Simplifying four-strand flexor tendon repair using double-stranded suture: a comparative ex vivo study on tensile strength and bulking
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J Hand Surg Eur Vol 2012 37: 101 originally published online 2 June 2011
DOI: 10.1177/1753193411409840

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What is This?
Simplifying four-strand flexor tendon repair using double-stranded suture: a comparative ex vivo study on tensile strength and bulking

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Abstract
We have compared a simple four-strand flexor tendon repair, the single cross-stitch locked repair using a double-stranded suture (dsSCL) against two other four-strand repairs: the Pennington modified Kessler with double-stranded suture (dsPMK); and the cruciate cross-stitch locked repair with single-stranded suture (Modified Sandow). Thirty fresh frozen cadaveric flexor digitorum profundus tendons were transected and repaired with one of the core repair techniques using identical suture material and reinforced with identical peripheral sutures. Bulking at the repair site and tendon–suture junctions was measured. The tendons were subjected to linear load-to-failure testing. Results showed no significant difference in ultimate tensile strength between the Modified Sandow [36.8 N] and dsSCL [32.6 N] whereas the dsPMK was significantly weaker [26.8 N]. There were no significant differences in 2 mm gap force, stiffness or bulk between the three repairs. We concluded that the simpler dsSCL repair is comparable to the modified Sandow repair in tensile strength, stiffness and bulking.

Keywords
Bulking, double-stranded suture, flexor tendon, loop suture, tendon repair, tensile strength

Date received: 23rd October 2010; revised: 14th March 2011; accepted: 18th April 2011

Introduction
Primary surgical repair of flexor tendon injury of the hand must have adequate strength to allow early postoperative digital mobilization. The repair strength can be increased by increasing the number of strands bridging repair [Aoki et al., 1995; Kusano et al., 1999; Shaib and Singer, 1997]. Numerous repair techniques have been developed to increase the number of strands from the conventional two-strand to four-, six- and even eight-strand repairs [Al-Qattan and Al-Turaiki, 2009; Angeles et al., 2002; Dinopoulos et al., 2000; Gill et al., 1999; Lee, 1990; Manchio et al., 2009; Savage, 1985; Vinikainen et al., 2007]. However, these multi-strand repairs are complex, time-consuming and involve repetitive tendon handling with repeated passage of needles and sutures through the tendon. In recent years, double-stranded or loop sutures have been used to produce multi-strand repairs [Cao and Tang, 2005; Dinopoulos et al., 2000; Kusano et al., 1999; Lee, 1990; Lim and Tsai, 1996; Tang et al., 1994; Tsuge et al., 1975; Wang et al., 2003]. They confer several advantages such as doubling the strands across the lacerated ends with each pass of the needle and simplifying suture locking to the tendon. Multi-strand repairs performed with loop sutures also have higher tensile strength than two-strand repairs [Barrie et al., 2000a; Dinopoulos et al., 2000; Gill et al., 1999]. However, some of these repairs require two or more loop sutures per repair [Lee, 1990; Lim and Tsai, 1996; Tang et al., 1994; Wang et al., 2003]. They also have knots on the tendon surface [Cao and Tang, 2005; Kusano et al., 1999; Tang et al., 1994; Wang et al., 2003]. These extratendinous knots increase the gliding resistance [Momose et al., 2000]. Furthermore, most of them use locking purchases similar to the Tsuge repairs which require using the loop end of the suture, thus limiting the loop suture to only a single use.
In this study, we tested a novel single cross-stitch locked repair using a double-stranded suture (dsSCL) to produce a four-strand repair (Figures 1 and 2A). It uses the locking purchase similar to the Sandow and MacMahon repair (Sandow and McMahon, 1996) and so has intratendinous knots. The dsSCL repair can be completed with a single double-stranded suture and the remaining suture can be used for another repair making it a more economical method. This repair is simple and requires only three bites of suture for each end of tendon. We report a biomechanical study of this new repair technique comparing its bulking and biomechanical properties with two other four-strand repairs.

**Materials and methods**

**Materials**

Following appropriate consent, thirty flexor digitorum profundus tendons were harvested from
the index, middle and ring fingers of five human fresh-frozen cadavers from the mid-palmar region to its insertion at the base of distal phalanx. None of the tendons showed gross abnormalities or degenerative changes. The tendons were then stored at −25°C for 3 weeks. On the morning of tendon repair, the frozen tendons were thawed to room temperature and wrapped with saline-soaked gauze to prevent desiccation. The temperature and humidity of the laboratory were maintained the same throughout the experiment.

