Does Strand Configuration and Number of Purchase Points Affect the Biomechanical Behavior of a Tendon Repair? A Biomechanical Evaluation Using Different Kessler Methods of Flexor Tendon Repair

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Abstract This study compares the mechanical properties of modified Kessler and double-modified Kessler flexor tendon repair techniques and evaluates simple modifications on both methods. Forty fresh sheep flexor tendons were divided equally into four groups. A transverse sharp cut was done in the middle of each tendon and then repaired with modified Kessler technique, modified Kessler with additional purchase point in the midpoint of each longitudinal strand, double-modified Kessler technique, or a combination of outer Kessler and inner cruciate configuration based on double-modified Kessler technique. The tendons were tested in a tensile testing machine to assess the mechanical performance of the repairs. Outcome measures included

gap formation and ultimate forces. The gap strengths of the double-modified Kessler technique (30.85 N, SD 1.90) and double-modified Kessler technique with inner cruciate configuration (33.60 N, SD 4.64) were statistically significantly greater than that of the two-strand modified Kessler (22.56 N, SD 3.44) and modified Kessler with additional purchase configuration (21.75 N, SD 4.03; Tukey honestly significant difference test, $P < 0.000$). There were statistically significant differences in failure strengths of the all groups (analysis of variance, $P < 0.000$). With an identical number of strands, the gap formation and ultimate forces of the repairs were not changed by additional locking purchase point in modified Kessler repair or changing the inner strand configuration in double-modified Kessler repair. The results of this study show that the number of strands across the repair site together with the number of locking loops clearly affects the strength of the repair; meanwhile, the longitudinal strand orientation and number of purchase points in a single loop did not affect its strength.

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Introduction

The primary goal of the flexor tendon repair is to perform a repair, which is strong and can withstand early active rehabilitation programs. It has been established that a healing tendon can be strengthened by the application of tension forces that lead to a more rapid recovery of the tensile force, fewer adhesions, improved excursion, and

better nutrition [2, 6, 9]. Clinical and experimental studies have shown that to minimize failure rates related to complications occurring during active rehabilitation, like gap formation or rupture, it is crucial that primary repair is performed using a reliable and strong suturing technique [5, 18, 26]. Many suture techniques were developed by investigators to improve the mechanical properties, particularly depending on the fact that number of the suture strands crossing the repair strongly influences the strength of the repair [10, 15, 24].

However, most current repair methods employ the technique described by Kessler or one of its many variations, which have reported to be associated with high rupture rates [17], and because of the complexity and technical demands, multi-strand suture methods, designed to strengthen the tendon repair, are not in widespread use. The four-strand core suture techniques are easy to perform with adequate strength to allow active mobilization [10, 15, 24]. The locking configuration of the core suture loop may influence tensile strength of the repair [8, 29]. Repairs usually rupture at suture knots, and a single external knot is superior to a knot within the repair site [2, 10, 15, 16].

The purpose of this study is to evaluate the mechanical properties of two- and four-strand core suture techniques and to assess the mechanical advantages of increasing purchase points, changing the inner strand configuration, and increasing the number of strands.

Materials and Methods

In this study, 40 fresh sheep forelimbs were dissected to obtain flexor digitorum profundus tendons. The sheep (average age 12–14 months) were all healthy adults and had been killed for selling purposes. This tendon has approximately 4–5 mm calibrations; the mean length was 10–12 cm. The tendons were removed from fresh limbs and kept moist in saline solutions during preparations, and

testings were performed on the same day. The specimens were randomly placed into four equal groups for tendon repair. Initially, tendons were attached to wooden plate at both ends by pins. A transverse sharp cut was performed in the midportion of each tendon, and then the repair was performed. Afterwards, tendons were divided into two main groups (A and B), each with two subgroups of ten specimens:

Group A1, two-strand modified Kessler suture in locking configuration whereby the transverse component lies superficial to the longitudinal components [8, 19] (Fig. 1a)

Group A2, two-strand modified Kessler suture with an additional purchase point, midway between the cut end and the transverse locking loops, on both sides of cut (Fig. 1b)

