Rupture of the CCL is the most common orthopedic condition encountered in small animal veterinary practice.1 Although successful treatment of a ruptured CCL has been achieved both medically and surgically, recent evidence suggests that dogs have a better prognosis after surgery.2 Unfortunately, most dogs will still have progressive osteoarthritis after treatment with most currently performed surgical techniques,3–5 perhaps because these techniques do not replace all mechanical duties of an intact CCL.8,9 Also, the extracapsular location for points of fixation and the isometry of those points have been debated.10–12

During ex vivo testing with cadavers, tibial osteotomy procedures limited cranial femoral-tibial translation during joint loading at midstance.13–16 However, in a case series, tibial plateau-leveling osteotomy reduced but did not eliminate cranial femoral-tibial translation,17 and analysis of recent in vivo kinematic evidence based on fluoroscopy and 3-D reconstruction revealed persistent femoral-tibial translation and internal rotation after these techniques in many cases.a Tibial osteotomy procedures appear to provide short-term (<1-year) success similar to that for extra-articular sutures but can have high rates for reoperation (15% to 20%)14,15 and progression of osteoarthritis (90% to 100%).18,19 In human medicine, the probability of reoperation for ACL repairs has been reported as between 3% and 5%, and <20% of adult ACL surgical patients develop arthritis by 2 years after repair.20 Although unique physiology for each species may explain some differ-

Mechanical strength of four allograft fixation techniques for ruptured cranial cruciate ligament repair in dogs

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OBJECTIVE
To test ex vivo mechanical properties of 4 allograft fixation techniques for cranial cruciate ligament (CCL) replacement.

SAMPLE
30 stifle joints from canine cadavers.

PROCEDURES
CCL-deficient stifle joints repaired by 1 of 4 techniques (n = 6/group) and CCL-intact stifle joints (control group; 6) were mechanically tested. Three repair techniques involved a patella-patella ligament segment (PPL) allograft: a tibial and femoral interference screw (PPL-2S), a femoral interference screw and the patella seated in a tapering bone tunnel in the tibia (PPL-1S), or addition of a suture and a bone anchor to the PPL-1S (PPL-SL). The fourth technique involved a deep digital flexor tendon (DDFT) allograft secured with transverse femoral fixation and stabilized with a tibial interference screw and 2 spiked washers on the tibia (DDFT-TF). The tibia was axially loaded at a joint angle of 135°. Loads to induce 3, 5, and 10 mm of femoral-tibia translation; stiffness; and load at ultimate failure with the corresponding displacement were calculated. Group means were compared with a multivariate ANOVA.

RESULTS
Mean ± SD load for the intact (control) CCL was 520.0 ± 51.3 N and did not differ significantly from the load needed to induce 3 mm of femoral-tibial translation for fixation techniques PPL-SL (422.4 ± 46.3 N) and DDFT-TF (654.2 ± 117.7 N). Results for the DDFT-TF were similar to those of the intact CCL for all outcome measures.

CONCLUSIONS AND CLINICAL RELEVANCE
The DDFT-TF yielded mechanical properties similar to those of intact CCLs and may be a viable technique to test in vivo. (Am J Vet Res 2015;76:411–419)
ences, the intra-articular ACL replacement surgical procedures currently performed in humans may better reproduce the anatomy and mechanical duties of a normal ACL. Arthroscopic placement of intra-articular autografts or allografts at the origin and insertion of the original ACL are the most commonly performed procedures. These grafts in humans commonly are obtained from the central third of the patellar ligament or hamstring tendons.  

