In dogs, the common calcaneal tendon consists of the paired gastrocnemius tendon (GT), superficial digital flexor tendon, and combined tendons of the biceps femoris, semitendinosus, and gracilis muscles. Acute traumatic injury has been reported as the most common cause of complete common calcaneal tendon rupture, which results in a plantigrade stance. Incomplete or partial tendon rupture with preservation of the superficial digital flexor tendon leads to hyperflexion of the tarsal and phalangeal joints. Chronic, repetitive stress on the GT can result in degenerative tendinopathy and enthesiopathy at the tendon’s insertion on the calcaneus.

In dogs with partial or complete rupture of the common calcaneal tendon, surgical intervention is generally necessary to counteract the large tensile forces encountered during ambulation and allow a return to normal function. Injuries to the common calcaneal tendon are most common in medium to large, active working and racing dogs, with a 30% complication rate reported following surgical treatment. In a study by Worth et al, only 70% of dogs eventually returned to work.

OBJECTIVE
To evaluate the effects of using an internal fixation plate to augment primary three-loop pulley (3LP) repair of canine gastrocnemius tendons (GTs).

SAMPLE
48 cadaveric GTs from 24 adult dogs.

PROCEDURES
GTs were dissected free from other tissues, transected, and randomly assigned to 4 groups (n = 12/group). GTs were repaired with 2-0 polypropylene with a 3LP repair alone or a 3LP repair augmented with a 3-hole veterinary cuttable plate (3VCP), a 5-hole veterinary cuttable plate (5VCP), or a 7-hole veterinary cuttable plate (7VCP). Biomechanical loads, construct stiffness, gap formation, and failure modes were compared between groups.

RESULTS
Yield, peak, and failure loads were all significantly increased for the 5VCP and 7VCP groups, compared with the 3LP alone group. Increasing plate length from 3VCP to 5VCP and from 3VCP to 7VCP increased yield, peak, and failure loads. No differences were found between the 3LP and 3VCP groups with regard to yield and peak loads, but failure load was increased in the 3VCP group. Loads to create 1-mm and 3-mm gaps were significantly greater for the 5VCP and 7VCP groups, compared with the 3LP alone and 3VCP groups. Mode of plate attachment failure differed among groups.

CLINICAL RELEVANCE
Tendon plate augmentation may be a viable surgical option to increase the strength of the tenorrhaphy in dogs. However, in vivo studies evaluating the effects of plate augmentation on the tendon blood supply and progression of healing are needed prior to clinical application.
procedures. The primary aim of surgical repair of GT injuries is to prevent formation of a > 3-mm gap between the tendon ends, and in dogs, the most commonly used core suture patterns for primary ten- dinous repair are the locking-loop and 3-loop pulley (3LP) patterns. Methods of providing additional support to primary tendon repairs include placement of epitendinous sutures, use of autologous tissues such as semitendinosus muscle, lateral digital flexor digitorum muscle, and fascia lata grafts, and addition of synthetic mesh, skin staples, or internal fixation plates.

Proposed advantages of supple- mentary tendon repairs with an internal fixation plate include providing higher tensile strength and greater resistance to gap formation, compared with sutured repairs alone. Internal fixation plates may also be used to manage a failed repair because the plate can span the repair site and act as an intrinsic scaffold to decrease the stress placed on individual sutures. Plate application with simple interrupted and figure-of-eight suture patterns significantly increased failure loads, compared with the use of locking-loop and 3LP repairs, in ex vivo equine deep digital flexor tendons and in rabbit calcaneal tendons biomechanically tested 0, 14, and 60 days after repair. In another study, plate augmentation of a 3LP repair of equine deep digital flexor tendons resulted in higher tensile strength, compared with 3LP repair alone. In rabbit calcaneal tendons, application of a 6-hole veterinary cuttable plate in conjunction with 3LP repair did not adversely affect tendon vascular- ture, as assessed by means of microangiography and histologic analysis, compared with 3LP repair alone, when evaluated 60 days postoperatively. Furthermore, that study showed that plate augmentation resulted in improved tendon vascular morphology and a dense and homogeneous collagen matrix. Although the benefits of plate augmentation for primary tendon repair have been demonstrated, to the authors’ knowledge, there has been no research conducted to evaluate the effects of plate augmentation in dogs or assess the effects of plate length. Previous studies evaluated a 10-hole plate ex vivo in equine tendons and a 6-hole plate in vivo in rabbit tendons. However, equine deep digital flexor tendons are larger and contain a greater number of collagen fibrils than do tendons in dogs, making it challenging to extrapolate data for horses to use in dogs.

