In dogs, the common calcaneal tendon is comprised of 3 distinct units, the gastrocnemius tendon (GT), the superficial digital flexor tendon, and the accessory tendon, formed from the combined tendinous contributions from the biceps femoris, gracilis, and semitendinosus muscles. These 3 units converge upon the calcaneus and function to maintain extension of the talocrural joint. Injury affecting both GTs comprises the most common tendinous injury in dogs. Canine tendon injuries occur due to traumatic laceration or primary degeneration, with varying degrees of collagenous disruption. Mechanisms of tendinous injury include acute, iatrogenic, or chronic degenerative processes. Standard of care treatment following grade III strain injury resulting in complete GT disruption in dogs is acute surgical intervention, which allows for realignment of tendon ends with the aim of restoration of tensile strength and return of limb function. In a study evaluating return to work in dogs following common calcaneal tendon repair, only 70% of dogs returned to full function while 28% had moderate persistent lameness. Surgical failure occurs most commonly due to suture pull-through or suture breakage. As such, there is currently a clinical need for a simple, reproducible, and cost-effective GT suture repair technique that provides optimal biomechanical properties while providing resistance.
to deformation. This may translate into superior outcomes and improvements in tendinous repairs in veterinary patients.5-9,15

A number of surgical techniques have been described for primary tendinous repair including but not limited to locking loop (LL), 3-loop pulley (3LP), Bunnell-Mayer, Mason-Allen, and Krackow patterns.22-25 Although the 3LP technique is commonly used, the double Krackow (DK) technique has recently demonstrated superiority regarding the patterns resistance to gap formation while requiring greater loads to failure compared to 3LP.20,24 Well suited for repair of flat tendons, the DK patterns is comprised of a series of interlocking suture loops that grasp tissue bundles, preventing suture slippage while opposing retraction of tendon ends.20 Core DK suture patterns are relatively simple to implement, providing resistance to suture pull-out without causing bunching when loaded under tension.25,26 Numerous epitendinous suture (ES) patterns, also known as peripheral circumferential sutures, have been described.27–29 Ex vivo canine research has shown ES augmentation to significantly increase the ultimate tensile strength of tenorrhaphies by 133% for the 3LP technique, while preventing the occurrence of gap formation prior to failure. A study by Cocca et al showed there was no difference in the type of ES pattern used for construct repair in dogs. The influence of DK + ES augmentation is an important step prior to clinical implementation to assess the biomechanical effects of ES use in dogs.

The objective of this study was to evaluate the effect of a DK suture pattern with and without ES augmentation on the biomechanical properties, gap formation, and failure modes in a canine GT model. Our hypothesis was that ES augmentation would improve the biomechanical properties of the repaired construct while decreasing the occurrence of gap formation with no difference in failure modes between groups.

Materials and Methods

Cadaveric specimen collection
Cadavers were serially acquired from a local animal shelter immediately following euthanasia for reasons unrelated to this study using an IV infusion of sodium pentobarbital. Due to the heterogenic nature of cadaveric specimen collection, medical history and patient demographics were not recorded. Paired hind limbs were harvested from 14 healthy medium to large-sized mixed-breed dogs (30 to 32 kg) > 1 year of age. Cadavers were excluded if there was evidence of orthopedic disease or abnormalities affecting the bone-muscle-tendon unit following a focused orthopedic examination by a single ACVS diplomate (DJD). The protocol for collection did not require Institutional Animal Care and Use Committee approval by the North Carolina State University Veterinary Teaching Hospital, Department of Clinical Sciences.

