A biomechanical analysis of multistrand repairs with the Silfverskiöld peripheral cross-stitch

K. M. Hirpara, P. J. Sullivan, O. Raheem, M. E. O’Sullivan
From Galway Regional Hospitals, Galway, Ireland

We compared the bulking and tensile strength of the Pennington modified Kessler, Cruciate and the Savage repairs in an ex vivo model. A total of 60 porcine tendons were randomised to three groups, half repaired using a core suture alone and the remainder employing a core and peripheral technique. The tendons were distracted to failure. The force required to produce a 3 mm gap, the ultimate strength, the mode of failure and bulking for each repair were assessed. We found that there was a significant increase in strength without an increase in bulk as the number of strands increased. The Cruciate repair was significantly more likely to fail by suture pullout than the Pennington modified Kessler or Savage repairs. We advise the use of the Savage repair, especially in the thumb, and a Cruciate when a Savage is not possible. The Pennington modified Kessler repair should be reserved for multiple tendon injuries.

Obtaining a good functional result from the repair of a flexor tendon is difficult, as adhesions, which form readily between the tendon and the surrounding soft tissues, limit the excursion of the tendon and hence the movement of the digit.

The most effective method of preventing the formation of adhesions is to allow early movement, be it active1 or passive.2 In order to permit early mobilisation the lacerated tendon must be repaired in such a fashion that it can withstand the forces required for movement of the digit. However, the repair must also be able to glide freely through the relatively tight pulleys of the hand.

In order to increase the strength of tendon repairs numerous suture techniques have been developed that increase the number of strands bridging the repair site. These methods have been criticised for being overly complex, requiring excessive handling of the tissues and taking longer to perform. There are also concerns that the repair site would be subject to increased ‘bulking’, leading to triggering at the pulleys. We aimed to assess the bulking, the force required to produce a 3 mm gap (FPG) and the ultimate strength of multiple-strand repairs augmented with the Silfverskiöld Type B peripheral cross-stitch3 in a linear-load-to-failure model.

Materials and Methods

A total of 60 profundus tendons were harvested from adult porcine forelimbs and frozen at -25°C within six hours of slaughter. They were then thawed, divided, repaired and tested. The tendons were kept moist by spraying with Hartman’s solution during repair and testing. Porcine flexor tendon was chosen as its structure and size is very similar to that of human tendon.4 The deep flexor tendons of the pig are usually larger than their human counterparts, but similar in size to the flexor digitorum profundus of the middle finger.5

The tendons were randomised into three groups of 20. Half of each group was repaired with a core suture alone and the remainder with a core plus a peripheral suture. All core repairs were performed using 4-0 braided polyester (Ethibond, Ethicon Inc., Somerville, New Jersey) and the peripheral repairs using 6-0 monofilament nylon (Ethilon, Ethicon Inc). All repairs were carried out by the first author (KMH) using 2.5 × loupe magnification.

The core repair for the first group was the Pennington modified Kessler6 (two strand), for the second the Cruciate7 (four strand), and the Savage8 (six strand) was utilised for the third (Figs 1 to 3). For these repairs, the locking loop (or locking cross for the Savage) was sited 10 mm from the cut end of the tendon. All peripheral repairs were performed using the Silfverskiöld cross-stitch as originally described,3 using deep bites9 6 mm from the cut end of the tendon (Fig. 4).

Following repair, the tendon was loaded into the pneumatic clamps of a Zwick Linear tensiometer (Zwick GmbH & Co. KG, Ulm,
The force applied was measured using a 2.5 kN load cell attached to a personal computer running Zwick TestXpert 11.02 software (Zwick GmbH & Co.) The tendons were subjected to a preload of 1 N and the maximum and minimum diameters were measured both at the repair site as well as 1 cm proximal and 1 cm distal to it, using a digital vernier caliper (Mitutoyo Corporation; Kawasaki, Kanagawa, Japan). The cross-sectional area of the tendon at these points was calculated using the formula for the area of an ellipse (\(\text{Area} = \pi r_{\text{min}} \times r_{\text{max}}\)). The average of the cross-sectional areas for the tendon 1 cm proximal and distal to the repair site was considered to be the ‘normal’ cross-sectional area. The percentage bulking was calculated using the area of the repair and the ‘normal’ cross-sectional area (\(\text{Bulking} = 100 \times (\text{Area}_{\text{repair}}/\text{Area}_{\text{normal}})\)).

