Mechanical testing of a new osteotomy design for tibial tuberosity advancement using the Modified Maquet Technique

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Keywords

Cranial cruciate ligament, Modified Maquet Technique, tibial tuberosity advancement, biomechanics

Summary

Objectives: To evaluate the mechanical properties of the distal cortical hinge associated with a new osteotomy design for the Modified Maquet Technique (MMT).

Study design: *Ex vivo* mechanical study.

Methods: The osteotomy was started 10 mm caudal to the tibial tuberosity and extended over 150% of the length of the tibial crest; it was slightly curved distally to stay at a distance of 2 to 4 mm from the cranial cortex, according to the body weight. Ninety-six tibiae were tested in advancement, and 60 tibiae were axially loaded perpendicular to the tibial plateau, until failure of the crest. Desired advancement was measured using the common tangent method in 60 tibiae. Angle of opening, thickness, and area of the cortical hinge were recorded.

Results: Desired advancement of 6 mm, 9 mm, 12 mm and 15 mm was recorded in 16, 12, 18 and 14 tibiae respectively. Mean maximal advancement in these bones was 15.6 ± 6.4 mm, 20.8 ± 5.2 mm, 21.3 ± 5.2 mm and 22.7 ± 5.2 mm respectively. The desired advancement was reached in all but one tibia. Advancement was mainly influenced by the angle of opening and the stiffness of the cortical hinge. Mean ultimate load to failure was 6.12 ± 2.4 times the body weight. It was significantly associated with the body weight, thickness, and area of the cortical hinge.

Clinical relevance: Mean maximal advancement was higher than clinically required without occurrence of fissure or fracture. Ultimate load to failure and maximal advancement could be predicted using calculated formulae.

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Introduction

Cranial cruciate ligament deficiency results in both translational and rotational instability of the canine stifle. Several surgical techniques have been developed to neutralize mainly the tibiofemoral shear forces, using either static or dynamic repairs (1-8). Tibial plateau levelling osteotomy and tibial tuberosity advancement (TTA) are the most commonly used techniques for dynamic repairs (6, 9, 10). A modification of the original TTA technique was described and named the Modified Maquet Technique (MMT). The MMT avoids the use of a plate as it leaves intact a distal osseous attachment, called the cortical hinge, with the tibial shaft; it also preserves soft tissue integrity because reflection of the periosteum along the tibial crest is minimal (11, 12). The MMT and TTA are derived from a surgical technique that was first introduced by Maquet to relieve pain in osteoarthritic and chondromalacic patellofemoral joints in humans (13).

As a discrepancy exists between the desired tibial tuberosity advancement and the truly achieved advancement, the tendency is currently to increase the cage size determined by preoperative planning (14). In our clinical experience with 50 cases, a limitation of the MMT is the formation of a fissure (33%) or a fracture (15%) of the cortical hinge during the advancement of the tibial crest (▶Figure 1) (unpublished data). As previously reported in a biomechanical study, fracture of the distal cortical attachment significantly decreases the mechanical strength of the repair, even when using a tension band wire; so conversion to a TTA has been recommended (11). However, according to our clinical experience, the use of a tension band when a fissure or fracture occurs is associated with osteotomy healing and a good outcome (unpublished data).

Our purposes were **1)** to develop a new osteotomy design to achieve adequate tibial tuberosity advancement without occurrence of a fissure; **2)** to determine factors affecting the maximal advancement and the ultimate load to failure; and **3)** to calculate two formulae which could predict maximal advancement and ultimate load to failure.

Our hypothesis was that the mechanical properties were positively correlated with the size of the cortical hinge.

Materials and methods

Specimen preparation

Pelvic limbs (n = 156) were collected by disarticulation of the coxofemoral joint in 78 skeletally mature dogs that were euthanatized for reasons unrelated to this study. The body weight of the dogs ranged from 7.6 to 54 kg (mean 23.5 ± 8.8 kg). Skin and soft tissues were removed, leaving only the tibia, patellar tendon and patella which were kept moist throughout the experiment by spraying the specimens with isotonic saline solution.

