Effect of the Centre of Rotation in Tibial Plateau Levelling Osteotomy on Quadriceps Tensile Force: An Ex Vivo Study in Canine Cadavers

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Vet Comp Orthop Traumatol 2019;32:117–125.

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Abstract

Objective The aim of this study was to determine the effect of the centre of rotation in tibial plateau levelling osteotomy (TPLO) on the tensile force of the quadriceps.

Materials and Methods Tibial plateau levelling osteotomy was performed on the left pelvic limbs from 20 normal adult Beagle cadavers. To replicate the tensile force of the quadriceps, gastrocnemius and stifle flexor muscles, these muscles were replaced with wires. The tensile force of each wire, cranial tibial displacement and internal tibial rotation were measured under the following conditions: intact cranial cruciate ligament, transected cranial cruciate ligament, ideally centred osteotomy TPLO (ICO group) and distally centred osteotomy TPLO (DCO group). The ratios of the tensile forces for the wires divided by the vertical force were used for analyses.

Results The mean intact and post-TPLO tibial plateau angles (TPA) in the ICO group were $30.3° \pm 1.9°$ and $6.1° \pm 1.6°$, respectively, and those in the DCO group were $29.8° \pm 2.4°$ and $6.8° \pm 0.9°$, respectively. The mean quadriceps tensile force after TPLO was significantly greater in the DCO group (3.9 ± 0.3) than the ICO group (3.3 ± 0.4) ($p = 0.006$). Both groups exhibited tibial caudal displacement after TPLO.

Clinical Relevance The tensile force of the quadriceps muscles changed in accordance with the centre of the osteotomy in TPLO. The DCO group had increased tensile force, which may cause patellar ligament thickening after TPLO. Setting the postoperative TPA at 6° may cause excessive rotation in patients with a normal tensile force of the stifle flexor muscles.

Keywords
- biomechanics of joints
- cranial cruciate ligament
- tibial plateau levelling osteotomy
- canine
- dog

Introduction

The patellar ligament moment arm (PLMA) is associated with stifle biomechanics, and is defined as the perpendicular distance between the patellar ligament force and the centre of the tibiofemoral contact.[1] Geometrically, the moment arm is the perpendicular distance from the line of force to the motion axis. A longer moment arm requires less force to move an object (the tibial tuberosity) compared with a short moment arm. The length of the PLMA is associated with the tensile force of the quadriceps when the stifle is extended.[2] When the stifle angle is unchanged, shortening of the PLMA increases the tensile force of the quadriceps, while lengthening of the PLMA decreases the tensile force of the quadriceps.[2,3]

Tibial plateau levelling osteotomy (TPLO) is performed to treat rupture of the cranial cruciate ligament (CrCL). The aim of TPLO is to provide dynamic craniocaudal stifle stability during the stance phase of the gait by reducing the slope of the tibial

received
April 12, 2018
accepted after revision
December 4, 2018

DOI https://doi.org/10.1055/s-0039-1677868.
ISSN 0932-0814.

plateau.[4] The tibial plateau angle (TPA) is modified to a target of 6.5° ± 0.9° using a radially shaped TPLO saw.[5,6] However, the PLMA is influenced by the position of the rotation centre of the cranial tibial fragment[2]; the PLMA is reduced when the centre of the TPLO is located below the stifle joint surface and caudal to the medial collateral ligament.[2] Conversely, the change in the PLMA is minimized and the cranial tibial displacement after TPLO is reduced by setting the osteotomy centre on the intercondylar eminence.[2,7]

Complications after TPLO include patellar ligament thickening and patellar desmopathy.[8–11] These conditions may be associated with an increase in the tensile force of the quadriceps after TPLO.[8] According to recent studies investigating the influence of patellofemoral alignment and change in stifle extensor mechanism load caused by TPLO and PLMA, the stifle extensor mechanism load does not differ between stifles that have undergone TPLO versus intact stifles. However, the location of the centre of rotation of the TPLO was set on the intercondylar eminence in these studies.[12,13]

The present study aimed to elucidate the effect of the location of the centre of rotation in TPLO on the tensile force of the quadriceps. We hypothesized that the tensile force of the quadriceps would not change when the centre of rotation in TPLO was set on the intercondylar eminence (ideally centred osteotomy [ICO] TPLO), and that the tensile force would increase when the centre of rotation was set distal to the stifle joint surface (distally centred osteotomy [DCO] TPLO).

Materials and Methods

Sample

Left hindlimbs, including the pelvis, were collected by disarticulation of the sacroiliac joint in the cadavers of 20 normal adult Beagles. The limbs were equally divided into a ICO TPLO group (mean age, 30.7 months), and a DCO TPLO group (mean age, 25.3 months). The dogs had no clinical or radiographical evidence of pathology in the hip, stifle or tarsal joints. All dogs were euthanatized by an intravenous overdose of pentobarbital sodium for reasons unrelated to the present study. The present study was approved by the Bioethics Committee at our university (approval number: 28S-56).