Group B1, four-strand double-modified locking Kessler core suture technique [10] (Fig. 2a)

Group B2, a four-strand core suture technique which is a combination of outer locking Kessler with inner cruciate core strands (outer Kessler+inner cruciate) technique (Fig. 2b)

All specimens were repaired using a 4/0 polypropylene monofilament core suture. Immediately after the repair, tendons were vertically held in the non-slipping jaws of soft-tissue clamps which were mounted into a material testing machine (model TIRA test 24500; Demgen, Werkzeugbau, GmbH). A pre-load of 1 N was applied. All the tendons were subsequently loaded to failure point at a static rate of 20 mm/min, and force-versus-displacement data were recorded. The force producing 2 mm gap (as detected visually with the aid of operating loupes) [30] and maximum force prior to rupture (ultimate force) were determined from all tests.

Data are presented as mean±standard deviation. Statistical analyses of the data were performed using two-way

Figure 1 Longitudinal sections of modified Kessler technique (a) and its modified form (b) with additional purchase in the mid-point between cut end and transverse loop.

Figure 2 Longitudinal sections of double-modified Kessler (a) and its modification (b) with inner cruciate configuration.

analysis of variance (ANOVA) followed by Tukey honestly significant difference (HSD) post hoc test.

Results

The results are shown in Table 1.

There were statistically significant differences in gap strengths and ultimate strengths of all groups (ANOVA, $P<0.000$).

There were no statistically significant differences in gap strengths between the two-strand modified Kessler technique and two-strand modified Kessler technique with additional purchase configuration (subgroups A1 and A2; Tukey HSD test, $P=0.959$).

No statistically significant difference was found in gap strengths between the four-strand double-modified Kessler technique and four-strand modified Kessler technique with inner cruciate configuration groups (B1 and B2; Tukey HSD test, $P=0.347$).

The gap strengths of the double-modified Kessler technique and double-modified Kessler technique with inner cruciate configuration were significantly greater than that of the two-strand modified Kessler and modified Kessler with additional purchase configuration (groups A, B; Tukey HSD test, $P<0.000$).

There were statistically significant differences in failure strengths of the all groups (ANOVA, $P<0.000$).

No statistically significant difference was found in failure strengths between the two-strand modified Kessler technique and two-strand modified Kessler technique with additional purchase configuration (subgroups A1 and A2; Tukey HSD test, $P=0.949$).

No statistically significant difference was found in failure strengths between the four-strand double-modified Kessler technique and four-strand modified Kessler technique with inner cruciate configuration groups (B1 and B2; Tukey HSD test, $P=0.701$).

The failure strength of groups B1 and B2 was significantly greater than that of groups A1 and A2 (Tukey HSD test, $P<0.000$).

All the specimens in groups A2, B1, and B2 failed owing to suture breakage in the suture knots. Only two specimens in group A1 failed owing to pullout through the tendon.

Discussion

Ideal tendon repair should provide sufficient strength throughout healing period to permit application of early motion stress to the tendon without impairing intratendinous microcirculation.

Table 1 The mechanical properties of flexor tendon repairs performed using four different repair techniques.

Group	Number of samples	Suture technique	2-mm separation-gap strength (N)	Breaking strength (N)
A1	10	Tow-strand modified Kessler	22.56 (3.44)	34.44 (2.33)
A2	10	Two-strand modified Kessler + additional purchase	21.75 (4.03)	36.06 (4.45)
B1	10	Four-strand double-modified Kessler	30.85 (1.90)	53.38 (8.09)
B2	10	Four-strand Kessler + inner cruciate configuration	33.60 (4.64)	50.23 (8.81)

Data are presented as mean (SD).

Many investigators searched the relation between the strength of the repair and number of the strands, loop configuration, number of knots, and circumferential epitenidinous sutures. Repair of the tendon is most frequently carried out using one of the popular modified Kessler techniques [14], which has lowest gliding resistance compared to other suturing techniques [31], but unacceptably high rupture rates have been reported in conjunction with active motion [7, 8, 21, 26]. The high rupture rate reflects insufficient strength of the simple modified Kessler suture for active finger flexion.