Intra-articular techniques have been described in dogs, but reported outcomes are not as promising as those described for osteotomies and extra-articular sutures. When use of a central-third PPL autograft was investigated in dogs, the graft did not possess the necessary mechanical properties to stabilize the stifle joint. A whole patella ligament (compared with the central third) has many mechanical properties that mirror those of the CCL obtained from a similar-sized dog, which suggests that it may be mechanically adequate if used as an allograft. The DDFT, when doubled on itself, appears to have mechanical properties that are also similar to those of the CCL (unpublished data) and has the benefit of a longer working length. Although these 2 allograft options may have adequate strength to replace a CCL, a graft fixation method with adequate mechanical properties in dogs has not been established. Multiple techniques for securing bone-ligament and ligamentous grafts, including interference screws, pins, spiked washers, and sutures, have been described. Interference screws are commonly used in humans, and when used in a repair technique, they reportedly have an in vitro strength between 463 and 1,358 N. Possible benefits of interference screws include ease of use and the ability to use appropriate sizes to accommodate grafts with different cross-sectional areas, which improves contact between the bone tunnel and graft. A cross-pin technique is an alternative fixation technique in humans for grafts that are folded to double the graft, such as for a DDFT. Cross-pin transfixation techniques involve passing a pin through the loop created at the fold in the graft. This limits fixation to only 1 site that can be secured with these techniques. Because it can be difficult to control the activity level of canine patients after surgery, it is important to identify whether CCL reconstruction techniques achieve mechanical properties similar to those of intact CCLs. The objective of the study reported here was to compare the mechanical properties of canine stifle joints with CCL replacement by various allograft fixation techniques with those of canine stifle joints with normal intact CCLs. Our null hypothesis was that allograft fixation techniques would result in mechanical properties similar to those of normal intact CCLs.

Materials and Methods

Sample  
Canine stifle joints (n = 30) were harvested from cadavers of young (age estimated on the basis of dental examination, < 5 years) skeletally mature dogs that weighed between 25 and 40 kg. Stifle joints were harvested within 3 hours after dogs were euthanized for reasons unrelated to this study. The patella and patellar ligament were harvested as a unit from each limb by transecting the muscular attachments on the proximal aspect of the patella and transecting the ligament attachment from its tibial insertion site. This served as the PPL allograft. After removal of the PPL, each stifle joint was visually examined to ensure that it appeared normal (free of angular or rotational abnormalities, asymmetric muscle mass, and abnormalities).

The DDFT was harvested from each limb. Briefly, a lateral incision was made that centered over the calcaneus and extended to the midtibia and midmetatarsal region. All components of the calcaneal tendon were incised at the proximal aspect of the calcaneus. The DDFT was identified deep to the calcaneal tendon and isolated. The tendon was isolated proximally until muscle fibers were identified. Distally, the DDFT was excised as the tendon separated into 4 components at the midmetatarsal region. The tendinous portion of the flexor digitorum medialis was excised at the point where it joined the DDFT. For inclusion in the study, a PPL graft or doubled DDFT graft had to be too large to fit through a 5-mm-diameter graft tunnel but small enough to fit through a 6-mm-diameter graft tunnel. The PPL and DDFT grafts were further prepared by removing nonligamentous tissue (eg, fat).

The femur and tibia were transected at the middiaphyseal region, and all muscles were removed. The remaining joint capsule, collateral ligaments, and cruciate ligaments were left intact. A No. 15 scalpel blade was used to remove the fat pad (to improve exposure) and CCL; care was used to ensure we did not damage the menisci or other ligamentous tissue. All specimens were wrapped in towels soaked in saline (0.9% NaCl) solution, sealed in plastic bags, and frozen at -80°C.

Repair techniques  
Stifle joint specimens (stifle joints and grafts) were assigned by use of a randomization technique (random number generator) so that each limb from a dog was assigned to a different group. Stifle joint specimens underwent intra-articular repair of a deficient CCL by 1 of 4 techniques (n = 6/group) or remained as an intact CCL (control group; 6).

Specimens were allowed to thaw at room temperature (21°C) for 24 hours before allograft fixation and mechanical testing. Three techniques involved use of a PPL allograft to repair the CCL: a tibial and femoral interference screw (PPL-2S), a femoral interference screw with the patella seated in a tapering bone tunnel in the tibia (PPL-1S), or a femoral interference screw and swivel lock (tapering bone tunnel in the tibia with a suture and a bone anchor on the femoral side; PPL-SL). The fourth technique involved use of a DDFT allograft secured with transverse femoral fixation (looped around a femoral crosspin) and stabilized...
with a tibial interference screw and 2 spiked washers on the tibia (DDFTF).