Cadaver specimen preparation
Paired GTs were isolated using blunt dissection from cadaveric hind limbs within a laboratory setting under surgical lighting at room temperature (21°C). Right and left hind limbs were labeled for their respective laterality. Paired GTs were isolated as complete musculotendinous units from their origin on the caudodistal femur to their insertion on the proximo-caudal aspect of the tuber calcanei. The accessory or common tendon (formed from the tendinous contributions from the biceps femoris, semitendinosus and gracilis muscles) was carefully dissected, and retinacular attachments and superficial digital flexor tendon were removed surrounding the enthesis of the GT. A sagittal bone saw (Delta Power Equipment; Anderson Inc) was used to transect the distal femoral metaphysis 30 mm proximal to the femorotibial joint articulation. Paired bones of the crus were removed after isolation and transection of the paired collateral ligaments at the femorotibial and talocrural articulations, respectively. On each pes, tissues distal to the talocrural joint were left intact to facilitate bone-clamp fixation. Saline (0.9% NaCl) solution was periodically applied to keep tissues moist. Following collection, specimens were placed within saline soaked laparotomy sponges and stored at −20°C in a freezer in large leak-proof bags (Ziplock; SC Johnson & Son Inc.).

Prior to testing, specimens were passively thawed for 10 hours at room temperature (21°C) with tendons undergoing a single freeze-thaw cycle. At the time of testing, tendons were sharply transected using a No. 10 scalpel blade in a transverse plane 20 mm distal to the musculotendinous junction within the mid body of the paired GTs. A sharp full thickness tenotomy was performed on a level, hard surface to facilitate a repeatable and uniform cut across the tissues. The distal cut surface of the GTs was then photographed alongside a surgical ruler at a standardized distance of 8 cm by a single investigator (YJC), which facilitated uniform measurement of tendon cross-sectional area (CSA). A trained investigator (YJC) calculated the CSA of all tendons using an imaging software program (ImageJ, v1.47; National Institutes of Health).

Surgical treatment groups
One of each pair of hind limbs was randomly assigned to either treatment group using a random number generator (Random number generator; Research Randomizer) prior to tendon transection and repair (n = 12/group). The contralateral limb from the same dog was then assigned to the opposite treatment group. A single board-certified surgeon (DJD) performed all repairs. A surgical ruler was used during tendinous repair to facilitate consistency of suture placement between constructs.

Tendons within the DK group were repaired as previously described by Wilson et al. The DK technique was performed as a locking suture by directing suture needle passes in a proximodistal direction in each respective tendon segment, with the suture needle passed through each created loop prior to taking the next respective tissue bite. Bites were started at a distance of 5 mm from the tenotomy site. Four staggered individual Krackow suture loops
(with bites measuring 3 mm in diameter from the medial and lateral aspects of the tendon, respectively) were placed 2 to 3 mm apart in each proximal and distal tendon stump, respectively, yielding a total of 8 suture loops, prior to the suture being tied using a single square knot followed by 3 additional throws (Figure 1).

Constructs in the DK + ES group were repaired initially as described above. Following DK completion, a simple continuous ES was placed around the circumference of the repair as previously described.10,11,20 Longitudinal bites were taken 2 to 3 mm apart, to an estimated depth of 1 mm, at a distance of 10 mm from the transection site. Suture material and size were based on the results of a recent study,31 with a new suture pack used for each limb. Size 0 USP polypropylene suture (Surgipro; Covidien Ltd) was used for the DK pattern while 3-0 USP polypropylene (Surgipro; Covidien Ltd) was used for the ES. Both core and peripheral components used a swaged V-20, 26-mm, half-circle taper needle.

In both groups, sutures were gradually tightened during the repair process to allow for close apposition of tendon ends while avoiding constriction and tissue bunching at the repair site. Sutures were tied using a square knot followed by 3 throws, and suture ends were cut to a length of 5 mm. Untenotomized control tendons from 2 other canine cadavers (n = 4 tendons) were used for validation of the biomechanical testing procedure and assessment of overall construct strength and stiffness.

**Biomechanical testing**

Uniaxial tensile testing was performed using a biomechanical testing device (Model 5967; Instron Inc) that simultaneously recorded time (seconds), load (newtons), and displacement (millimeters). All testing was performed at room temperature (21°C). Testing was recorded at 100 frames/s using a high-speed, high-definition digital camera (Lumix DMC-FZ200; Panasonic Corp) positioned level with the repair site at a standardized distance of 15 cm. Video recordings were synchronized with the test system software using an automatic triggering system, that allowed for synonymous evaluation of both video and load data. A millimeter ruler was mounted parallel and directly adjacent to the repaired constructs to aid in computed assessment of gap formation and subsequent analysis.