Specimen Preparation

The hindlimbs were stripped of all muscular tissues, except the quadriceps (a stifle joint extensor), semitendinosus (a stifle joint flexor) and gastrocnemius (a tarsal joint extensor). All soft tissues of the distal talocrural joint, including the skin, were preserved.

Origins and Insertions of Each Muscular Group

The present study required the replication of the tensions of the extensor (quadriceps) and flexor (semitendinosus) of the stifle joint and the extensor (gastrocnemius) of the tarsal joint. To preserve the muscular origins and insertions and replicate muscular tensions, holes were drilled in the insertion sites of the muscles. After the holes were drilled, a 0.8-mm or 1.0-mm stainless steel wire was inserted into each of the holes. The origin and insertion points of each muscular group were identified as previously reported,[14] and these muscles were removed.

Intra-Articular Preparation of the Stifle Joints

Incisions were made in the cranio-medial and cranio-lateral articular capsules of each stifle joint.[15] A 3.0-mm stainless steel spherical marker (Stainless steel ball 3 m/m; Tokyu Hands Inc., Tokyo, Japan) was implanted in each specimen at the femoral medial epicondyle, and a 1.0-mm lead spherical marker (Lead ball 1 m/m; TokyuHands Inc., Tokyo, Japan) was implanted at the tibial tuberosity to enable evaluation of the femorotibial relationship in the sagittal plane. Additionally, 1.0-mm lead spherical markers (Lead ball 1 m/m; Tokyu Hands Inc., Tokyo, Japan) were implanted at the cranial and caudal edges of the medial condyle of the tibia to enable measurement of the TPA. A 1.5-mm Kirschner wire was inserted into the extensor fossa, and a 3.0-mm stainless steel spherical marker (Stainless steel ball 3 m/m; Tokyu Hands Inc., Tokyo, Japan) was implanted in the top of the greater trochanter to enable determination of the femoral abduction angle.

Pelvic and Hip Joint Angles

To determine the pelvic angle, three 3.0-mm Steinmann pins were inserted into the sacroiliac joint. The pelvis and Steinmann pins were fixed with acrylic resin (OSTRON 2; GC Corp., Tokyo, Japan) at a pelvic angle of 32°.[14] To maintain the abduction angle at 102° and flexion angle at 115°, the hip joint and the proximal femur were fixed in acrylic resin with 2.7-mm Steinmann pins.[14] The origin of the quadriceps was defined as the trochanteric fossa, and a hole was drilled into the resin-fixed hip joint to replicate this origin.

Each specimen was wrapped in towels soaked in 0.9% NaCl solution, frozen at −30°C until the day before testing, and then thawed at 5°C for 12 hours prior to analysis. After confirming that the limbs were fully thawed, each specimen was mounted and attached to an acrylic testing frame using 3.0-mm screws.

Joint Angles

The hip abduction angle, and the angles of the pelvis, hip joint, stifle joint and tarsal joint were configured at mean ± standard deviation values of 102° ± 5°, 32° ± 5°, 115° ± 5°, 137° ± 5° and 129° ± 5° respectively (►**Fig. 1**).[14] The hip abduction angle was determined in 10 standing Beagles (20 hindlimbs). Circular markers were placed on the femoral lateral epicondyle and greater trochanter, and an image (caudal view) was recorded. The centre of each marker was connected with lines, and the intersection of the lines was measured as the hip abduction angle. These angles for the pelvis, and the hip, stifle, and tarsal joints corresponded to the form of the peak vertical force detected for 65 steps in eight Beagles walking at a mean velocity of 1.2 ± 0.1 m/s.[14]

The angles of the stifle and tarsal joints were adjusted using a wire lock (Rize Lock KL50; Rize Enterprises LLC, New York, New York, United States) and turnbuckle (Turnbuckle bright chromate, 2 mm; Yahata Neji Corp., Aichi, Japan). The movable joints were the stifle and tarsal joints, while the hip joint was fixed.

