In vitro mechanical evaluation and comparison of two crimping devices for securing monofilament nylon and multifilament polyethylene for use in extracapsular stabilization of the canine stifle

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Keywords
Cruciate, crimp, multifilament polyethylene, monofilament nylon, PowerX, universal

Summary
Objective: To compare the tensile strength and stiffness of non-absorbable suture loops created with two types of crimping devices.

Methods: Loops of monofilament nylon leader line (MN) of 18 kg, 36 kg, and 45 kg multifilament polyethylene (MP) with a crimp and MP with a crimp and knot were mechanically tested to failure in quasistatic tensile loading after being created with either a wave pattern crimp device or three applications of a single crimp device. Each testing group consisted of five samples. Tensile loading to failure at a rate of 0.5 mm/s was used. Failure was defined as a sudden drop in the recorded force.

Results: All suture materials failed by breaking near the crimp tube with both crimp devices, with exception of the MP without knot, which slipped through the crimp tube using both devices. Sutures secured with the wave pattern crimping device were significantly stronger with a higher load yield, maximum load, displacement yield, failure displacement, and maximum displacement than the single crimp device. Loops of MP suture crimped with either device plus the addition of a surgeon’s knot resulted in a significantly stronger construct than unknotted crimped MP constructs. Crimped MP combined with knot were significantly stiffer, but not stronger, than crimped 45 kg MN.

Clinical significance: Performing extracapsular repair for ruptured cranial cruciate ligaments with the wave pattern crimp system may result in lower failure rates due to the construct being significantly stronger than the single crimp system.

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Introduction
Cranial cruciate ligament disease is one of the most common causes of canine hind-limb lameness (1). Rupture of the ligament results in a cranial-caudal instability due to the unrestrained, cranially directed, tibiofemoral shear force. Numerous surgical techniques have been developed over the years to address this instability. These techniques are often divided into categories of intracapsular, extracapsular, and proximal tibial osteotomy methods (1–5). Despite the popularity of osteotomy-based techniques such as tibial tuberosity advancement and tibial plateau levelling osteotomy, to date no studies have demonstrated an overall superior method for treating cranial cruciate ligament deficient stifles (6, 7).

The extracapsular lateral fabella suture technique is commonly performed by passing a suture around the lateral fabella, through a bone tunnel in the proximal region of the tibial crest, and securing the loop of suture with a knot (5, 8, 9). Monofilament nylon (MN) has become a popular suture choice, however, the stiffness of MN results in large, bulky knots with poor security (10–14). Large knots increase the amount of foreign material that remains in the patient, which is a potential source for chronic irritation, seroma formation and infection (15, 16). In contrast, multifilament sutures generally have superior handling characteristics and better knot security (17). Additionally, a recent study using polymerized caprolactam, a type of multifilament suture, for cranial cruciate ligament deficient stifle stabilization reported no occurrences of draining tracts (18).

Crimping systems replace the need for knots by securing the suture within a metallic tube (crimp) (15). Crimping offers numerous advantages over knot tying, including decreased material bulk and retained foreign material, decreased elongation of the construct, and increased strength of the repair (15, 16, 19, 20). In

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Materials and methods

Experimental design

Two main groups were investigated, the wave pattern crimp group and the single compression crimp group. The wave pattern crimp device is designed with a continuous interlocking wave pattern in the jaws, which is equal to the length of the stainless steel titanium-nitrate-coated crimp tube, thus requiring one pinch of the device to complete the crimp deformation. The jaws of the single compression crimp device are narrow and create a single point of compression on the stainless steel crimp tube, requiring three successive, equally-spaced pinches of the device to complete the crimp deformation (Fig. 1). Each group consisted of five samples of 18 kg MN, 36 kg MN, 45 kg MN, number 5 MP crimped only, and number 5 MP with a knot in addition to the crimp (Table 1). All sutures evaluated were sterilized with ethylene oxide prior to testing. Each suture material tested was secured with a corresponding crimp tube size (i.e. 18 kg, 36 kg, 45 kg MN and MP crimp tubes); the crimp tubes for each device are the same shape and design, and both are stainless steel. The only difference between the two being that the crimp tube used with the wave crimp device is coated in titanium-nitrate, which reduces glare.

