suture will withstand up to a higher tensile load before rupturing. Thus, failure by suture pullout is more likely to occur as the repair strength exceeds the suture pullout load.

This study was done with limitations. Firstly, no epitendinous sutures were made for the repairs. This might cause variations in the loading mechanism of the repairs in vivo. Secondly, the asymmetric repair was not subjected to cyclic testing, which mimics the physical loading of the repairs. In the future, a follow-up study on the biomechanical performance of asymmetric repair with epitendinous sutures under cyclic loading will be carried out.

In conclusion, we have performed a biomechanical study of a novel asymmetric flexor tendon repair technique, which has higher ultimate tensile strength as compared with the modified Lim-Tsai repair technique. We also believe that further optimization of the 6-strand flexor tendon repair technique is possible in order to improve its biomechanical performance.

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Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

This article does not contain any studies with human or animal subjects.

Statement of Informed Consent

Informed consent was obtained when necessary.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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