**PPL-2S**—A drill guide was positioned such that it extended from the center of the femoral insertion site of the CCL to a point on the caudolateral aspect of the femur at 35° to the long axis in the frontal plane of the femur (measured with a goniometer). A 3.5-mm drill bit was used with the drill guide to create a pilot femoral bone tunnel. After it was confirmed that the pilot tunnel was correctly placed, a 6-mm drill bit was used

*Figure 1*—Schematic illustration of the medial (left), cranial (middle), and lateral (right) views of canine cadaver stifle joints indicating the entry (1) and exit (2) and angulation of bone tunnels for CCL repair. (Medical illustration by D. K. Haines © 2014 The University of Tennessee)

*Figure 2*—Schematic illustrations of CCL-deficient transected, deficient CCLs in canine cadaver stifle joints that underwent intra-articular repair by 1 of 3 techniques involving a PPL allograft. In the image on the left, the PPL allograft is secured with a tibial and femoral interference screw (PPL-2S). In the middle image, the PPL allograft is secured with a femoral interference screw and stabilized with the patella seated in a tapering bone tunnel in the tibia (PPL-1S). In the image on the right, the PPL allograft is stabilized with a femoral interference screw and a suture and a bone anchor on the femoral side and a tapering bone tunnel in the tibia (PPL-3S). See Figure 1 for remainder of key. (Medical illustration by D. K. Haines © 2014 The University of Tennessee)
with the drill guide to enlarge the bone tunnel. This procedure was repeated at the tibial insertion of the CCL to create a 6-mm bone tunnel at 55° to the long axis of the tibia in the frontal plane (Figure 1). The patella was removed from the PPL, thus creating a patellar ligament allograft with no bone attached. Then, size-0 nylon was secured to the free ends of the patellar allograft in a modified finger-trap pattern. The graft was passed in a distal-to-proximal direction so that equal lengths of ligament were in the tibial and femoral bone tunnels. The graft was then secured in the tibial bone tunnel with an interference screw inserted into the articular surface. The stifle joint was positioned at an angle of 135°. Tension of 13 kg (as measured with a handheld scale attached to the sutures placed in the proximal aspect of the graft) was placed on the patellar graft, and the graft then was secured to the articular surface with an interference screw (Figure 2).

**PPL-1S**—Femoral and tibial bone tunnels were prepared as described for the PPL-2S. The distal exit of the tibial bone tunnel was enlarged to 1.2 cm by drilling (12-mm conical tapering drill bit) from the cortex toward the joint for a distance of 1 cm. Then, size-0 nylon was secured to the free end of the PPL in a modified finger-trap pattern. The free end of the ligament was passed in a distal-to-proximal direction through the tibial bone tunnel such that the patella would lodge in the narrowing tibial bone tunnel and did not require securing by any other means. The free end of the graft was passed in a distal-to-proximal direction through the femoral bone tunnel. The stifle joint was positioned; tension was placed on the PPL and the graft secured in a manner similar to that for the PPL-2S (Figure 2).

**PPL-SL**—Femoral and tibial bone tunnels were prepared as described for the PPL-1S, including creation of the conical tibial bone tunnel and passage of the PPL. Tension was placed on the graft as described previously, and the graft was secured with a suture connected to a bone anchor. An interference screw was then placed in the femoral bone tunnel to secure the graft to the articular surface (Figure 2).

**DDFT-TF**—Femoral and tibial bone tunnels were prepared as described for the PLL-2S. The DDFT graft was doubled; the loop end was passed in a distal-to-proximal direction and secured by use of transverse femoral fixation. The 2 distal ends of the DDFT were passed through the tibial bone tunnel; tension was applied and the graft secured with two 4.5-mm post and spiked washers. An interference screw was then placed in the tibial bone tunnel to secure the graft to the articular surface (Figure 3).