**Figure 1**—Diagram illustrating tendinous repair with the level of mid body gastrocnemius tendon (G) transection depicted by the red line. A—Double Krackow (DK) repair using size-0 USP polypropylene suture. B—A DK repair augmented with a circumferential simple continuous epitendinous suture using 3-0 USP polypropylene. L = Lateral. M = Medial.
Distal femora were then secured proximally after drilling a 4.5-mm bone tunnel in a mediolateral direction across the femoral condyle and secured using a 4.0-mm stainless steel bolt that was then connected to a jig mounted on the cross head of the testing machine. Distally, the pes was secured using a manually compressing bone clamp (SKU-1652-1; Sawbones) connected to a 500-N load cell affixed to the testing apparatus. Specimens were loaded into the testing apparatus, force zeroed, and preconditioned to 2 N. The tensile testing machine was then recalibrated to zero prior to collecting load displacement (LD) measurements to ensure a consistent starting parameter among repairs. Tension was then applied, and constructs were distracted to failure at a rate of 20 mm/min with LD data collected at a frequency of 100 Hz.

Testing software created LD curves from which yield, peak, and failure loads and construct stiffness were determined using a coded program (Matlab v.R2018b; Mathworks). This program allowed for the precise identification of examined loads. Yield force was defined as the point at which there was a change from elastic to plastic deformation, identified by deviation in linearity of the LD curve. Peak force was defined as the maximum force (apex of the curve) measured for each test. Failure force was defined as the point of construct failure, due to either the suture pulling through the tendinous tissue, failure of the suture itself, or tissue failure distant to the repair site, respectively. Lastly, construct stiffness was defined as the extent to which repaired constructs resisted deformation when load was applied calculated at 50% to 90% of yield force over the elastic region of the LD curve. Mode of failure was recorded during testing and confirmed, following review of the video recordings by a single investigator (YJC). Control specimens were tested using the same methodology until complete failure, identified as a > 50% decrease in the applied load observed during testing.

Gap formation was evaluated following download of video recordings after test completion. Gap formation was determined by visual identification and separation of tendon ends at the repair site using the minimum distance between tendon ends to measure 1 and 3 mm, respectively. This was performed by calibrating a digital ruler to the millimeter ruler of known length placed within the field of view during testing. Assessment of gap formation was determined prior to the occurrence of failure using a commercially available program (ImageJ, v.1.47; National Institutes of Health). Frame data from individual recordings were sequentially assessed by a single study investigator (YJC) to determine the time at which 1- and 3-mm gaps occurred at the repair site. This time was then cross-referenced with biomechanical data to establish the load (newtons) applied at the time of gap formation.

Statistical analysis

Based on the results of prior ex vivo studies and pilot testing, a priori power analysis determined that ≥11 dogs per group would provide an 80% power to detect a mean difference of 30 ± 5 N at a 95% CI in evaluated measures between groups. Data were collected during 3 separate testing sessions, and the results were collated. Data were assessed for normality using the Shapiro Wilk test and reported as mean ± SD for continuous variables. The Student t test was used to compare construct stiffness and was reported as mean ± SD. Differences in loads among groups were assessed using a mixed linear model. Experimental groups were considered a fixed effect while cadavers were assessed to be a random effect. The Fisher exact test was used to compare the frequency of gap formation when it occurred between experimental groups and the mode of construct failure. All analyses were performed using a statistical software program (SAS v.9.4; SAS Institute Inc).

Results

Specimen preparation, tenotomy, and biomechanical testing were performed without observed procedural or experimental error. All suture utilized for tendinous repair were visually free of manufactured defects. In total, 24 GTs and 4 intact control constructs were tested with all tendons included within the final analysis. Left and right GTs were equally distributed among groups (χ²-test, P > 0.99). Mean ± SD tendon CSA in the DK group was 0.108 ± 0.023 cm² and in the DK + ES group was 0.115 ± 0.028 cm², with no difference in CSA among experimental groups (P = 0.103) or hind limb laterality from each cadaver (P = 0.759).

