Effect of laceration and trimming of a tendon on the coefficient of friction along the A2 pulley

AN IN VITRO STUDY ON TURKEY TENDON

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We carried out lacerations of 50%, followed by trimming, in ten turkey flexor tendons in vitro and measured the coefficient of friction at the tendon-pulley interface with loads of 200 g and 400 g and in 10°, 30°, 50° and 70° of flexion. Laceration increased the coefficient of friction from 0.12 for the intact tendon to 0.3 at both the test loads. Trimming the laceration reduced the coefficient of friction to 0.2. An exponential increase in the gliding resistance was found at 50° and 70° of flexion (p = 0.02 and p = 0.003, respectively) following trimming compared to that of the intact tendon.

We concluded that trimming partially lacerated flexor tendons will reduce the gliding resistance at the tendon-pulley interface, but will lead to fragmentation and triggering of the tendon at higher degrees of flexion and loading. We recommend that higher degrees of flexion be avoided during early post-operative rehabilitation following trimming of a flexor tendon.

Materials and Methods

The coefficient of friction and the gliding resistance were calculated using a method devised by Uchiyama et al., who suggested that a tendon sliding through the curved pulley was analogous to a belt wrapped around a mechanical pulley. Where the direction of movement is from $F_1$ to $F_2$, with the assumption that the total arc of contact between the belt and pulley is $\theta$ and that the tensions in the belt are $F_1$ and $F_2$, the friction coefficient $F_C = \frac{\ln[(F_2/F_1)]}{\theta}$ and the gliding resistance $G_R = F_2 - F_1$ are measured.

Turkey tendons were used for this study, as they are anatomically similar to human tendons in both shape and size. The proximal phalanx from the middle digit of the toe of the turkey with the intact deep flexor tendon and the equivalent of the A2 pulley (Fig. 1) were dissected out. The superficial tendons were removed to exclude variables that could affect gliding resistance and secondary rupture have been described with lacerated tendons that remained untreated.

Trimming the edges of the partially lacerated flexor tendon has been recommended, based on excellent clinical results obtained in 93% of adult sheep, with absence of triggering when guidelines for protected mobilisation were used. Based on a cadaver study, in the absence of triggering unrepaired partial lacerations of the flexor tendon caused the least friction, followed by trimmed tendons and then by those repaired surgically. However, the effect of triggering on friction at the A2-pulley interface was not studied. The influence of the degree of flexion on friction after laceration of the tendon has also not been recorded in the current literature.

The purpose of this biomechanical study was to assess the effect of partial laceration and trimming of a tendon on the gliding resistance and the coefficient of friction at the tendon-pulley interface at different loads and angles of flexion.
Miniature Load Cell, Sensotec Inc., Columbus, Ohio) on both sides of the tendon. We used Silk Shock monofilaments of fishing thread with a high modulus of elasticity of 7 N/Tex, compared with 5.2 N/Tex for prolene and 5.5 N/Tex for vicryl suture materials, in order to reduce stretching of the thread by the loads. We chose load cells with a range of 50 g to 500 g, as we used 200 g (1.962 N) and 400 g (3.924 N) loads for our study. The values obtained by the load cells were therefore within the plateau phase of the transducers’ recording. The load transducers were connected to two amplifiers which recorded the forces produced at either end of the tendon. The load transducer on the proximal end of the tendon was connected to a weight to maintain the tendon in tension, with the fishing thread passing over a low-friction pulley. The second load transducer was similarly connected to a testing machine (Losenhausen GB Ltd., Sutton Coldfield, United Kingdom), which moved the tendon in and out of the pulley using a hydraulically operated central ram that moved vertically. Movement of the tendon from proximal to distal into the pulley represented extension and the outward movement represented flexion. The term ‘excursion’ was used to describe a single movement of the tendon in and out of the pulley. During the movement of the tendon from proximal to distal, the output from the load transducer at the distal end of the tendon was F2, and during movement in the opposite direction the output from the load transducer at the proximal end was recorded as F2.

In order to obtain control values, experiments were first conducted on ten intact tendons using two different loads of 1.962 N and 3.924 N and four different angles of flexion of 10°, 30°, 50° and 70°. Each intact tendon was therefore tested under eight different conditions. The actuator was set to move 20 mm each way, with each excursion lasting three seconds, giving an average velocity of 13.3 mm/s, to allow enough time for detailed observation of the tendon during each excursion. The load transducers were calibrated before the start of each experiment as they were highly sensitive to environmental heat and noise.

Each tendon was then subjected to a volar laceration of approximately 50% and the experiments were repeated. A previous survey of 1000 hand surgeons had found that 86% did not use callipers to measure the exact depth of a laceration, and their decisions on management were based on visual estimations of the approximate depth.20 We did not use callipers, but discarded tendons with a laceration of more than 60%, which was measured at the end of the experiment. The tendons were then trimmed and the same experiments were repeated. All the procedures were performed by the same surgeon (LH) under 3× magnification at room temperature. Normal saline was used for tendon hydration and continuous lubrication of the tendons during their movement in and out of the pulley.

The forces F2 and F1, the coefficient of friction and the gliding resistance were calculated for each experiment. Statistical analysis. The distribution of the data was found to be positively skewed and required log transformation to achieve normality. A repeated-measures analysis of variance (ANOVA) was used to investigate the effect of laceration and trimming, the flexion angle and the load on the coefficient of friction and the gliding resistance. The independent-samples t-test was used to compare the mean gliding resistance for the intact and trimmed tendons at different angles of flexion.