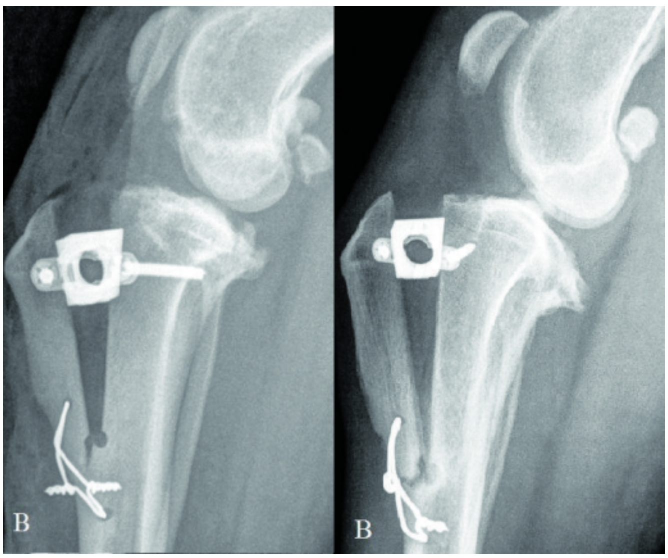

Figure 1 Original osteotomy design for the Modified Maquet Technique (MMT). Postoperative radiographs for MMT showing a fissure **(left)** and a fracture **(right)** of the cortical hinge at the level of the distal hole.

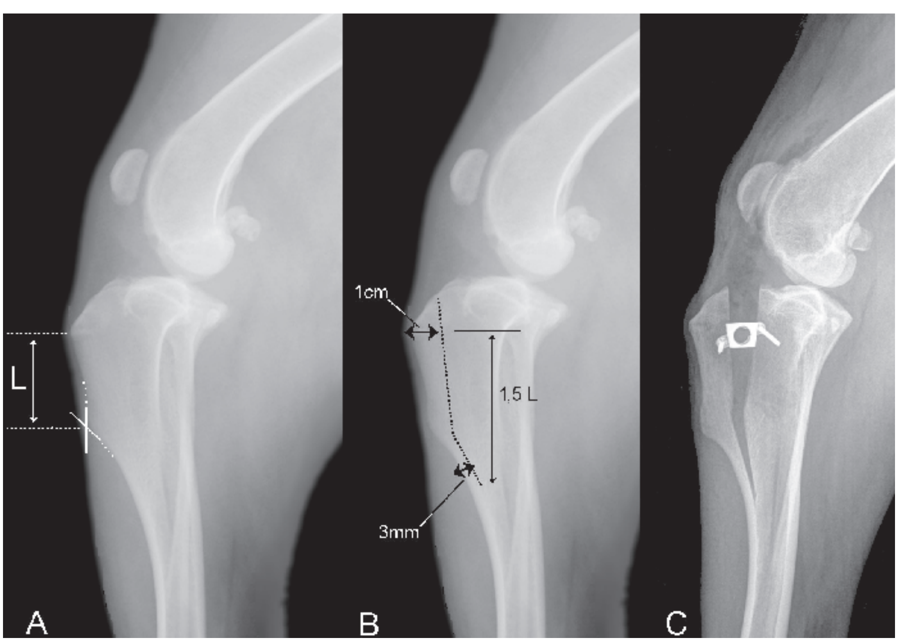

Figure 2 New osteotomy design for the Modified Maquet Technique (MMT). **A)** Preoperative radiograph for MMT: two white dotted horizontal lines delineate the limits of the tibial crest proximally and the tibial diaphysis distally as well as the length of the tibial crest (L). The crossover of the two other lines defines the most distal part of the tibial crest. **B)** The most distal point of the osteotomy is located at 1.5 x L from the level of the tibial tuberosity. **C)** Immediate postoperative view of a stifle after MMT illustrating the new osteotomy design. The osteotomy is curved slightly caudally in its distal part and is parallel to the cranial border of the tibia.

Osteotomy design

The osteotomy was started at a point 10 mm caudal to the tibial tuberosity and it then extended over a distance equivalent to 150% the length of the tibial crest (▶Figure 2). The distance of 10 mm was chosen so that there was sufficient bone remaining to enable conversion of the MMT into a TTA procedure if a fracture of the cortical hinge occurred.

The osteotomy was started with a straight proximal part along the whole length of the tibial crest, and then it was curved slightly caudally to finish as a straight distal part over a distance equal to 50% the tibial crest length. The thickness of the cortical hinge, which varied according to the body weight of the dog, was 2 mm (<15 kg), 3 mm (15 to 25 kg), or 4 mm (>25 kg). The saw blade was directed perpendicularly to the medial aspect of the tibial shaft throughout the entire process of executing the osteotomy.

