A biomechanical comparison of six different double loop configurations for use in the lateral fabella suture technique

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Summary

Six different double loop configurations which could be applied to the lateral fabella suture (LFS) technique were subjected to in vitro mechanical testing. Three double loop, single strand and three double loop, double strand configurations were tested. The strongest configuration, with a significantly higher mean ultimate load and load at yield, was the interlocking loop configuration. This is a novel configuration which has not previously been reported. The three double loop, single strand configurations all had higher mean ultimate loads than the double loop, double strand configurations. The double strand group with uneven loop length performed very poorly, with significantly lower mean stiffness and ultimate load than all of the single strand groups. This group also developed unacceptably high levels of elongation during high level cyclic loading.

Keywords

Cranial cruciate ligament, double loop, Securos®, crimp tubes, mechanical testing

Introduction

Cruciate disease is the most common orthopaedic condition to affect the canine stifle joint (1), and the most commonly performed repair technique for this condition is the extracapsular, lateral fabella suture (LFS) technique (2, 3). The goal of this surgery is to stabilise the joint temporarily until periarticular fibrosis provides permanent stability (4, 5). Previous authors have noted that the complication and failure rates for this technique are higher in active and larger dogs (5–8). However, despite this, extracapsular techniques, such as the LFS, are still the most favoured for large and giant breed dogs worldwide (2). In larger dogs, two suture loops have been recommended in order to cope with the higher loads being transmitted through the stifle (4, 9) Surgical suppliers have appreciated this recommendation and manufacture cruciate needles with two swaged on strands of monofilament nylon leader line (NLL) to facilitate this goal (10, 11).

When employing a double loop construct there are several different configurations that can be used in order to achieve the same goal. Apart from the self locking knot configuration (12), previous descriptions of the LFS technique either describe how to place a single loop, or do not provide any description of the actual surgical technique (4–7, 13, 14).

The aim of this study was to compare six different double loop configurations (Figs. 1, 2) that could be applied to the LFS technique. Comparisons were conducted in vitro using biomechanical testing methods. Three of the configurations consisted of one crimp tube and a single strand of NLL looped double; double loop, single strand (DL-SS) configurations. The other three configurations required two crimp tubes and two individual strands of NLL; double loop, double strand (DL-DS) configurations. The null hypothesis for the study was that there is not a difference in the biomechanical properties of the six different loop configurations.

Materials and methods

Loop preparation

The three DL-SS configurations depicted in Figs. 1A, B and C were designated; simple double (SD), locking loop (LL) and interlocking loop (IL). The three DL-DS configurations depicted in Figs. 2A and B were given the following terms: simple single (SS), figure of eight (F8) and uneven (UL). The uneven group had the same configuration as the simple single group; however one of the loops was 2 mm shorter than the other.

For all of the different configurations, Securos® (Securos Inc., Charlton, MA, USA) instrumentation and materials were used in loop preparation. Thirty-six kilogram Hard Type Monofilament NLL (Mason Tackle Company, Otisville, MI, USA) was employed along with the corresponding crimp tubes (CR12520P – Securos online catalogue). This is the size recommended by Securos for medium and large dogs. The crimps were applied using the Securos universal tensioning device.

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To facilitate standardisation between suture loops, they were all prepared on a jig constructed with two large IMEX® external skeletal fixation (ESF) connecting bars. The connecting bars were fixed at a distance 124 mm apart (as measured from the outer edge of each connecting bar) using IMEX clamps and intramedullary pins in a similar fashion to a method described by a previous investigator (15). To make the longer loop for the uneven configuration the distance between the connecting bars was increased to 126 mm.

The crimp tubes were attached by passing each nylon strand around the jig in the desired configuration and through the primary tube in opposite directions. A secondary tube was placed on each strand and the ends of the strands were clamped with artery forceps. The artery forceps were used to hold the strands in gentle tension and the primary tube was positioned centrally between the tensioning crimp tubes. The secondary tubes

Fig. 1  A) Simple double (SD) configuration; B) locking loop (LL) configuration; C) interlocking loop (IL) configuration.

