Mechanical testing of a modified stabilisation method for tibial tuberosity advancement

S. Etchepareborde1; N. Barthelemy1; J. Mills2; F. Pascon3; G. R. Ragetly4; M. Balligand1
1Department of Clinical Sciences, School of Veterinary Medicine, University of Liège, Belgium; 2Scarsdale Veterinary Hospital, Derby, UK; 3Department of Architecture, Geology, Environment and Constructions, University of Liège, Belgium; 4Department of Veterinary Clinical Medicine, University of Illinois, Urbana, Illinois, USA

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Introduction
Cranial cruciate ligament (CCL) insufficiency is one of the most common causes of lameness in dogs (1). Partial or complete CCL rupture causes stifle joint instability and triggers a cascade of secondary pathological changes including progressive osteoarthritis and subsequent meniscal injury (2, 3). Numerous surgical techniques have been described to manage CCL insufficiency, each having potential or proven advantages and disadvantages (4). Over the past 25 years, the focus has shifted to the concept of creating dynamic stability in the CCL-deficient stifle by altering bone geometry. Tibial wedge osteotomy (TWO) and then tibial plateau levelling osteotomy (TPLO) were first described for the treatment of CCL rupture in 1984 and 1993 respectively (5, 6). In 2002, Montavon first postulated that tibial tuberosity advancement (TTA) could neutralise the cranially directed stifle shear forces (cranial tibial thrust) responsible for cranial tibial subluxation during weight-bearing in dogs affected by CCL rupture (7). The aim of the TTA is to modify the angle between the patellar tendon and the tibial plateau by advancing the tibial tuberosity. The new position is achieved by the osteotomy of the tibial crest and the insertion of a space-occupying titanium cage. Stabilisation is achieved with a dedicated titanium plate that attaches to the tibial crest with a multi-pronged fork and to the tibial diaphysis with screws. Initial clinical studies report very promising results, similar to those obtained with TPLO (8).

Advancement of the patellar tendon in humans has been described since 1976 by Maquet to diminish the patellofemoral pressure, and to reduce morbidity from osteoarthritis of the knee or chondromalacia of the patella (9, 10). Original models showed that a 2 cm advancement of the patellar tendon reduced pressure by approximately 50% during the phases of the gait when the quadriceps muscle contracts, that is to say at the beginning of weight-bearing (9). Theoretical controversy continues, but the consensus seems to hold that, with proper indications and accurate technique, the Maquet procedure still plays a role in treating patellofemoral cartilage degeneration in people (11, 12).

Triple tibial osteotomy (TTO), combining features of the TTA and the TWO, has been described in dogs to treat CCL rupture (13). Three cuts are made in the proximal tibia to create a partial wedge osteotomy caudal to a partial tibial crest osteotomy. The tibial plateau is made perpendicular to the patellar tendon by rotating the proximal tibial fragment to close the wedge osteotomy while simultaneously advancing the tibial tuberosity (Fig. 1).

Summary
Objectives: This in vitro study evaluated three modified techniques of tibial tuberosity advancement (TTA). Loads to failure were calculated for each technique.

Methods: A 9 mm TTA procedure was performed in the tibiae of dogs weighing between 32 and 38 kg. In group 1 (n = 12), the distal part of the tibial crest was left attached to the tibia by the cranial cortex, and a figure-of-eight wire was added for stabilisation. In group 2 (n = 12), the tibial crest was left attached but no additional device was used for stabilisation. In group 3 (n = 12), the tibial crest was completely separated from the tibia and fixed by a figure-of-eight wire so that, in this group, only the wire opposed avulsion of the tibial crest. Unidirectional axial force was applied via the patella to determine the maximal load to failure of the model.

Results: There was no significant difference between group 1 and group 2. These two groups both had a significantly stronger construct than that of group 3.

Clinical significance: We described modifications to the TTA procedure without plate fixation that warrant clinical investigation. When the crest is broken during its advancement, the tension sustained by the repair is significantly weaker from a biomechanical point of view and the use of such a repair clinically is not recommended by the authors.