Testing protocol

Tibial tuberosity advancement

The tibiae were placed in a custom jig, with the osteotomy plane parallel to the transverse crossbar of a calibrated servohydraulic testing machine[a] (▶Figure 3). A right-angled 2.5 mm pin was inserted into a 2.8 mm hole drilled in the tibial crest immediately caudal to the tibial tuberosity. To eliminate any slack, the pin was preloaded using a turnbuckle, taking care not to induce any displacement of the crest. Advancement of the crest was performed at a rate of 1 mm/s. The maximal displacement was recorded when the tibial crest failed. Failure of the tibial crest was defined as a sudden drop in the load deformation curve. The angle of opening and the stiffness of the cortical hinge were calculated and all data were recorded using the testing system software[b] (▶Figure 4). In the absence of failure of the tibial crest, the advancement test was stopped between 25 and 30 mm as we considered this value sig-

[a] Instron 3366: Instron, Boechout, Belgium
[b] Bluehill V2.3: Instron Corporation, Boechout, Belgium

nificantly above the required advancement in any clinical cases.

Tibial tuberosity axial loading

The tibiae were fixed into a custom jig, maintaining the tibial plateau in a horizontal position. The tibial tuberosity was advanced using a 6 mm cage in dogs <15 kg and a 9 mm cage in dogs >15 kg. Loading was exerted at a rate of 10 mm/s in a direction perpendicular to the tibial plateau, via the patellar tendon and the patella that was fixed with in a rigid split cup connected to the cross-bar of the Instron machine (►Figure 5). Ultimate load to failure was considered clinically relevant if it reached two times the bodyweight.

Imaging study

Medio-lateral radiographic views of the stifle at 135° extension were taken before harvesting the tibia. Supplementary radiographic views of each tibia were taken just before advancement, with the radiographic beam projected in the same plane as the osteotomy, and perpendicular to the medial aspect of the tibia.

The thickness of the cortical hinge and the tibial cranial cortex were accurately measured on these radiographs using scientific image analysis software[c]. At the completion of the advancement test, all the cortical hinges were cut transversally and the cross-sectional area of the cut bone was recorded using the same image analysis software[c].

Statistical analysis

All data were expressed as mean ± standard deviation. The effects of the angle of opening, thickness, area and stiffness of the cortical hinge and body weight on maximal advancement before failure were studied using univariate and multivariate linear regression analysis. The effect of the osteotomy shape (cutting plane, isthmus) was determined using an analysis of covariance. Correlation between maximal advancement of paired tibiae from the same dog and stiffness, area and thickness of the cortical hinge were measured using a Spearman test. The effects of thickness, area, stiffness of the cortical hinge, and body weight on ultimate load to failure were studied using univariate and multivariate linear regression analysis. A value of $p < 0.05$ was considered significant.

Results

Tibial tuberosity advancement

Ninety-six tibiae were tested by advancement of the tibial tuberosity. The mean body weight of dogs from which bone was harvested was 23.8 ± 8.4 kg.

For the last 60 harvested tibiae, the desired distance of tibial tuberosity advancement was determined using the common tangent method on the medio-lateral