The tendon was subsequently subjected to distraction at a rate of 10 mm/min. Force versus displacement curves were plotted for each tendon and a record was made of the mode of failure, the FPG and the ultimate strength. The FPG was assessed by observing the repair with a 2.5 \(\times\) loupe magnification while being subjected to stress in the tensiometer. When a gap of 3 mm had formed at the repair site, as measured using a digital vernier caliper, a button was pressed on the computer that caused the point of interest to be marked on the force vs displacement curve, allowing subsequent assessment of the force applied to the tendon.
Table I. Results for bulking and strength of the tendon repairs

<table>
<thead>
<tr>
<th></th>
<th>Bulking</th>
<th>3 mm gap Stress</th>
<th>Ultimate strength</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>(N)</td>
<td>(N)</td>
<td></td>
</tr>
<tr>
<td>PMK†</td>
<td>122.09</td>
<td>7.29</td>
<td>1.46</td>
<td>26.23</td>
</tr>
<tr>
<td>Cruciate</td>
<td>137.88</td>
<td>23.84</td>
<td>3.22</td>
<td>41.66</td>
</tr>
<tr>
<td>Savage</td>
<td>125.35</td>
<td>12.70</td>
<td>44.07</td>
<td>75.08</td>
</tr>
</tbody>
</table>

* bulk, repair area/normal area
† SD, standard deviation of the mean
‡ PMK, Pennington modified Kessler

All testing was performed by the first author (KMH) and verified by the second (PJS). Blinding was not attempted, as the core repairs are easily recognisable by virtue of the locking configuration, especially for the Savage repair, or the number of strands crossing the repair site.

**Statistical methods.** Power analysis was performed prospectively using the G* Power program (Heinrich Heine University, Düsseldorf, Germany).10 The estimated results were obtained from the work of Thurman et al11 and Barrie et al.12 These papers provided means and standard deviations for their results, thus allowing estimation of the group size required to yield sufficient power. We used a standard deviation of 22.5, the largest standard deviation described by Thurman et al,11 and an α of 0.05. In order to attain a power of 0.95, a minimum group size of nine was required, and therefore we used 10 tendons per group.

**Data analysis.** The data for bulking, FPG and ultimate strength were tested for normality using the Shapiro Wilk W Test.13 As three sets of the data, namely the bulking of the Cruciate & Silfversköld cross-stitch, the FPG of the Savage core repair and the bulking of the Savage & Silfversköld cross-stitch, could not be shown to be from a normal distribution, the data was analysed using the Kruskal-Wallis test as a non-parametric alternative to analysis of variance (ANOVA).13,14 Data analysis for mode of failure of the core repairs was carried out using Fisher’s exact test.

**Results**

The results of the experiments are summarised in Table I, and illustrated diagrammatically in Figure 5.

The increase in bulking of the core repairs when supplemented by a peripheral repair is illustrated in Figure 6. The Kruskal-Wallis testing revealed no significant difference between any of the groups for the core repair alone, or for the core repair supplemented by a peripheral suture. When the influence of the peripheral repair was considered using the Kruskal-Wallis test, there was a significant increase for the Pennington modified Kessler (p = 0.0004) and the Savage (p = 0.0189) repairs. There was no significant difference for the Cruciate repair (p ≥ 0.9651).

The Cruciate repair was significantly stronger than the Pennington modified Kessler (Kruskal-Wallis test, p = 0.0005 for ultimate strength and FPG). The Savage was significantly stronger than the Cruciate (Kruskal-Wallis, p = 0.0005 for ultimate strength and FPG). Thus there was a significant increase in strength as assessed by ultimate strength and FPG as the number of strands crossing the repair site increased.

Similar findings were seen for repairs supplemented with a peripheral stitch. The Cruciate repair was significantly stronger than the Pennington modified Kessler (Kruskal-Wallis, p = 0.0025 for ultimate strength and Kruskal-Wallis, p = 0.0043 for FPG). The Savage was significantly stronger than the Cruciate (Kruskal-Wallis, p = 0.0015 for ultimate strength and Kruskal-Wallis, p = 0.008 for FPG). Thus, as for the core repair alone, there was a significant improvement in strength as the number of strands crossing the repair site increased.

