Flexor Tenorrhaphy Tensile Strength: Reduction by Cyclic Loading

In Vitro and Ex Vivo Porcine Study

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Received: 2 July 2008 / Accepted: 31 October 2008 / Published online: 17 December 2008
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Abstract The integrity of the repair is critical to maintain coaptation of the severed flexor tendon end until healing has advanced sufficiently. In our hospital, we use a modified Savage repair (four-strand Adelaide technique) using 3–0 Ethibond (Ethicon, Somerville, NJ, USA) for acute flexor tenorrhaphy and an active postrepair mobilization protocol. To explain the apparent differences between the theoretical and actual repair strength of a multistrand repair in a single tension test and the reduced strength of a repair subjected to cyclic loading, we compared single and cyclical tensile loading with different suture in vitro configurations of 3–0 Ethibond (Ethicon, Somerville, NJ, USA; one, two, and four strands) and an ex vivo four-strand repair of freshly divided porcine tendon to calculate the ultimate tensile strength (UTS). Mechanical testing was repeated 15 times with both single tensile and cyclical loading for each suture configuration and porcine repair. In the in vitro model, the presence of a knot in a single strand reduced the UTS by 50%. The stiffness of a knotted strand was substantially less than the unknotted strand but became identical after cyclical loading. There was no statistical

significance of the UTS between single and cyclical loading with different numbers of strands in this model. In the ex vivo four-strand porcine repair model, there was a significant reduction in UTS with cyclical loading, which equated to the number of strands times the strength of the knotted strand. This discrepancy can be explained by the change in stiffness of the knotted strand after cyclical loading and has important implications for previous studies of suture tendon repair using single tensile loading where the UTS may have been overestimated. We believe that cyclical loading is more representative of physiological loading after acute flexor tendon repair and should be the testing model of choice in suture tenorrhaphy studies.

Keywords Flexor · Tenorrhaphy · Cyclic loading · Stiffness

Introduction

Maintaining approximation of the severed flexor tendon ends is critical after repair to achieve healing and there have been multiple techniques and extensive research to identify the optimal tenorrhaphy method [3, 5, 6, 13]. Successful flexor tenorrhaphy can depend on a number of factors including the tensile properties of suture material, integrity of each suture grasp, the type of suture repair, and the surgical expertise available [1, 9, 11, 12]. On the basis of previous research in our unit, we use a four-strand single cross grasp suture repair (Fig. 1) modified from the Savage technique [10], and active mobilization is started as early as possible (either the same day or day after operation) under the care of the physiotherapist.

While the in vitro and ex vivo testing of various suture constructs is important to identify the optimal technique, the differences between the theoretical and actual repair

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strength of a multistrand repair [10] and the apparent reduced strength on a repair subjected to cyclic loading [4, 8] have not been explained by this previous work. Many studies have investigated the mechanical properties of suture repair with single tensile loading [1], but few have compared single tensile and cyclical loading [8].

To investigate these discrepancies, we assessed the mechanical performance of our preferred tenorrhaphy technique during cyclic and static loading in an *in vitro* and *ex vivo* situation. The conduct of this study was to firstly analyze, in both single tension and cyclic loading conditions, the mechanical properties of *in vitro* 3–0 braided polyester suture material (Ethicon, Somerville, NJ, USA) with different strand configurations (single strand without knot, single strand with knot, two strands with knot, and four strands with knot) and then a four-strand *ex vivo* porcine tendon repair.

Methods

The study was conducted in two parts: Firstly, an *in vitro* study to test the mechanical performance of the suture material in various configurations and secondly, an *ex-vivo* study to test the performance of the multistrand repair in an animal tendon model. A Hounsfield mechanical testing machine (Hounsfield H25KM Universal Testing Machine, Hounsfield Testing Equipment Ltd, Surrey, UK; Material Testing System (MTS)) was used to measure stiffness during cyclic loading and ultimate tensile load both for the different suture configurations and the porcine four-strand tendon repairs for both single tensile and cyclical loading tests, with each particular test being repeated 15 times. A standardized technique was used for testing both the suture configurations and tendon repairs, with 3–0 Ethibond (Ethicon, Somerville, NJ) suture. Different configurations of single strand with and without a knot, two strands with a knot, and four strands with a knot were tested.