**Mechanical testing**

For all surgical fixation groups, grafts were placed in a neutral position (no twisting). Although manual application of tension is accepted in human medicine, a tensioner was used in the present study. Also, at the completion of securing each graft, tension was assessed by digital palpation to confirm that the cranial drawer sign had been eliminated, which would mimic a clinical situation. Only specimens that were stable throughout a full range of motion (no cranial drawer sign) were used for mechanical testing. Mechanical testing was initiated shortly after graft placement; specimens were kept moist throughout testing.

The femur and tibia were embedded in a 2-part urethane casting resin. Limbs were embedded to within 4 cm of the joint surface to help prevent bone fracture before CCL rupture. Limbs were placed into a materials testing machine with the specimens oriented at a joint angle of 135° (Figure 4). The tibia was rigidly secured to the load frame actuator, whereas the femur was allowed free translation on a linear slide table. The mechanical setup applied a load to the tibia that simulated a ground reaction force. Given that the limbs were oriented at 135° with axial loading, the resultant force induced femoral-tibial translation. Vertical displacement was measured with the load frame actuator. Horizontal displacement (femoral-tibial translation) was measured by securing a linear variable differential transducer to the slide table. A static axial compression force of 10 N was...
applied for 60 seconds, which was followed by cyclic tensile loading to 98 N (force of approx 30% to 40% of a dog’s weight) at 1 Hz for 100 cycles. At the conclusion of 100 cycles, specimens were tested until failure (> 20 mm of femoral-tibial translation) with force applied at a rate of 2.5 mm/s. The chosen rate, although slower than that for a physiologic load, allowed for determination of the type of failure. All mechanical testing procedures were videotaped with a single camera. Stiffness, femoral-tibial translation, and ultimate strength were recorded. Visual and video inspection of the testing procedures and dissection of the stifle joints after testing were used to identify the type of failure.

**Statistical analysis**

The relationship between vertical and horizontal displacement as axial load was tested by generating a correlation coefficient. A multivariate ANOVA was used to test for mean differences by treatment on the basis of 2 sets of dependent variables grouped on the basis of cyclic or failure mechanical testing. When significant differences were found, a Tukey post hoc test was used to determine treatment means that differed significantly. Multivariate ANOVA assumptions were met for all variables except ultimate strength, which had extreme differences in treatment variances. Ultimate strength was tested with a univariate ANOVA and Dunnett T3 multiple comparison test for unequal variances. Values of \( P \leq 0.05 \) were considered significant for all tests. All analyses were conducted with statistical software.

For cyclic testing, femoral-tibial translation for the repair techniques was compared with that of the control group. For load-to-failure testing, the load at 3, 5, and 10 mm of femoral-tibial translation was assessed between groups. These points were chosen on the basis of a previous study that revealed a normal intact CCL can have up to 3 mm of elastic elongation in axial tension and also on the basis of clinical experience that a cranial drawer sign can more consistently be detected when 5 to 10 mm of displacement is present.

**Results**

Dogs included in the study appeared similar in size and conformation to American Staffordshire Terriers. Given that each limb from a dog was assigned to a different group, mean body weight was not evaluated. All specimens were free from pathological lesions as determined via visual inspection before surgery. All specimens in the repair groups had no cranial drawer sign after graft fixation as assessed by palpation throughout a range of motion. All 30 specimens were successfully tested through cyclic fatigue and load to failure. Similar to results of another study, magnitudes of the vertical and horizontal displacements were extremely similar (\( r = 0.998 \)), which suggested that application of an axial force to the tibia resulted in femoral-tibial translation.