Currently, plate selection for augmentation of primary tendon repairs is based on patient size, equipment availability, and surgeon preference. Ex vivo studies have shown that for canine tendons, increasing the distance of suture placement from the repair site and increasing the depth of suture placement in the tendon axis improve the repair site strength, but information is not available on the effects of using plates of different lengths when augmenting primary tendon repairs. Potentially, plate length may be associated with the overall tensile strength of the construct, the interaction between suture material and tendon substance, and the resistance to gap formation. A study by Hale et al showed that in equine tendons, suture pattern is an important factor when using these plates, but that study did not include a core suture pattern as part of the tendon repair.

The objectives of the study reported here were to evaluate the biomechanical characteristics and effects on gap formation from use of an internal fixation plate to augment a primary 3LP repair of ex vivo canine GTs and to determine whether use of veterinary cuttable plates of different lengths would alter those characteristics. Our primary hypothesis was that use of a plate would increase the tensile strength of the construct (ie, yield, peak, and failure loads) and increase the load required to cause gap formation between the tendon ends, compared with use of a 3LP repair alone. Our secondary hypothesis was that tensile strength of the construct and the load required to cause gap formation would increase as length of the internal fixation plate increased.

Materials and Methods

Specimen preparation
Forty-eight GTs harvested from 24 healthy adult mixed-breed dogs weighing between 25 and 33 kg were used in this study. All dogs had been euthanized at a local animal shelter for reasons unrelated to the present study. Approval by the North Carolina State University Institutional Animal Care and Use Committee was not required because the study involved only use of cadaveric tissues. All specimens were harvested and dissected within 4 hours after dogs were euthanized; following euthanasia, dogs were held at room temperature (21 °C) until specimen collection. Prior to specimen collection, an orthopedic examination was performed by a single investigator (DJD) to evaluate for any gross evidence of hind limb musculo-oskeletal abnormalities. Specimens were excluded if any abnormalities were detected.

Each GT was isolated from its origin on the supracondylar eminence of the caudodistal aspect of the femur to its insertion on the proximocentral aspect of the tuber calcanei. The superficial digital flexor tendon and combined tendons of the biceps femoris, semitendinosus, and gracilis muscles were carefully removed from the musculotendinous junction to the enthesis. All other surrounding soft tissues and collateral ligaments were removed and discarded. The femur was then transversely sectioned with a sagittal bone saw (DeWalt Reciprocating Saw) 1 cm proximal to the femoral trochlear groove. A 4.5-mm bone tunnel was drilled across the femoral condyles to facilitate later construct fixation. Each bone-muscle-tendon unit was wrapped in gauze soaked in saline (0.9% NaCl) solution, and paired GTs from each dog were placed in a sealed impervious bag (Ziplock; SC Johnson & Son Inc) and stored at −20 °C. Prior to testing, specimens were thawed for 12 hours at room temperature (21 °C).

On the day of testing, a sharp, transverse tenotomy of the GT was performed 2 cm proximal to the tuber calcanei with a No. 10 scalpel blade, and
a digital photograph (iPhone XR; Apple Inc) of the cut surface placed next to a millimeter surgical ruler (Medline) was obtained for later measurement of the tendon’s cross-sectional area (CSA). CSA was subsequently measured with a software program (ImageJ; National Institutes of Health) by a single investigator (Y-JC).

