Effect of Tibial Plateau Leveling on Stability of the Canine Cranial Cruciate–Deficient Stifle Joint: An In Vitro Study

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Objective—To evaluate the effect of tibial plateau leveling on joint motion in canine stifle joints in which the cranial cruciate ligament (CCL) had been severed.

Study Design—In vitro cadaver study.

Animals—Six canine cadaver hind legs.

Methods—Radiographs of the stifle joints were made to evaluate the tibial plateau angle with respect to the long axis of the tibia. The specimens were mounted in a custom-made testing device to measure cranio-caudal translation of the tibia with respect to the femur. An axial load was applied to the tibia, and its position was recorded in the normal stifle, after transection of the CCL, and after tibial plateau leveling. Further, the amount of caudal tibial thrust was measured in the tibial plateau leveled specimen while series of eight linearly increasing axial tibial loads were applied.

Results—Transection of the CCL resulted in cranial tibial translation when axial tibial load was applied. After tibial plateau leveling, axial loading resulted in caudal translation of the tibia. Increasing axial tibial load caused a linear increase in caudal tibial thrust in all tibial plateau–leveled specimens.

Conclusions—After tibial plateau leveling, axial tibial load generates caudal tibial thrust, which increases if additional axial load is applied.

Clinical Relevance—Tibial plateau leveling osteotomy may prevent cranial translation during weight bearing in dogs with CCL rupture by converting axial load into caudal tibial thrust. The amount of caudal tibial thrust seems to be proportional to the amount of weight bearing.

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MULTIPLE SURGICAL techniques have been described for treatment of cranial cruciate ligament (CCL) rupture in the canine stifle. The majority of these techniques attempt to mimic the function of the previously intact CCL, which are prevention of cranial tibial translation and limitation of tibial internal rotation and hyperextension of the stifle.[1] In 1993, the Tibial Plateau Leveling Osteotomy (TPLO) was introduced[2] and since then has gained in popularity.[3] In contrast with most surgical techniques, TPLO does not attempt to restore the passive constraint of the CCL, and therefore cranial translation can still be elicited manually after surgical intervention.[4] Tibial Plateau Leveling Osteotomy is supposed to functionally stabilize the stifle joint during weight bearing, by decreasing cranial tibial thrust and therefore preventing cranial translation.[2,5] This procedure involves a tibial osteotomy and rotation of the tibial plateau until a tibial plateau angle of 5° is achieved.[4]

Joint motion after severance of the CCL ligament

has been investigated using three-dimensional kinematics.[6] In this study, cranial tibial translation occurred throughout the weight-bearing phase of the stride with only minimal translation occurring during the swing phase.[6] This suggests that cranial tibial translation is linked to weight bearing. An in vitro study on porcine stifles showed increased in situ forces in the CCL after application of axial compressive forces.[7] It appears therefore that weight bearing is an important factor in eliciting cranial tibial translation in the canine and the porcine stifle. In contrast, the human knee joint has been studied in numerous in vitro and in vivo experiments, and some studies suggest that compressive forces result in increased joint stability.[8,9] The different effect of compressive forces on joint stability may be attributed to the different inclination of the tibial plateau, which is inclined caudally from the horizontal for about 20 to 30° in the canine stifle joint,[10] 15 to 25° in the porcine stifle joint, and only 10° in the human knee.[7]

The purpose of this in vitro study was to evaluate joint stability in canine stifle joints placed under axial tibial load before and after TPLO. Three hypotheses were proposed. Hypothesis 1: Axial tibial loading results in cranial tibial thrust in the CCL-deficient stifle. Hypothesis 2: Axial tibial loading results in caudal tibial thrust after tibial plateau leveling osteotomy. Hypothesis 3: Increased axial tibial loads after tibial plateau leveling osteotomy result in increasing caudal tibial thrust.

