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Ex vivo biomechanical evaluation and comparison of lateral femoro-fabella ligament suture and lateral suture with bone anchor for cranial cruciate ligament repair in cats

Chiara Tassani, BVSc[1,2*]; Anika A. de Witt, BVSc[1]; Geoffrey T. Fosgate, DVM, PhD, DACVPM[3]; Ross C. Elliott, BVSc, MMedVet[1]

[1]Department of Companion Animal Clinical Studies, Faculty of Veterinary Science, University of Pretoria, Pretoria, South Africa
[2]Department of Veterinary Medical Sciences, University of Bologna, Bologna, Italy
[3]Department of Production Animal Studies, Faculty of Veterinary Science, University of Pretoria, Pretoria, South Africa

*Corresponding author: Dr. Tassani (chiara.tassani2@unibo.it)

OBJECTIVE
To compare the biomechanical properties of lateral femoro-fabella ligament suture (FFLS) and lateral suture with a bone anchor suture (BAS) for management of feline cranial cruciate ligament disease.

ANIMALS
12 femurs from 6 mature cat cadavers.

METHODS
The samples were collected from April to June 2023. The specimens had an FFLS and, subsequently, BAS placed and were positioned into a biomechanical testing machine, preloaded from 5 N to 15 N for 100 cycles, and subsequently, a load to suture failure was applied. The displacement at 5 N and 15 N, the total precycle displacement (millimeters), the force at 3 mm displacement and at failure (newtons), the displacement at failure (millimeters), and the stiffness to failure (Newton:millimiter) were recorded. Nonparametric Wilcoxon signed-rank tests were used to compare data between the 2 groups.

RESULTS
The displacement at 5 N and 15 N and the total precycle displacement were significantly higher in the FFLS group compared to the BAS group. Additionally, the FFLS group results showed less consistent displacement and marked variability. The force (newtons) at 3 mm displacement was higher in the BAS group. There was no significant difference in force and no significant difference in displacement at failure between the 2 groups. However, the stiffness to failure (N/mm) was significantly higher in the BAS group.

CONCLUSION
BAS represented a more stable and reliable femur attachment for extracapsular suture in cats.

CLINICAL RELEVANCE
To demonstrate the stability and reliability between BAS and FFLS and influence implant selection in the treatment of cranial cruciate ligament rupture in cats with evaluation of biomechanical properties.

Keywords: cranial cruciate ligament, femoro-fabella ligament, bone anchor, cat, lateral suture

The cranial cruciate ligament (CrCL) plays a vital role in providing stability in the stifle joint.[1] The CrCL prevents hyperextension of the stifle, reduces excessive internal rotation, and prevents cranial tibial translation.[2–4] The etiology of CrCL rupture in cats is unclear, although many studies[1,5,6] hypothesize trauma to be the most common cause. Rupture of CrCL leads to instability of the stifle joint, which in turn causes osteoarthrosis, a decrease in range of motion, and thus loss of normal stifle kinematics. The prevalence of this disease in cats is low compared to dogs, but detecting lameness in cats can be challenging.[5] Treatment options include conservative management and surgical stabilization. According

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to previous studies,[4,5] surgical management results in an earlier return to normal function compared to conservative management and decelerates the progression of osteoarthrosis, although findings are often based on subjective outcomes. The extracapsular technique for stifle stabilization is the most commonly used surgical technique in cats with cranial cruciate disease.[1–3,5,7] Osteotomy techniques produce favorable outcomes in dogs compared to extracapsular procedures, and there are a small number of case series in cats documenting promising results with tibial osteotomy techniques.[8–13] The biomechanical properties of these 2 techniques used for stifle joint stabilization, with both osteotomies and extracapsular fixation, have been widely evaluated in dogs.[14–21] Nevertheless, there are limited reports available that assess the biomechanical behavior of extracapsular techniques for stifle stabilization in cats.[7,22–24] A biomechanical study[7] on cat cadaveric stifle joints demonstrated that a lateral femoro-tibial suture with the screw placed at the quasi-isometric point provides better stabilization to the joint in the proximal-distal plane compared to a standard lateral suture. Recently, different techniques used for cat stifle stabilization have been compared using a limb press machine.[3,23,24] To the best of the authors' knowledge, a study that objectively compares the biomechanical behavior of a lateral femoro-fabella ligament suture (FFLS) and a lateral suture with a bone anchor (BAS) placed at isometric points in the distal femoral metaphysis in cats has not been reported. The objective of this study was to compare the biomechanical properties of 2 commonly used techniques, lateral FFLS and lateral BAS, to manage CrCL disease in cats. Our hypothesis was that BAS would provide a more stable and reliable technique associated with less displacement during physiological loading compared to FFLS for the management of CrCL disease in cats.