**Tendon repair**

Each GT was randomly assigned to 1 of 4 groups (n = 12/group) with a random number generator, with the restriction that paired left and right GTs from the same cadaver were not assigned to the same group. For all specimens, 2-0 polypropylene suture (Surgipro; Covidien Ltd) with a swaged-on, V-20, 26-mm, half-circle taper needle was used to place the core suture pattern and to suture the internal fixation plate, regardless of plate length, to the tendon.

All specimens were first repaired with a 3LP suture pattern as previously described, with loops placed 60° apart and 5, 10, and 15 mm from the repair site. For all specimens in which a plate was applied, an open plate hole was positioned directly over the repair site. For specimens assigned to group 1, only the 3LP suture pattern was applied (Figure 1). For specimens assigned to group 2, a 3-hole, straight, 1.5-mm veterinary cuttable plate (3VCP) that was cut to length from a 30-hole, 1.5-mm standard plate (Veterinary Cuttable Plates; DePUy Synthes Vet) with a small-plate pin cutter (Key Surgical) was placed on the dorsocentral aspect of the tendon with the central hole positioned over the repair site. The tendon plate was affixed to the underlying tendon with simple interrupted sutures that passed through the hole of the plate and center of the tendon plate itself. All biomechanical data were collected for later measurement of the tendon’s cross-sectional area (CSA). CSA was subsequently measured with a software program (Matlab R2018b; Mathworks) by a single investigator (Y-JC) and separately with a software program (ImageJ; National Institutes of Health) by a single investigator (Y-JC).

**Biomechanical testing**

Repaired specimens were loaded into a uniaxial material tensile testing machine (Model 5967; Instron Inc). Specimens were fixed distally with a modified bone clamp (SKU 1652-1; Sawbones) attached to the pes. A preload of 2 N was applied to remove slack from the construct and achieve a consistent resting length between specimens. The load cell was then calibrated and zeroed, and distraction was applied at a rate of 20 mm/min until failure occurred or there was a sudden decrease in load of > 50%. The high-definition digital camera was used to record each test at a distance of 25 cm from the construct at a rate of 50 frames/s. Video data were synchronized with the testing machine data by an automated trigger that started recording when the defined preload was reached.

Load-displacement data were collected at a frequency of 100 Hz (Bluehill 3; Instron Inc), and a software program (Matlab R2018b; Mathworks) was used to generate a graph to allow calculation of yield, peak, and failure loads and construct stiffness. Yield load was defined as a first deviation from linearity in the load-displacement curve. Peak load was defined as the load when the repair failed or there was decrease of > 50% in the applied load. Construct stiffness was defined as the extent to which repaired constructs resisted deformation when load was applied and was calculated at 50% to 90% of the yield load over the elastic region of the load-displacement curve.

Video recordings were assessed to determine the points when minimum gaps of 1 and 3 mm first developed between the tendon ends. Time at which the gaps occurred were cross-referenced with the load data to calculate the applied load when each gap occurred.

Mode of core suture failure and mode of plate attachment failure were separately assessed and classified as suture breakage, suture pull-through, tissue failure distant to the repair site, and failure of the tendon plate itself. All biomechanical data were collated by a single investigator (Y-JC) and separately evaluated by another investigator (DJD).
Statistical analysis

An a priori power analysis indicated that ≥11 tendons/group would be required to provide at least an 80% power to detect a mean difference of 30 N between groups at a 95% confidence level with an SD of 6 N. Data were assessed for a parametric distribution with the Shapiro-Wilk test. Continuous variables were found to be normally distributed and therefore were reported as mean ± SD. Differences in group means were assessed with a mixed linear model controlling for tendon CSA while including group as a fixed effect and cadaver as a random effect. Pairwise comparisons of least squares means were conducted with a Bonferroni adjustment for multiple comparisons. Proportional distributions of modes of failure were compared between groups with a Fisher exact test. All analyses were performed with standard software (SAS version 9.4; SAS Institute Inc), with values of $P < 0.05$ considered significant.

Results

All 48 specimens were included in the final statistical model, with no specimens rejected during collection or testing. Left and right limbs were equally distributed among groups ($P = 0.198$), with no significant ($P = 0.315$) difference in tendon CSA between groups.