MATERIALS AND METHODS

Specimen Collection and Preparation

Hind legs were removed from six large-breed dogs free of orthopedic conditions (age, 2 to 3 years; mean body weight ± SD, 30.0 ± 2.4 kg) that had been euthanized for a different study. All soft tissues proximal to the tarsal joint were removed from the specimen except for the lateral and medial collateral ligaments, the cranial and caudal cruciate ligaments, the menisci, and the joint capsule of the stifle, which were carefully preserved. The cranial aspect of the joint capsule was incised, and the patella and the patellar ligament were removed. After removal of the infra-patellar fat pad, the joints were carefully inspected. Integrity of the cranial and caudal cruciate ligament was confirmed in all specimens. A 10-cm–long, 2-mm diameter Kirschner wire was placed in the caudal proximal aspect of the tibia in a caudal to cranial direction and at approximately 90° to the long axis of the tibia. This wire served as a reference pin in the osteotomized specimen.
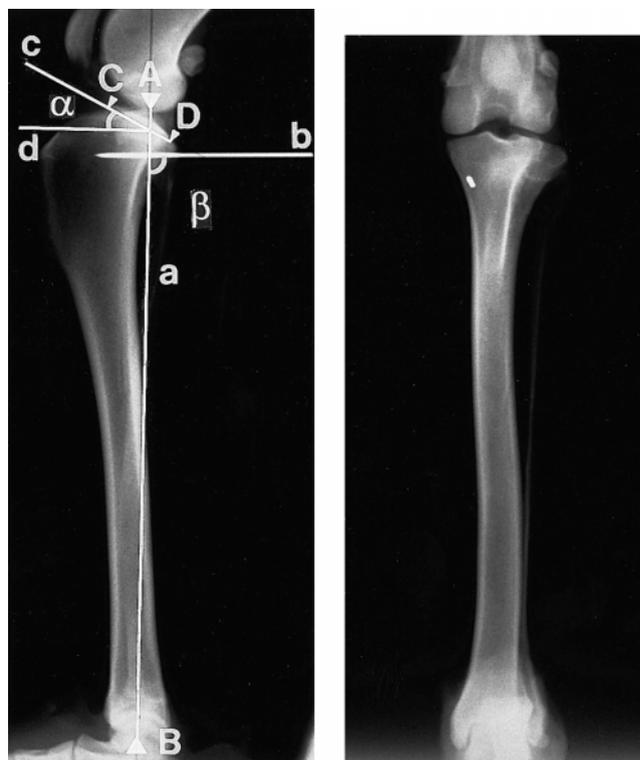

Fig 1.   Medio-lateral and caudo-cranial radiograph of a specimen. The intercondylar eminences (A) and the center of the tarsal joint (B) define the functional axis of the tibia (a). The tibial plateau (c) is outlined by its cranial (C) and caudal (D) ends. The tibial plateau angle (α) is defined by the tibial plateau (c) and a line perpendicular to the functional axis of the tibia (d). The reference pin angle (β) is defined by the reference pin (b) and the functional axis of the tibia (a).

Radiographic Technique and Measurement of the Tibial Plateau Angle

Medio-lateral and caudo-cranial radiographs of the specimens that included the stifle, the whole tibia, and the tibio-tarsal joint were taken with the beam of the radiograph tube centered over the stifle joint (Fig 1). For the lateral view, the lateral side of the specimen was placed on a radiographic cassette with the stifle and hock joint at approximately 90° of flexion. While the toes, the hock, and the stifle of the specimen were in direct contact with the cassette, the proximal femur was kept elevated from the cassette for 2 to 3 cm to mimic the previously removed soft tissues. Positioning of the specimen was adjusted, and radiographs were repeated until superimposition of the femoral condyles was achieved (Fig 1). The long axis of the tibia (a) was defined by a line drawn from the mid-point between the intercondylar eminences (a) to the center of the tarsal joint (B). The medial tibial plateau was defined by its most cranial (C) and most caudal (D) radiographic margins. The tibial plateau angle (α) between the tibial plateau (c)

and a line perpendicular to the functional axis of the tibia (d) was measured on the lateral radiographs. The reference pin angle (β) between the reference pin (b) and the functional axis of the tibia (a) was determined (Fig 1).