Evaluation of yield, peak, and failure loads showed that the DK + ES technique was superior to the DK technique alone (Supplementary Figure S1). Mean yield, peak, and failure forces were 48% (P = 0.017), 45% (P < 0.001), and 47% (P < 0.001) greater, respectively, in the DK + ES group versus the DK group. Construct stiffness was 36% greater in the DK + ES group versus the DK group (P = 0.04). All assessed biomechanical parameters were greater for all evaluated control specimens (P < 0.001; Table 1).

There was no difference regarding the occurrence of 1-mm gap formation between construct groups (P = 0.478). However, the force required to produce a 1-mm gap was significantly (P < 0.001) greater for DK + ES constructs. In 100% (12/12) of DK constructs and 83% (10/12) of DK + ES constructs, a 1-m gap was observed. In 100% (12/12) of DK constructs, a 3-mm gap formed, compared with 33% (4/12) of DK + ES constructs (P < 0.001). When gapping to 3 mm was observed, loads were 3.8 times greater for DK + ES constructs (P = 0.004; Table 2).

Mode of construct failure differed between groups (P = 0.037). For DK alone, failure occurred exclusively by core suture breakage in 100% (12/12) constructs. In contrast, 58% (7/12) of DK + ES constructs failed by suture breakage, and 42% (5/12) by tissue failure distant to the repair site, occurring by proximal muscle tearing at the musculotendinous junction of the GT at its origin on the caudal distal femur. Control constructs failed in a similar fashion as DK + ES constructs, 100% (4/4) by proximal muscle tearing at the musculotendinous junction of the GT.
Table 1—Mean ± SD yield, peak, and failure forces for canine gastrocnemius tendons that underwent transverse tenotomy and repair with a double Krackow suture pattern (DK; n = 12) or epitendinous suture augmentation (ES; 12) and control tendons (4).

| Suture pattern | Yield force (N) | Peak force (N) | Failure force (N) | Stiffness (N/m) |
|---------------|----------------|----------------|------------------|----------------|
| DK           | 101.27 ± 37.17<sup>b</sup> | 135.77 ± 19.06<sup>b</sup> | 131.53 ± 22.28<sup>a</sup> | 3.66 ± 1.67<sup>a</sup> |
| DK + ES      | 149.56 ± 53.26<sup>b</sup> | 197.03 ± 32.71<sup>b</sup> | 193.75 ± 31.43<sup>b</sup> | 4.99 ± 1.93<sup>b</sup> |
| None         | 312.8 ± 28.1<sup>c</sup> | 485.4 ± 29.0<sup>c</sup> | 478.6 ± 23.4<sup>c</sup> | 18.30 ± 1.40<sup>c</sup> |

Values with different superscript letters are significantly (P < 0.001) different.

Table 2—Proportions of the constructs in Table 1 in which 1- and 3-mm gaps occurred between tendon ends during biomechanical testing and the mean ± SD force required to produce those gaps.

| Suture pattern | 1-mm Gap | 3-mm Gap |
|---------------|----------|----------|
|               | Proportion (%) | Force (N) | Proportion (%) | Force (N) |
| DK           | 12/12 (100) | 23.719 ± 10.44<sup>a</sup> | 12/12 (100) | 44.15 ± 15.51<sup>a</sup> |
| DK + ES      | 10/12 (83)  | 144.73 ± 28.59<sup>b</sup> | 4/12 (33)  | 168.83 ± 48.90<sup>b</sup> |

Values with different superscript letters are significantly (P < 0.001) different.

Discussion

In this study, we evaluated a DK pattern with and without ES augmentation in a canine GT model. We demonstrated that mean yield, peak, and failure force and construct stiffness for the DK + ES technique were 48%, 45%, 47%, and 36% greater, respectively, than for the DK technique alone. In support of our hypothesis, ES augmentation improved the biomechanical properties of repaired constructs. Use of a DK + ES pattern required greater loads to cause 1-mm gapping while decreasing the occurrence of 3-mm gap formation. ES augmentation increased the likelihood of tissue failure distant to the repair site.