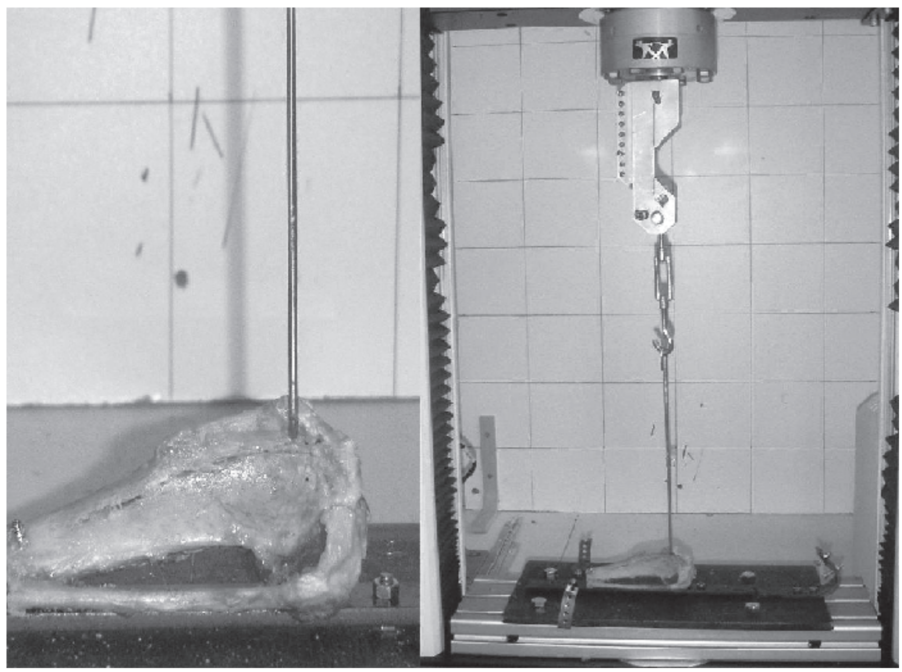

Figure 3 Tibia positioned in the servohydraulic testing machine for testing the tibial tuberosity advancement.

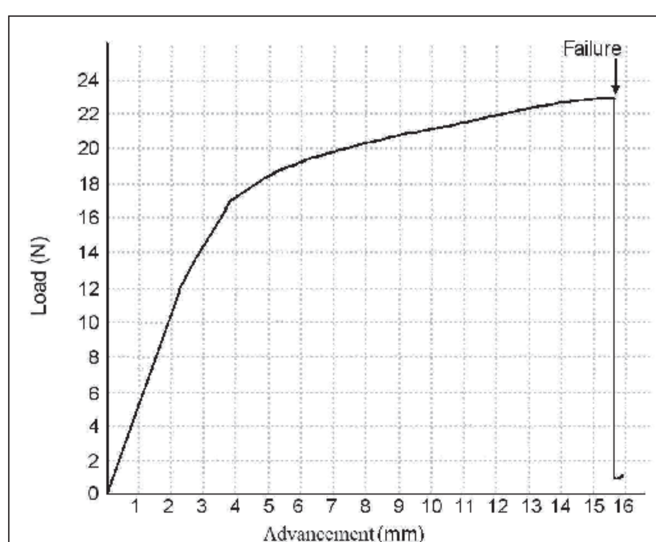

Figure 4 Load displacement curve of the tibial tuberosity. Failure was defined as a dramatic drop in the load.

[c] ImageJ: US National Institutes of Health, Bethesda, MD, USA; Available from: http://imagej.nih.gov/ij/

radiographic views of the stifle at 135° extension. The desired distance of the tibial tuberosity advancement was 6 mm (16 tibiae), 9 mm (12 tibiae), 12 mm (18 tibiae), and 15 mm (14 tibiae).The mean maximal distance of advancement achieved during testing was 15.6 ± 6.4 mm, 20.75 ± 5.2 mm, 21.25 ± 5.2 mm, and 22.7 ± 5.2 mm respectively. The desired amount of tibial tuberosity advancement was reached in all but one tibia; in this bone, an advancement of 15 mm was planned with the common tangent method, however the tibial crest fractured at 13 mm.

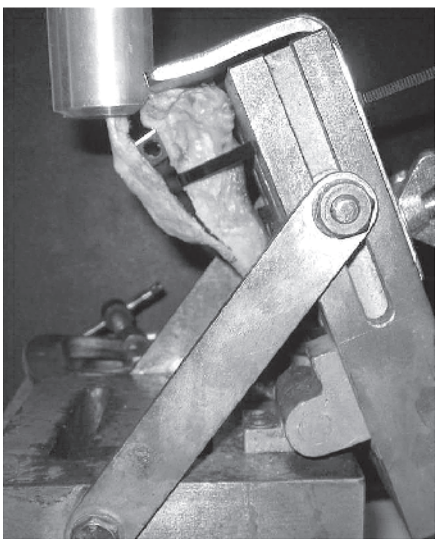

Figure 5 Axial loading of the tibial crest via load applied that is perpendicular to the tibial plateau. The patella was fixed in a rigid split cup connected to the cross-bar of the servohydraulic testing machine and axial load was applied to the tibial tuberosity via the patellar tendon.