Tibial Osteotomy

A circular osteotomy of the proximal tibia was performed on each specimen by one of the authors (D.H.) following a technique described by Slocum.[11]

Testing Device

The distal portion of the leg was discarded and the specimen was mounted in a custom-made testing device (Figs 2 and 3). The cranio-caudal translation of the proximal tibia with respect to the femur was measured by means of a potentiometer that converted changes in position into electrical output. Simultaneously the tibia could be loaded along its longitudinal axis. The specimen was mounted at a stifle flexion angle of 60°, which corresponds to the position of the stifle during weight bearing.[6] The femur (f) was fixed in position by two 5-mm transcortical pins connected to the testing device. Two bone screws secured the proximal tibial segment in a custom-made circular frame (cf), which had a curvature identical to the radial osteotomy. This was attached to the testing device (Figs 2 and 3). The tibial segment could be rotated along the circular frame by loosening the two bone screws. Initially, the tibial segment was mounted at the same reference pin angle (β) between

Fig 3. Front view of the testing device. Load (l) is placed on the loading table of the testing device and converted into axial compression of the specimen. The femur (f) and the circular frame (cf) securing the tibial segment can be seen. A force gauge (fg) measures the force necessary to create cranial translation of the tibia. The potentiometer (po) measures cranial caudal translation and corresponds to the hock joint of the specimen.
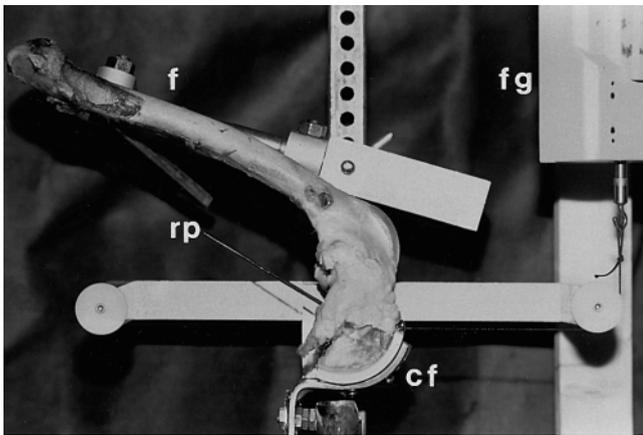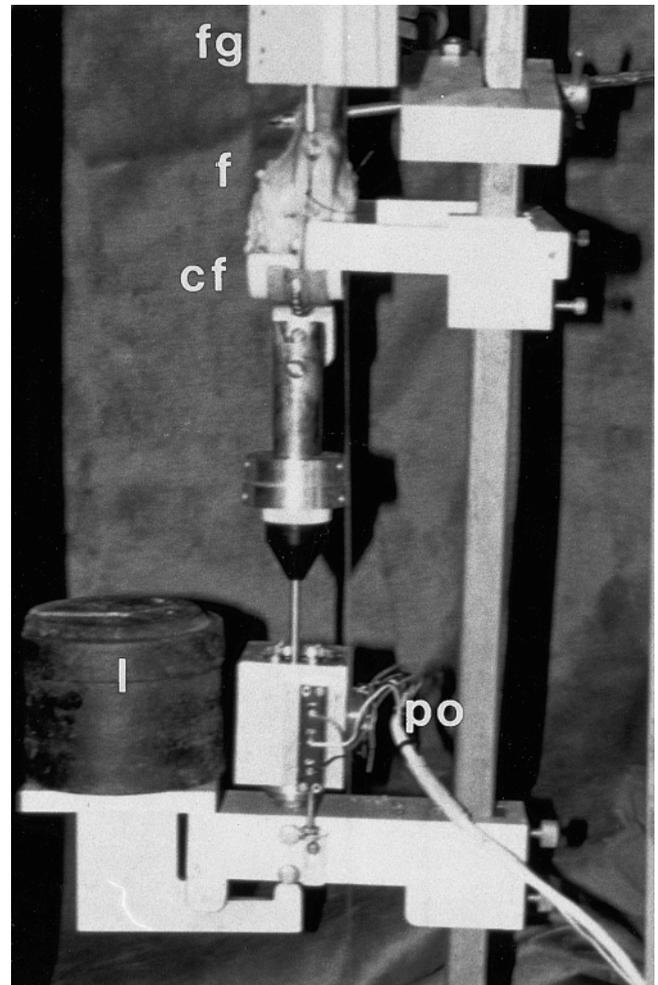