Fig. 2  A) Simple single (SS) configuration; B) figure of eight (F8) configuration.
were positioned one crimp tube length from the primary tube and crimped three times using the manufacturer’s instructions. The Securos universal tensioning device was used to the 15th step on its ratchet mechanism to tension the suture loop. The primary tube was crimped three times as per the manufacturer’s instructions. The forceps were removed and the strands were cut from the suture loop approximately 3 mm from the primary tube. The two operators performed the same actions for each loop. This method of loop preparation was based on a method described by a previous investigator (15).

**Mechanical testing**

The constructs were tested using an Instron 5584 load frame (Instron Ltd., High Wycombe, UK) in the Department of Engineering. The loop constructs were secured to the load arm and static arm of the load cell by two cylindrical pins securely mounted in parallel. Tension was applied equally across the suture loops by distraction of the cylindrical pins at a rate of 200 mm/min for all experiments. All of the constructs were pre-loaded under tension to 5N prior to testing.

Data, including load (in Newton), elongation (millimeters), and the time elapsed (seconds) were collected at 500 Hz using a personal computer and Instron Bluehill Software (Instron Ltd., High Wycombe, UK). Data were imported into Excel (Microsoft, Redmond, WA, USA) and load versus elongation curves were generated for each test. Elongation was determined by the distance between the load arm and static arm of the load cell. This distance increased as load was applied. The following variables were calculated from the raw data and the load versus elongation curves: ultimate load (N), load at yield (N), elongation at yield (mm), stiffness (N/mm) and failure mode. Stiffness was calculated from the gradient of the linear portion of the load vs. elongation curve (N/mm). The yield point was defined as the point where the initial linear portion of the load versus elongation curve changed shape and reduced gradient. Yield point was determined by eye, using a ruler. The following testing protocols were employed:

- **Low level cycling followed by loading to failure.** Each construct was cycled from 0 to 300N five times then tensile loading to failure was performed. This part of the experiment was repeated 10 times for each loop configuration (i.e. there were 10 constructs in each group). This protocol was designed to mimic a short period of cyclical loading followed by an acute episode of high load, e.g. walking a short distance then jumping. All of the suture loop configurations were subjected to this phase of the experiment.

- **High level cyclical loading:** Each construct was pre-loaded to 5N and then cycled from 300 – 450N 100 times. This part of the experiment was repeated three times for all suture loop configurations; the protocol being designed to mimic an extended period of high level cyclical loading, e.g. running. All of the suture loop configurations were subjected to this phase of the experiment.

**Statistical analysis**

Data were analysed with Graph Pad Prism 3.0 (Graph Pad software, San Diego, CA, USA). The values are reported as the mean ± standard error. The data for each parameter tested for normality using the One Sample Kolmogorov-Smirnov test. The data was analysed using one way ANOVA with Tukey HSD (honest significant difference) post-hoc testing. Significance was accepted if the p value was <0.05.

**Table 1** Load at failure, stiffness, load at yield and elongation at yield for the six different configurations following cyclical loading to 300N five times then loading to failure at 200 mm/min (n=10).

<table>
<thead>
<tr>
<th>Loop configuration</th>
<th>Load at failure (N)</th>
<th>Stiffness (N/mm)</th>
<th>Load at yield (N)</th>
<th>Elongation at yield (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double loop- single strand (DL-SS)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interlocking loop (IL)</td>
<td>835±  ± 2.4</td>
<td>85.5± 0.501</td>
<td>319± 2.04</td>
<td>3.8± 0.07</td>
</tr>
<tr>
<td>Simple double (SD)</td>
<td>693± 28.7</td>
<td>111± 0.495</td>
<td>282± 4.25</td>
<td>2.5± 0.04</td>
</tr>
<tr>
<td>Lacking loop (UL)</td>
<td>662± 25.6</td>
<td>97.6± 0.725</td>
<td>287± 4.71</td>
<td>3.1± 0.08</td>
</tr>
<tr>
<td><strong>Double loop-double strand (DL-DS)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple single (SS)</td>
<td>649± 13.0</td>
<td>110± 3.01</td>
<td>295± 1.42</td>
<td>2.8± 0.10</td>
</tr>
<tr>
<td>Figure of 8 (F8)</td>
<td>605± 11.9</td>
<td>105± 1.65</td>
<td>299± 4.24</td>
<td>3.0± 0.11</td>
</tr>
<tr>
<td>Uneven loop (UL)</td>
<td>546± 15.8</td>
<td>46.7± 0.230</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Data expressed as mean ± standard error. Different letters denote values that are significantly different from one another for a given parameter (single-factor ANOVA with post-hoc Tukey HSD analysis, P<0.05).
failed by pull through. The IL’s failed mainly by pull through (60%), though some failed by breakage within the looped portion of the nylon leader line (3/4) or the crimp tube (1/4). For all of other configurations, the mode of failure was pull through.