Biomechanical data

Yield load differed significantly ($P < 0.001$) among groups (Table 1), with significant differences detected between the 3VCP groups and 5VCP groups ($P = 0.038$), 3VCP and 7VCP groups ($P < 0.001$), and 5VCP and 7VCP groups ($P < 0.001$). There was no significant ($P = 0.054$) difference in yield load between the 3LP alone group and 3VCP group. Peak loads also differed significantly, with the same significant differences between groups observed as for yield load. Failure load differed significantly ($P < 0.001$) among groups, with significant differences detected between the 3LP alone and 3VCP groups ($P = 0.04$), 3VCP and 5VCP groups ($P < 0.001$), and 5VCP and 7VCP groups ($P < 0.001$). Construct stiffness differed significantly ($P < 0.001$) among groups, with significant differences detected between the 5VCP and 7VCP groups ($P < 0.001$) and the 3VCP and 7VCP groups ($P < 0.001$). Stiffness did not differ significantly between the 3LP alone and 5VCP groups ($P = 0.789$) or the 3VCP and 5VCP groups ($P = 0.141$).

Gap formation

Load required to cause a 1-mm gap between the tendon ends differed significantly ($P < 0.001$) among groups (Table 2), with load required to cause a 1-mm gap significantly higher for the 7VCP group than for the 5VCP ($P = 0.019$), 3VCP ($P < 0.001$), and 3LP alone ($P < 0.001$) groups. There was no significant ($P = 0.062$) difference between the 3LP alone and 3VCP groups. All 48 specimens developed a 1-mm gap during testing.

Load required to cause a 3-mm gap between the tendon ends also differed significantly ($P < 0.001$) among groups, with load required to cause a 3-mm gap significantly higher for the 7VCP group than for the 5VCP ($P = 0.008$), 3VCP ($P < 0.001$), and 3LP alone ($P < 0.001$) groups. There was no significant ($P = 0.053$) difference between the 3LP alone and 3VCP groups. A 3-mm gap was detected in 10 of the 12 7VCP group specimens, 8 of the 12 5VCP group specimens, 8 of the 12 3VCP group specimens, and all 12 3LP alone group specimens. Percentage of specimens that developed a 3-mm gap did not differ significantly ($P = 0.127$) among groups.

Mode of construct failure

There was no deformation or failure of the plate in any of the evaluated specimens. For all 48 specimens, the core suture pattern failed as a result of suture pulling through the tendon.

Mode of plate attachment failure differed significantly ($P < 0.001$) among the 3VCP, 5VCP, and 7VCP groups. Plate attachment failure was a result of suture pull-through in 11 of the 12 3VCP group specimens, 10 of the 12 5VCP group specimens, and 6 of the 12 7VCP groups specimens. Plate attachment failure was a result of suture breakage in 1 of the 12 3VCP group specimens, 2 of the 12 5VCP group specimens, and 4 of the 12 7VCP specimens.

In the remaining 2 7VCP group specimens, the plate remained attached to the underlying tendon, but the core sutures pulled through the tendon.

<table>
<thead>
<tr>
<th>Group</th>
<th>Yield load (N)</th>
<th>Peak load (N)</th>
<th>Failure load (N)</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3LP alone</td>
<td>55.72 ± 12.66a</td>
<td>67.08 ± 13.35a</td>
<td>65.51 ± 13.15a</td>
<td>3.67 ± 0.97a</td>
</tr>
<tr>
<td>3VCP</td>
<td>81.87 ± 16.28b</td>
<td>88.15 ± 15.01a</td>
<td>87.92 ± 15.27b</td>
<td>3.36 ± 0.85a</td>
</tr>
<tr>
<td>5VCP</td>
<td>102.73 ± 36.64b</td>
<td>133.75 ± 22.41b</td>
<td>132.87 ± 23.22c</td>
<td>4.41 ± 0.85a</td>
</tr>
<tr>
<td>7VCP</td>
<td>159.84 ± 34.28b</td>
<td>197.24 ± 36.37c</td>
<td>195.37 ± 35.18d</td>
<td>6.51 ± 2.26b</td>
</tr>
</tbody>
</table>

Each tendon was tested in tension until failure occurred or there was a sudden decrease in load of >50%.