Fig 2. Side view of the testing device. Two large pins fixed to a connecting bar hold the femur (f) in place. Note the reference pin (rp) inserted in the caudal part of the tibia, which is in a TPLO position. The proximal tibial segment is secured to a circular frame (cf) by two bone screws. Loosening of the bone screws allows rotation of the tibial segment along the circumference of the osteotomy site. A force gauge (fg) is connected to the tibia by a string and measures the force necessary to create cranial tibial translation.

the reference pin and the functional axis of the tibia as previously measured on the lateral radiograph. The distal part of the testing device replaced the discarded portion of the tibia and was connected to the universal joint of the potentiometer (po) corresponding to the tibio-tarsal joint. The tibial plateau was freely movable in a proximal to distal, sagittal, and transverse plane, and internal and external rotation of the tibia was allowed.

Tibial Translation

In the first part of the study, cranial translation of the proximal tibia with respect to the femur was measured (Fig
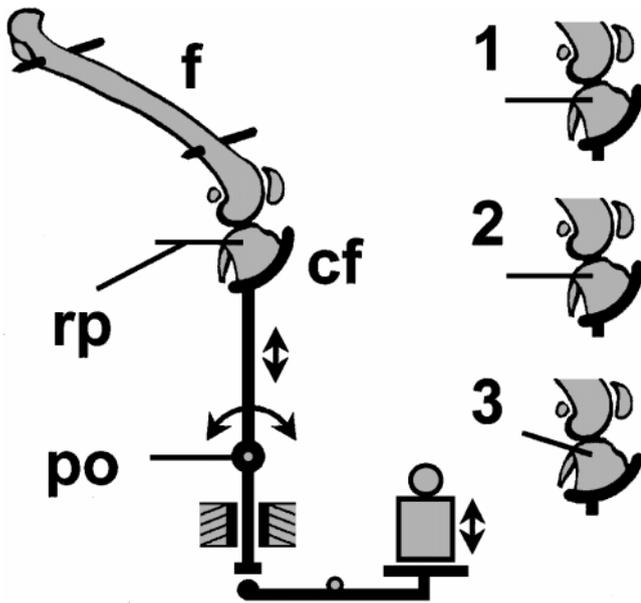
Fig 4. First part of the study: The position of the tibial segment mounted in a circular frame (cf) respect to the femur (f) is measured. The reference pin (rp) allows the tibia to be mounted at the same tibial plateau angle as measured on lateral radiographs. Cranio-caudal translation is converted into electrical output by a potentiometer (po) at the level of the hock joint and recorded by a computer. Each specimen is tested as an intact stifle (1), after transection of the CCL (2), and after TPLO.

4). The intact stifle was mounted in the testing machine, a 22 N axial load was applied, and the position of the proximal tibia was recorded. This position of the intact stifle was chosen as the reference position. After CCL transection and application of 22 N axial load, the position of the proximal tibia was recorded and the amount of cranial translation relative to the reference position (z_1) was calculated using equation 1.

$$z = 2r \sin\left(\frac{\gamma}{2}\right) \qquad (1)$$

where z is the distance from the reference position (cranial translation); r is the distance from the center of the potentiometer to the tibial plateau, which equaled 24 cm; and γ is the difference in radians relative to the reference position measured by the potentiometer.

Tibial plateau leveling was achieved by rotating the tibial segment along the arc of the radial osteotomy site so that the angle of rotation equaled the tibial plateau angle of the specimen minus 5°.[4,11] The amount of rotation (δ) along the arc of the osteotomy site was computed from equation 2.

$$\delta = \frac{(\alpha - 5°) \cdot 2\pi r}{360°} \qquad (2)$$

where δ is the arc intercepting the tibial plateau rotation; $\alpha - 5°$ is the previously determined tibial plateau angle minus 5° and; r is the radius of the osteotomy.