The suture was attached to the testing apparatus by means of two smooth 1 cm bars, 60 mm apart (Fig. 2). In the tests using a closed loop (i.e., knotted two- and four-strand knotted repairs), the strands were passed around the

Figure 1 Illustration demonstrating four-strand Adelaide repair used for flexor tenorrhaphy.

Figure 2 Photograph of a two-strand Ethibond (Ethicon, Somerville, NJ, USA) suture configuration with knot looped around restraining bars of Hounsfield tensile machine.

bars. Where the repairs were not a closed loop (i.e., single strand knotted and unknotted configurations), the free ends of the two end strands were secured to the bar by multiple wrapping and then adhesive tape over the entire wrap (Fig. 3). Preliminary studies showed this technique of fixation achieved no appreciable creep under the testing conditions. A minimum of five square throws were performed to secure the knot where used.

For the single tensile load testing, the suture configurations were preloaded to one Newton and then a tensile force applied until ultimate failure. Cyclical tensile tests were applied loading at 10 N per strand for ten cycles prior to loading to ultimate failure. This level of submaximal cyclic loading was chosen to eliminate the slack within the knot prior to testing to tensile failure.

It was assumed that at the rate of loading used, the viscoelastic effect is negligible. The rate of loading used is best defined as quasistatic and changes within this range have negligible influence on ultimate tensile strength (UTS) and construct stiffness. Testing at 500 mm/s would most likely create different viscoelastic loading effects, but this was not assessed in this study:

1. *In vitro* study: The initial study was to assess the *in vitro* properties of the commonly used tenorrhaphy suture, 3–0 Braided Polyester (Ethibond, Ethicon, Somerville, NJ, USA), when subjected to testing in both single tensile and cyclic loading conditions. A single strand with and without a knot and then two- and subsequently four-strand configurations were tested
2. *Ex vivo* study: Thirty porcine forefoot flexor tendons were freshly prepared which were similar in size and appearance to human flexor profundus tendon. The tendons were divided with a sharp blade and a four-strand Adelaide repair performed with 3–0 Ethibond

Figure 3 Illustration demonstrating unknotted and knotted single suture strand between restraining bars.

(Ethicon, Somerville, NJ, USA). The tendon ends were attached to securing clamps of the MTS. Fifteen single and 15 cyclical tests before loading to ultimate tensile strength were then applied under standardized conditions. Using computer software, the results were extrapolated to produce a load displacement curve for each test

The mean of both the in vitro suture tension tests and ex vivo four-strand tendon repairs were calculated. Statistical analysis was applied using the student *t* test to compare the single and cyclical loading tension tests for each suture configuration or four-strand repair. Using computer software, a curve of best fit for each test of the suture configurations was plotted. This allowed assessment of stiffness of the particular strand configuration by visualization of the slope of the curve at different points. Quantifying the stiffness is achieved by dividing the load by the displacement (N/mm).

Results

Each suture configuration was tested to failure following either a single tension loading or a cyclic loading sequence. In all knotted strands, failure occurred at the site of the knot. Quantifying the stiffness is achieved by dividing the load by the displacement (N/mm). This is simple for linear materials like the unknotted and perfectly secured unknotted strand (i.e., a 5-mm displacement for 10 N load=2 N/mm); however, when the knot slips, there is a nonlinear and unpredictable initial stiffness. The stiffness is initially low and ramps up to the unknotted equivalent stiffness.