Correspondence to:
Sebastien Etchepareborde, DVM
Boulevard de colonster 20
4000 Liège
Belgium
Phone: +33 679 5549 82
Fax: +32 4366 4213
E-mail: sebetche@yahoo.com

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After reviewing papers about TTO in dogs where the tibial tuberosity is advanced without additional stabilisation of the tibial crest, we hypothesised that a modified tibial tuberosity advancement technique without plate fixation might still withstand the tension acting on the tibial tuberosity. This cadaveric study was intended to: 1) evaluate the mechanical strength of TTA without plate stabilisation, and 2) to compare the effect on mechanical strength of additional support made with a figure-of-eight wire.

Material and methods

Specimen preparation

Pelvic limbs (n = 36) were collected by disarticulation of the coxofemoral joint in 24 adult dogs weighing 32–38 kg that were euthanatized for reasons unrelated to this study. Cranio-caudal and mediolateral radiographic views were taken of each stifle to ensure there was no radiographic evidence of pathology. Tibial plateau angle (TPA) was measured for each stifle on the mediolateral radiographs, using a previously reported methodology (14). On the same radiograph, the thickness of the cranial cortex of the tibia was assessed 1 cm distal to the level of the most distal part of the tibial crest. After imaging, all limbs were wrapped in isotonic saline-soaked towels, and stored in sealed plastic bags at –20°C until testing. In preparation for testing, the limbs were thawed to room temperature overnight. Skin and soft tissues were removed, sparing the patella and patellar tendon. The quadriceps tendon was transected perpendicularly to the straight patellar ligament. (Reprinted from Bruce WJ et al. Vet Comp Orthop Traumatol 2007; 20: 159-168).

Treatment groups

In group 1, one 1.5 mm diameter hole was drilled in the tibial diaphysis 1 cm distal to the distal end of the osteotomy and 5 mm caudal to the cranial edge of the tibial crest and the osteotomy. A 1 mm diameter stainless steel cerclage wire was tied by the same operator (SE) in a figure-of-eight pattern using two twist knots. The figure-of-eight wires were tightened with a wire trister/shear cutter and tension was judged adequate by a single operator (SE) based on their clinical experience.

In group 2, the additional 1.5 mm holes were not drilled, the cerclage wire was not placed, and only the intact cranial cortex stabilised the advanced tibial crest. Left and right hindlimbs of 12 dogs were randomly assigned (by a coin toss) to groups 1 and 2.

A third group (group 3) was made by harvesting at random (via coin toss) the left or the right hindlimb of the remainder 12 dogs so that 12 samples were tested in this group. After the osteotomy, the cortical hinge was purposely broken so that the tibial crest was detached from theibia. After placement of the cage, the distal part of the crest was placed back at its original location and the tibial crest was secured to the tibia using a cerclage wire placed as in group 1.

Testing protocol

Each construct was then fixed into a vice that was adapted to accept the cylindrical...
The rigid fixation kept the base, and hence the tibial plateau, horizontal within the materials-testing machine. This ensured that the patellar tendon-TPA was 90°. Minimal preload was applied to straighten the patellar tendon by adjusting the turnbuckle (Fig. 2).

Tension was applied on the patellar tendon at a rate of 20 mm/second until failure occurred. The mode of failure and the maximal load-to-failure were recorded.

**Statistical analysis**

All data were expressed as mean ± standard deviation. Maximal load-to-failure was compared between the three groups with a risk factor of less than 0.05 considered as significant. Despite the similar morphology of all dogs, independence of the limbs was not assumed. Statistical differences were evaluated between the groups with a mixed linear regression using a SAS MIXED procedure from commercial software. Dog, side, and treatment were classification effects and maximal load-to-failure was the mean model for the data. Unstructured forms were chosen for the within-subject variance-covariance matrix. Pairwise comparison was performed with Tukey adjustments.

**Results**

All dogs were skeletally mature. The weight of the dogs ranged from 32 to 38 kg (mean: 34.6 ± 2.1 kg). None of the stifle joints had radiographic signs of osteoarthritis.