After performing the TPLO and application of 22-N axial load, the position of the proximal tibia was recorded and the difference between this and the reference position (z_2) was calculated using equation 1.

Caudal Tibial Thrust

The relation between axial tibial load and the force necessary to create cranial tibial translation was investigated in the leveled specimen in the second part of the study. The tibial plateau–leveled specimen was placed under a series of eight linearly increasing axial loads ranging from 13 to 45 N (Fig 5). Cranial tibial translation was induced by applying a 5-mm/s constant pull on the tibial crest in a cranial direction and perpendicular to the tibial axis while a digital force gauge (model DFG-50; Omega Engineering Inc, Stanford, CT; 0 to 25 kg ± 0.01 kg) measured the force necessary to create cranial tibial translation. The potentiometer and the force gauge were connected to a 12-bit analogue to digital converter, and all data were recorded simultaneously by a computer using a data acquisition program (Dataq Instruments Inc, AT-Codas Data Acquisition, Akron, OH). Before
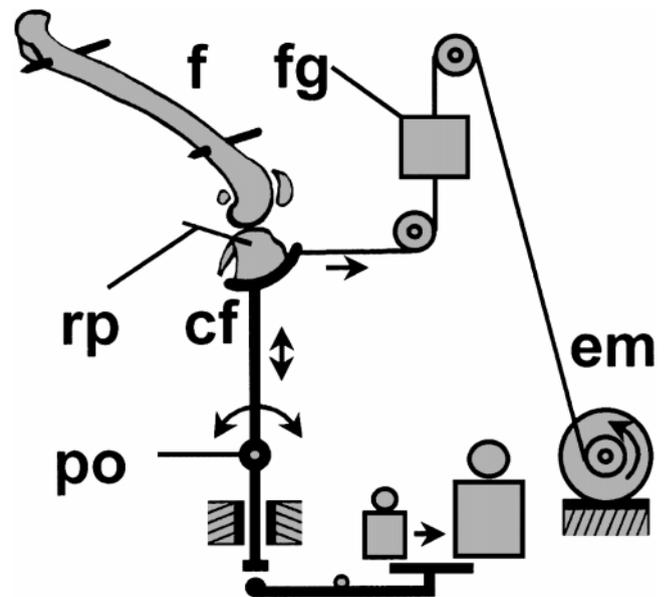

Fig 5. Second part of the study: Note the femur (f) fixed to the testing device and circular frame (cf) securing the tibial segment with the reference pin (rp). The tibial plateau–leveled specimen is placed under increasing axial loads. While an electric motor (em) applies a constant cranial pull at the level of the tibial crest, a force gauge (fg) measures the force necessary to create cranial tibial translation. The data emitted from the force gauge and the potentiometer (po) are recorded by a computer.
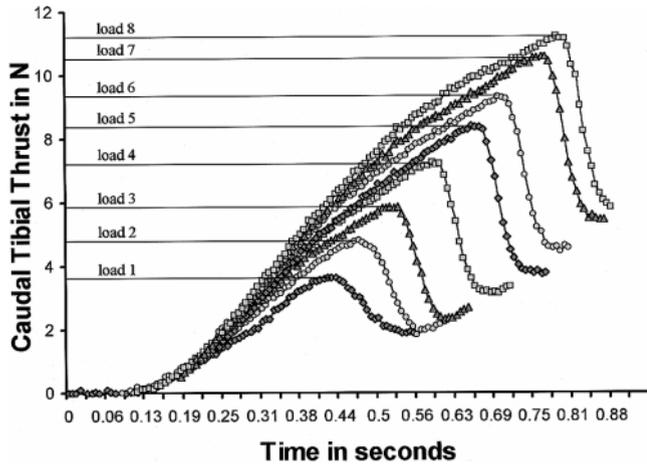
Fig 6. Caudal tibial thrust measured in specimen one after application of a cranial pull of 5 mm/s. The eight curves show the results of eight linear increasing axial loading conditions (13 to 45 N). After cranial pull was applied to the specimen, resistance to cranial subluxation (caudal tibial thrust) steadily increased. At a certain point, the tibia subluxated cranially and the force necessary to create cranial translation suddenly decreased. After this point, the axial tibial load had to be removed to return the tibia to the TPLO position. The amount of caudal tibial thrust that had to be overcome to induce cranial subluxation of the tibia was determined as the maximal caudal tibial thrust of the specimen at a specific axial load. Ten repetitions for each loading condition were obtained to calculate the results of Fig 7.