The tendons were divided into three groups of ten tendons each. Each tendon was then secured to a board by a needle at each end with the volar surface of the tendon facing upward. The volar surfaces were identified by the absence of vinculae on the surfaces. All the tendons were transected transversely at their mid-point. The tendons were then repaired by a single surgeon with 2.5× loupe magnification. Similar steps of repair were applied to all tendons. First, a simple running peripheral suture was placed in the posterior wall (dorsal surface) of the tendon, followed by the placement of the core suture assigned to each group. The repair was completed by placing the peripheral suture in the anterior wall (volar surface) of the tendon. All the peripheral sutures were standardized by using a 6-0 monofilament polypropylene suture (Prolene, Ethicon, Somerville, NJ) with identical purchase (2 mm), depth (1 mm), number of purchases (8) and single intratendinous knot of three throws (2-1-1).

The three different types of four-strand core suture techniques were the single cross-stitch locked repair performed with a double-stranded suture (dsSCL) (Figure 1 and 2A), the Pennington Modified Kessler repair (Pennington, 1979) performed with double-stranded suture (dsPMK) (Figure 2B), and the four-strand cruciate cross-stitch locked repair (Modified Sandow) (Barrie et al., 2000b) performed with a single strand suture (Figure 2C). The double strand sutures were 4-0 Supramid loop sutures [Supramid Extra II, S. Jackson, Inc., Alexandria, VA, USA]. At the end of both core repairs, the loop end of the Supramid sutures was divided and each end was knotted separately to the opposite end of the suture thus forming two intratendinous knots. For the Modified Sandow repair with single strand suture, one of the two threads of the 4-0 Supramid loop suture was cut near the suture-needle junction to produce a single strand suture of same material and size as the two previous groups. This repair produced a single intratendinous knot. Several parameters of the core repairs were standardized. The suture material, and the size and needle specification were the same. All repairs were tied with the same knot (2-1-1). The sutures of the core repairs gripped the tendons 10 mm from the cut ends. The sizes of the suture locks, however, were different. Both the dsPMK and modified Sandow repairs had locks of 2 mm in width while the dsSCL repair had locks of 3 mm in width. Table 1 summarizes the properties of the three repairs.

### Bulking of the tendon repair: data collection and analysis

After the repair, the maximum and minimum diameters of the tendon were measured with a digital vernier caliper at several sites: the repair site, both the proximal and distal tendon-suture junctions (core suture purchasing areas) and 20 mm further away from the repair site. The cross-sectional area of the tendon at these points was calculated using the formula for the area of an ellipse (Area = π \( r_{min} \times r_{max} \), with \( r \) as the radius of the measured site) (Hirpara et al., 2007). The cross-sectional area at the repair site was obtained directly from the calculation. For the tendon-suture junction, the average of the proximal and distal areas of core suture purchase site was chosen, while the average of the cross-sectional areas for the tendon 20 mm proximal and 20 mm distal to the repair site was considered to be the

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Table 1. Comparisons between the three types of four-strand repair

<table>
<thead>
<tr>
<th>Types of four-strand repair</th>
<th>Single cross-stitch locked</th>
<th>Modified Kessler</th>
<th>Modified Sandow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of suture</td>
<td>Double stranded</td>
<td>Double stranded</td>
<td>Single stranded</td>
</tr>
<tr>
<td>Number of bites per tendon end (total bites)</td>
<td>3 (6)</td>
<td>3 (6)</td>
<td>6 (12)</td>
</tr>
<tr>
<td>Number of forceps’ grasps per tendon end</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Number of loops per tendon end</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Types of loop</td>
<td>Cross-stitch lock</td>
<td>Grasping or Simple lock*</td>
<td>Cross-stitch lock</td>
</tr>
<tr>
<td>Number of intratendinous knots</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

* Determined by the orientation of the vertical strand to the longitudinal strand of suture.
‘normal’ cross-sectional area. The bulking at the repair sites and at tendon–suture junctions were calculated using the formula:

\[
\text{Bulking}_{\text{site of interest}} = \left( \frac{\text{Area}_{\text{site of interest}}}{\text{Area}_{\text{normal}}} \right) \times 100\%
\]

The repaired tendons were restored at −25°C for a further week.

The mechanical testing: data collection and analysis

The tendons were thawed to room temperature on the morning of biomechanical testing and wrapped with saline-soaked gauze to prevent desiccation. Each tendon was clamped at both ends with two hemostat forceps at a distance of 20 mm from the repair site. The forceps were then held by the upper and lower clamps of a tensile testing machine [Model 4469: Instron Corp., UK]. The tendon was subjected to a load-to-failure test. The force and the corresponding distraction distance were recorded with a software program (Series IX: Automated Material Testing System 7.51.00). Several parameters of the test were standardized for all the tendons. The initial distance between the two forceps was 40 mm. The preload was set at 1.0 N. The distraction rate was set at a constant speed of 20 mm/min. The distraction was terminated once the repaired tendon failed. No slippage was noted between the tendon and the hemostat forceps or between the forceps and the clamps during the tensile testing.