For cyclic fatigue testing, stifle joints with CCL repair via PPL-1S and PPL-2S had significantly more femoral-tibial translation, compared with that for control stifle joints with intact CCLs, but there was no difference in femoral-tibial translation between the PPL-SL or DDFT-TF and the control stifle joints. A comparison of treatment groups during cyclic fatigue testing revealed a significant difference between the DDFT-TF and PPL-1S.

Mean load at 3, 5, and 10 mm of femoral-tibial translation was significantly greater in the stifle joints with intact CCLs, compared with those for CCL repair via PPL-1S and PPL-2S. There was no difference in mean load among the control group, DDFT-TF and PPL-SL at 3, 5, and 10 mm. The proportion of the load at 3 mm of horizontal displacement, compared with
the load of the intact CCL, was 26% for PPL-1S, 28% for PPL-2S, 81% for PPL-SL, and 125% for DDFT-TF. Stiffness for all repair groups was significantly less than that of the control group, except for DDFT-TF, which was significantly stiffer than the PPL-1S and PPL-2S (Table 1).

All control specimens failed in the form of mid-body tears of the CCL, except for 2 limbs that failed in the form of bone or resin fracture that occurred before complete CCL rupture. In both of those limbs, the CCL had >10 mm of laxity. Repair specimens uniformly failed in the form of ligament pullout from the interference screw, swivel-lock suture, or spiked washers.

**Discussion**

On the basis of analysis of results for the present study, the null hypothesis that PPL-2S, PPL-1S, and PPL-SL allograft fixation techniques have mechanical properties similar to those of a normal intact CCL was rejected. However, for stabilization with the DDFT-TF, the null hypothesis was not rejected. Results for the DDFT-TF did not differ significantly from those of the intact CCL for any mechanical variable evaluated. The finding that the DDFT-TF was mechanically superior to the other graft fixation techniques evaluated was similar to findings in previous mechanical studies.

Although different grafts were used in those studies, a transverse femoral fixation has been found to be superior to other fixation methods.

It is unclear which initial mechanical characteristics (eg, stiffness, load to failure, and load to 3 mm of elongation) might be required for a graft reconstruction technique to provide a chance of biological graft survival (vascular and cellular ingrowth) and permanent joint stability in dogs. Additionally, many biological challenges may need to be overcome in some CCL-deficient dogs. Intuitively, a graft reconstruction technique is better suited to sustain biological challenges if it is most mechanically similar to an intact CCL. During typical daily use, a dog applies loads to the CCL that are only 25% to 33% of its ultimate strength. The testing protocol described here was an approximation of these mechanical demands, and only the PPL-SL and DDFT-TF performed similarly to stifle joints with an intact CCL. The canine CCL reportedly resists 50 N of force during walking and between 400 and 600 N of peak vertical force during vigorous play. Also, it has been reported that vertical ground reaction forces at a walk are approximately 40% of a dog's body weight (eg, for a 25-kg dog, ground reaction force is approx 100 N). On the basis of analysis of the ex vivo data, all repairs described in the present study may resist forces encountered at a walk, but only the DDFT-TF; and perhaps the PPL-SL, may withstand the physiologic forces encountered during more substantial activity after surgery.

Although strength of the canine CCL has been reported, most studies have involved testing of the CCL in axial tension. For example, CCLs from healthy Beagles (body weights were not reported) had a tensile strength of 210 to 556 N. Failure loads of 1,151 and 1,656 N were reported in other studies of mixed-breed dogs (body weights not reported). Investigators of another study found that the angle used for testing of the stifle joint in Beagles affects ultimate strength (0° = 1,181 N, 45° = 454 N, and 90° = 428 N). Normal CCLs from Rottweilers (mean body weight, 42 kg) tested at 130° of flexion and loaded in a cranial direction had an ultimate strength of 2,130 N and failed at 1,738 N when tested along the axis of the ligament. The CCLs from Greyhounds (mean body weight, 31 kg) tested at 130° of flexion and loaded in a cranial direction had an ultimate strength of 1,799 N and failed at 1,781 N when tested along the axis of the ligament.