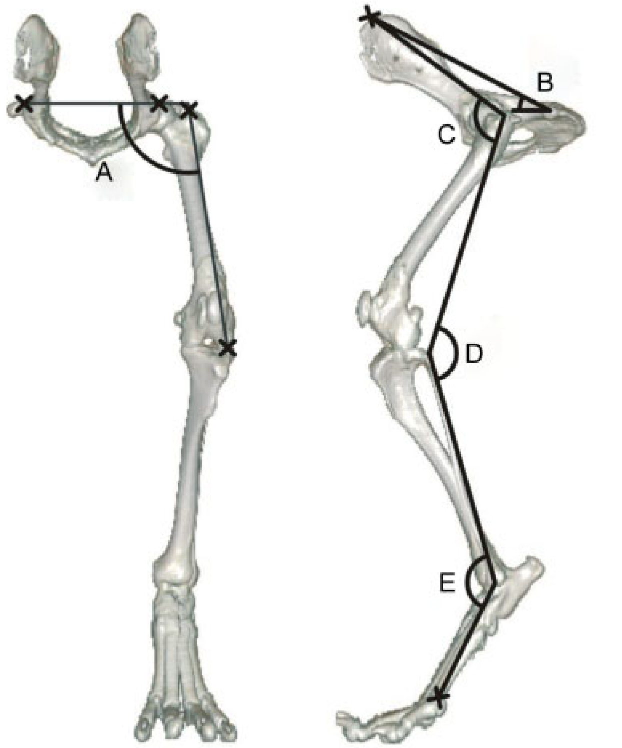

Fig. 1 Craniocaudal (left) and lateral (right) views of the hip abduction angle and joint angles used in the present study. The angles of the joints were established on the basis of the angles at the peak vertical force in Beagles walking at a velocity of 1.2 m/s, except for the hip abduction angle, which was determined in standing Beagles. The tolerance of the angles was fixed at ± 5°; mean ± standard deviation angles of the hip abduction (**A**), pelvis (**B**), hip joint (**C**), stifle joint (**D**) and tarsal joint (**E**) were 102 ± 5°, 32 ± 5°, 115 ± 5°, 137 ± 5° and 129 ± 5° respectively.

Tibial Plateau Levelling Osteotomy

The TPLO procedure was performed by veterinarians who had undergone specific TPLO training (Tibial plateau levelling osteotomy seminar, Slocum Enterprises, Eugene, Oregon, United States). TPLO was performed using a jig (Jig for use in small osteotomies; Slocum Enterprises, Eugene, Oregon, United States) and an 18-mm biradial saw (Biradial saw, 18 mm; Slocum Enterprises, Eugene, Oregon, United States). In the ICO group, the centre of the osteotomy was set on the intercondylar eminence. In the DCO group, the centre of the osteotomy was set on the insertion of the medial collateral ligament. In the ICO group, we used the method reported by Woodbridge and colleagues to ensure the accuracy of the location of the centre of the osteotomy.[16] On a preoperative radiograph, we measured the distances from the patellar ligament insertion to two points on the planned tibial osteotomy line, and from the most caudal margin of the tibial plateau to the point where the intended tibial osteotomy transected the caudal tibial cortex. The osteotomies were then performed based on the distances calculated via this method. In the DCO group, the insertion of the medial collateral ligament was defined as the most proximal point that was not movable by extension and flexion of the stifle joint; this point was marked with a pen, and the centre of the osteotomy was identified. After TPLO, the TPA was modified to a target angle of 6.5°. After the tibial osteotomy, the tibial plateau segment was rotated, and a 1.0-mm Kirschner wire was placed through the tibial tuberosity into the tibial plateau segment. We then confirmed that the postoperative TPA was 6.5° ± 1° using mediolateral radiograph of the stifle joint. A 2.7-mm TPLO plate (VP TPLO plate, 2.7 mm; DePuy Synthes Japan VET, Tokyo, Japan), 2.7-mm locking screw (VP locking screw, 2.7 mm; DePuy Synthes Japan VET, Tokyo, Japan) and 2.7-mm cortex screw (Self-tapping cortex screw for Vet, 2.7 mm; MIZUHO Co., Tokyo, Japan) were applied to stabilize the osteotomy. After the TPLO, the jig was removed and the articular capsule of the stifle was closed routinely.

Muscular Tensile Force

The tensions of the 1.0-mm stainless steel wires that replicated the force of the quadriceps, gastrocnemius and stifle flexor muscles (semitendinosus, semimembranosus and biceps femoris) were measured. Quadriceps tension was measured using a tension gauge (LT10S-50; SSK Co. Ltd., Tokyo, Japan) mounted between the wire and turnbuckle; the sensor had a rated capacity of 490 N and a resolution of 4.9×10^{-2} N. The tensions of the gastrocnemius and stifle flexor muscles were measured using a tension gauge (LR6S-30; SSK Co. Ltd., Tokyo, Japan) mounted between the wire and turnbuckle; the sensor had a rated capacity of 294 N and a resolution of 2.9×10^{-2} N.

The wires that replicated the quadriceps and gastrocnemius muscles were adjusted to a tension that constantly maintained the configured stifle joint and tarsal joint angles throughout the experiment. The wire that replicated the stifle flexor muscles was then adjusted to a tension of 22.8% of bodyweight,[17] as this is reportedly approximately equal to the force of the canine stifle flexor muscles when the peak vertical force occurs during walking.[17]

Specimen Loads

To reproduce in vivo conditions, a static axial load was applied using water bags until 65.3% of the bodyweight had been loaded onto a specimen paw.[14] This value corresponded to the peak vertical force detected in Beagles walking at a velocity of 1.2 m/s. The vertical force on the paw was measured using a force gauge (L350S-20; SSK Co. Ltd., Tokyo, Japan) located under the paw; the sensor had a rated capacity of 196 N and a resolution of 2.0×10^{-2} N.