The authors are aware of no evidence within the literature demonstrating the superiority of a single ES pattern; therefore, a pattern that is easily instituted, repeatable, and consistent among surgeons is recommended. In the present study, we found the addition of a simple continuous ES increased yield, peak, and failure loads by approximately 50% while increasing construct stiffness by approximately 35%. These findings may be attributed to the circumferential nature of the ES augmentation that distributed applied tensile loads around the repair, while incorporating a greater amount of tissue with each bite compared with DK repairs alone. Distribution of tension across the repair site may improve load sharing between the core and peripheral components, which may prevent sites of stress concentration and constriction of collagen fibers isolated to loading zones. An increased number of suture strands spanning the repair site has been correlated with increased tensile and gap strength. The addition of an ES, placed through the same surgical approach, increases the number of strands crossing the repair site with little need for additional peritendinous dissection. This is a relatively simple technique modification that significantly improves repair-site strength.

Factors that were not examined as part of this ex vivo model included the effect of the ES technique and its impact on the tendon’s vascular supply in vivo. However, in surgery of the human hand, locking patterns are widely utilized and recommended for use in clinical patients with excellent results and early implementation of finger mobilization protocols. Results of prior studies indicate that the benefits of increasing the tensile strength of the construct when using an ES outweigh possible drawbacks associated with increased suture use and a greater number of needle punctures made into tendon during suture placement. Our results are in agreement with prior literature corroborating the benefits of ES use; however, further study regarding their effect on the local tendon vascular supply is warranted.

Biomechanical comparisons of 3LP and DK patterns for canine tendon repair have yielded disparate results in previous studies. In a study using canine patella tendons, the 3LP technique achieved higher loads to failure with an increase in mean construct stiffness, compared with the modified Krackow technique. In contrast, in a canine GT model, the DK technique was shown to be biomechanically superior to the 3LP technique regarding failure loads and force to 3-mm gapping. The results of our study yielded similar failure loads (mean ± SD, 131.53 ± 22.28 N) to those previously reported in the literature for the DK patterns alone (106.89 ± 12.74). This demonstrates that despite surgeon variability and transaction location, the DK pattern demonstrates consistent biomechanical properties among studies. A study by Moores et al estimated that a 30-kg dog generates a force of approximately 400 N through its common calcaneal tendon at the trot. Following primary GT repair, the sutured anastomosis is protected to prevent acute overloading and failure. Repair protection should still be recommended following DK + ES repair based on our results and those of control tendons, especially during the period of postoperative rehabilitation. Although talocrural immobilization during the first 6 weeks significantly reduces GT strain and force placed directly on the repair site, the continued effects of isometric muscle contraction support the use of a functionally strong repair such as the DK + ES technique. Use of ES augmentation to supplement the primary repair
is a simple technique modification that adds considerable strength and stiffness to the final construct. It should be noted, however, that the forces exerted through the GT alone are unknown at this time and represent an area for future focused investigation.

The ability to resist gap formation is a mitigating factor in preventing the occurrence of gap formation since this has been associated with the development of adhesions, delayed healing times, poor functional outcomes, and decreased limb function. In a canine GT avulsion model, DK repair alone demonstrated greater mean resistance to 3-mm gap formation with higher tolerance to repair site deformation, compared with 3LP repair (DK, 77.22 ± 9.72 N; 3LP, 55.85 ± 9.91 N), demonstrating that the DK pattern was superior to 3LP pattern for GT repair. In the study reported here, loads required to produce a 1- and 3-mm gap were 5X and 3.8X greater, respectively, when the DK + ES technique was used. In addition, the occurrence of 3-mm gapping was decreased by 67%. Gap formation < 3 mm is important to minimize the risk of rerupture during the protracted phases of normal tendinous healing.