Differences in testing setup, specimen preparation (frozen, fresh, or sterilized), testing angle, displacement rate, displacement at the reported load, and breed distribution make it difficult to make comparisons among reports. Although many variables (eg, study design, dog age, and dog breed) may affect the findings for these types of studies, we suggest that the loads sustained by normal intact CCLs in the present study were similar to values reported in previous studies.

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**Table 1**—Mean ± SD results for cyclic mechanical testing of canine cadaver stifle joints that underwent intra-articular repair of a deficient CCL via 1 of 4 techniques (n = 6/group) or that had a normal intact CCL (control group: 6).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>PPL-1S</th>
<th>PPL-2S</th>
<th>PPL-SL</th>
<th>DDFT-TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclic displacement (mm)</td>
<td>0.29 ± 0.06a</td>
<td>1.19 ± 0.10a</td>
<td>1.05 ± 0.28c</td>
<td>0.62 ± 0.17a</td>
<td>0.40 ± 0.20c</td>
</tr>
<tr>
<td>3 mm of displacement (N)</td>
<td>520.0 ± 51.3a</td>
<td>136.8 ± 40.1b</td>
<td>145.5 ± 44.8c</td>
<td>422.4 ± 46.3c</td>
<td>654.2 ± 117.7a</td>
</tr>
<tr>
<td>5 mm of displacement (N)</td>
<td>1,014.5 ± 90.7</td>
<td>295.3 ± 47.2b</td>
<td>249.3 ± 55c</td>
<td>653.4 ± 69.0b</td>
<td>1,001.1 ± 153.8c</td>
</tr>
<tr>
<td>10 mm of displacement (N)</td>
<td>1,636.9 ± 172.6</td>
<td>607.2 ± 127.2b</td>
<td>493.5 ± 73.4b</td>
<td>917.0 ± 135.8b</td>
<td>1,545.9 ± 218.2a</td>
</tr>
<tr>
<td>Ultimate strength (N)</td>
<td>2,077.9 ± 131.6b</td>
<td>1,130.2 ± 167.6b</td>
<td>1,203.0 ± 110.6b</td>
<td>1,170.9 ± 198.6b</td>
<td>2,186.6 ± 452.2b</td>
</tr>
<tr>
<td>Displacement at ultimate strength (mm)</td>
<td>13.9 ± 1.5b</td>
<td>17.8 ± 2.8b</td>
<td>23.3 ± 3.2b</td>
<td>12.8 ± 1.7b</td>
<td>15.3 ± 2.0b</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>219.1 ± 24.7b</td>
<td>63.0 ± 9.6a</td>
<td>50.4 ± 10.4</td>
<td>128.4 ± 13.2a</td>
<td>204.4 ± 32.5c</td>
</tr>
</tbody>
</table>

Three techniques involved use of a PPL allograft: a tibial and femoral interference screw (PPL-2S), a femoral interference screw and the patella seated in a tapering bone tunnel in the tibia (PPL-1S), or the addition of a suture and a bone anchor to PPL-1S (PPL-SL). The fourth technique involved a DDFT allograft secured by use of transverse femoral fixation and stabilized with a tibial interference screw and 2 spiked washers on the tibia (DDFT-TF).

a,b,cWithin a row, values with different superscript letters differ significantly (P ≤ 0.05).
It has been suggested\(^9\) that graft fixation technique is a major limiting factor of the mechanical properties for anterior cruciate reconstruction surgery in humans. Given the mechanical properties of a whole PPL\(^4\) and findings for the present study that all failures involving the PPL were a result of ligament pullout at the interference screw or site of the secondary fixation (ie, graft sutured with a whip stitch, with suture attached with a screw), we suggest that this is also true for CCL reconstruction surgery in dogs. Spiked washers may resist graft slippage better than do the other graft fixation techniques tested. This cannot be determined directly because spiked washers were not used with the PPL graft because of limited graft length. The added length of the DDFT graft provides increased flexibility for repair options; this likely contributed to superior performance of this graft fixation technique over that of other graft fixation methods.