For the 96 tibiae, the distance of advancement of the tibial tuberosity at failure was significantly related to the angle of opening (R^2 = 0.77; p <0.0001), the body weight (R^2 = 0.17; p <0.0001), as well as the thickness (R^2 = 0.22; p = 0.0002) and the stiffness of the cortical hinge (R^2 = 0.41; p = 0.0498). However, no significant correlation was found between the maximal advancement of the tuberosity and the cross-sectional area of the cortical hinge (R^2 = 0.00; p = 0.9930).

Maximal advancement of the tibial tuberosity could be predicted with the following formula (R^2 = 0.90):

ADV_{max}(mm) = -5.44 + 0.868α + 0.291 body weight (kg)

α = Angle of opening

There was a moderate correlation between the paired tibiae for each dog (r = 0.69; p <0.0001) for the distance of maximal advancement achieved.

Tibial tuberosity axial loading

Sixty tibial crests were used for testing by axial loading of the tibial tuberosity until failure. Mean body weight of the dogs from which bones were harvested for testing was 23.1 ± 9.6 kg.

Mean ultimate load to failure was 1348 ± 504 N, which was approximately six times the body weight (▶Figure 6).

Two out of 60 tibiae failed at a load less than two times the body weight. Ultimate load to failure was significantly influenced by the body weight, as well as the area (R^2 = 0.70; p <0.0001) and thickness of the cortical hinge (R^2 = 0.71; p <0.0001). The ultimate load to failure could be predicted using the following formula (R^2 = 0.61):

Ultimate LOAD (N) = -417.561 + 15.680 BODY WEIGHT (Kg) + 508.116 THICKNESS of cortical hinge

Seventeen tests were interrupted before failure of the crest because of patellar fracture or avulsion from the patellar tendon. Stiffness was correlated with the cross-sectional area (r = 0.68; p = 0.0005) but not with the thickness (r = 0.20; p = 0.2991) of the cortical hinge.

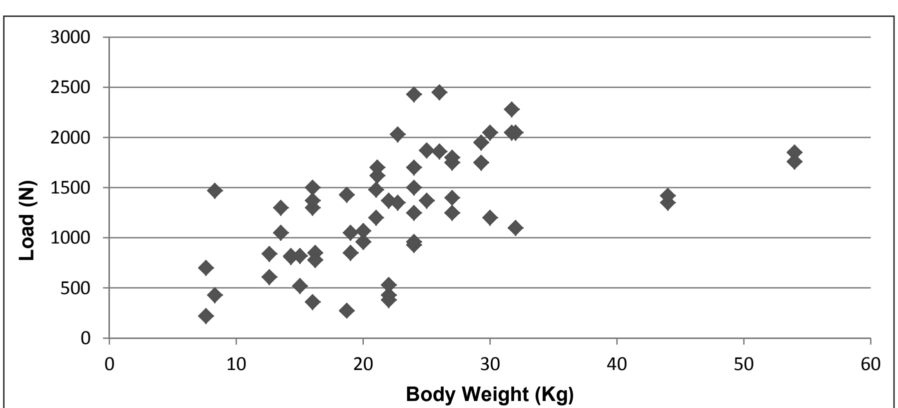

Figure 6 Ultimate load at failure of the tibial tuberosity plotted against body weight of the dogs from which tibiae have been harvested for the tibial tuberosity axial loading.

Discussion

The new osteotomy was longer and curved slightly caudally to run parallel to the cranial tibial cortex in its distal part. The thickness of the cortical hinge was varied from 2 to 4 mm in order to find a good compromise between sufficient resistance of the hinge to fracture (cortex thick enough) and sufficient ductility (cortex not too thick) to allow the required displacement. Mean maximal advancement was higher than usually clinically required and ultimate load to failure was approximately six times the body weight. Factors influencing maximal advancement were mainly the angle of opening and the stiffness of the cortical hinge as well as technical errors such as variation in the osteotomy plane or presence of an isthmus. The thickness of the cortical hinge and the body weight had a moderate effect on the maximal advancement. Factors mainly influencing the ultimate axial load to failure were the body weight, the cross-sectional area and the thickness of the cortical hinge. Maximal advancement and ultimate load to failure could be predicted using the calculated formulae reported in this paper.