When DK constructs were sequentially loaded, the loops of the DK tightened causing tissue constriction and the presence of a readily identifiable gap between tendon ends. In contrast, DK + ES constructs showed superior end-to-end tendon apposition and appeared to pull the tendon ends toward one another when viewed in multiple planes. As DK + ES constructs were distracted further under tension, the compressed tendon had room to elongate prior to gapping becoming apparent. Tightening of the DK suture loops was seen at greater loads when an ES was used, suggesting that load sharing between the core and peripheral components occurred.

Factors shown to affect how experimental constructs fail include the inherent strength and integrity of tissues anastomosed, core suture size, and the number of suture strands crossing the repair. In the present study, suture breakage was the predominant mode of failure among DK repairs. The DK pattern has fewer load-bearing strands that are individually susceptible to stress concentration and overloading leading to construct failure. ES augmentation resulted in a 25% decreased occurrence of repair failure caused by suture breakage. Overall, 42% of DK + ES constructs failed by tissue failure, distant to the repair site, similar to results for intact control specimens with constructs failing by proximal tissue tearing at the musculotendinous junction. The failure force for DK + ES constructs that failed in this location was approximately 40% lower than that of unnotomized controls. These findings suggested that the DK + ES pattern allows uniform load distribution that is not directly concentrated at the surgical site and once construct elongation has occurred, the myotendinous junction becomes the weakest part of the construct. We hypothesize that the DK + ES technique has greater capability of withstanding forces placed upon the individual musculotendinous units than the DK technique alone.

Our results contrast with those of Putterman et al and Duffy et al who demonstrated suture pull through seen in 59.7% and 100% of tested canine constructs, respectively, using similarly sized sutures. These study findings support prior results that the DK technique may be biomechanically superior to the 3LP and LL techniques in vitro. Suture failure is observed when the applied force at the tendon-suture interface exceeds the inherent strength of the suture material used. Our results are in agreement with those of Wilson et al, where 100% of their DK repairs failed by suture breakage, in contrast to the 3LP constructs that failed by suture pullout. In the study presented here, ES repairs were performed using 3-0 USP suture. We expect that that differing results may be appreciable if a larger sized ES were used for augmentation. In the Wilson et al study, it should be noted that their design utilized bone tunnels drilled in the proximal calcaneus for distal suture attachment, rather than midbody tendinous repair as presented here.

The authors appreciate that the DK technique may not be appropriate for repair of all canine tendons. Limitations pertinent to this study include the ex vivo nature and use of fresh frozen cadaveric tendons. Extensive locking sutures spanning the repair can inadvertently cause constriction of the microcirculation and vincula leading to tenomalacia, necrosis, decreased repair site strength, and predisposition to failure. Failure loads and mode of construct deformation in this study were evaluated using a continuous rate linear distraction model to simulate acute force application in the immediate postoperative period. However, it has been shown that repairs subjected to continuous cyclic distraction may fatigue and potentially fail below their ultimate strength. The study authors recognize that ultimate repair strength is not representative of all the biomechanical properties alongside the inherent strength contributed by autogenous tissues surrounding the repair in vivo. During clinical cases, tendon rupture caused by trauma or secondary degenerative processes can lead to irregularly shaped or compromised tendon ends due to fraying. However, tendinous debridement is routinely performed to create a uniform anastomosis prior to tendon repair in clinical cases by the senior author.

In conclusion, use of the DK + ES technique was biomechanically superior to the DK technique alone, increasing the mean yield, peak, and failure forces by 48%, 45%, and 47%, respectively. Construct stiffness was 36% greater in the DK + ES group. The DK + ES technique decreased the occurrence of 1- and 3-mm gapping requiring 5X and 2.8X greater loads to cause these respective gaps between tendon ends. The DK + ES technique increased the likelihood of tissue failure distant to the repair site. Tenorrhaphies must withstand the forces encountered during controlled ambulation, resist gap formation, and foster a favorable microenvironment to allow for tendon healing. Clinically, these findings may be used to guide suture pattern selection for repair of canine GT injury.
Acknowledgments

The authors of this study declare no conflicts of interest and no outside funding was provided for the purpose of this study.

Suture material utilized for this study was provided by Medtronic, Inc., Mansfield, MA.