each trial, the testing device and the force gauge were calibrated. The sensitivity of the system to detect cranial tibial translation was at least ± 0.7 mm. The cranial pull was counteracted by caudal tibial thrust, which was induced by the axial tibial load. Eventually cranial translation of the tibia was initiated. After a steady increase in the force necessary to create cranial translation, a rapid decrease in this force was noted. This marked the point at which cranial tibial subluxation occurred. After subluxation occurred, axial load was removed to return the tibia to the TPLO position. The greatest value at this point of the curve was chosen as the maximal caudal tibial thrust of the specimen at a specific axial load (Fig 6). A total of 10 tests were performed for each of the eight loading conditions.

Statistical Analysis

Tibial translation in the three groups (Intact, CCL-deficient, and TPLO) was compared by means of a two-factor ANOVA (group-fixed, dog-random). Post-hoc group comparisons were performed by means of Tukey's test, with the 0.05 level considered significant. Data were presented as the mean $\pm$ SD, and P values were reported.

Load-related changes in the magnitude of the force necessary to generate cranial translation in the leveled

specimens were evaluated using a two-factor ANOVA (axial load-fixed, dog-random). Post-hoc comparisons of the effect of load on the force necessary for cranial translation were evaluated by means of linear regression, and the correlation coefficient (R^2) was reported. Using the "least-square" method, the data from each specimen were described by equation 3. The P values and the slope (m) of the linear equation were reported.

$$y = m \cdot x + b \qquad (3)$$

where y is the amount of axial tibial load; m equals the slope; x is the amount of force necessary for cranial translation; and b equals the y intercept.

RESULTS

The average tibial plateau angle $\pm$ SD was 25 $\pm$ 2.0° and ranged from 22° to 28° (Table 1).

Transection of the CCL allowed a mean cranial tibial translation $\pm$ SD of 14 $\pm$ 2.3 mm. After tibial plateau leveling, the cranial translation decreased and resulted in a mean cranial translation $\pm$ SD of minus 2 $\pm$ 2.9 mm with respect to the intact stifle group. This indicates a caudal translation of plus 2 mm. The results obtained from the six specimens are shown in Table 1.

During the second part of the study, it was found that the force necessary to create cranial tibial translation increased ($P = .001$) in all tibial plateau–leveled specimens when additional axial tibial load was applied. Overall the increase was highly linear

Table 1. Cranio-Caudal Translation and Correlation Between Axial Load and Caudal Tibial Thrust After Tibial Plateau Leveling

Specimen No.	Tibial Plateau Angle (α)*	CCL–Deficient Stifle†§	TPLO Stifle‡§	Slope (m) of Equation 2¶
1	24°	13 mm	0 mm	0.32
2	22°	14 mm	−1 mm	0.16
3	24°	10 mm	−4 mm	0.07
4	26°	16 mm	−0 mm	0.21
5	25°	15 mm	−7 mm	0.25
6	28°	16 mm	0 mm	0.11
Average	25°	14 mm	−2 mm	0.19
SD	2.0	2.3	2.9	0.08

Abbreviations: CCL, cranial cruciate ligament; TPLO, Tibial Plateau Leveling Osteotomy.

* Measured on lateral radiographs.

† Cranial tibial translation of the CCL–deficient stifle with respect to the intact stifle (z_1).

‡ Cranial tibial translation after TPLO with respect to the intact stifle (z_2) (note the negative values indicating caudal translation).