- **High level cyclical loading:** None of the configurations failed during this part of the experiment.

- **Tensile loading to failure:** All of the IL’s failed by nylon breakage at the point where the loops locked together. Ninety percent (9/10) of the IL’s failed by pull through and 10% (1/10) of the IL’s failed by nylon breakage within the looped portion of the NLL. The SDs all failed by suture pull through.

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**Low level cycling followed by load to failure**

For all of the measured variables, values were normally distributed as determined by the Kolmogorov-Smirnov test.

One way ANOVA revealed a significant difference between groups for ultimate load ($F(5, 54) = 26.41; P \text{ value} < 0.0001$). The IL configuration had the highest ultimate load, followed by the SD, LL, SS, F8 and UL groups (Table 1). All of the DL-SS configurations had higher loads to failure than the DL-DS configurations. The IL configuration was significantly higher ($P \text{ value} < 0.001$) than all of the other groups. For the IL group, the load at failure was 29% higher than the best performing DL-DS configuration and 53% higher than the worst performing DL-DS configuration. The UL group had the lowest load to failure, significantly lower ($P \text{ value} 0.01$) than all of the other groups except the F8 group.

One way ANOVA revealed a significant difference between groups for load at yield ($F(4, 45) = 15.58; P \text{ value} < 0.0001$). The IL group had a significantly higher load to yield than all of the other groups ($P \text{ value} < 0.01$) (Table 1, Fig. 5). For the uneven group, it was not possible to calculate a yield point as the load versus elongation curve had a sigmoid shape.

One way ANOVA revealed a significant difference between groups for stiffness ($F(4, 45) = 279.4; P \text{ value} < 0.0001$). The SD configuration had the highest stiffness (Table 1) followed by the SS, F8, LL, IL and UL groups. The three groups with the highest values; the SD, SS and F8 groups, were not significantly different from one another. The UL group was significantly lower ($P \text{ value} < 0.001$) than all of the other groups.

One way ANOVA revealed a significant difference between groups for elongation at yield ($F(4, 45) = 36.65; P \text{ value} < 0.0001$). The IL had a significantly higher elongation than all other groups ($P \text{ value} < 0.001$) (Table 1). As previously mentioned, it was not possible to establish the yield point for the UL group, thus making the determination of load at yield impossible for this group.
High level cyclical loading

In order to evaluate the data from the high level cyclic loading phase of the experiment a graph was prepared of peak elongation at 450 N versus cycle number (Fig. 3, Fig. 4). The data from all of the trials and all configurations was pooled to create the chart. The pattern of elongation (rate and extent) was very similar for all configurations apart from the UL group (Fig. 4). This construct elongated in two major steps to 1.1 mm after four cycles and then to 2.2 mm after 15 cycles. All of the remaining configurations quickly reached a steady state of elongation which reached a plateau between approximately 1.1 and 1.2 mm after 100 cycles. Of these, the IL had a slightly greater relative extension for the duration of the experiment.

Table 2 Load at failure, stiffness, load at yield, elongation at yield for the single strand configurations following loading to failure at 200 mm/min (n = 10).