Effect of Knot—Single Strand In Vitro Repair

The mean ultimate tensile load for a single strand 3–0 Ethibond (Ethicon, Somerville, NJ, USA) was 34 N under single tensile loading and 36 N under cyclical loading conditions (n.s. $p>0.05$). The presence of a knot with a

single strand reduced the ultimate tensile load by approximately 50% ($p<0.05$) in both cyclic loading and single tension testing groups (Fig. 4).

Number of Suture Strands

In both single and cyclical loading tests, increasing the number of strands increased the ultimate tensile load (Table 1). Doubling the suture strand from single strand to double strand with knot and from double strand to four strands with knot slightly more than doubled the ultimate tensile load.

Single Versus Cyclical Loading

All groups were compared with single tensile and cyclical loading. There was no statistical difference found with a single strand, single strand with knot, and double strand with knot with different loading tests. There was a slight decrease in ultimate tensile load in the four-strand group with cyclical loading (Fig. 4), but this was not significant ($p>0.05$). With the four-strand tendon (ex vivo) repair,

Figure 4 Bar chart demonstrating effect of cyclic loading on in vitro strand configurations and four-strand ex vivo porcine repair.

Table 1 In vitro 3–0 Ethibond (Ethicon, Somerville, NJ, USA) suture and ex vivo four-strand tendon repair mean ultimate tensile strength (N).

	Single tensile loading (variance)	Cyclical loading (variance)	<i>p</i> value
1 strand (no knot)	34 (8)	36 (6)	n.s.
1 strand with knot	16 (9)	18 (4)	n.s.
2 strand with knot	39 (13)	41 (10)	n.s.
4 strand with knot	90 (10)	87 (9)	n.s.
4 strand tendon repair	80 (9)	70 (6)	<0.05

there was a decrease from 80 N in the single tensile loading group to 70 N in the cyclical loading group ($p < 0.05$).

Stiffness of Single Strand Group

For the single strand configurations (single strand with and without knot), all 15 tests were expressed as a linear line of best fit for a load displacement curve. The relative stiffness of the suture material was represented by the slope of the load displacement curve. It was found that the knotted single strand was less stiff than a single strand (mean stiffness = stiffness value) under tensile loading ($p < 0.05$; Fig. 5); however, after cyclical loading, the single strand and the single strand with a knot had the same stiffness represented by the same slope on the load displacement graph (Fig. 6).

Variance in Mean Ultimate Tensile Strength

There was found to be less variance in ultimate tensile load with cyclical loading in all groups (Table 1).

Figure 5 Load displacement curve demonstrating effect of single tensile loading on unknotted and knotted single suture strand.

COMPARISON BETWEEN UNKNOTTED AND KNOTTED CYCLIC TENSILE TEST BEHAVIOUR

Figure 6 Load displacement curve demonstrating effect of cyclic loading on unknotted and knotted single suture strand.

Discussion

An active postrepair mobilization protocol places increasing stresses on the suture construct as it is the suture material itself which maintains the integrity of the tendon repair until the healing is sufficiently advanced. In an effort to improve the ultimate mechanical strength of repairs, multi-strand techniques have been introduced. To identify the best suture materials for tendon repair, in vitro and ex vivo studies of suture ultimate tensile strength of different techniques of acute flexor tenorrhaphy have previously been described [1, 2, 7, 9, 11, 12].

In the first part of this study, the mechanical strengths of different numbers of strands of suture material was reviewed. Savage [9] has previously shown the weakest area being at the site of a knot. This was confirmed in our study which showed the ultimate tensile strength of a single suture strand to be reduced by approximately 50% with the presence of a knot (Fig. 6). Savage and Rositano [10] also suggested that in a multistrand repair in a frictionless environment, each strand should share the load and the construct should fail once the weakest strand (i.e., the knotted strand) has exceeded its ultimate tensile. Previous studies [8, 10] have documented a discrepancy of this simple arithmetic formula (strength of the weakest (knotted) strand times the number of strands) with a higher measured UTS on single tension testing being attributed to some form of friction in the experimental system. Aoki et al. identified that the tensile strength of a tenorrhaphy following cyclic loading was less than the same repair under single tension testing loads. Again, the difference is attributed to the effects of friction in the testing system.