Craniocaudal Force of the Paw

Each paw was mounted on a custom-made moveable platform that allowed the establishment of a craniocaudal force. After the position of the paw in the CrCL-intact specimen had been determined, the moveable platform was attached to a digital force gauge (AD-4932A-50N; A&D Co. Ltd., Tokyo, Japan) that was secured to the table with adhesive tape. The positions of the digital force gauge, frame and table did not change during the experiment. The frame was also secured to the table with adhesive tape. Cranial force was defined as positive, and caudal force as negative. The sensor had a rated capacity of 50.00 N and a resolution of 10^{-2} N.

Testing Procedure

The loading of each specimen was performed in the following test sequence: intact CrCL, transected CrCL, and TPLO (ICO or DCO). After the tests for the intact CrCL condition had been completed, every load for each specimen was removed. The CrCL of each specimen was then transected using a scalpel, and the joint capsules were sutured using 3–0 nylon. Each specimen was refixed to the testing frame, and the same load was applied for the transected CrCL condition. After testing in the transected CrCL condition, each specimen was removed from the testing frame to perform the ICO or DCO TPLO. After TPLO, each specimen was fixed to the testing frame, and the same load was applied (►Figs. 2 and 3). The tensile forces of the wires were adjusted to maintain the configuration of the joint angles.

Data Acquisition

Lateral radiographical views were obtained for each condition (intact CrCL, transected CrCL and TPLO [ICO or DCO]) to enable

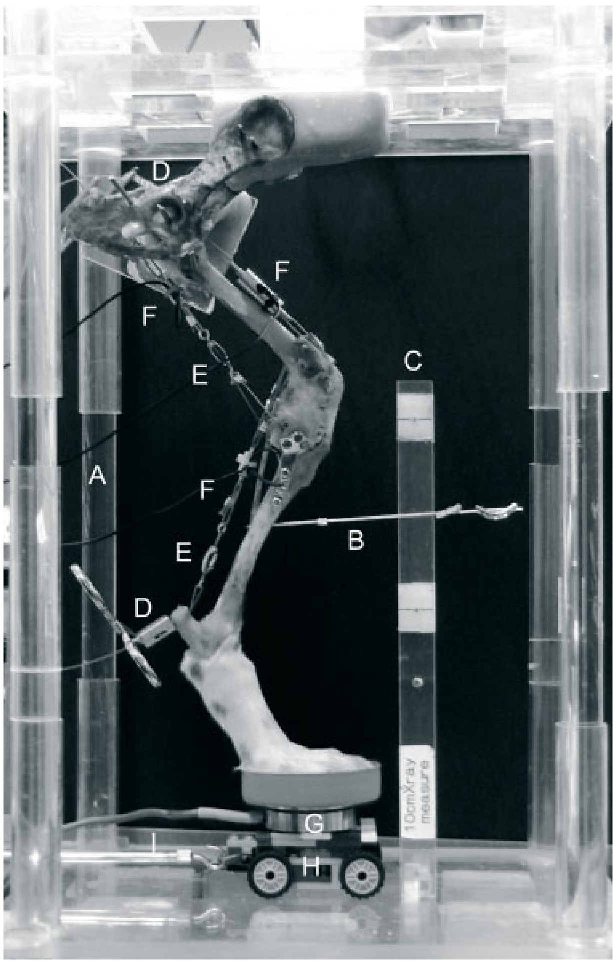

Fig. 2 Lateral view of a Beagle cadaver. The frame consisted of an acrylic board (**A**). A 1.5-mm Kirschner wire (**B**) was inserted into the tibia to measure the internal rotation of the tibia. A 100-mm marker (**C**) was placed on the frame floor to measure the craniocaudal displacement of the tibia. The angles of the stifle joint and tarsal joint were adjusted using a wire lock (**D**) and turnbuckle (**E**). The wire tension was measured using tension gauges (**F**). The vertical force on the paw was measured using a force gauge (**G**) that was secured on a moveable platform (**H**) connected to a digital force gauge (**I**).

measurement of the joint angles, tibial displacement, PLMA, TPA, and centre of rotation using image analysis software (ImageJ, version 1.41o; National Institutes of Health, Bethesda, MD. Available at: rsb.info.nih.gov/ij/. Accessed January 7, 2012). Tibial displacement was measured on lateral radiographs using a 100-mm marker (►Fig. 2). Cranial tibial displacement was calculated as the difference from the CrCL-intact stifle joint position (►Fig. 3). The joint angles[14] and TPA[5] were measured as previously described. The PLMA was measured as the perpendicular distance between the cranial edge of the patellar ligament and the centre of the tibiofemoral contact point in the CrCL-intact and TPLO stifles; this was a modified version of a previously reported method (►Fig. 4).[18] The location of the centre of rotation in the TPLO was measured from the X–Y coordinates. The X-axis was parallel to the tibial plateau, and the Y-axis was perpendicular to the X-axis. The origin of the X–Y coordinate was set on the intercondylar tubercle. The centre of rotation was determined by the custom-made template of the biradial saw. Displacement from the origin was defined in accordance with the X–Y coordinate system, and each component was recorded in mm (►Fig. 5A).