The increase in FPG and ultimate strength of the core repairs when supplemented by a peripheral repair is illustrated in Figure 6. When statistical analysis was performed using the Kruskal-Wallis test, there was a significant increase in the FPG and ultimate strength of the Pennington modified Kessler (p ≤ 0.0001), Cruciate (p ≤ 0.0001) and Savage (p ≤ 0.0001) repairs.

The results for the comparison of the modes of failure are given in Table II. Only the analyses of the core repairs are shown, as all the peripheral repairs failed by breakage of the suture. The difference between the failures for the Cruciate and the Pennington modified Kessler was significant (core repair Kruskal-Wallis, p = 0.0027; core and peripheral repair, p = 0.0433). The Savage repair was not analysed separately as the difference was even greater than that of the Pennington modified Kessler.

**Discussion**

The repair of injured flexor tendons is still one of the most difficult problems in hand surgery. A poor functional outcome can occur despite perfect operative techniques, as adhesions between the tendon and surrounding tissues limit excursion and therefore restrict digital movement.

Many methods to limit the formation of adhesions have been tried experimentally. Chemical and genetic modulations are theoretical avenues with promising early results.15 Inert overlays designed to prevent contact of the tendon with surrounding structures have also been tried, but early results have been disappointing.16 At present the most successful way of preventing adhesion formation is to allow active1 or passive2 movement at an early stage after operation. This creates concern about the integrity of the tendon repair, and a high incidence of ruptures has been reported with simpler techniques, such as the two-strand Pennington modified Kessler repair,17 when early movement is allowed. In our experiments, forces of ultimate strength in the region of 53 N were achieved with the Pennington modified Kessler repair, and according to Strickland18 passive movement only required 5 N of force, with light pinch only requiring 14 N. This raises the
question why does the repair fail when it would appear to be sufficiently strong?

The reason for the failure of tendon repairs at forces lower than their maximum strength is complex. First, the figures given by Strickland were measured in a ‘normal’ hand. There had been no injury to the flexor tendons, and therefore none of the associated inflammation and oedema was present. The inflammatory response to injury has been shown to significantly increase the work of flexion and hence the forces experienced by the tendon repairs.

Secondly, the usual figures quoted for the strength of tendon repairs are for a linear distraction to failure mode. The work of Pruitt, Manske and Fink, Pruitt et al, Barrie et al and McLarney et al has shown that tendon repairs subjected to a cyclic load of only a fraction of their ultimate strength will fail, despite being well within their supposed tolerance.

Thirdly, the figures for ultimate strength are not necessarily the best measure of how a tendon repair performs. Gelberman et al’s work in the canine model has shown that the work of flexion remains relatively low with gaps of less than 3 mm at the repair site. Once a 3 mm gap has formed, the work of flexion increases, with an associated large increase in the amount of force experienced by the tendon repair when carrying out an early mobilisation regimen, compared with that experienced by uninjured tendon. Thus, the repair can quite quickly reach its ultimate failure strength. Gelberman et al found that with a 4 mm gap the repair was incapable of passing through the pulleys in the hand, indicating that catching of the repair at the pulleys is responsible for a considerable amount of failure.

Even if the repair does not gap sufficiently to cause catching, a bulky repair will not pass smoothly through...
the pulleys, thus increasing the work of flexion and the risk of failure. We did not find a significant increase in the amount of bulking, and therefore it can be assumed that the increased strength of repair with increasing strands does not come at the cost of an increase in work of flexion. This agrees with the findings of Aoki et al,23 who showed that multiple-strand repairs do not increase the work of flexion. Although it might be expected that the Salvage repair would be prone to increased bulking compared with the other core techniques, we believe that the amount of suture material present has relatively little influence on the cross-sectional area of the repair. The most important factor in repair bulk is the bunching of the substance of the tendon caused by shortening of the repair, particularly seen when securing the knot. Techniques of repair that allow sliding of the locking configuration, with associated shortening of the repair, will be more prone to bulking than those that grasp the tendon securely. The locking configuration of the Savage repair allows no sliding of the suture, whereas the Pennington modified Kessler technique allows a little, and the Cruciate allows the most. When tying the knot the Savage repair is less likely to shorten and cause bunching of the repair, counteracting any influence because of the increased amount of suture material at the repair site.

