Free Body Diagram Analysis for Investigation of Flexor Tendon Repair

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***Abstract*—The load dynamic of multi-strand flexor tendon repair is still unclear as a high friction of suture at the locking loops. The purpose of this study is to find out the equivalent forces acting on the multi-strand flexor tendon repairs by using free body diagram analysis. Forty porcine flexor tendons were harvested and transversely cut from the middle of tendons to facilitate tendon repairs. 6-strand Lim-Tsai repair, consisting of 2 Lim-Tsai loops, and 4-strand Cruciate repair, with 3 cross-stitch loops, were adopted to repair the 40 tendons equally. Ultimate tensile strength was recorded. The repair strength of 6-strand Lim-Tsai repairs (90.8±11.3N) had no statistically difference as compared to 4-strand Cruciate repairs (89±10N) despite of having different number of strands. This is because only the 2 strands connected to the end knot was in "Tension" mode due to natural pulling of strands while tying the knot. The other strands were only tensioned after the 2 strands ruptured. This "step down" phenomenon could be caused by the uneven load bearing associated with the Lim-Tsai repair configuration. This method could be very useful to analyse the loading mechanism of different flexor tendon repairs which leads to the development of new repair techniques.**

***Index Terms*—flexor tendon repair, multi strand, uneven load bearing, free body diagram**

I. Introduction

Tensile strength of flexor tendon repair is crucial for early active motion in flexor tendon repair [1]-[3]. Many studies showed that the tensile strength of flexor tendon repair is proportional to the number of strands/core sutures crossing the repair site [4]-[6]. Different flexor tendon repair techniques were therefore designed and categorized according to the number of strands: 2-strand repairs, Kessler [7] and Tsuge [8]; 4-strand repairs, Cruciate [6] and Tang [9]; 6-strand repairs, Savage [10] and Lim-Tsai [11]; 8-strand repairs, modified Kessler [12].

Many studies have investigated the tensile strength of 4-strand and 6-strand repair techniques [1]-[6], [13]. These studies found that the tensile strength of flexor tendon repairs was influenced by different looping configurations. On the other hand, other studies revealed that there was no significant difference in tensile strength when different looping configurations of 4-strand repair techniques were compared [14], [15]. These studies did not investigate the load dynamic of flexor tendon repair with different suture materials.

Suture material is one of the key factors that affect the biomechanical performance of flexor tendon repairs. Nitinol wire is a shape memory alloy with high tensile strength and stiffness, which makes it a popular choice of suture material for flexor tendon repairs. In fact, some advanced suture materials have been developed to improve the strength of flexor tendon repairs. Monofilament nylon, monofilament polypropylene, coated braided polyester, and braided polyblend sutures are used in flexor tendon repair. As compared to other materials, braided polyblend suture has higher tensile strength and stiffness. However, it is also found that the coating of polyblend and polyester suture could weaken the knot holding capacity and therefore more throws per knot were essential to prevent knot unraveling. It seems that the new suture materials could affect the loading mechanism of repairs and then cause uneven load bearing problems.

As mentioned above, braided polyblend is one of the strongest sutures currently in the market and is being used more and more for flexor tendon repairs to achieve higher tensile strength. However, it has a rough surface and will have more friction at between the suture-tendon interface, especially at the locking loops. Friction at the suture-tendon interface is something that is not often discussed and this could affect the load dynamics and be a cause of unexpected biomechanical performance of flexor tendon repairs. We observed this phenomenon in our study of 4-strand Cruciate and 6-strand Lim-Tsai repairs using 4-0 braided polyblend suture, in which no statistically difference was found in their repair strengths when we would have expected the 6-strand repair to outperform the 4-strand repair [16].