Results
Tendons under control conditions glided within the pulley without any significant changes in the gliding forces, irrespective of increases in the angles of flexion or the load (Fig. 3). The peaked values in these figures are related to artefacts arising from environmental noise. However, the gliding forces in partially lacerated tendons increased significantly with increases in the angle of flexion, but not with increases in the load. The plateau part of the graph correlates to prolonged triggering as the lacerated tendon became trapped at the distal edge of the pulley when trying to slide under it. The overall gliding forces in the trimmed tendons were reduced at both loads compared with the partially lacerated tendons, but were still higher than the gliding forces of the intact tendons. However, increasing the angle of flexion led to a significant increase in the gliding forces at both loads in both the lacerated and the trimmed tendons.

The gliding resistance doubled after partial laceration of the tendon and was reduced to about 1.5 times that of the control value after trimming. The coefficient of friction increased by 68% after partial laceration and was reduced after trimming, but was still 26% higher than that of the intact tendon (Table I).

A repeated-measures ANOVA was conducted to assess whether there were differences between the intact, partially lacerated and trimmed tendons. The following...
assumptions were tested: independence of observations, normality and sphericity. The independence of observation and normality were met, but assumption of sphericity was violated. The Greenhouse-Geisser correction was therefore used.

Repeated-measures analysis showed that partial laceration and trimming (p < 0.001, Wilk’s λ test) and increasing the angle of flexion (p = 0.003, Wilk’s λ test) significantly increased the gliding resistance, whereas increasing the load had no significant effect (p = 0.92). Tests for within-subject effects also showed that partial laceration and trimming (p < 0.001, Huynh-Feldt test) and increasing the angle of flexion (p = 0.03) showed a significant increase in gliding resistance, whereas increasing the load (p = 0.85) had no significant effect.

Partial laceration and trimming (p < 0.001, Wilk’s λ test) and increasing the angle of flexion (p < 0.001, Wilk’s λ test) caused a significant increase in the coefficient of friction, whereas increasing the load had no significant effect (p = 0.91). Tests for within-subject effects also showed that partial laceration and trimming (p < 0.001, Huynh-Feldt test) and increasing flexion (p = 0.02) had a significant increase on the coefficient of friction, whereas increasing the load had no significant effect (p = 0.88).

There was an overall increase in the gliding resistance of the trimmed tendons compared to the intact tendons (Fig. 4). Using the independent-samples *t*-test, the mean gliding resistance at 10° and 30° of flexion was not significantly higher than that of the intact tendon at 10° and 30° (p = 0.32 and p = 0.18, respectively). However, the mean gliding resistance increased significantly at 50° and 70° in the trimmed tendon (gliding resistance 0.88 N) compared with that of the intact tendon (gliding resistance 0.43 N) (p = 0.02 and p = 0.003, respectively).
Intact tendons moved during the excursion without any triggering. However, following partial laceration, triggering became more pronounced at higher angles of flexion and following the increase in load. Trimmed tendons showed softer triggering which became more pronounced at 50° and 70° of flexion. No tendons ruptured during the experiments.

Discussion

Maximum physiological forces of failure, the force above which irreversible damage is caused to the tendon, to 120 N have been recorded during an active unresisted tip pinch.21 Tendons lacerated to 75% of their cross-sectional area still retain a tensile strength of 140 N to 200 N,16,22 and surgical repair of lacerations of up to 70% has been shown to reduce the tendon strength.23 Increasing the strength is therefore not the primary aim of treatment in superficial lacerations of the flexor tendons, and for this reason we did not measure the tensile strength of the tendons in our experiment.

The main problem is the friction of the partially lacerated tendon across the tendon-pulley interface which may cause attrition, a poor range of movement and subsequent rupture. Edge resection of partial lacerations involving < 30% of the cross-sectional area of the tendon has been recommended and has given good functional results, with reduced triggering or rupture.5 Excellent results have also been achieved with deeper lacerations of > 50% of the tendon.24 As the direct repair of these partial lacerations creates higher gliding resistance and triggering than those of the trimmed tendon,16 trimming the partially lacerated tendon is an acceptable method of treatment.

Our results are similar to those of other published series.9-15 The partially lacerated tendon showed a rise of 117% in the gliding resistance compared with that of the intact tendon at all angles of flexion. The gliding resistance was reduced by 30% after trimming compared with that of the partially lacerated tendon, but was still 50% higher than in the intact tendon (Table I). We have been able to measure the coefficient of friction at the tendon-pulley interface accurately in these settings, which shows a similar trend to the gliding resistance (Table I).

The relationship between the angle of flexion and the gliding resistance in an intact tendon was linear and constant (Fig. 4). Following partial laceration, we observed an exponential and significant increase in the mean gliding resistance. When the tendon was trimmed, a linear and constant relationship was found between the gliding resistance and the angle of flexion at 10° and 30°, which was not notably higher than that of the intact tendons, followed by an exponential and significant rise at 50° and 70°. Triggering was also more pronounced at 50° and 70°.

Based on these results we believe that the raised gliding resistance and triggering under high angles of flexion will leave the already injured tendon at greater risk of rupture, despite the common practice of trimming the pulley at the time of surgery. Lower angles of flexion should be considered in early post-operative rehabilitation.

Trimming partially lacerated tendons leads to a lower coefficient of friction than in the lacerated tendon but does not return to that of the intact tendon. We recommend that high angles of flexion should be avoided during early post-operative rehabilitation following trimming of the tendon, as the raised gliding resistance and triggering at higher angles could lead to further injury.

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<th>Table I. Means (SD) of the gliding resistance and coefficient of friction of the intact tendons and after partial laceration and trimming</th>
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Graph showing a linear and constant relationship between the angles of flexion and the mean gliding resistance is seen in the intact tendon and an exponential increase following partial laceration at all angles. Trimmed tendons at 50° and 70° of flexion showed a significant rise in the mean gliding resistance compared to the intact tendons or trimmed tendons at 10° and 30° of flexion.
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References