§ Sensitivity of the testing device was at least $\pm$ 0.7 mm.

¶Correlation between axial load and caudal thrust after TPLO (Fig 7).

with a correlation coefficient (R^2) of 0.996. The results obtained from the six specimens are shown in Fig 7. The slope (m) calculated by linear regression between axial tibial load and the force necessary to create cranial tibial translation ranged between 0.07 and 0.32 with a mean $\pm$ SD of 0.19 $\pm$ 0.08.

DISCUSSION

This study design mimics the indirect drawer or tibial compression test[12] and as expected produced cranial tibial translation in stifle joints with a severed CCL. This test simulates weight bearing in the stifle joint by compressing the tibia between the tarsus and the femoral condyles. The resulting load is transferred along the tibial axis and is translated into cranial tibial thrust at the level of the stifle joint.[5] In stifle joints without an intact CCL, the generated cranial tibial thrust leads to cranial tibial translation.[12] In our specimens, transection of the CCL lead to cranial tibial translation, which confirmed our first hypothesis (Table 1). An axial tibial load of 22 N was chosen because sufficient cranial tibial translation was generated in all specimens.

After rotation of the tibial plateau, the effect of axial load on the stifle joint changed. Caudal tibial translation with respect to the intact stifle joint was measured. Only after additional application of a cranially directed force could cranial tibial translation be elicited. This was achieved by applying a constant pull in a cranial direction to counteract caudal tibial thrust. Eventually the force directed cranially exceeded the caudal thrust resulting in cranial subluxation of the tibia. As frictional forces in the stifle joint are minimal,[13] the amount of force necessary to initiate cranial tibial translation equals the amount of caudal tibial thrust. After a steady increase in the force necessary to initiate cranial tibial translation, a sudden decrease in the force was seen. At this point, cranial subluxation of the tibia occurred. Once subluxated in a cranial position, the axial tibial load had to be removed to return the tibia to its previous position. To quantify the amount of caudal tibial thrust in the different loading positions, the minimum force necessary to create cranial subluxation was identified. It could therefore be demonstrated that after TPLO, axial tibial load generates caudal tibial thrust, thereby confirming the second hypothesis. As the caudal cruciate ligament acts as the primary constraint for caudal tibial translation in the canine stifle,[1] it can be assumed that after
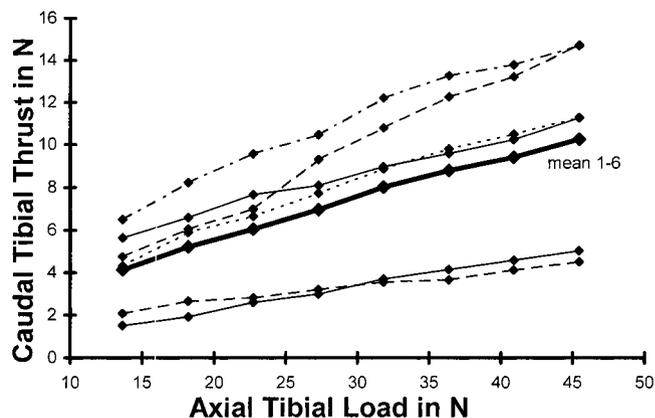

Fig 7. The effect of axial tibial load on the caudal tibial thrust following TPLO. The results obtained from the six specimens and mean values (mean 1-6, bold line) are shown. Note the linear behavior of all specimens.

TPLO, forces within the caudal cruciate ligament increase with increasing axial tibial loads.

Comparing the intact stifle joints with the TPLO group, the position of the proximal tibia moved 2 $\pm$ 2.9 mm in a caudal direction in the TPLO group. The variation between the single specimens in the TPLO group may have been caused by the rotation of the tibial segment. As the tibial plateau is rotated with respect to the long axis of the tibia, it is brought into a more flexed position with respect to the femoral condyles. During the rotation, the circular frame followed the proximal tibial segment, which is limited in its movements by the medial and lateral collateral and the caudal cruciate ligaments. The position of the circular osteotomy on the tibia determined the plane of rotation between the proximal segment and the circular frame. This might be in part responsible for the variation in the TPLO group.