<table>
<thead>
<tr>
<th>Loop configuration</th>
<th>Load at failure (N)</th>
<th>Stiffness (N/mm)</th>
<th>Load at yield (N)</th>
<th>Elongation at yield (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interlocking loop (IL)</td>
<td>830 ± 17.3</td>
<td>71.7 ± 1.62</td>
<td>278 ± 4.83</td>
<td>4.36 ± 0.10ab</td>
</tr>
<tr>
<td>Simple double (SD)</td>
<td>714 ± 24.3</td>
<td>107 ± 0.852</td>
<td>259 ± 5.78b</td>
<td>2.57 ± 0.09b</td>
</tr>
<tr>
<td>Locking loop (LL)</td>
<td>635 ± 28.2</td>
<td>85.0 ± 2.25</td>
<td>259 ± 3.01b</td>
<td>3.72 ± 0.30b</td>
</tr>
</tbody>
</table>

Data expressed as mean ± standard error. Different letters denote values that are significantly different from one another for a given parameter (single-factor ANOVA with post-hoc Tukey HSD analysis, P < 0.05).

Tensile loading to failure

For all of the measured variables, values were normally distributed as determined by the Kolmogorov-Smirnov test.

One way ANOVA revealed a significant difference between groups for load to failure (F (2, 27) = 17.68; P value <0.0001). The IL configuration had the highest load to failure, followed by the SD and IL groups (Table 2, Fig. 5). The IL group failed at significantly higher loads (P value <0.01) than all other groups.

One way ANOVA revealed a significant difference between groups for load to yield (F (2, 27) = 5.733; P=0.0084). The IL group had the highest load at yield, followed by the SD and LL groups (Table 2, Fig. 6). The mean values for the SD and LL group were identical. The IL group had a significantly higher load at yield than all other groups (P value <0.05).

One way ANOVA revealed a significant difference between groups for stiffness (F (2, 27) = 111.9; P value <0.0001). Stiffness was highest for the SD configuration (Table 2), followed by the LL and IL groups. Differences between the groups were statistically significant (P value <0.001).

One way ANOVA revealed a significant difference between groups for elongation at yield (F (2, 27) = 23.47; P value <0.0001). The IL group had the highest elongation at yield, followed by the LL and the SD configurations (Table 2). The SD configuration had significantly lower load at yield than both other groups (P value <0.001).

Discussion

Monofilament NLL is a widely used and well accepted material for the LFS technique (16). Previous studies have shown that it has the ideal biomechanical properties for this purpose (16–18). In addition to this, NLL is biologically inert, has minimal infection potentiating effect (6, 16) and is unaffected by sterilisation (16, 19).

The use of crimp tubes has been strongly advocated as a means of fastening the two ends of a LFS. Loops secured with a crimp tube have been found to withstand a stronger load before failure, elongate less and elongate in a more uniform fashion than equivalent loops secured with various types of knot (19–22).
A recent publication (23) demonstrated that the Securos 36 kg NLL/crimp system resulted in the preparation of loops that were significantly stronger and stiffer than a rival 45 kg system. In addition to this, the ultimate load resisted by loops prepared by operators with differing grip strengths was less variable. Due to these demonstrated advantages we employed the Securos 36 kg monofilament NLL with its corresponding crimp tubes and forceps for fastening all constructs used in this study.

The first two DL-DS configurations evaluated in this study are configurations which are commonly used clinically. The SS configuration has been described and recommended for larger dogs (4, 9, 10). The UL configuration was deliberately designed to mimic a situation where the loops that are placed are of an uneven length. In a clinical setting, this can occur in a number of different ways. Firstly, loops can be placed through separately drilled bone tunnels in the proximal tibia. Secondly, a second loop might be placed by a second pass of a fabella needle behind the fabella – the needle is highly unlikely to be placed in exactly the same position both times, almost guaranteeing uneven loop length. Finally, separate fastening of two separate loops can result in uneven loop length. In this instance, the second loop placed is likely to be tighter and shorter because the stifle is held stable by the first loop. This means that greater tightening can be achieved with the second, resulting in a shorter loop. This is easy to observe in a clinical situation, when after the second loop is placed the original loop doesn’t appear to be as tight as it was initially. Due to the potential for uneven loop length occurring in the clinical application of a LFS, the authors were keen to investigate the biomechanical implications of this configuration. A minor discrepancy in length was chosen (2 mm difference in loop length) to simulate the aforementioned scenarios.