Loop formation

A custom-designed jig was used for loop formation. The jig contained two arms of 12.7 mm diameter that were positioned 60 mm apart. Each suture sample was cut into 180 mm length segments and then looped around the arms of the custom jig. Primary and secondary crimps were then placed onto the loops. The secondary crimps were crimped on the ends of the suture and, using the suture-tensioning instrument, tension was applied by moving the slider to the 15th slot. The primary crimp was then crimped and the secondary crimps removed leaving a suture overhang of approximately 5 mm. For the knotted MP test groups, a surgeon’s knot was tied with five throws after the primary crimp was crimped. The test samples for each type of suture material were created by alternating between use of the two crimping devices. The samples were made in the following order (5 samples of each, created in alternating fashion): crimped MP with knot, crimped MP without knot, 45 kg MN, 36 kg MN, 18 kg MN. Crimping with the single compression device was performed by three single sequential applications of the crimp device jaws evenly spaced along the crimp tube (20). The crimping procedure was similar for the wave device, with the ex-
Table 1 Estimated mean (standard differentiation) stiffness, load, and displacement measurements for the two crimping systems.

<table>
<thead>
<tr>
<th>Device</th>
<th>Suture</th>
<th>Mechanical parameter</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Stiffness (N/mm)</td>
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<tr>
<td><strong>Comparison of devices - all suture sizes combined</strong></td>
<td></td>
<td></td>
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<tr>
<td>Single crimp (n = 25)</td>
<td>MP</td>
<td>62.15 B</td>
</tr>
<tr>
<td></td>
<td>(14.989)</td>
<td>(16.869)</td>
</tr>
<tr>
<td></td>
<td>MP knot</td>
<td>67.36 BC</td>
</tr>
<tr>
<td></td>
<td>(2.558)</td>
<td>(19.771)</td>
</tr>
<tr>
<td></td>
<td>MN 18</td>
<td>25.22 D</td>
</tr>
<tr>
<td></td>
<td>(1.363)</td>
<td>(36.333)</td>
</tr>
<tr>
<td></td>
<td>MN 36</td>
<td>45.45 CD</td>
</tr>
<tr>
<td></td>
<td>(0.238)</td>
<td>(30.118)</td>
</tr>
<tr>
<td></td>
<td>MN 45</td>
<td>60.43 BC</td>
</tr>
<tr>
<td></td>
<td>(3.641)</td>
<td>(28.829)</td>
</tr>
<tr>
<td>Wave crimp (n = 5 for each)</td>
<td>MP</td>
<td>82.76 B</td>
</tr>
<tr>
<td></td>
<td>(16.784)</td>
<td>(40.593)</td>
</tr>
<tr>
<td></td>
<td>MP knot</td>
<td>120.32 A</td>
</tr>
<tr>
<td></td>
<td>(26.960)</td>
<td>(34.266)</td>
</tr>
<tr>
<td></td>
<td>MN 18</td>
<td>28.65 D</td>
</tr>
<tr>
<td></td>
<td>(0.623)</td>
<td>(4.928)</td>
</tr>
<tr>
<td></td>
<td>MN 36</td>
<td>46.82 CD</td>
</tr>
<tr>
<td></td>
<td>(1.071)</td>
<td>(7.126)</td>
</tr>
<tr>
<td></td>
<td>MN 45</td>
<td>63.49 BC</td>
</tr>
<tr>
<td></td>
<td>(0.813)</td>
<td>(11.089)</td>
</tr>
</tbody>
</table>

Key: Values are shown as the mean (standard deviation); means with different capital superscript letters are significantly different at the 0.05 level for comparisons within a column. MP = multifilament polyethylene; MN = Monofilament nylon.