References

1. Stuart C, William GM. Muscle and tendon disorders. In: Johnston SA, Tobias KM, eds. Vol 2. Veterinary Surgery: Small Animal. 2nd ed. Elsevier; 2018:1316–1323.
2. Johnson J, Austin C, Breur G. Incidence of canine appendicular musculoskeletal disorders in 16 veterinary teaching hospitals from 1980 through 1989. Vet Comp Orthop Traumatol. 1994;07(2):56–69.
3. Thomopoulos S, Parks WC, Rifkin DB, Derwin KA. Mechanisms of tendon injury and repair. J Orthop Res. 2015;33(6):832–839.
4. Corr SA, Draffan D, Kulaenda E, Carmichael S, Brodbelt D. Retrospective study of Achilles mechanism disruption in 45 dogs. Vet Rec. 2010;167(11):407–411.
5. Duffy DJ, Main RP, Moore GE, Breur GJ, Millard RP. Ex vivo biomechanical comparison of repair strength and standard polypropylene suture for acute tendon laceration in a canine model. Vet Comp Orthop Traumatol. 2015;28(4):263–269.
6. Gersoff W, Bozynski C, Cook C, Pfeifer F, Kuroki K, Cook J. Evaluation of a novel degradable synthetic biomaterial patch for augmentation of tendon healing in a large animal model. J Knee Surg. 2019;32(5):434–440.
7. James R, Kesturu G, Balian G, Chhabra AB. Tendon: biology, biomechanics, repair, growth factors, and evolving treatment options. J Hand Surg. 2008;33(1):102–111.
8. Worth A, Danielsson F, Bray J, Burbidge H, Bruce W. Ability to work and owner satisfaction following surgical repair of common calcaneal tendon injuries in working dogs in New Zealand. NZ Vet J. 2004;52(3):109–116.
9. Strickland JW. Development of flexor tendon surgery: twenty-five years of progress. J Hand Surg. 2000;25(2):214–235.
10. Puttermann AB, Duffy DJ, Kersh ME, Rahaman H, Moore GE. Effect of a continuous epitenodinous suture as adjunct to three-loop pulley and locking-loop patterns for flexor tendon repair in a canine model. Vet Surg. 2019;48(7):1229–1236.
11. Cocca CJ, Duffy DJ, Kersh ME, Kim W, Groenewold A, Moore GE. Biomechanical comparison of three epitenodinous suture patterns as adjuncts to a core locking loop suture for repair of canine flexor tendon injuries. Vet Surg. 2019;48(7):1245–1252.
12. Duffy DJ, Chang YJ, Gaffney LS, Fisher MB, Moore GE. Effect of bite depth of an epitenodinous suture on the biomechanical strength of repaired canine flexor tendons. Am J Vet Res. 2019;80(11):1043–1049.
13. Duffy DJ, Cocca CJ, Kersh ME, Kim W, Moore GE. Effect of bite distance of an epitenodinous suture from the repair site on the tensile strength of canine tendon constructs. Am J Vet Res. 2019;80(11):1034–1042.
14. Gall TT, Santoni BG, Egger EL, Puttlitz CM, Rooney MB. In vitro biomechanical comparison of polypropylene mesh, modified three-loop pulley suture pattern, and a combination for repair of distal canine Achilles’ tendon injuries. Vet Surg. 2009;38(7):845–851.
15. Pijanowski GJ, Stein LE, Turner TA. Strength characteristics and failure modes of suture patterns in several great toe tendons. Vet Surg. 1989;18(5):335–339.
16. Berg RJ, Egger EL. In vitro comparison of the three loop pulley and locking loop suture patterns for repair of canine weightbearing tendons and collateral ligaments. Vet Surg. 1986;15(1):107–110.
17. Moores AP, Comerford EJ, Tarlton JF, Owen MR. Biomechanical and clinical evaluation of a modified 3-loop pulley suture pattern for reattachment of canine tendons to bone. Vet Surg. 2004;33(4):391–397.
18. Moores AP, Owen MR, Tarlton JF. The three-loop pulley suture versus two locking-loop sutures for the repair of canine achilles tendons. Vet Surg. 2004;33(2):131–137.