Methods

Bone model

Twelve femurs from 6 skeletally mature disease-free cadaveric cats were obtained from a single veterinary hospital after euthanasia for reasons unrelated to this study, from April to June 2023. Permission from the owners to use the cat femurs in this study was granted. Ethics approval from the research and animal ethic committees were obtained (REC029-22). Cats with no macroscopically evident stifle pathology or a history of stifle disease met the inclusion criteria. The cadaveric cats were frozen immediately after euthanasia and were thawed for 24 hours before dissection. The femurs were macroscopically inspected to verify that all stifles appeared disease free. The femoro-fabellar ligament and proximal attachment of the gastrocnemius on the distal femur were preserved, with all other muscles dissected and removed. Subsequently, the proximal femurs were placed in a polyester cylinder, potted in resin (Demotec 95), and left to set for 15 minutes until the resin was dried and completely hardened. A tunnel was drilled in the distal portion of the pipe to allow the femurs to be fixed to the material-testing machine plate. Specimens were covered in a saline-soaked cloth and stored in a deep freezer at –20 °C.[25] Before performing the biomechanical testing, specimens were left at room temperature to thaw for 2 hours. The 12 femurs had both sutures placed in the opposite side and were randomly assigned to having an FFLS or BAS placed on either the lateral or medial aspect of the femur.

Suture material

Commercial 0.7-mm polyethylene braided suture (Boss Braid's Leader Braid) was selected as the suture material. This material was chosen because it is strong and can be used to produce a secure loop with the use of double 1.8-mm wire crimps (crimp sleeves; Halco) with a reinforced surgeon's knot **(Figure 1)**.

Figure 1—Biomechanical properties of femoro-fabella ligament lateral suture (FFLS) and bone anchor lateral suture (BAS) were tested on 12 feline cadaveric femurs. The image shows the loop used for FFLS group (black arrow) and BAS group (white arrow). The suture is secured by double 1.8-mm wire crimps and reinforced by a surgeon's knot (white arrowhead). Every loop was secured by a double crimp and surgical knot to prevent variability during tension loading. The femur is placed in a polyester cylinder with resin (Demotec 65) (black arrowhead), and the material testing system is fixed with a screw placed through the base of the pipe (black star).

The femoro-fabella ligament and bone anchor suture

Only 1 surgeon placed all of the sutures. The suture material was swaged into a regular curved stainless-steel needle and then passed around the femoro-fabella ligament. The needle was removed, and a loop was created and secured with double crimp and surgeon's knot. The 2 mm X 20-mm bone anchor (Veterinary Orthopedic Implant; Movara) was placed on the opposite side in the quasi-isometric point as previously described[26] by drilling a tunnel with 1.5-mm Kirschner wire. The suture was secured through the eye of the bone anchor. Each specimen underwent testing with the FFLS first, followed by testing of the BAS.

Positioning

Before positioning, the width, the distance between femoral epicondyles; and the depth, the distance between distal patella surface and the most caudal point of intercondyloid fossa; of each distal femur, were measured by a caliber and recorded. Each specimen was fixed to the material-testing system (Instron model 4440; Illinois Tool Works Inc) with a screw placed through the base of a polyvinyl chloride pipe. This was secured in a custom-made jig to maintain the position on the testing platform. The femurs were oriented at a 70° angle relative to the base of the machine, and the load bar was positioned to apply the load on the suture loop at an angle of 150°.[25] The positioning of the femurs was based on a previous canine study[25,27,28] that defined the orientation of the femur and the constructs associated with a dog in the stance phase of locomotion **(Figure 2)**.