$^a$In each column, values with different superscript letters were significantly ($P < 0.05$) different.
Discussion

Results of the present study supported our hypotheses. Specifically, following transsection of canine GTs, augmentation of a primary 3LP repair with an internal fixation plate significantly increased the failure load, compared with the failure load associated with a 3LP repair alone. Augmentation with a 5-hole or 7-hole plate increased the yield and peak loads; and augmentation with a 7-hole plate increased the overall construct stiffness. In addition, augmentation with a 5-hole or 7-hole plate increased the loads required to cause 1-mm and 3-mm gaps between the repaired tendon ends. Use of a 7-hole plate versus a 5-hole or 5-hole plate increased yield, peak, and failure loads; construct stiffness; and loads required to cause 1-mm and 3-mm gaps.

The common calcaneal tendon is subject to a load of approximately 400 N in a 30-kg dog at a trot,14 and the most commonly used tenorrhaphy techniques to repair canine GTs, such as the LL and 3LP suture patterns, are insufficient to counteract these forces.15 In our study, the 5VCP and 7VCP groups had yield, peak, and failure loads approximately 2 to 3 times those for the 3LP group alone. A previous study demonstrated that the ultimate failure strength of a semicylindrical hourglass-shaped equine deep digital flexor tendon and plate attached with size-2 polydioxanone was 3 times that of a 3LP repair alone. A report of a dog in which a common calcaneal tendon repair failed with prior use of LL and 3LP suture patterns described the use of a 16-hole, 2.7-mm veterinary cuttable plate with figure-of-eight, size-1 polypropylene sutures combined with a core Bunnell pattern and 2 horizontal mattress sutures. An abstract by Watt et al described ex vivo evaluation of a 3LP suture pattern augmented with a plate in canine common calcaneal tendons and reported that plate augmentation resulted in increased tensile strength and greater force to cause 1-mm and 3-mm gaps. In the present study, we chose to use a simple interrupted suture pattern to attach the tendon plate to the underlying tendon because it was easy to place while allowing close apposition between the plate and underlying tendon. Comparing the results of our study with those of previous studies is difficult because of differences in the suture pattern used to attach the plate to the underlying tendon, suture size used for plate attachment, plate length and type, size of the tendon, and species used. However, results of these studies are in concordance with our results and demonstrate that plate augmentation is superior to core suture use alone in terms of biomechanical properties of tendon repairs.

In our study, increasing the plate length from 5 to 7 holes increased the number of holes available for placing sutures proximal and distal to the repair site, which may have allowed for better distribution of applied loads along the length of the sutured construct.23 Plate augmentation allows load sharing between the plate and underlying tendon, with the plate acting as a scaffold to redirect the applied load and remove the load applied directly to the tendon repair site. Increasing the number of plate holes could potentially reduce the risk that any individual suture would fail, thus decreasing the overall risk of construct failure, as suggested previously.23 Because a 7VCP was the longest plate used in the present study and only 1.5-mm plates were used, it is possible that use of a longer or larger plate (eg, 2.0-mm veterinary cuttable plate) would have additional effects on the biomechanical properties of the construct. This is an area for future investigation.

In the present study, application of the 5-hole or 7-hole plate was relatively simple and did not substantially increase the time to complete each repair but did significantly increase yield, peak, and failure loads and loads required to cause 1-mm and 3-mm gaps. In a clinical situation, application of an internal fixation plate may require greater surgical exposure, which might indirectly compromise the blood supply to the tendon or surrounding tendon sheath. However, results of multiple human studies indicate that increasing the tensile strength of a tenorrhaphy repair outweighs potential drawbacks associated with an increased volume of suture material, a greater number of suture needle punctures in the tendon, or any effects on tendon blood supply. The blood supply to the common calcaneal tendon is poor, and preservation of the blood supply to the repair site is an important consideration because it directly affects the progression of tendon healing in vivo.12,17,37 We postulate, on the basis of results of a previous study, that by minimizing the force on the repair site, use of a plate to augment the primary tendon repair in dogs may allow for better revascularization and collagenous realignment.