Our study, however, suggests that the discrepancy in the UTS of the multistrand repair between single tension and

cyclic loading can be explained by the behavior of the knot during initial and subsequent loading. The load displacement curves for a knotted and unknotted strand for both single tensile and cyclical loading (Figs. 5 and 6) were compared. It was clear that the stiffness of the knotted strand was substantially less than the unknotted strand (represented by the slope of the curve) for a single tensile test. After cyclical loading, the stiffness of the knotted strand was identical to that of the unknotted strand, but the UTS remained the same being 50% weaker in the presence of a knot.

This difference in the stiffness can explain the discrepancy in the UTS of the four-strand tendon repair in this study. With the ex vivo model, there was a mean decrease from 80 N for single tensile to 70 N for cyclical loading ($p < 0.05$). The reduction in the stiffness gradient of the knotted strand effectively delays the ultimate maximal loading of the knotted strand. In a multistrand repair where there is friction which prevents immediate equilibration of the strand tension, the unknotted strand which has a higher stiffness strands (i.e., the unknotted strands) will take a proportionally greater load across the tenorrhaphy resulting in higher value of UTS with single tensile testing. The slight redundancy within the knot causing the reduced stiffness in that strand can be corrected by cyclical loading such that the stiffness of a knotted strand becomes identical to the stiffness of an unknotted strand (Fig. 6).

In this study, cyclical loading of the ex vivo tendon repair does reduce the mean UTS (80 N for single tensile to 70 N for cyclical) to a value that is very close to the arithmetic formula of the knotted strand times the number of strands ($17 \text{ N} \times 4 = 68 \text{ N}$). In a physiological situation where cyclic loading will occur in the course of active and passive mobilization, the stiffness of the unknotted strand will maximize, the loading between the various strands will be even, and the UTS will approach the weakest strand strength times the number of strands.

This study has not investigated the presence of grasp migration or the viscose elastic deformation of 3–0 Ethibond (Ethicon, Somerville, NJ, USA) which contribute to differences in the mean UTS between the in vitro and ex vivo four-strand models. The main difference can be attributed to the effect of friction combined with the variation in stiffness of the knotted and unknotted strands in the testing model.

We conclude that the UTS of a given knotted length of suture will be constant, regardless of single or cyclic loading. However, the knotted strand is both the weakest and has a lower stiffness (during initial loading) than other strands in a multistrand repair. During single tension testing, if the strands of a repair cannot undergo immediate equilibration due to friction, a lower knotted strand stiffness is evident and this leads to delayed rate of loading until

maximum loading and ultimate failure when compared to the loading of the stiffer unknotted strands. This in turn leads to an incorrectly elevated estimate of the likely UTS. This discrepancy can be addressed by cyclic loading of the construct which maximizes (or normalizes) the stiffness of the knotted strand. This change in the knotted systems stiffness occurs because slack within the knot cannot be completely removed by hand during construction and is removed during initial tensile loading. This removal of slack within the knot during the initial loading phase produces a reduction in system stiffness until a point where the slack is completely removed. At this point, the knotted system will exhibit identical stiffness to an unknotted system; however, the knotted system will fail at significantly lower UTS due to the knot acting as a 'stress raiser'.

These findings are clinically important because slack within the knot could tighten causing a gap between tendons. The magnitude of the gap would be minimized with increasing numbers of strands. Cyclical mechanical loading is a more exacting technique and more closely reproduces physiological loading of a flexor tendon repair which has important clinical implications for previous studies concerning strength of tendon repair. We therefore recommend the use of cyclical mechanical testing techniques in the future study of tendon repair techniques as single tensile testing of tendon repairs may give falsely generous results with regards to UTS. Removing the slack from the knot within the knotted system allows more accurate measurement of the ultimate system strength and stiffness.

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