A ruler with 1 mm graduated marking was placed parallel and co-planar to the tendon during distraction. The distance of separation of the stumps was recorded by a digital video camera projecting perpendicular to the tendons at the level of the tendon repair site. The force to produce a 2 mm gap (FTG2mm) was defined as the force that separated the tendon ends at the repair site by 2 mm. Gap formation was often non-uniform across the width of the tendon. Thus, frame-to-frame analysis of the video recording was used to determine the frame at which the center of the tendon reached a gap of 2 mm and the time of that frame was noted. To avoid bias, three independent, blinded observers analyzed the video recordings. The mean of their three readings were then used to determine the corresponding distraction and force from the load–deformation data.

The ultimate strength of the repairs was the peak force recorded during the test, which appeared just before ultimate failure of the repairs.

The value was obtained directly from the load–deformation data.

The stiffness of a composite tendon repair is the force required to produce a unit displacement of the tendon. Its value was derived from the load–displacement curve. The curve was separated into two parts by the point of failure of peripheral sutures (Figure 3). The first part represented the curve of the composite repair and it ended as the peripheral suture failed. In the second part of the curve, the core suture continued to bear the tensile load until it failed. The tangent of the linear segment of the first part of the curve represented the stiffness of the composite repair. This tangent was determined by performing linear regression of a series of consecutive points along the linear segment of the curve. The linear regression line with the best coefficient of determination was used to represent the tangent of the load–displacement curve in its most linear region.

The mode of failure for a composite repair is defined as the event causing the initial drop in force after reaching the ultimate tensile strength. This was determined by examining the peripheral and core sutures at the end of each tensile load test and by analyzing the video images for each tendon and its load–deformation curve.

Statistical methods

The sample size requirements were predetermined by a power calculation. A level of significance (α error) of 0.05 and a power (1−β error) of 0.80 were set. Statistical analysis was carried out with
Table 2. Results of bulking of the tendon repairs

<table>
<thead>
<tr>
<th>Core</th>
<th>Bulking at repair site [%]</th>
<th>Bulking at tendon–suture junction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>dsSCL</td>
<td>140.3</td>
<td>21.5</td>
</tr>
<tr>
<td>dsPMK</td>
<td>143.0</td>
<td>21.3</td>
</tr>
<tr>
<td>Sandow</td>
<td>134.2</td>
<td>18.2</td>
</tr>
</tbody>
</table>

a statistical software program [SPSS 12.0 for windows: SPSS Inc., Chicago, IL, USA]. Data was analyzed by one-way analysis of variance (ANOVA). When the analysis indicated significant difference among data then multiple comparisons were performed with the Tukey post hoc test. A level of significance of $p < 0.05$ was considered to be statistically significant.

Results

Bulking of the tendon repairs

The results of bulking of the tendon repairs at the repair site and tendon–suture junction are detailed in Table 2. The results of the one-way ANOVA showed no significant difference between any of the three groups of repair with regards to bulking at both repair site and at tendon–suture junction.

Tensile strength of the tendon repairs

The force to produce a 2 mm gap (FTG2mm) and the ultimate strength of the repairs are shown in Figure 4. For the FTG2mm, there was no significant difference between the three repair groups. However, the one-way ANOVA analysis for ultimate tensile strength showed a significant difference between the three repair groups. The Modified Sandow and dsSCL core repairs had a significantly higher ultimate strength compared to the dsPMK core repair with $p$ values of $<0.001$ and $<0.05$ respectively. There was no significant difference in the ultimate strength between the Modified Sandow group and the dsSCL group.

Stiffness of the composite repairs

There was no significant difference between the three repair groups (Figure 5).

![Figure 4. Results of the forces to produce 2 mm gap formation and ultimate forces for the three groups of repair. Values are presented as the mean ± SD with standard error bars. $P$ values are presented if any comparison shows significant difference ($p < 0.05$).](image)

Mode of failure of the tendon repairs

All the peripheral repairs failed before the core repair. After the peripheral suture failed, the tensile load was then borne by the core suture until its own failure. The core suture was observed to fail at a higher load than composite repair in all the repairs except in four tendons; one in the dsSCL group and three in the dsPMK group. Thus in all but those four repairs, the ultimate strength occurred just before the core suture failed. By the earlier definition of the mode of failure of the composite repair (the event causing the initial drop in force after reaching the ultimate tensile strength) the mode of failure of the core repairs did not represent the mode of failure of the composite repair in those four cases (Table 3).
Discussion

Multi-strand repairs produce stronger repairs but their complex techniques require time and repeated trials to master in order to produce the repair strength consistently similar to those of laboratory testing. An ideal repair should be simple to perform with minimal tendon handling, but still maintaining sufficient tensile strength [Strickland, 1995].