The DL-SS configurations in this study were novel configurations that, to the best of the authors’ knowledge, had not been reported in the literature. They were chosen because they were simple configurations which would be easy to apply clinically. The only double loop configuration described is the McKee Miller self locking knot (12) and this is secured with a knot rather than a crimp tube.

**Failure mode**

In this study, failure occurred by two methods; pull through of the two strands of the monofilament leader line through the crimp tube and by breakage of the NLL. Interestingly, the only configurations where loop breakage occurred were the LL and IL configurations. The remainder of the configurations all failed by pull through. For the LL group, breakage always occurred in the area where the two loops joined. In this region, the monofilament NLL was bent at a very acute angle. For the IL group, breakage occurred almost exclusively in the looped portion. Previous investigators have noted that the knot is always the weakest point of a knotted suture loop. This is because tensile forces are reoriented at an acute angle to the suture material and converted into shear forces. The strands are compressed against one another, causing narrowing and decreasing local material properties (24–27). A previous investigator noted a lower load to failure for knotted suture loops prepared with two sliding half hitches compared with clamped square knots and surgeon’s knots. This effect was consistent for a variety of suture materials. The investigator hypothesised that this effect was caused by the initial throws of this knot creating more of an acute angle between the strands of suture than the other knots evaluated (28). In this study, the LL configuration resulted in the strands of NLL being oriented at very acute angles to each other. This may explain the very high rate of breakage for this configuration. The interlocking loop configuration had more gentle curves and less acute angles. This may explain why this group experienced a lower rate of breakage with failure occurring predominantly by pull through.

**Load to failure following low level cyclical loading**

The amount of load a LFS needs to withstand is a point of considerable conjecture, and definitive figures have yet to be estab-
lished. Extrapolating from previous biomechanical studies of normal cruciate ligaments (29, 30), the load transmitted through the cranial cruciate ligament of a 25 kg dog has been estimated as 400–600N during vigorous activity (16).

Synthetic materials, such as NLL, are unable to respond to stress by gaining strength and stiffness in the same way that autogenous grafts do (30), thus their strength should ideally exceed that of the intact cruciate ligament. In human cruciate surgery, when a prosthesis is used, an ultimate tensile strength of twice the intact cruciate is a stated goal (31).

If it is anchored at non-isometric points, a LFS may be exposed to additional loads at certain angles of stifle joint motion (32, 32A). This is clearly the case for the traditional technique described (4, 5). Thus, how much force a LFS needs to withstand remains unknown.

In clinical cases, failure of the LFS before adequate fibrosis has occurred will cause stifle instability, leading to damage to the cartilage, menisci and failure of the repair (33). It is well recognised that failure of this technique to maintain stability is a common problem. The recurrence of cranial drawer following the LFS technique has been noted by previous investigators (23, 34). Repeat surgery to address meniscal tears (8) and premature failure due to crimp slippage (35) are both common complications. These failures may be caused by exposure to forces beyond the ultimate strength of the repair. In light of this, choosing a technique with a high ultimate strength makes sense.

In our study, all of the DL-SS configurations had higher mean ultimate loads than the DL-DS configurations. There are many potential reasons for the apparent superior strength of these configurations. The crimp tube or knot is always the weak point in auture loop construct; the double strand constructs had two of these weak points, compared with one for the single strand constructs. As the single strand constructs employ one continuous strand of nylon leader line there may be better equilibration of tension over the construct.

The IL configuration had a mean ultimate load that was significantly higher than all of the other groups. There are several theories which may potentially explain why this configuration was the strongest. Firstly, the interlocking loop configuration has increased strand on strand contact, which generates greater friction due to a greater contact area. A possible frictional effect was noted by a previous investigator (16) in comparing loops of monofilament NLL attached between two hooks or from a cadaver fabella to a hook. The fabella to hook loops were able to resist higher loads at all elongations compared with the hook to hook model. The investigator hypothesised that friction with the soft tissues protected the knot. This frictional effect in the strands of the interlocking loop configuration may have helped to resist pull out through the crimp tube. Secondly, the interlocking loop had an advantage over the locking loop because the strands were oriented at less acute angles to each other, making breakage before pull through less likely. Finally, the interlocking loop is a single strand construct and has an advantage over double strand configurations as previously outlined.