When treating cranial cruciate ligament deficiency, the required distance of advancement of the tibial tuberosity is mainly influenced by the tibial plateau angle, the size of the tibia (indirectly the body weight) and the method of measurements (14, 15-18). Initially, cages[d] designed for TTA ranged in size from 3 to 12 mm. However it became obvious that giant breed dogs and dogs with a very large tibial plateau angle would need bigger advancement. A technique to increase the advancement using the existing 12 mm cage associated with a cancellous bone block was described (19). Nowadays, the size of available TTA cages ranges from 3 to 16 mm. Advancement of 15 mm is readily feasible using the conventional TTA technique because the tibial crest is freed completely from the proximal tibia. However, when performing the MMT, a cortical hinge must be left intact and advancement relies on its deformation. Advancement of 9 mm has been studied *in vitro* and clinically but very few data exist about larger advancement (11, 12).

Originally, placement of a distal drill hole was described to prevent formation of a fissure as recommended by Maquet (11, 13). Our clinical experience revealed that fissure or fracture of the tibial crest always happened at the level of the hole. Moreover, studies of human total hip prosthesis have demonstrated that placement of a drill hole at the tip of a longitudinal fissure in bone does not prevent fissure propagation (20). For this reason, we described a modified osteotomy that was curved and longer, without drilling a distal hole. Indeed, Slocum had previously described a stress-relief osteotomy distal to a V-shaped tibial tubercle recession for the treatment of the caudal cruciate ligament deficient stifle. This manoeuvre allowed the tibial tubercle to be moved caudally without breaking (21). Advantages of our modified osteotomy are ease of technique and tolerance of axial loads to failure of approximately six times the body weight. On a three-dimensional biomechanical model of the canine hindlimb tested at a slow walk, at 80% of the stance phase, maximal force in the patellar tendon produced by the summation of the quadriceps muscles forces was approximately 0.95 times the body weight (22). Because of the lack of published data, we measured via a load cell the force exerted on a quadriceps tension band of an *ex vivo* hindlimb model (unpublished pilot study) when 75% of body weight was applied on the limb by a servohydraulic press, corresponding to hindlimb peak vertical force at a trot *in vivo*. The recorded force in the quadriceps tension band reached up to two times the body weight. Hence we arbitrarily defined two times the body weight as a safe requirement in clinical cases. In our study, the mean ultimate load to failure was 6.12 ± 2.4 times the body weight.

For the same angle of opening, a longer osteotomy allows a bigger advancement (▶Figure 7). It was our impression that having the osteotomy parallel to the cranial tibial cortex in the distal part of the osteotomy would decrease the stiffness of the cortical hinge and thus increase the maximal advancement. Whereas the area of the cortical hinge was correlated with stiffness, the thickness of the cortical hinge was not. One explanation could be that the ultimate load to failure at the maximal advancement is recorded after the cortical hinge has plastically deformed (kinking), always far beyond the yield point, whereas the stiffness has been calculated in the elastic deformation phase of the cortical hinge, and therefore was not yet affected by the kinking which reduces its thickness.

The concerns about safety of an osteotomy of the tibial crest that is prolonged distally in the tibial shaft are not limited to the resistance to traction of the tibial crest itself, but also to the resistance to fracture of the tibial shaft under loading. We hypothesized that the mechanical performance of the tibia would be decreased compared to an intact tibia, yet no precise data are known regarding the required performances of the tibial shaft in physiological conditions. Our unpublished studies of 75 clinical cases (50 original MMT and 25 modified MMT) did not reveal any tibial fracture or bone remodelling of the tibial shaft after a three-month follow-up. The present study revealed the deleterious effect of technical errors that affect the biomechanical properties of the cortical hinge. Maintaining the entire osteotomy in a medio-lateral plane was essential in prevention of early failure of the tibial tuberosity advancement. Changing the osteotomy plane distally might create complex constraints hence premature failure at the level of the cortical hinge upon placement of the cage. An isthmus could also precipitate failure of the crest during advancement as it would act as a stress riser (▶Figure 8).