A servo-hydraulic testing machine<sup>8</sup> with a 2000 N load cell was used for all mechanical testing. Quasistatic tensile loading to failure was performed at a rate of 9.5 mm/s. Failure was defined as a drop in the recorded force by 50%. Data were collected using commercial software<sup>1</sup> and recorded at 10 Hz. Data were imported into spreadsheets from which load versus load-point displacement curves (N/mm) were generated. Stiffness, yield load, failure load, maximum load, yield displacement, failure displacement, and maximum displacement were calculated. Stiffness was calculated by determining the maximum slope of the elastic portion of the load versus load-point displacement curve, which was determined using linear regression analysis for a best fit. Yield load was calculated by determining the load at which the sample began to plastically deform. Failure load was calculated by determining the load at which the sample failed (point at which the load dropped by 50%). Maximum load was calculated by determining the greatest load value on the load versus load-point displacement curve. Similarly, yield displacement was calculated by determining the displacement at which the sample began to plastically deform. Failure displacement was calculated by determining the displacement at which the sample failed (point at which the load dropped by 50%).

<sup>1</sup> Bluehill 3 Testing Software for Mechanical Testing Systems: Instron, Norwood, MA, USA
<sup>2</sup> Microsoft Excel: Microsoft, Redmond, WA, USA
<sup>8</sup> Instron Model 5544: Norwood, MA, USA
mum load was calculated by determining the greatest displacement value on the load versus load-point displacement curve. It should be noted that in certain cases, failure displacement and maximum displacement will equal the same value. This can be attributed to the fact that the suture may partially tear or slip, resulting in a drop in load by 50% (considered a point of failure), but continue to extend or displace until complete tearing or slipping occurs.

Statistical analysis

Data for six measurements were analysed with a commercial software package: stiffness, yield load, maximum load, yield displacement, failure displacement, and maximum displacement. All measurements were analysed for the groups of MP, MP with knot, MN 45, MN 36 and MN 18. Two-factor multivariate analysis of variance (MANOVA) was used to analyse for the effects of device and material across the measurements. The Kolmogorov–Smirnov test was used on the residuals from the MANOVA to ensure that data satisfied the assumption of normality of the underlying error term. For each measurement, the estimated mean values of the measurements for the two devices that obtained from the MANOVA were compared directly; the five materials were compared to each other using Tukey’s multiple comparison post-hoc test, as were combinations of device and materials. For all tests and procedures, p-values of <0.05 were considered significant.

Results

The MANOVA found that the means across all constructs for all six mechanical parameters were greater for the wave crimping device than for the single compression device (p <0.0001) (Table 1). The load yield (strength) of all constructs using the wave device was greater than that for constructs using the single compression device (p <0.05) (Fig. 2). Loops of MP suture crimped by either device plus the addition of a surgeon’s knot resulted in a significantly stronger construct than unknotted crimped MP constructs. Crimped MP combined with a knot were significantly stiffer than crimped 45 kg MN.

Fig. 2  Box and whisker plots of load yield for various devices and materials. The centre bar of the box represents the median and the ‘+’ represents the mean. MP = multifilament polyethylene; MN = monofilament nylon.
All suture materials failed by breaking near the crimp tube with both crimp devices with exception to the MP without a knot, which slipped through the crimp tube using both devices.

Discussion

The results of our study show that suture loops crimped using the wave crimping device were significantly stronger and stiffer with a higher load yield, maximum load, displacement yield, failure displacement and maximum displacement than those crimped using the single compression device. Neither crimp system prevented failure of the MP suture loop from slippage, indicating that when using MP suture, tying a surgeon's knot after crimping results in a significantly stronger and stiffer construct than unknotted MP crimped constructs. Additionally, crimped MP with a knot was significantly stiffer than crimped 45 kg MN with similar load yields.