Internal rotation of the tibia was measured on dorsoventral radiographs using the connection between the 1.5-mm Kirschner wire inserted into the tibia and the Steinmann pin inserted from the hip joint to the pelvis. Internal rotation of the tibia was calculated as the difference in rotation from the CrCL-intact stifle joints using image analysis software (ImageJ, version 1.41o; National Institutes of Health, Bethesda, MD. Available at: rsb.info.nih.gov/ij/. Accessed January 7, 2012).

The mechanical medial proximal tibial angle was measured on craniocaudal radiographs of the CrCL-intact and TPLO stifles using image analysis software (ImageJ, version 1.41o; National Institutes of Health, Bethesda, MD. Available at: rsb.info.nih.gov/ij/. Accessed January 7, 2012) as previously described.[19]

The intact CrCL condition was assigned a value of zero for the craniocaudal force on the paw.

Tensile forces measured from the wires that were used to replicate the forces of the quadriceps, stifle flexor muscles, and gastrocnemius and the vertical force in the paw were collected continuously for 5 seconds after each specimen was subjected to the above-described test conditions. The data collection rate was 1,000 Hz. Data were collected from each sensor via a sensor interface (PCD-300B; Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan), and analysed using dynamic data acquisition software (DAS-100A; Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan). The tensile forces for the quadriceps, stifle flexor muscles and gastrocnemius were divided by the vertical force (65.3% of the bodyweight), and the ratios were used for analyses.

Statistical Analysis

The Shapiro–Wilk test was used to test the normality of the values of the bodyweight, TPA, centre of rotation, PLMA, each joint angle, cranial displacement of the tibia, internal rotation of the tibia, vertical force, cranial force on the paw and every tensile force outcome. The homoscedasticity of each value was then examined by Levene's test. After homoscedasticity was