We hypothesize that *Free Body Diagram* (FBD) analysis can be adopted to analyze the force equilibrium of the repaired tendons. In structural analysis, FBD is a classical model which determines the unknown forces graphically on the components of structures subjected to static or dynamic load [17], [18]. This study aims to determine the equivalent forces acting on the strands and anchor points of the repair tendons, by breaking down the measured total tensile load into respective component forces, so that the tensile load distributed within each strand and anchor point of repaired tendons is identified. It is hypothesized that the FBD analysis can explain why

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the tensile strength of 4-strand Cruciate repairs is equal to the 6-strand Lim-Tsai repairs despite having different number of core suture crossing the repair site.

II. MATERIAL AND METHOD

A. Flexor Tendon Specimens

Forty porcine flexor digitorum profundus tendons from the second digit and the proximal segment of the extensor digiti quarti proprius tendon were harvested from porcine forelimbs. The average diameter and length of each porcine tendon are 5 ± 1mm and 60 ± 10mm respectively, which is similar to the flexor digitorum profundus tendons in humans [19]. A transverse cut across the middle of each porcine tendon was done to simulate a complete tendon injury. The porcine tendons are then randomly allocated into two groups. Twenty of the porcine tendons were repaired using the 6-strand Lim-Tsai repair, and the remaining twenty were repaired using 4-strand Cruciate repairs.

B. Lim-Tsai and Cruciate Repairs

The Lim-Tsai repair, was adopted to represent a 6-strand tendon repair. The Lim-Tsai repair was demonstrated by sequencing the number of strands passing through the injury site, as shown in Fig. 1 [3]. Two Lim-Tsai locking loops, one on each side of the laceration, were incorporated. A squared knot with 5 throws (double-single-single-single-single) was employed, and it was placed on the surface of the tendon. For the 4-strand repair, the Cruciate method, described by Strickland [20], was adopted. It was demonstrated by the strand-number sequence as shown in Fig. 2. Three cross-stitch locking loops were anchored, with two on one side of the injury, and one on the other side with the end knot. The same squared knot with 5 throws was made, and placed on the tendon surface. A ruler was placed beside the tendon to ensure that the loops and knot are 10mm away from the laceration site. No epitendinous repair was done for the purpose of study. Braided polyblend single loop suture material (FiberLoop 4-0, Arthrex, Naples, FL, USA) was used for the Lim-Tsai repairs, while the same suture material with single strand (FiberWire 4-0, Arthrex, Naples, FL, USA) was used for Cruciate repairs.

C. Mechanical Testing

An Instron 3343 (Instron Corp., Canton MA, USA) was used for mechanical testing. The ends of repaired tendons were mounted onto pneumatic grippers. The vertical distance between the two grippers was maintained at 25mm. 2N preload was applied to exercise the repaired tendon for 5 cycles and it was then pulled until failure. The strain rate of the mechanical tester was 20mm/min. 40% of load drop threshold was set to cease the test. Ultimate tensile strength was determined from the recorded load displacement curves.

D. Statistical Analysis

Mean and standard deviation of the data were calculated. Two-tailed Student's t-test was adopted to compute the statistical difference of mean values for the variables. A *P* value of less than 0.05 was considered to be statistically significant.

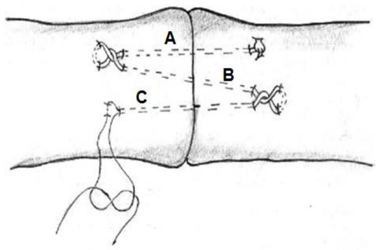

Figure 1. 6-strand Lim looping Lim-Tsai repair technique.

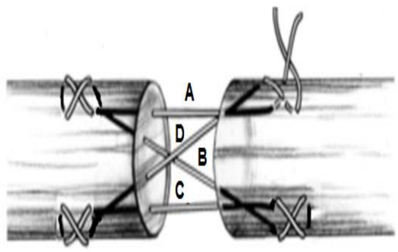

Figure 2. 4-strand cross-stitch looping Cruciate repair technique.

III. RESULTS

The ultimate tensile strength for the 6-strand Lim-Tsai and the 4-strand Cruciate repairs were similar as shown in Table I.