Not surprisingly, the uneven group had the lowest load to failure. Load applied to this group, initially only engaged the shorter loop. As the shorter loop elongated, the second loop was engaged, allowing load sharing between loops. Presumably, the load applied solely to the shorter loop weakened it, making it more susceptible to premature failure.

The range of mean ultimate loads in this study varied between 546–835N. This is much higher than the mean load to failure (336.9N) noted in a previous study employing exactly the same crimp tubes and leader line but in a single loop construct i.e. one simple single loop (23). The leading two DL-SS configurations in this study had at least twice that value (835 and 695N). For the UL group, the advantage was not nearly as dramatic, with only a 62% increase in mean ultimate load. This emphasises the fact that if uneven loop length occurs during loop placement the mechanical advantage gained by placing an extra loop is markedly reduced.

The values for load to yield were similar for all groups apart from the IL group. The mean value for this group was significantly higher than all other groups. Its advantage in this parameter is probably due to the same reasons as previously postulated for its superiority in ultimate load. As mentioned in the Results section, it was not possible to accurately determine a yield point for the uneven group. The difference in the curve for this group (compared with all other groups) was probably due to its configuration, with stiffness and thus gradient increasing as the second loop was engaged. From the shape of the graph this occurred before an initial yield point was reached.

Stiffness, as a material property is dependent on the dimensions of the material (length, area) and the material properties (modulus) (30). For structures, such as the loop constructs tested in this study, the configuration also plays a role in the stiffness. If the UL group is excluded, the configuration with the lowest stiffness was the IL group. This configuration also employed the longest length of NLL due to its looped portion. This may help to explain why this configuration did not perform as well in this parameter. Another potential explanation for the lower stiffness observed with this group is its configuration. Previous investigators have noticed increased elongation with knotted loops compared with crimped loops, due to tightening occurring within the knot (17, 19–21, 36) and a similar phenomenon is perhaps occurring with this configuration, albeit to a lesser degree. The interlocking loop portion acts a little bit like a knot, with tightening leading to increased elongation compared with other groups. The UL configuration performed very poorly in this parameter with a stiffness that was significantly lower than all of the other groups. For this loop configuration, initially all the load was taken by the shorter of the two loops until sufficient elongation occurred to engage the longer loop. Thus, the value for stiffness was similar to that which could be expected in a single loop construct. Not surprisingly, the stiffness was less than half that of the SS configuration and was similar to the value (60.6 N/mm) obtained in a recent study testing a single loop of the same nylon leader line and crimp tube (23).

The IL group had a significantly higher elongation at yield compared with all of the other groups. There are two possible explanations for this finding. Firstly, this group also had a significantly higher load at yield. As elongation increases with load applied, it follows that the higher the load at yield, the higher the value for elongation will be. Sec-
ondly, this group had significantly lower stiffness than all of the other groups apart from the UL group. This is probably due to greater elongation occurring due to its overall length and tightening in the looped portion as discussed previously.

**High level cyclical loading**

The amount of cranio-caudal draw present in a normal stifle has been measured as 0.72–1.8 mm (38, 39). Based on these studies, an objective of restricting tibial draw to less than 2.0 mm at physiologic loading has been proposed as an essential goal for a suitable CCL replacement (16). With the LFS technique, elongation of the suture loop(s) results in an increase in the amount of cranial draw. The amount of ‘draw’ that occurs is determined by multiplying the length of the loop elongation by cos of the angle between the suture loop and a line perpendicular to the long axis of the tibia. Given this mathematical relationship between the two variables, an increase in loop length will result in a proportional increase in cranio-caudal draw. Limiting cranial draw by limiting loop elongation is an essential goal for suture loop constructs employed in the LFS technique.