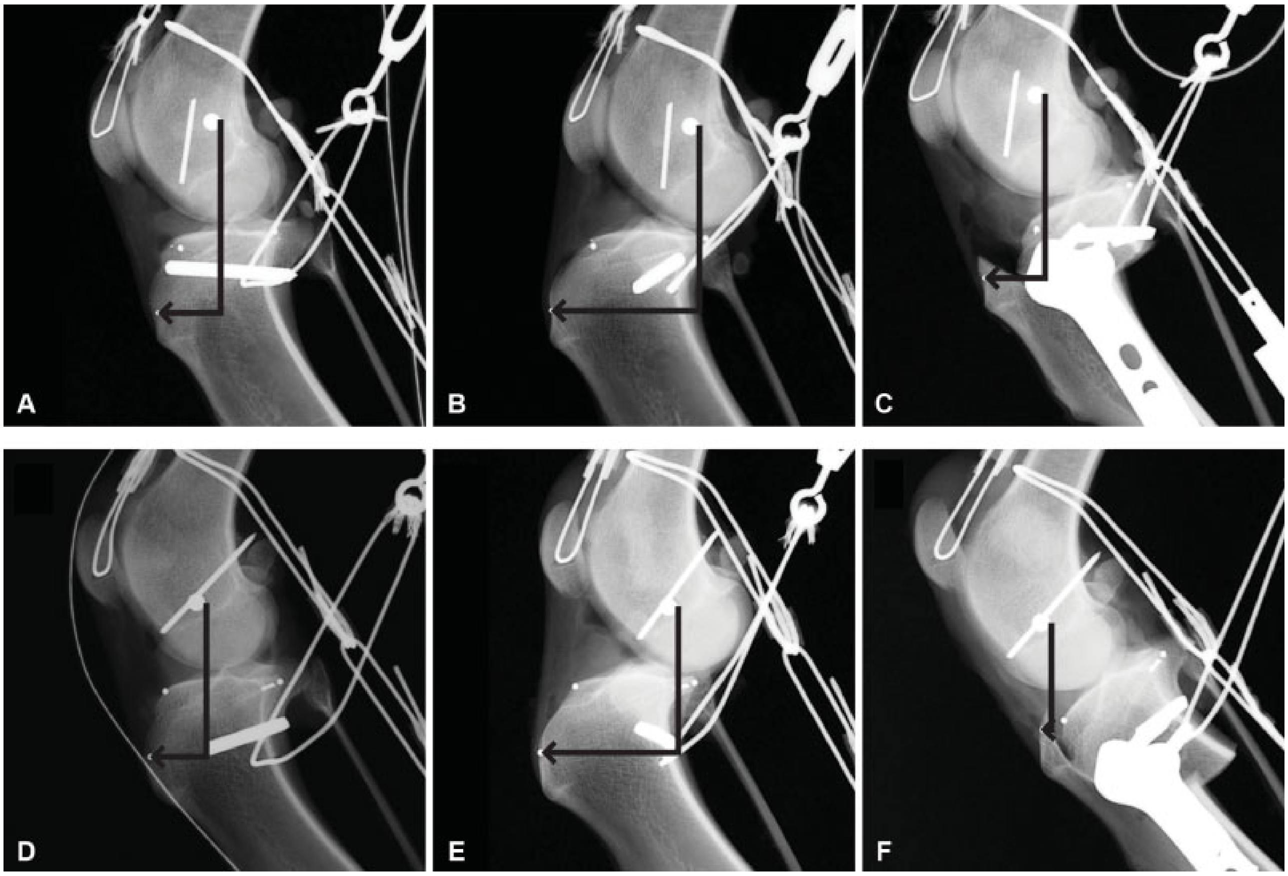

Fig. 3 Lateral radiographical views of the hindlimbs of Beagle cadavers for each of the four test conditions. The first three images are of specimens from the ideally centred osteotomy group with (**A**) an intact CrCL, (**B**) a transected CrCL and (**C**) an ideally centred osteotomy TPLO. The subsequent images are of specimens from the distally centred osteotomy group with (**D**) an intact CrCL, (**E**) a transected CrCL and (**F**) a distally centred osteotomy TPLO. Cranial tibial displacement was measured as the change in the position between the femoral and tibial markers. CrCL, cranial cruciate ligament; TPLO, tibial plateau levelling osteotomy.

confirmed for each outcome, significant differences were confirmed by the two-sample *t*-test. When normality was not observed in an outcome, significant differences were confirmed using the Mann–Whitney U test. Every outcome was compared between the ICO and DCO groups, and values of $p < 0.05$ were considered significant. Only the PLMAs of the ICO and DCO groups after TPLO were compared with the PLMA of the intact condition. The normality of the data of each outcome was confirmed by the Shapiro–Wilk test. When normality was observed, data were analysed with the paired *t*-test. When normality was not observed, data were analysed with the Wilcoxon signed-rank test. $p < 0.05$ was considered significant. A statistical analysis software package was used to perform all statistical analyses (SPSS, version 16.0.1; SPSS Inc., Chicago, Illinois, United States).

Results

One specimen in the ICO group failed during testing, and was thus excluded due to incomplete data collection; in this excluded specimen, the patella fractured at the insertion of the 0.8-mm stainless steel wire under a static axial load. Thus, the ICO and DCO groups contained 9 and 10 samples respectively. The mean bodyweights in the ICO and DCO groups were similar ($p = 0.053$, ►**Table 1**). There was also no significant difference between the ICO and DCO groups in the intact TPA ($p = 0.6$), or the TPA after TPLO ($p = 0.303$, ►**Table 1**). The centre of rotation in the TPLO in the DCO group was located caudally (X-axis, $p < 0.001$) and distally (Y-axis, $p = 0.003$) significantly more often than that in the ICO group (►**Table 1**; ►**Fig. 5B**, **5C**). The ICO group had a significantly greater mean PLMA in the TPLO stifle than the DCO group ($p = 0.001$, ►**Table 1**).

The ICO and DCO groups had similar mean mechanical medial proximal tibial angles and joint angles (►**Table 2**).

The mean tibial displacements in the ICO and DCO groups in the transected CrCL condition were similar ($p = 0.905$, ►**Table 3**). In contrast, the mean tibial displacement after TPLO in the ICO group was significantly greater than that in the DCO group ($p < 0.001$, ►**Table 3**). The ICO and DCO groups had similar values for internal rotation, vertical force and cranial force on the paw (►**Table 3**).

After TPLO, the tensile force of the quadriceps was significantly lesser in the ICO group compared with the DCO group ($p = 0.006$, ►**Table 4**). The tensile forces of the other muscles did not significantly differ between the ICO and DCO groups (►**Table 4**).

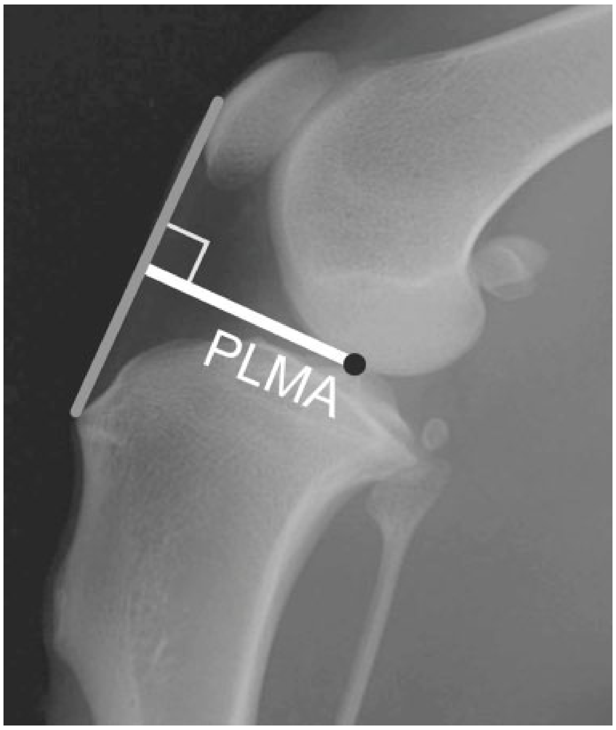

Fig. 4 Lateral radiographical view of the stifle. The patellar ligament moment arm is represented by the perpendicular distance between the cranial edge of the patellar ligament and the centre of the tibiofemoral contact point. PLMA, patellar ligament moment arm.