Mean maximal load-to-failure was 1265 ± 275 N, 1123 ± 394 N, and 613 ± 77 N for group 1, 2, and 3, respectively (Fig. 3).

The difference between group 1 and 2 was not significant (p = 0.4022). There was a significant difference between group 1 and 3 and group 2 and 3 (p < 0.001, respectively).

In group 1, nine out of 12 samples failed by avulsion of the tibial crest after fracture of the cranial cortex at the thinner distal extremity, two out of 12 failed by fracture of the diaphysis of the tibia at the insertion into the pot, and one out of 12 by fracture of the patella through the hole used for fixation to the materials-testing apparatus. In group 2, six out of 12 samples failed by avulsion of the tibial crest, five out of 12 failed by fracture of the diaphysis of the tibia at the insertion into the pot, and one out of 12 by fracture of the patella through the hole used for fixation to the materials-testing apparatus. In group 3, all 12 samples failed by failure of the figure-of-eight cerclage wire (breakage or untwisting of the knots).

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Fig. 2 A) The tibial tuberosity has been advanced. The distal end of the proximal tibial diaphysis is embedded in the resin potting material. Note the aluminium spacer, and also the figure-of-eight wire as this particular specimen was from group 1. B) The tibia is secured to the testing machine by means of a vice adapted to the cylindrical shape of the pot and a turnbuckle linking the load applicator to a pin through the patella.

Fig. 3 Bar graph of mean load to failure of each group with standard deviations indicated.
Discussion

Tibial tuberosity advancement is now a well accepted technique to treat CCL rupture (8, 16). Any modification of the standard procedure must adequately protect the tibial crest from avulsion. Our results justify further studies to confirm whether fixation with a plate and fork as originally described is necessary.

In the TTO procedure, the tibial tuberosity does not need protection by implants to prevent avulsion in most cases (17). However TTO only employs modest advancement as the relative contribution of the TTA to the total correction angle is 33% (13). In the TTO procedure, and in our modified TTA procedure, the advancement provides 100% of the correction. This greater advancement is expected to increase stress concentration at the distal end of the incomplete osteotomy compared to the situation in TTO. The incidence of propagation of cracks might therefore be higher in our modified TTA procedure than in the TTO procedure. For this reason, the TTA without protection by implants that has been validated for TTO can not be simply transferred to TTA. A hole drilled at the distal extent of a partial osteotomy will theoretically decrease stress concentration. This technique has proved effective in obviating crack propagation in materials other than bone and has been successfully employed in the aerospace industry. This technique has been rarely described in bone fracture biomechanics (18). Studies have revealed that the stress around a defect, such as a surface scratch or a fissure, is much higher than expected. In fact, it may be shown generally that the true stress near such a defect σt, is given by: σt = k. σ where σ is the average stress and k is a factor that always exceeds a value of 2. For cracks in bone: k = D/r where in our cases, D is the length of the osteotomy and r is the smallest radius of a developing crack (distal end of the osteotomy) (19) (Fig. 4).

Due to concerns with the thinness of the cranial cortex, and because fracture of the tibial crest is a reported serious complication in the TTO procedure, we tested some samples with the addition of a wire cerclage (group 1) (13). Ideally, the tension to which the wires were tightened should have been standardised by using a calibrated tightening device. Unfortunately we did not have access to such a device at the time of the study. This variation could potentially alter the results of this study. The average tension obtained by using twist knots on cerclage wire was reported to be 82 N and the experience and the strength of the wire fixation in group 3 was significantly lower than in groups 1 and 2. We do not think that our technique of tightening was sub-optimal as the strength of the wire fixation in group 3 was comparable with strengths reported in previous studies (23, 24). The diameter of the wire was chosen based on our clinical experience. It has been reported that 1.0 mm wire will fail at a load of 450 N to 510 N (24).

Fig. 4

The true stress near a defect is proportional to the average stress by a factor k with k = D/r. D is the length of the osteotomy and r is the width at the end of the osteotomy (radius of the hole in our case). Both pictures show the same osteotomy length (D) but on the left, the width at the end of the osteotomy corresponds to the thickness of the saw blade, whereas on the right, this width corresponds to the radius of the hole. The width being much smaller on the left, the true stress will be much higher.