Figure 2—Positioned specimen for biomechanical testing. The femurs were positioned at a 70° angle relative to the base of the machine. The femoro-fabella ligament suture was placed and connected to a load bar (black arrow) to perform the mechanical test.

Biomechanical testing

The lateral suture was always tested first to prevent microfracture from the failure of the bone anchor affecting the results. A preload test was conducted to mimic the physiological forces acting on the stifle joint. Previous studies[25,28] considered that the load on CrCL in a 4.5-kg cat was estimated to be 13 N and that a load range from 0% to 20% weight was representative of the cat in motion.[28] In this study, a preload of 5 N was applied, and the displacement (millimeters) for each technique was recorded. It was assumed that 0 mm displacement was present at 0 N of applied load. In order to mimic physiological loading, a precyclic load of between 5 and 15 N for 100 cycles at 5 Hz was applied. The displacement (millimeters) at 5 N and 15 N and the total displacement (millimeters) at the end of the 100 cycles were recorded graphically and numerically. The force (newtons) at 3 mm displacement, which is considered to result in stifle instability, was recorded.[28] Femurs were subsequently loaded until failure at 5 Hz, and the force at failure (newtons), displacement at failure (millimeters), stiffness to failure (N/mm), and mode of failure were recorded.

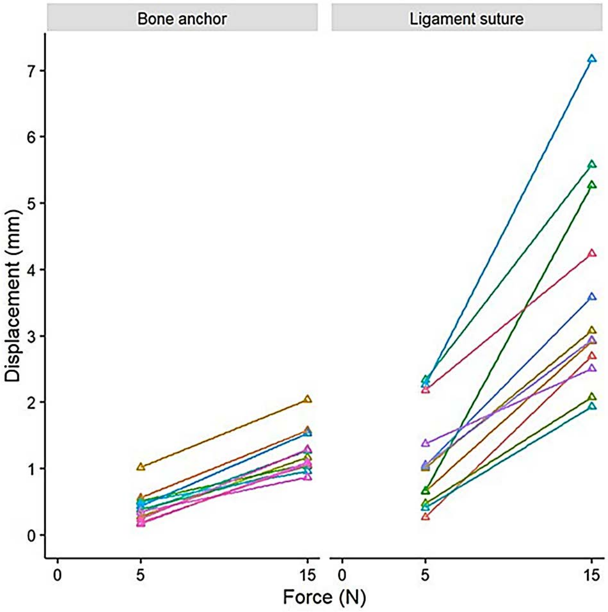

Figure 3—Descriptive presentation of displacement (millimeters) for 12 cat femurs receiving both a femoro-fabella ligament suture (FFLS) and, subsequently, bone anchor suture (BAS) undergoing precycling of between 5 and 15 N. Each coloured triangle represents the minimum and maximum displacement reached by each sample during the 100 cycles from 5 to 15 N. The displacements registered for the same femur are connected with a line.

Table 1—Biomechanical properties of femoro-fabella ligament lateral suture (FFLS) and bone anchor lateral suture (BAS) were tested on 12 feline cadavericic femurs.

	FFLS	BAS	
Measurement	**Median (range)**	**Median (range)**	***P* value[a]**
Precycle displacement at 5 N (mm)	1.02 (0.27–2.33)	0.36 (0.17–1.02)	.034
Precycle displacement at 15 N (mm)	3.01 (1.93–7.17)	1.13 (0.87–2.03)	.002
Total precycle displacement (mm)	2.17 (1.13–4.91)	0.91 (0.46–1.10)	.002
Force at 3 mm displacement (N)	13.7 (8.0, 71.7)	86.5 (51.7–137.0)	.002
Force at failure (N)	230.1 (15.0–474.9)	274.6 (198.1–343.4)	.308
Failure displacement (mm)	11.89 (5.70–21.67)	7.73 (5.93–12.97)	.060
Stiffness to failure (N/mm)	19.66 (2.09–31.99)	33.09 (21.84–44.92)	.002

[a]Based on Mann-Whitney *U* tests.
Descriptive statistics and comparison of biomechanical results between FFLS and BAS techniques in 12 pelvic cadaveric limbs.