Discussion

In the present study, the PLMA of the DCO group was shortened as a result of the centre of the osteotomy being set distal to the recommended position. Additionally, the tensile force in the quadriceps that was required to maintain a predetermined stifle angle in the DCO group was significantly increased compared with the force required in the ICO group. This suggests that the tensile force of the quadriceps increased when the PLMA decreased. Therefore, if the centre of the osteotomy is located on the distal attachment of the medial collateral ligament, the PLMA shortens and the tensile force of the quadriceps increases after TPLO. Although the TPLO procedure in clinical cases is performed using a jig, and the osteotomy line is determined based on the patellar ligament insertion, the actual centre of the osteotomy tends to become caudal and distal to the ideal centre of the osteotomy.[20] This increased force may lead to patellar ligament thickening in the long-term. Dogs with a narrow tibial tuberosity are reportedly more likely to develop severe patellar ligament thickening after TPLO, and forceful contraction of the quadriceps mechanism may transfer a high tensile force to the small cranial remnant of the tibial tuberosity, resulting in secondary pathological changes to the patellar ligament.[8] This high tensile force may be derived from the shortening of the PLMA.

The PLMA was significantly longer in the ICO group than in the DCO group and in the intact CrCL stifles of the ICO group. The increase in the PLMA may be related to the location of the centre of the osteotomy, which was located slightly cranially and proximally to the tibial intercondylar eminence. If the centre of the osteotomy is located on the tibial intercondylar eminence, the PLMA will be shortened in accordance with the thickness of the TPLO saw blade.[2] However, this shortening of the PLMA after TPLO may be avoided by moving the centre of the osteotomy slightly cranially and proximally, as in the ICO group. In contrast, a distally located centre of the osteotomy will result in a shortened PLMA, as in the DCO group. These changes in the PLMA length may be caused by the movement of the proximal tibial long axis point, namely the tibial intercondylar eminence. A previous study used mathematical analysis to evaluate the effect of osteotomy position on postoperative TPA, and revealed that the tibial long axis is shifted when the centre of the osteotomy is set at a location other than the tibial intercondylar eminence[21]; this caused the movement of the tibial intercondylar

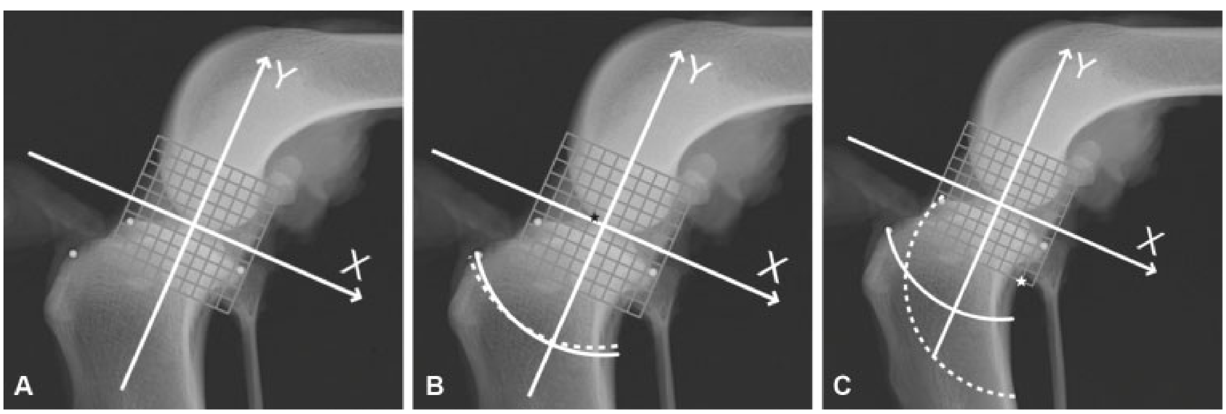

Fig. 5 Lateral radiographical view of the stifle. (**A**) The X-axis was defined as a line parallel to the tibial plateau, and the Y-axis as a line perpendicular to the X-axis. The origin of the X-Y coordinate is set on the top of the tibial intercondylar tubercle. The grid represents 1-mm increments. The lead spherical markers were placed at the cranial and caudal edges of the tibial medial condyle, and were used as markers to clarify the tibial plateau slope. (**B**) Image of the osteotomy line in the ideally centred osteotomy (ICO) group. The white line is the osteotomy line centred on the intercondylar tubercle, the white dotted line is the osteotomy line in the ICO group and the black star indicates the centre of rotation in the ICO group. (**C**) Image of the osteotomy line in the distally centred osteotomy (DCO) group. The white line is the osteotomy line centred on the intercondylar tubercle, the white dotted line is the osteotomy line in the DCO group and the white star indicates the centre of rotation in the DCO group.