TABLE I. RESULTS FOR ULTIMATE TENSILE STRENGTH (UTS) OF REPAIRED TENDONS

	Lim Tsai	Cruciate
UTS (N)	90.8±11.3	89.0±10
P value	0.598	
Failure mechanism (Percentage, %)		
Suture breakage	25	50
Suture pullout	60	35
Knot unraveling	15	15

Typical load displacement curves for Lim-Tsai and Cruciate repairs under tensile loading are shown in Fig. 3 and 4 respectively. In order to compare the load dynamics of both flexor tendon repairs, Fig. 3 and Fig. 4 illustrate the load displacement profiles for the same mechanism of failure i.e. suture breakage. FBDs of flexor tendon repairs supplement the load displacement curves to depict the tension distribution within strands as well as the load on anchor points.

Based on the observation of load displacement profile for Lim-Tsai repair, its load dynamics is complicated and can be divided into 3 stages (see Fig. 3). In stage I, the tensile load was increased and reached to the repair's ultimate tensile strength. The 2 strands with label C usually failed first. The tensile stress was immediately reduced to 35% of ultimate tensile strength, as the remaining 2 strands with label A started to bear the loading. The tensile loading increased again until the 2 strands failed at the end of stage II. The remaining 2 strands with label B had to bear the tensile loading during stage III. Due to the loss of integrity of all Lim-Tsai locking loops, the 2 strands were unable to withstand high tensile load and therefore they were pulled out until the test was stopped by the 40% load drop threshold.

A significant difference was observed from the load displacement curve for Cruciate repair (see Fig. 4). The tensile load only increased until the ultimate tensile strength of the repair, where one of the strands with label A or D connected to the end knot failed. Similar to Lim-Tsai repair, these strands are tensioned while tying the knot whereby the other 2 strands were relax due to uneven load bearing at the cross stitch locking loops. Unlike Lim-Tsai repair in which the strands failed with “step down” fashion, the strands with label A or D failed once the ultimate tensile strength was reached. The tensile load was then dropped closely to zero because the other 2 strands were unable to bear the tensile load due to the loss of integrity of all cross stitched locking loops.

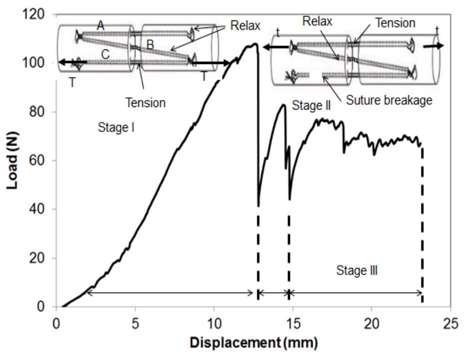

Figure 3. Load displacement curve with FBD of Lim-Tsai repair.

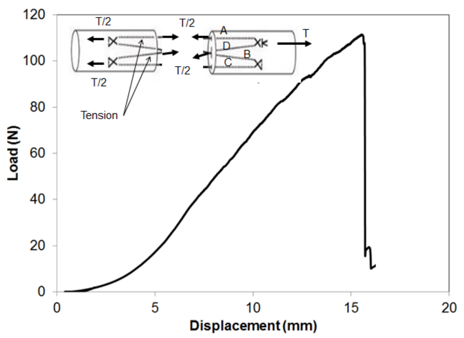

Figure 4. Load displacement curve with FBD of Cruciate repair.

IV. Discussion

The above mentioned load dynamic of flexor tendon repair is known as “step-down” fashion. We propose that due to the high friction of suture at the Lim-Tsai locking loop, the flow of tension within the strand pairs was restricted. This caused uneven load bearing within the strands. As it is practically not possible for a surgeon to tie the knot and make the Lim-Tsai locking loops with equivalent strength at the exact location, the tension within the 3 pairs of core sutures in the Lim-Tsai repair is never equal. As such, the 2 strands with label C were under tension right from the start, whereas the other 2 pairs of strands were not. Therefore, the 2 strands with label C always fail first, followed by the 2 strands with label A and B.