The correlation between axial tibial load and the resulting caudal tibial thrust was evaluated in the second part of the study. Additional axial tibial load generated an increase in caudal tibial thrust in all specimens (Figs 6 and 7). This increase was proportional and highly linear (R^2 = 0.996) and therefore confirmed the third hypothesis. Because TPLO does not attempt to restore the passive constraint of the CCL, cranial translation can still be elicited manually after surgical intervention.[4] During weight bearing, however, TPLO is supposed to reduce cranial tibial thrust and lead to a functional stabilization by enhancing the effectiveness of the hamstring and biceps femoris muscles.[4] Based on our model, we believe that TPLO transforms axial tibial load into caudal tibial

thrust. The amount of caudal tibial thrust depends on the amount of axial tibial load generated during the stride. During strenuous activity, forces transferred through the stifle joint increase, and consequently caudal tibial thrust increases, making it more difficult to create cranial tibial subluxation.

However, increased caudal tibial thrust increases the amount of load placed on the caudal cruciate ligament. Eventually the load could exceed the ability of the caudal cruciate ligament to withstand tensile stress and ultimately lead to caudal cruciate ligament rupture. One study showed that the amount of rotation of the tibial plateau seems to be proportional to the stress placed on the caudal cruciate ligament under axial tibial load[14] and over-rotation of the tibial plateau should therefore be avoided. Within the confines of our experiment, the correlation between axial load and caudal thrust was described by the slope (m) of equation 2 and varied between 0.07 and 0.32. A slope close to zero might not be sufficient to prevent cranial translation, whereas an increased slope could lead to a faster increase in caudal tibial thrust and therefore could cause increased tensile stress in the caudal cruciate ligament during strenuous activity. The variation between the specimens seems to reflect multiple subjective factors, which may have influenced our results such as positioning of the limb during radiography, measurement of the tibial plateau angle, positioning of the specimen in the testing device, and rotating the specimen to a leveled position.

The stifle flexion angle may also have influenced the effect of axial load on cranio-caudal tibial translation. The specimens were mounted at a stifle flexion angle of 60° corresponding to the angle during weight bearing.[6] Although flexion and extension of the stifle occurs mainly during the swing phase of the stride, the stifle flexion angle changes as well throughout the weight-bearing phase.[15] Sliding between the articular surfaces of the canine stifle joint is distributed uniformly over the whole angulation range.[16] While the stifle is extended, the cranial and less angulated part of the tibial plateau is in contact with the femoral condyles, and during flexion, the caudal and steeper part of the tibial plateau is in contact with the femur. A study on porcine stifles evaluated the combination of axial compressive forces and anterior tibial loads on in situ forces in the CCL.[7] When 100 N anterior tibial loads were applied without axial compression, no significant differences in the CCL in situ forces

between 30°, 60°, and 90° of flexion were seen. Addition of 200 N axial compression to the anterior load resulted in an average increase of 34%, 68%, and 84% in the CCL in situ forces at 30°, 60°, and 90°, respectively. The increase caused by axial compression was smallest in extension where the tibial plateau is less angulated, and the largest increase was seen in flexion where the tibial plateau is steeper. This might also be true in the canine stifle. However, different angles were not investigated in this study nor were muscle forces incorporated in our in vitro model.

Our results contrast with those found in human knee joints where axial tibial compressive forces result in increased joint stability.[8,9] The different effect of axial tibial load on joint stability can be mainly attributed to the different inclination of the tibial plateau.

CONCLUSIONS

Our results suggest that TPLO transforms axial tibial load into caudal tibial thrust. It seems that after TPLO the amount of weight bearing is directly proportional to the amount of caudal tibial thrust. During strenuous activity, forces transferred through the stifle joint increase and consequently caudal tibial thrust increases, making it more difficult to create cranial tibial subluxation. Conversely, the resulting increase in caudal tibial thrust may lead to increased stress placed on the caudal cruciate ligament.

ACKNOWLEDGMENT

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