Crimps have become a popular alternative to knotted suture for a number of reasons (15, 16, 19, 20). Decreased suture bulk, decreased elongation of the construct, ease of maintaining suture tension during crimping, and increased strength of the repair are some of the reported benefits of crimped over knotted suture loops. (14–16, 18). The holding power of a crimp system is generated by the friction developed between the crimp tube and the suture when it is compressed. We suspect the increased strength of the wave crimp construct is attributable to its improved holding power, which is a result of ‘wave style’ crimp pattern (Fig. 1). This crimp pattern produces more surface contact and friction between the inner wall of the crimp tube and the suture material. Instead of the three separate crimp contact points produced with the single compression device, the wave pattern increases the friction throughout the tube with five contact points.

Multifilament suture has superior handling characteristics and produces smaller knots that undergo less elongation than knotted MN (21). Multifilament polyethylene is a multifilament suture that has been shown to be stronger and stiffer than MN in previous studies (21). However, crimped MP has been shown to be weaker than knotted MP and equal to crimped MN (21). Multifilament sutures may slip through the crimps more than MN. This is possibly because MN is more deformed by the crimping action, which produces increased friction. The increased crimp security and construct stiffness afforded by the combination of a knot placed on top of the crimped MP is provided by the knot being an additional point of ‘fixation’. The previously reported mean stiffness of crimped MP was approximately 175N/mm with a mean strength of 290N (21). In our study, the mean stiffness of wave crimped MP was 82.7N/mm and wave crimped MP with a knot was 120.3N/mm while the mean strength of the wave crimped MP was 302.96N and the wave crimped MP with a knot was 677.48N. The results of the mean stiffness of crimped MP in this study are less than previously described, however the strength is comparable between the two studies. Clearly, knotting the MP results in a stronger construct. While limiting knot usage in order to minimize the material remaining in a patient is ideal, the combination of the crimp and a single knot with MP was significantly stiffer than all other knotted or crimped suture constructs tested in this study.

Limitations

In vitro studies such as this one attempt to find the strongest and stiffest constructs assuming that the findings will translate into fewer repair complications in vivo. However, it is clear that multiple technique factors and patient parameters influence short and long-term stability of extracapsular suture stabilizations and therefore the maximum strength and stiffness characteristics are not necessarily an absolute requirement of a stable repair. Our data illustrate that there is no mechanical disadvantage that accompanies use of the wave-style crimping system. We cannot conclude that the improved suture construct strength described herein will in-turn decrease recurrent cranial tibiofemoral shear instability in patients. The mechanical testing performed in this report oversimplifies the forces acting on suture constructs in vivo. The in-vivo biomechanics of the stifle, with natural stifle loading were not evaluated. Mechanical testing of the cyclic loading characteristics of different suture constructs crimped with the wave-style crimper is worthy of additional study. Also, the sutures were tested in vitro in a dry environment and it is unknown what effect fluid would have on the friction generated between the suture and the crimp and therefore the construct performance in vivo.

In order to minimize variability and maximize repeatability, a single individual (AK) prepared all the samples for testing. In theory, if this individual prepared all of the samples incorrectly it may not be detected since there were no other individual’s results to compare to. However, the testing performed was modelled after published testing protocols and the individual performing the crimping was highly experienced with the system (20). Alternatively, determining the ability of the wave-style crimper to produce consistent results among a variety of users with variable system experience would be useful information.

Conclusions

In conclusion, we have shown that loops formed by crimping with the wave-style crimping device are superior in strength to crimping with the single compression crimper. We have also shown that combining MP crimp with a surgeon’s knot results in the strongest and stiffest fixation amongst the groups tested, using both crimper systems. Clinically, this information can be used to guide implant, technique and instrument selection for repair in cranial cruciate ligament deficient stifles.

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Conflict of interest

Co-author Matthew Barnhart receives royalties from the sales of some Securos products but not from the implant systems described in this paper. Co-author Andrew Kazanovicz is an employee of Securos.