At least 1 interference screw was used in the fixation of the grafts for all repair groups. Interference screws are widely used in human medicine, often as the only method of stabilization. When interference screws are used alone, pullout strengths of 463 to 1,358 N have been achieved\(^26,27\); although the load to failure in the dogs of the present study was within this range, < 200 N was achieved before reaching 3 mm of displacement. Variables that could influence findings include differences in the screws used (manufacturer and material), differences in grafts used, tunnel-to-graft diameter ratio, and direction and velocity of the load applied. In the present study, size of screws was determined on the basis of the manufacturer’s recommendations. Considering that it can be difficult to control the activity level of canine patients after surgery, we thought it was important to determine the similarity of the mechanical properties achieved by various CCL reconstruction techniques with those of intact CCLs.

To the authors’ knowledge, there are no reports that a graft fixation technique approaches the mechanical properties of a normal intact CCL. Prior to in vivo investigation, Cranial cruciate ligament replacement has been evaluated with an allograft CCL, fascia autografts and allografts, and partial PPL autografts. Investigators of 1 study\(^40\) replaced the CCL with CCL allografts in mixed-breed dogs. In that small, short-term study,\(^40\) 2 dogs that had stable stifle joints immediately after surgery had a full recovery to a visually normal gait, but the remaining 5 allografts were unstable immediately after surgery; those dogs failed to recover, which suggested that allograft repair, if initially stable, can provide effective CCL repair. In another study,\(^11\) 6 dogs received allografts whereby the segment was secured with only suture material; all dogs had unstable stifle joints when euthanized 9 months after surgery. Other investigators performed a similar study\(^12\) in which they implanted CCL allografts in 11 patients, 3 of which developed infections and were removed from the study. At 4 months after surgery, 5 of the remaining 8 dogs were lame.\(^43\) In that study,\(^43\) grafts were not inserted through a bone tunnel or stabilized, and there was no description of graft size. Grafts in the present study had to fit through a 6-mm-diameter hole and were matched to a similar-sized bone tunnel. In the previous studies,\(^40,41\) allografts were achieving 10% to 59% of the ultimate strength of an intact CCL. In a study\(^46\) with more encouraging results, 28 dogs received allografts. Only 3 graft failures were detected, and dogs were monitored for 18 weeks in the group with the longest follow-up period. Clinical assessment of the dogs was not discussed, but allografts achieved 90% of the ultimate strength of a normal intact CCL at 36 weeks after surgery.\(^36\) Collection and storage of the grafts, surgical technique, postoperative monitoring, and assessment all differed among those studies. In addition, many dogs had unstable stifle joints immediately after surgery, which likely limited their likelihood of a successful outcome. Previous reports inconsistently include descriptions of graft strength, size, placement, or stabilization method. Thus, it is possible that historical failures of intra-articular graft repairs were attributable to inappropriate mechanical properties of the graft or graft stabilization technique.

In the present study, we focused on allograft tissues for CCL replacement. Although use of the DDFT provided encouraging mechanical data for CCL reconstruction, no data are available to address the biological reaction of a DDFT allograft. However, in a 2014 systematic review and meta-analysis,\(^43\) there was no significant difference in outcome between human patients undergoing ACL reconstruction with a hamstring autograft and those undergoing ACL reconstruction with a soft tissue allograft. Extrapolation of results for the present study in canine cadavers to an in vivo setting should be done cautiously. In the present study, biological limitations to allograft replacement in dogs were not addressed, limbs were tested at only 1 angle, there were only 6 dogs/group, there was no confirmation that dog body weight was similar among groups, precise ligament dimensions were not recorded, and postimplantation evaluation was not performed to confirm graft placement.

In the present study, graft stabilization technique significantly affected mechanical performance of intra-articular repair techniques. The DDFT-TF stabilization technique for CCL repair resulted in mechanical properties similar to those of a normal intact CCL.

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**Footnotes**

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