Mason and Allen,24 in experiments performed on immobilised tendons, found that the repairs should be several orders of magnitude stronger than required for mobilisation as the repair weakened during the initial 30 days. Winters et al25 and Hitchcock et al26 have subsequently shown that this ‘softening’ of the repair does not occur if the tendons are subjected to loading during healing. They also showed that the resultant healed tendon is structurally superior and mechanically stronger than one that has been immobilised. These benefits are seen only if the tendon does not rupture during rehabilitation, and in order to overcome the increased work of flexion evident in the early phase of tendon healing a repair should have a considerably stronger FPG than is required to perform the exercises prescribed. There is no information about how much stronger the repair should be, and thus testing the linear-load-to-failure is useful for comparing repairs prior to their clinical use. Two-strand repairs have been shown to be inadequate for early mobilisation.1,2 We feel that, in view of the progressive failure of cyclically-loaded tendons and the increase work of flexion of tendons subjected to injury, a tendon repair should have a mean FPG of at least 40 N to 45 N if early mobilisation is to be considered.

We have shown that the Savage repair is very strong and not excessively bulky. Maximum grasp on the tendon is also achieved by the locking configuration, as evidenced by all repairs failing because of breakage of the suture. In contrast, the Cruciate repair, albeit significantly stronger than the Pennington modified Kessler repair, failed half the time because of pullout of the suture. The locking loops of the Cruciate repair do not provide sufficient grasp on the tendon to fully utilise the strength of the four strands. The poor strength of the Pennington modified Kessler repair is entirely a result of the small number of strands crossing the repair site. As in the Savage repair, the locking configuration of the Pennington modified Kessler provides adequate hold on the tendon so that the strength of all the strands is fully utilised. However, the strength of two strands is sufficient not to allow early mobilisation. The principle advantage of the Pennington modified Kessler repair is its simplicity.

All of the repairs we have assessed have an application. The Savage repair is the strongest, but its complexity and the number of strands restrict its use to relatively large tendons and few repairs. It is particularly useful in lacerations of tendons in the thumb, an area with a disproportionately high rate of rupture.27

Table II. Summary of the method of failure of core repairs

<table>
<thead>
<tr>
<th>Core Repair</th>
<th>Pullout*</th>
<th>Breakage†</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMK‡</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Cruciate</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Savage</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Core plus peripheral repair</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>PMK‡</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Cruciate</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Savage</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

* pullout indicates core failure due to the suture pulling out of the tendon substance
† breakage indicates core failure by snapping of the suture, generally at, or near, the knot
‡ PMK, Pennington modified Kessler

Graph to illustrate the percentage increase of each parameter caused by the addition of a peripheral repair to the core repair.
The Cruciate repair is significantly stronger than the Kessler and only slightly more complex. It is suitable for the majority of tendon lacerations, as the superior strength makes up for its inability to grasp the tendon adequately. Modifications of the locking configuration of the Cruciate repair have been published, and these reduce the tendency for pullout. If increased purchase is desired the Cruciate repair may be used in one of these variations, at the expense of some of its simplicity.

The simplicity of the Pennington modified Kessler makes it ideal for injuries requiring large numbers of tendon repairs, such as in hand reimplantation or multiple tendon lacerations at the wrist. In these situations early mobilisation is often not possible, and therefore its poor strength characteristics are not a concern.

At present, the standard of care for tendon lacerations demands that a core repair must be supplemented with a peripheral repair in order to smooth the junction and to increase the strength of the construct. Our results showed an increase in FPG of between 197% and 495% and in ultimate strength of between 141% and 208%, depending on the technique of core repair. Although supplementation of the core causes a moderate increase in bulking, the large increase in the strength of the repair easily justifies the addition of a peripheral suture. We find the Silfverskiöld cross-stitch technique to be simple, and the literature shows that it is superior to a simple running suture.

Our results show that there is a significant increase in the strength of repair with increasing numbers of strands. This does not cause increased bulking and applies to both ultimate strength and the resistance to 3 mm separation. We have also shown that the Silfverskiöld type B peripheral cross-stitch greatly increases the strength of the core repair, especially for techniques using two and four strands.

References