Fig. 5

A) The stifle is at 135° after advancement of the tibial crest. The large black arrow represents the force pulling on the tibial crest, perpendicular to the tibial plateau. B) The stifle has now flexed and the patellar tendon-tibial plateau angle is less than 90°. The force pulling the tibial crest (white arrow) can be divided on its 2 components (small black arrows): one force parallel to the tibial plateau pulling the crest against the tibia and one perpendicular to the tibial plateau, inferior to the resultant force.

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crest and the weaker it becomes. In our clinical experience, most dogs between 30 and 40 kg need a 9 mm cage. In all our specimens (32–38 kg), we arbitrarily decided to use a 9 mm advancement rather than a 6 mm one in order to replicate the most stressful situation for the tibial tuberosity. Indeed, the stress being proportional to the advancement, it is intuitive that if the cortical hinge has adequate strength after placement of a 9 mm advancement, it would also have adequate strength for a 6 mm advancement in a similar sized dog. Conversely, a 12 mm advancement in a similarly sized dog cannot be assumed to leave the cortical hinge with adequate strength. Thus we can not currently comment on the possible suitability of our modified TTA for use with a 12 mm advancement, or in dogs smaller than 30 kg where a 9 mm cage would advance the tibial crest through a relatively greater angle, focusing more stress on the distal cortical hinge.

Kinematic analysis of the gait of normal dogs suggests that the angle of stifle flexion at the mid-point of the stance, when the limb will be substantially loaded, is between 120° and 140° (25, 26). The goal of the TTA procedure is to achieve an angle of 90° between the patellar tendon and the tibial plateau when the stifle is in 135° extension. Therefore when the limb is substantially loaded the patellar tendon-tibial plateau angle will be 90° or less. When this angle is less than 90°, the force applied to the tibial tuberosity can be divided in two force vectors including one perpendicular to the tibial plateau pulling the tibial tuberosity proximally. This force tends to avulse the tibial tuberosity, and it is maximal when the patellar tendon-tibial plateau angle is 90°. The second force vector is parallel to the tibial plateau pressing the tibial tuberosity and is maximal when the stifle is in 135° extension.

The testing process used unidirectional axial force and cannot reproduce all the forces acting \textit{in vivo}. Acute axial loading does not model the cyclical loading experienced by a TTA osteotomy during the post-operative repair phase. Our study is a pilot for further studies and should be read as such.

The stifles we used were tested after being thawed from −20°C. Ideally, specimens should be tested immediately after euthanasia, but this was not practical. Several studies have shown that freezing bone has no effect on torsion, bending and compression properties (28, 29). None has been published about the effect on tension.

Our study did not allow evaluation of the contribution of soft tissues to the stability of the tibial tuberosity. Surgeons performing the TTO technique frequently observe how the tibial crest segment often does not displace substantially despite complete osteotomy, because of the soft tissue attachments.

The use of the technique we described to advance the tibial crest in clinical cases would not allow the tibial crest to be displaced proximally as recommended originally (15). The discussion on this particular point is beyond the scope of this study and further studies on the modifications of the patellofemoral joint after advancement of the tibial tuberosity and their clinical consequences have yet to be published.

Despite its recognised limitations, our study suggests that an intact distal cortical hinge may adequately resist tibial crest avulsion. This is supported by the good clinical results that we have obtained using this technique and which we hope to publish in the near future (Fig. 6). Although intraoperative assessment of the integrity of the cranial cortex of the tibial crest after advancement may be difficult, we pay particular attention to this point as fracture of the crest will decrease dramatically the mechanical strength of the repair. The mean load-to-failure of models when the crest is broken suggests that when it is obvious that the tibial crest has ruptured during advancement, standard TTA plate fixation is preferable. Therefore, we continue to position the osteotomy as in the standard
TTA technique so that plating may be used as an alternative strategy if the cranial cortex hinge breaks.

In conclusion, we propose that a modified TTA procedure warrants clinical investigation.

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