As shown in Fig. 3, the FBD of Lim-Tsai repair could help to explain the observed phenomenon. For a stable system, the forces at the support end of each tendon have to be T in order to have equal forces. Due to the uneven load bearing issue as mentioned above, the knot and the opposite Lim-Tsai locking loop were under same tensile load, T. Obviously, the 2 strands with label C were tensioned as per described previously and the rest of strands were relax, meaning they were not subjected to tension yet. When the ultimate tensile strength was reached, the 2 strands with label C failed and the subsequent tensile load, t was taken by the 2 strands with label A immediately at stage II. Ideally, the 2 strands with label A were supposed to bear the same tensile load as the strands with label C. In this case, the tensile load of strands with label A can only reach 80N before they failed. The reason could be due to the sudden tensile loading on the strands. After the failure of 2 strands with label A, the last 2 strands with label B started to bear the tensile load. However, these 2 strands were failed by suture pullout due to the loss of integrity of all Lim-Tsai locking loops. Therefore, the strength at stage III was lower than the one measured at stage I and II.

The FBD of Cruciate repair was also analyzed and validated by comparing with the FBD of Lim-Tsai repairs. Theoretically, there are several possible FBD analyses available for Cruciate repair. However, only the end knot and its opposite cross stitched locking loop were under tensile loading (T) producing the FBD according to the observation from experiments and the measured UTS of Lim-Tsai and Cruciate repair.

If the maximum tensile strength of a single strand is assumed to be F, the ultimate tensile strength of the Lim-Tsai and Cruciate repair can be computed according to their FBDs, as in

$$T = 2F \tag{1}$$

It implies that the Lim-Tsai and Cruciate repair cannot have more than 2F ultimate tensile strength. Therefore, The FBD of Lim-Tsai and Cruciate repair was supported by the experimental result that the repair strength of the 2 tendon repair techniques had statistically no difference.

The mechanism of failure also provided evidence to support this finding. The cruciate repairs experienced the suture pullout rate at 35%. This failure rate was 25% lower than that of the Lim-Tsai repair (60%). The uneven load problem actually caused only 2 strands labeled A in the Lim-Tsai repair under tensile load. Due to higher ultimate tensile strength of 2 strands, the pullout load of the Lim-Tsai locking loop was reached first before the maximal tensile load of strands. As shown in Fig. 2, the top view of flexor tendon repair shows that the area bounded by 2 strands (strands labeled A and D or strands labeled B and C) are spread to a wider area due to the diagonal configuration of strand labeled B and D for Cruciate repair. This area is different from the specimen cross section area because not the whole cross sectional area of specimen is under tensile load. Larger coverage area has better load distribution so that each locking loop of Cruciate repair bears lesser tensile load as compared to the Lim-Tsai locking loop whereby the tensile load only concentrate on the 2 strands labeled A. Therefore, the Lim-Tsai repairs had more suture pullout than cruciate repairs.

As this study uses a linear tensile test, its limitations include not being able to address the influence of angular pull on repair strength, bulk of repair on gliding resistance of tendon within the sheath, and biological in vivo changes to the tendon during healing. On the other hand, we also assumed that the repairs were performed uniformly because it is practically not possible for a surgeon to stitch the suture precisely with a symmetrical pattern on the tendon and tie the knot with equal strength. For the suture materials, we did not consider the effect of frictional force in between the contact surface of suture material and tendon interface as well as the locking loops because it requires precise measurement of friction coefficient of suture-tendon interface.

This study revealed a new approach to analyze the load dynamic of flexor tendon repairs, using FBD as the analytical model. With the help of load displacement curves, it explained explicitly the load dynamic of flexor tendon repairs. In the future, this approach can be very useful for analyzing the biomechanical performance of multi-strand flexor tendon repair technique, and for providing a guide for the development of new repair devices and techniques.

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