With tendon repair, development of a > 3-mm gap between the tendon ends has been demonstrated to increase the risk of rerupture between 21 and 42 days after surgery.12 Gap formation is also a major factor in the formation of adhesions in the first 6 weeks after surgical treatment of flexor tendon rupture in people.12 Previous studies have demonstrated that repair site augmentation with epitendinous sutures, and synthetic material increases the load required to cause a 1-mm or 3-mm gap between the tendon ends. In the present study, loads required to create 1-mm and 3-mm gaps increased by approximately 50% and 100%, respectively, when the length of the plate was increased from 3 holes to 5 holes and from 3 holes to 7 holes.

Interestingly, there were no significant differences between the 3LP alone and 3VCP groups with
regard to the loads required to cause 1-mm and 3-mm gaps. We hypothesize that the 3VCP did not offer increased resistance to gap formation because sutures placed through the plate were positioned at a distance from the repair site similar to that of the core 3LP sutures. Research has shown that increasing the distance of suture purchase from the repair site increases the load required to cause gap formation.\(^{30}\) In a previous study,\(^{20}\) peripheral sutures alone placed closer to the repair site had greater stiffness, but these sutures pulled through the tendon tissue earlier during loading, leading to earlier gap formation and failure at lower loads. With longer plates (eg, 5VCP and 7VCP), the distance between the sutures used to attach the plate to the tendon and the repair site increases. This may more evenly distribute tension acting on the repair site, allowing greater load sharing between the plate and core sutures.\(^{40}\)

In our study, the 3LP suture pattern failed as a result of suture pull-through in all 48 specimens, in agreement with the findings of previous studies.\(^{10,22,41,42}\) A previous study\(^{41}\) demonstrated that use of larger-caliber sutures (size-0 and 2-0) cause the interaction between the suture and collagen fibers to be the weakest component of the repaired construct and thus show that failure is a result of suture pull-through, as was the case in the present study. In contrast, smaller-caliber sutures (3-0, 4-0, and 5-0) are predisposed to failure by suture breakage, so that the suture itself becomes the weakest component.\(^{41,43}\) In the present study, plate attachment failure was most often a result of suture pull-through, although suture breakage became more common as the length of the plate was increased from 3 to 7 holes. In addition, in the 7VCP group, the sutures used to attach the plate to the tendon remained intact, but the core 3LP suture pattern failed by suture pull-through. We postulate that tendon elongation between the proximal and distal plate holes on either side of the repair site allowed for core suture pull-through without breakage or pull-through of the plate sutures. Material properties of the internal fixation plate, suture size, and suture pattern may all influence the mode of failure following plate augmentation of tendon repair, and all of these factors should be considered when designing future studies.

Limitations of the present study included its ex vivo nature, which cannot accurately represent the effects of inflammatory changes associated with tendon rupture or the effects of plate application on the local blood supply and progression of tendon healing. We used a single distraction-to-failure test method in an attempt to duplicate conditions associated with acute overloading in clinical cases. However, cyclical testing may be more representative of normal activity in vivo in dogs.\(^{44}\) The canine cadavers used in our study were of uniform breed, size, and weight. In clinical situations, variations in patient size, location of the tendon rupture, and length of the tendon being repaired may affect the ability for plate use. Lastly, we only evaluated a maximum plate length of 7 holes and used a single suture pattern to attach the plate to the tendon.

In conclusion, for transected canine GTs, augmentation of a primary 3LP repair with an internal fixation plate significantly increased yield, peak, and failure loads and loads required to cause 1-mm and 3-mm gaps, as did increasing the length of the plate used. Further studies evaluating plate augmentation in vivo are needed to determine the effect of internal fixation plate augmentation on the tendon blood supply and progression of healing.

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