Statistical analysis

The normality assumption for collected data was assessed by calculating descriptive statistics, plotting histograms, and performing the Anderson-Darling test in commercial software (MINITAB Statistical Software, release 13.32; Minitab Inc). Data were described using the median and range. Data were descriptively presented using scatter plots in the ggplot2 package[29] within R.[30] Average stiffness prior to failure was calculated as the force at failure (newtons) divided by the linear displacement (millimeters). Nonparametric Wilcoxon signed-rank tests were used to compared data between the FFLS and BAS groups. Descriptive statistics and comparisons between groups were performed using commercial software (SPSS Statistics, version 25; IBM Corp) with significance set at $P < .05$.

Results

The width between the femoral epicondyles femurs ranged from 15 to 20 mm, with a median measurement of 18 mm. The depth between the patella surface and intercondyloid fossa ranged from 15 to 20 mm, with a median measurement of 18 mm. At the end of precycling, the median displacement at 5 N was significantly higher for the FFLS group (1.02; 0.27 to 2.33) compared to the BAS group (0.36; 0.17 to 1.02); $P = .034$. At the end of precycling for 100 cycles, the median displacement at 15 N was significantly higher in the FFLS group (3.01; 1.93 to 7.17) compared to the BAS group (1.13; 0.87 to 2.03); $P = .002$. Also, the total precycle displacement (millimeters) was significantly higher in the FFLS group (2.17; 1.13 to 4.91) compared to the BAS group (0.91; 0.46 to 1.10), $P = .002$. In addition, the FFLS group results were less consistent than the BAS group, graphically showing marked variability **(Figure 3)**. The force (newtons) at 3 mm displacement was significatively higher in BAS group (86.5; 51.7 to 137.0) compared to the FFLS group (13.7; 8.0 to 71.7); $P = .002$.

There was no significant difference in force at failure (newtons) between the FFLS group (230.1; 15.0 to 474.9) and BAS group (274.6; 198.1 to 343.4); $P = .308$. There was also no significant difference in displacement at failure (millimeters) between the FFLS group (11.89; 5.70 to 21.67) and BAS group (7.73: 5.93 to 12.97); $P = .060$. Interestingly, the stiffness to failure (N/mm) was significantly higher in the BAS group (33.09; 21.84 to 44.92) compared to the FFLS group (19.66; 2.09 to 31.99); $P = .002$ **(Table 1)**. Lastly, the mode of failure was recorded, and in the FFLS group femoro-fabella ligament rupture resulted in suture failure and was associated with the dislocation of the fabella in all FFLS tests. All of the tests performed never showed knot slippage during loading and at the failure point. In the BAS group, the most common cause of failure was suture breakage at the contact point between the eye of bone anchor and suture material, occurring in 7 of 12 specimens. Furthermore, 2 samples had anchor pullout, and 3 fractured at the femoral condyle.