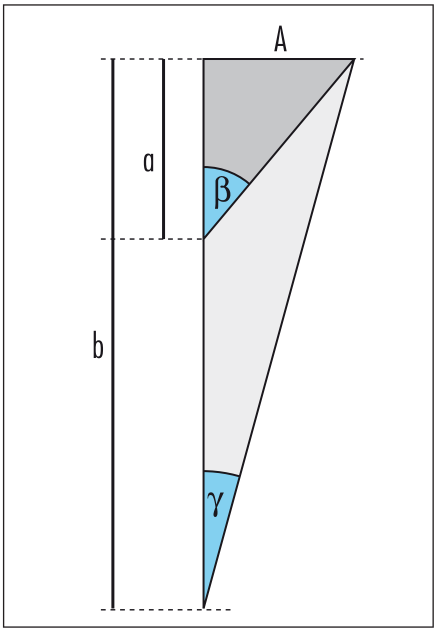

Figure 7 Decrease of angular opening with length of the osteotomy. γ is smaller than β as the distance b is longer than a.

In cases of fracture of the tibial crest, a sudden drop in resistance should be easily felt during manual advancement. However, a fissure may be more subtle and difficult to detect. Should a fracture happen during surgery, a tension band wire must be added to stabilize the crest or the MMT may be converted to a conventional TTA (11). This explains why the width of the tibial crest is maintained at 10 mm (width of the Kyon® drill guide). The two formulae should be useful to approximate the expected maximal advancement and ultimate load to failure of the tibial crest. The expected maximal advancement can be predicted using one formula and should be higher or at least equal to the desired advancement measured preoperatively. With the other formula, it is possible to approximately determine the minimal thickness of the cortical hinge necessary to obtain an ultimate load to failure higher than two times the body weight, keeping in mind that in this latter case the coefficient of determination has a value of only 0.61. A limitation in our axial loading testing protocol was that the loading test was interrupted in several

[d] Kyon, Zurich, Switzerland

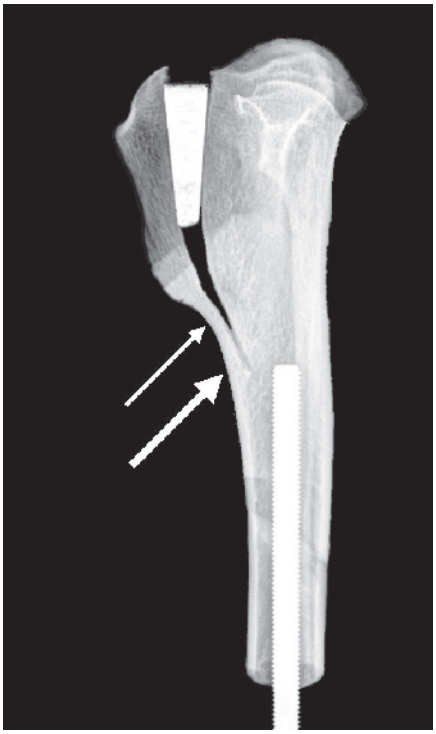

Figure 8 Illustration of an isthmus. For better visualization, a spacer was placed into the gap. The osteotomy created a narrowing along the distal part of the tibial crest (small arrow) compared to the cortical hinge (large arrow).

specimens harvested from some of the heaviest dogs by patellar avulsion from patellar tendon or patellar fracture before fracture of the tibial crest occurred. This loss of data may have resulted in an underestimation of the ultimate load to failure.

In physiological loading conditions, the mode of cortical bone deformation is predominantly elastic. Advancement of the tibial tuberosity deforms the bone of cortical hinge in an unphysiological way, leading to plastic deformation being reached long before fracture occurs. For this reason we defined the maximal advancement as being the ultimate load to failure instead of the yield point (23).

The precise age of the dogs used for our study could not be determined although we confirmed that all were skeletally mature, based on radiographs. It is known from human bone analysis that cortical bone becomes more brittle with aging (23). Cortical porosity, which is mainly due to variations in the number, length and diameter of Haversian and Volkmann canals, can vary from less than 5% to almost 30% and is positively correlated with the age (24-26). This could explain why three tibial crests fractured unexpectedly after a little advancement despite the absence of technical errors. Therefore, it would have been interesting to study the influence of bone mineral density on biomechanical properties of the cortical hinge; analysis of bone mineral density using dual-energy X-ray absorptiometry should be part of a further study.

In conclusion, we have described a new osteotomy design for MMT. Bone mechanical properties associated with this new osteotomy appeared satisfactory, with mean maximal advancement values that were higher than the expected clinical requirements in the majority of cases and ultimate axial load to failure more than six times the body weight. Further clinical studies, including more cases and a longer follow-up, are warranted to confirm our *ex vivo* observations.

Acknowledgements

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Conflict of interest

None declared.

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