From the graph of elongation versus cycle number (Fig. 3), it can be observed that the pattern of elongation (rate and extent) was very similar for all of the configurations except for the the UL group. This configuration elongated in two major steps to 1.1 mm after four cycles and then to 2.2 mm after 15 cycles. By the end of the 100 cycles, the relative extension had reached 2.4 mm. This was almost twice the relative elongation of all of the other configurations at the same stage.

All of the remaining configurations quickly reached a steady state of elongation, which reached a plateau between approximately 1.1 and 1.3 mm after 100 cycles. Of these, the interlocking loop configuration had a slightly greater relative extension from the 1st or 2nd cycle onwards, but the difference was still less than 0.2 mm for the duration of the testing, and was 45% less than the UL configuration.

The UL group undoubtedly performed poorly due to the differing loop length, with the shorter loop initially taking all of the load and essentially functioning as a single loop construct for the early cycles, allowing far greater elongation compared with all of the other configurations. Previous investigators have noted increased stiffness and decreased elongation for DL-DS constructs compared with single loop constructs (22, 36). Because the load was shared between the two loops for all of the other configurations their relative elongation was much lower. The marked similarity of the curves for these remaining constructs suggests that elongation in this load range is a function of the material rather than the configuration of the construct. The IL configuration had a slightly greater relative extension for the duration of the experiment. This is probably due to its increased length and tightening within its looped portion as discussed previously. While this configuration did allow slightly more elongation, the difference compared with the other configurations was minimal (within 0.2 mm for the whole 100 cycles) and was nowhere near the 2.4 mm that occurred with the UL group towards the end of the 100 cycles.

**Tensile loading to failure**

The aim of this part of the experiment was to provide a more comprehensive evaluation of the performance of the single strand configurations. There was concern that the initial period of low level cyclical loading may afford certain loop configurations a protective advantage.

However, this was not the case. The values for ultimate load were very similar to those recorded following low level cyclic loading and the order of the different groups remained unchanged. The values for stiffness and load at yield tended to be slightly lower than the corresponding values for the low level cyclical loading phase. In contrast, values for elongation at yield were slightly higher. Again, the order of the different groups was largely unchanged for all parameters.

**Clinical application**

Apart from the superior biomechanical characteristics noted in this study, DL-SS configurations have other advantages over DL-DS configurations. Only one crimp tube needs to be secured, which results in decreased cost, foreign material and surgical time. For the locking loop and interlocking loop configurations the nylon need only be passed once around the back of the fabella, resulting in a further saving in surgical time. Since the completion of this study, the authors have employed the IL configuration on clinical cases. It has proven to be easy to place and it is faster than placing single loop configurations where the tensioning and crimping of two tubes is required. Short-term clinical results have been encouraging but long-term follow-up is not yet available.

**Limitations**

In an ideal study, loop constructs would be created with a uniform circumference and under uniform tension. In our study the same frame was employed to create all of the constructs, thus ensuring that the loop circumference remained constant and that all of the constructs were prepared with the tensioning device following the same protocol for tensioning to reduce variation. However, loop tension was not directly measured during loop preparation. Previous investigators have measured tension during loop fastening (16, 17, 21). Although variability in initial loop tension may be greater for our method, all of the configurations were secured by the same method, meaning that each of the groups were exposed to the same level of variation. Furthermore, the method of creating initial loop tension that we employed is one that is widely used in a clinical setting.

**Conclusions**

The most significant finding in this study was the poor biomechanical performance of the UL group. This group had the lowest values for ultimate load and stiffness and an unacceptable high level of elongation in the high level cyclic loading. In a clinical situation, any DL-DS configuration can easily be placed in such a way that loop length is uneven. During different phases of the gait cycle, this may mean that one single loop...
bears all of the load transmitted through the stifle. This effect could be accentuated by non-isometric loop placement. If this occurred, it would be reasonable to assume that biomechanical performance of the construct would be similar to the UL group in this study. Based on these findings, the authors strongly advocate employing DL-SS configurations in preference to DL-DS configurations. Of the DL-SS configurations, the IL configuration can be recommended with confidence. Its ultimate strength was significantly higher than all other groups and its elongation under high level cyclic loading was similar to the other groups (apart from the UL group). In addition, its configuration makes it easy to place clinically with a single pass of an eyed graft passer.

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