19. Krackow KA, Thomas SC, Jones LC. A new stitch for ligament-tendon fixation. Brief note. J Bone Joint Surg Am. 1986;68(5):764–766.
20. Wilson L, Banks TA, Luckman P, Smith B. Biomechanical evaluation of double Krackow sutures versus the three-loop pulley suture in a canine gastrocnemius tendon avulsion model. Aust Vet J. 2014;92(11):427–432.
21. Krackow KA. The Krackow suture: how, when, and why. Orthopedics. 2008;31(9):931–933.
22. Montgomery RD, Barnes SL, Wenzel JL, Terry GC. In vitro comparison of the Krackow and locking loop suture patterns for tenorrhaphy of flat tendons. Vet Comp Orthop Traumatol. 1994;7(1):31–34.
23. Renberg WC, Radinsky MG. In vitro comparison of the locking loop and continuous cruciate suture patterns. Vet Comp Orthop Traumatol. 2001;14(1):15–18.
24. Waltert WI, Rist P. Achilles tendon repair in dogs using the semitendinosus muscle: surgical technique and short-term outcome in five dogs. Vet Surg. 2009;38(6):770–779.
25. Sherman SL. Editorial commentary: the Krackow stitch: more than 30 years of tendon repair and still holding strong. Arthroscopy. 2018;34(3):669–670.
26. McKeon BP, Heming JF, Fulkerson J, Langeland R. The Krackow stitch: a biomechanical evaluation of changing the number of loops versus the number of sutures. Arthroscopy. 2006;22(1):33–37.
27. Lister GD, Kleinert HE, Kutz JE, Atasoy E. Primary flexor tendon repair followed by immediate controlled mobilization. J Hand Surg. 1977;2(6):441–451.
28. Wade PJF, Watherell RM, Amis AA. Flexor tendon repair: significant gain in strength from the halsted peripheral suture technique. J Hand Surg Br. 1989;14(2):232–235.
29. Silfverskiöld KL, Andersson CH. Two new methods of tenorrhaphy of the extensor digitorum lateralis graft to augment the surgical site on the tensile properties of various circumferential tendon suture techniques. J Hand Surg. 1996;21(4):474–480.
30. Hirpara KM, Sullivan PJ, Raheem O, O’Sullivan ME. A biomechanical analysis of multistrand repairs with the Silfverskiöld peripheral cross-stitch. J Bone Joint Surg Am. 2007;89(10):1396–1401.
31. Duffy DJ, Curcillo CJ, Chang YJ, Moore GE. Effect of suture caliber on the tensile strength of tenorrhaphies in cadaveric canine tendons. Am J Vet Res. 2020;81(9):714–719.
32. Kubota H, Aoki M, Pruitt DL, Manske PR. Mechanical properties of various circumferential tendon suture techniques. J Hand Surg. 1996;21(4):474–480.
33. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons—an experimental study on the early stages of tendon-healing in dogs. J Bone Joint Surg Am. 1999;81(7):975–982.
34. Eby AC, Duffy DJ, Chang YJ, Gaffney L, Fisher MB, Moore GE. Influence of barbed epitenodinous sutures combined with a core locking-loop suture to repair experimental flexor tendon lacerations. Vet Surg. 2020;49(8):1590–1599.
35. Lister SA, Renberg WC, Roush JK. Efficacy of immobilization of the tarsal joint to alleviate strain on the common calcaneal tendon in dogs. Am J Vet Res. 2009;70(1):134–140.
36. Duffy DJ, Curcillo CP, Chang YJ, Gaffney L, Fisher MB, Moore GE. Biomechanical evaluation of an autologous flexor digitorum lateralis graft to augment the surgical repair of gastrocnemius tendon laceration in a canine ex vivo model. Vet Surg. 2020;49(8):1545–1554.

Supplementary Materials

Supplementary materials are posted online at the journal website: avmajournals.avma.org

AJVR

7