Different methods advocated increasing tensile strength of tendon sutures, like increasing the number of core sutures across the tendon stumps [22] or using a complicated locking technique in core suture [12]. Cao and Tang [3] reported an increase in the strength of the repair by using a four-strand modification of the Tang technique that uses fewer sutures and fewer knots on the tendon surface. Again modification of peripheral sutures enhances tensile strength of the tendons greatly [4, 25]. While several laboratory investigations have confirmed superior tensile properties of multi-strand core sutures [15, 22], concerns regarding technical demands and skill acquisition, as well as repair bulk and lengthier operating times, may reduce the clinical feasibility and limit their use. Zhao et al. [31] had reported an increasing gliding resistance observed as the number of strands and knots increased. Lawrence et al. [11] studied the operating time in two- and four-strand suture techniques, they found that single-cross four-strand repair tolerates superior loads yet is no more technically demanding than the modified Kessler and can be reliably performed without additional operating time.

Depending on these facts, we chose to assess simple modifications on the two-strand locking modified Kessler [19] and double-modified four-strand Kessler suture techniques. In group A, the additional locking purchase (A2) has not changed the gap strength and the ultimate failure force compared to modified Kessler technique (A1). Comparing the mode of failure, no pullout was observed in group A2 compared to only two in group A1, which may be due to the effect of the additional purchase point; however, larger series are required to confirm this advantageous modification.

These results are in accordance with the previous study done by Hotokezaka and Manske [8] who stated that a single locking configuration at both ends of each strand yields the maximum tensile strength and reduces gapping at the repair site. However, Mashadi and Amis [13] in their study found that locking loops did not contribute towards the strength when small diameter sutures (5/0) of various materials were used. Larger diameter sutures (4/0) slightly reduced the risk of failure of locking loops, but they still collapsed at low loads.

In our study, both four-strand techniques had superior gap and failure strengths compared to the two-strand modified Kessler. These results are in accordance with previous studies comparing two- and four-strand configurations [1, 27, 28]. Our study shows no difference in the mechanical properties between the double-modified Kessler and the combination of the outer Kessler and inner cruciate technique as the number of locking loops remain the same in both. These results are also in accordance with the previous study done by Wada et al. [29], who found that the gap and breaking strengths of the double-modified locking Kessler technique were significantly greater than those of the locking cruciate technique. In that study, the double-modified locking Kessler technique incorporated eight rectangular locking configurations, whereas the locking cruciate technique incorporated four oblique locking configurations [29].

Our study shows that changing the configuration of the inner strands to cruciate did not lead to statistically significant changes in the strength of the repair as the number of the locking loops remained similar. The mode of failure, gap strength, and failure strength remained similar. Considering the practical and technical demands, parallel strands are easier to apply than the cruciate strands; furthermore, the main vascular supply, which reaches the flexor tendon through the vincula, runs in a longitudinal way along the dorsal aspect.

In vivo measurement of the force in an uninjured flexor tendon had shown that active finger motion generates more tension in the flexor tendons than passive motion of the tendons. Passive motion of the fingers generates 1 to 9 N, whereas active motion generates 1 to 29 N (mean 19 N), and a safe repair should withstand these forces [23].

Our study obviously revealed that the four-strand double-modified Kessler technique was sufficiently strong to withstand these forces than two-strand technique, and the longitudinal orientation of the inner strands does not affect the strength of the repair.

In conclusion, the results of this study show that the number of strands across the repair site together with the number of locking loops clearly affects the strength of the repair; meanwhile, the longitudinal strand orientation and number of purchase points in a single loop did not affect its strength. Considering the longitudinal configuration of intratendinous microcirculation and depending on these mechanical facts, we prefer to use parallel strands to cruciate strands, and we think that searching for better suture materials must be ongoing.

While this is an experimental study on sheep flexor tendons which may differ in structural quality to those of the human, they are readily available in our country, less costly, and used in a previous biomechanics study [20]. We used noncyclical load, and the effect of healing tissue was

not taken into consideration. Furthermore, these laboratory tests should be supported by in vivo experimental studies to evaluate the effects of these changes and modifications on the healing properties.

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