Our new repair, dsSCL and the popular, modified Kessler technique are both simple to perform. Only three passages of suture are needed on each end of the tendon and only one grasp of the surgical forceps for each end since locking purchases are completed on one end before the steps are repeated on the opposite end. When performed with double-stranded sutures, the two techniques produce a four-strand repair. As neither repair utilizes the loop end to perform a lock, a single suture can be used to repair more than one tendon laceration. Between these two simple techniques, the dsSCL showed a significantly higher ultimate tensile strength than the dsPMK. This is because a cross-stitch lock grasps a greater cross-sectional area than a simple Pennington-type lock (Barrie et al., 2001; Croog et al., 2007). Increasing the cross-sectional area of locking increased the tensile strength of repair [Dona et al., 2004; Hatanaka and Manske, 1999]. Secondly, it is possible that not all the loops of the dsPMK repair group were locking loops. As the tendon was opaque, we could not be certain if the longitudinal strand passed deep to the transverse strand to produce a locking Pennington loop or passed superficial to the transverse strand to produce a grasping loop [Pennington, 1979]. This occurrence of an ‘accidental grasping loop’ is not just a limitation of our study but rather a true operating scenario faced during actual tendon repair with a modified Kessler technique. The weaker holding strength of the simple locking

Table 3. Results of the mode of failure of the composite repairs

<table>
<thead>
<tr>
<th>Core</th>
<th>Failure of peripheral sutures</th>
<th>Failure of core sutures</th>
<th>Suture pullout</th>
<th>Suture breakage</th>
<th>Knot unravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>dsSCL</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>dsPMK</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sandow</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Stiffness of the composite repair of the three groups of repair. Values are presented as mean ± SD with standard error bars. There was no significant difference between any of the three repair groups.
loops and the ‘accidental grasping loops’ could also explain the higher rate of core suture pullout in dsPMK.

The Modified Sandow has a superior ultimate tensile strength compared to most four-strand repairs (Angeles et al., 2002; Barrie et al., 2000b). The repair is, however, complex to perform, requiring a total of six bites per tendon end and two separate grasps of each tendon end with forceps as only one out of two locking loops can be completed with one grasp of the forceps on the tendon end. This complex repair did not have significantly superior ultimate tensile strength compared with the simpler dsSCL. Despite having one less locking loop in the dsSCL, the cross-sectional area caught by the larger single locking loop in the dsSCL approximated the total area caught by the two smaller loops of the modified Sandow. Thus the tensile strengths of both repairs were comparable.

The bulking of tendons at their repair site can be affected by the bunching of the tendon substance from core suture overtensioning (Hirpara et al., 2007; Tang, 2007). To avoid this, the tendon ends were first approximated with a running peripheral suture on the posterior wall. The core repairs were then tensioned and knotted to adequately approximate the tendon ends without causing further shortening and bunching of tendon. Despite the difference in the number of intratendinous knots, there was no significant difference in the bulking in the repair site between the three repairs. This finding is consistent with Hirpara et al. (2007), who concluded that the amount of suture material present has relatively little influence on the bulking of the repair and that the most important factor is the bunching of the tendon substance caused by shortening of the repair during tensioning and knotting. The bulking at the tendon–suture junction was also not significantly affected by the differences in the types and number of loops between the three groups.

There were no significant differences in the stiffness and the FTG2mm between the three groups. This could be due to the presence of the peripheral sutures that masked the effect of the core sutures (Cao et al., 2006; Croog et al., 2007). This peripheral suture effect was explained by Lotz’s concept of inequality of load-sharing between the peripheral and core sutures (Lotz et al., 1998). Due to the differences of geometry, material properties and suture–tendon interface, the peripheral suture receives more load than the core suture when tensile force is applied to a composite repair and thus contributes considerably towards the stiffness and the FTG2mm results.

We believe that the dsSCL repair is an excellent primary intrasynovial flexor tendon repair. It is simple to perform with minimal tendon handling. Its tensile strength is comparable to the proven modified Sandow technique. It is easy to perform in small tendons such as the flexor tendons of the little fingers and in children as only one locking loop is required at each end of tendons. Thus, we recommend the new dsSCL repair as a simpler alternative to the four-strand modified Sandow repair without compromising repair strength. We do not recommend dsPMK repair due to the possibility of an ‘accidental grasping loop’ that we believe may weaken the repair significantly.

Acknowledgements
The authors thank Professor Kulenthiran for statistical analysis consultation; Aziz, for assisting with the biomechanical testing; Jefri, Terence and Mogannadass for the blinded observation.

Funding
This work was supported by the postgraduate study grant from University of Malaya.

Conflict of interests
All named authors hereby declare that they have no conflicts of interest to disclose.

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