Discussion

The aim of this study was to evaluate and compare the biomechanical behavior of FFLS and BAS. The testing included the evaluation of displacement (millimeters) during expected physiological loading. Femur specimens were preloaded based on a previous study,[27,28] oscillating between 5 and 15 N for 100 cycles to mimick the physiological loading of the cats. The displacement (millimeters) at 5 N and 15 N and total displacement (millimeters) after precycling were significantly higher in the FFLS group compared to the BAS group. This confirmed that the BAS provides a more stable attachment point for suture material compared to the FFLS. Notably, the median total displacement (millimeters) for both the FFLS (2.17 mm) and BAS (0.91 mm) was below 3 mm. However, in some specimens, the FFLS displaced more than 3 mm during precycling, which is different to the BAS group, where none of the specimens underwent more than 3 mm of displacement. Additionally, the median precycle displacement for FFLS group at 5 N had a median of > 3 mm, whereas the median for the BAS was well under 3 mm. These results show that the FFLS can result in stifle instability during physiologic loading.[31,32] Furthermore, above this 3 mm displacement, fixation is considered failured according to piglets and canine biomechanical studies.[25,27,28] The BAS group provided less variability compared to the FFLS group (Figure 3). This finding is consistent with what has been previously reported in dogs.[25] The variability shown in the FFLS group for total cycling displacement (millimeters) provides evidence that the BAS offers a more reliable and less variable anchor point compared to the FFLS. It should be noted that the variability in cycling displacement (millimeters) could be caused by poor execution of FFLS placement, for example, the FFLS not engaging in the femoro-fabella ligament. These variable results stress the importance for surgeons to adequately engage the suture around the femoro-fabella ligament. In contrast, the position of suture attachment point for the BAS is well defined by the quasi-isometric points associated with the lateral collateral ligament, thus making it a more consistent point of attachment.[25] Furthermore, other factors could account for the variability seen with FFLS being that the femoro-fabella ligament might differ in composition and strength between cats.[25,33–35] The force at failure was not significantly different between the 2 groups, but the values in the FFLS group had a wider range of 15 N to 474.9 N. Again, this might occur due to an improper technique of placing a lateral suture around the femoro-fabella ligament, and placement of FFLS is arguably more challenging to achieve than BAS with described isometric points.[25] Moreover, there was no significant difference in displacement (millimeters) at failure between the 2 groups, and displacement at failure was more than 3 mm in both groups. Therefore, instability occurred before failure in both the FFLS and BAS groups. This displacement, at supraphysiological loads, might represent suture material elongation rather than attachment failure, leading to similar displacements for both groups. In the lateral ligament suture, the mode of failure was femoro-fabella ligament rupture with dislocation of the fabella in all samples. This is likely due to ligamentous tissue being more sensitive to tension load compared to bone.[26,36] Although the stiffness to failure (N/mm) was significantly higher in the BAS group compared to the FFLS group, it should be noted that the results have limited clinical relevance as the force at failure (newtons) is higher than the normal physiological force a cat is able to apply to the ligament. Previous canine cadaveric studies[15] identified screw pull-out as the most common suture anchor mode of failure, whereas in the present study the primary mode of failure was suture breakage, with only 2 samples having anchor pull-out as a cause of failure. Given the small sample size, it is difficult to draw conclusions from this, but it might be a limiting factor in smaller cats for BAS placement. Interestingly, the femurs that fractured had the smallest epicondylar width of all the specimens. In specimens measuring > 17 mm epicondylar width, bone anchor pull-out was the mode of failure. The biomechanical properties of the 2 techniques were compared in isolation, and this is a limitation of the study. The suture material and technique for securing loops were the same for both groups, using double crimps and a secure knot, to prevent variability during tension loading. Indeed, of all the tests performed never showed knot slippage during loading and at the failure point. The biomechanical properties of the 2 techniques were not correlated to the weight or size of the cats. Further studies are needed to estimate this correlation using a larger number of specimens and stratifying by weight or dimension of bone. Although the femurs were positioned to mimic the commencement of the stance phase, the ex vivo evaluation poses limits on the static cadaveric model as the mechanical test was unilateral and uniplanar, with the absence of all forces acting on a cat stifle joint during normal activity.[25,37] Ex vivo studies involve the use of tissues that have been frozen and then thawed, and there are several contradictory human and animal studies on the biomechanical effect of these processes on tendons and ligaments.[38–40] Furthermore, the acceptable location of the bone anchor placement, which limits tibial thrust, was not verified radiographically. However, the isometric points for placement were identified, and if they were not achieved, it still should not have had a great impact on the outcome of the mechanical test. Further studies that evaluate the appropriate position of the bone anchor with radiographs and the biomechanical effects are needed. Another limitation of this study was that both the medial and lateral femoro-fabella ligament was used for the FFLS or BAS to increase the number of tests. Arguably, there are differences between the medial and lateral femoro-fabella ligament that could affect the results, but these were not investigated. In conclusion, this study provides evidence that BAS provides a more stable and reliable fixation technique compared to FFLS. The BAS was associated with less displacement (millimeters) at forces that are expected to be applied at physiological loads and less variability in displacement (millimeters) and required significantly higher forces for 3 mm of displacement to occur compared to the FFLS. In vivo clinical studies with a larger population size should be considered to compare the FFLS and BAS and include complications and clinical outcomes.

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