Table 1 Comparison of bodyweight, tibial plateau angle, centre of rotation and moment arm in the ICO and DCO groups

	BW (kg)	TPA (°)		Centre of rotation (mm)		PLMA (mm)	
		Intact	TPLO	X-axis	Y-axis	Intact	TPLO
ICO group	10.5 ± 0.9	30.3 ± 1.9	6.1 ± 1.6	-0.8 ± 1.3	0.1 ± 1.6	19.7 ± 1.0	20.9 ± 0.9[c]
DCO group	9.4 ± 0.9	29.8 ± 2.4	6.8 ± 0.9	4.0 ± 2.0	-5.1 ± 2.9	20.5 ± 0.9	18.9 ± 1.1[d]
p-Value	0.053	0.6	0.303	< **0.001**[a]	**0.003**[b]	0.06	**0.001**[a]

Abbreviations: BW, bodyweight; DCO group, cadavers in which distally centred osteotomy TPLO was performed ($n = 10$); ICO group, cadavers in which ideally centred osteotomy TPLO was performed ($n = 9$); PLMA, patellar ligament moment arm; SD, standard deviation; TPA, tibial plateau angle; TPLO, tibial plateau levelling osteotomy.
The reported values are the mean ± SD, and were compared between the ICO and DCO groups. For the centre of rotation variables, the positive values indicate caudal distances (X-axis) and proximal distances (Y-axis). *p* values for post hoc pairwise comparisons are given where analysis of variance testing indicated significant differences. Bold values indicate statistical significance.
[a]Two-sample *t*-test, $p < 0.01$ versus LC group.
[b]Mann–Whitney *U* test, $p < 0.01$ versus LC group.
[c]Wilcoxon signed-rank test, $p < 0.05$ versus ICC group–Intact ($p = 0.021$).
[d]Paired *t*-test, $p < 0.01$ versus LC group–Intact ($p < 0.001$).

Table 2 Comparison of joint and bone angles in the ICO and DCO groups

Joint angle (°)	Pelvis	Hip		Stifle		Tarsus		mMPTA	
		Flexion	Abduction	Intact	TPLO	Intact	TPLO	Intact	TPLO
ICO group	29.0 ± 2.8	119.0 ± 5.4	96.2 ± 3.6	136.0 ± 1.3	137.3 ± 1.5	128.8 ± 1.6	127.6 ± 1.5	93.3 ± 2.7	89.4 ± 3.4
DCO group	31.4 ± 2.1	123.2 ± 3.9	94.9 ± 3.6	136.4 ± 1.3	137.5 ± 1.8	127.6 ± 1.9	127.9 ± 1.5	92.7 ± 3.2	90.8 ± 4.3
p-Value	0.05	0.067	0.458	0.467	0.653	0.699	0.140	0.661	0.661

Abbreviations: DCO group, cadavers in which distally centred osteotomy TPLO was performed ($n = 10$); ICO group, cadavers in which ideally centred osteotomy TPLO was performed ($n = 9$); mMPTA, mechanical medial proximal tibial angle; SD, standard deviation; TPLO, tibial plateau levelling osteotomy.
The reported values are the mean ± SD, and were compared between the ICO and DCO groups. For the centre of rotation variables, the positive values indicate distal and proximal distances. *p*-Values for post hoc pairwise comparisons are given where analysis of variance testing indicated significant differences.

Table 3 Comparison of cranial tibial displacement, tibial internal rotation, vertical force and cranial displacement force on the paw in the ICO and DCO groups

	Cranial displacement (mm)		Internal rotation (°)		Vertical force (% of BW)		Cranial force on the paw (cranial force/VF × 100)
	CrCL-T	TPLO	CrCL-T	TPLO	Intact	TPLO	TPLO
ICO group	12.0 ± 1.4	−1.9 ± 1.7	17.5 ± 2.7	6.2 ± 3.0	64.8 ± 1.1	64.7 ± 1.3	−1.7 ± 2.6
DCO group	11.5 ± 2.9	−5.3 ± 1.1	16.3 ± 4.9	2.2 ± 5.7	64.4 ± 0.7	64.5 ± 0.9	−1.9 ± 3.5
p-Value	0.905	< **0.001**[a]	0.528	0.079	0.133	0.655	0.720

Abbreviations: BW, bodyweight; CrCL-T, stifles in which the cranial cruciate ligament was transected; DCO group, cadavers in which distally centred osteotomy TPLO was performed ($n = 10$); ICO group, cadavers in which ideally centred osteotomy TPLO was performed ($n = 9$); SD, standard deviation; TPLO, tibial plateau levelling osteotomy; VF, vertical force.
The reported values are the mean ± SD, and were compared between the ICO and DCO groups. For the cranial force variables, the negative values indicate distal force. *p*-Values for post hoc pairwise comparisons are given where analysis of variance testing indicated significant differences. Bold values indicate statistical significance.
[a]Two-sample *t*-test, $p < 0.01$ versus LC group.

eminence after TPLO.[21] Additionally, the same previous study showed that an osteotomy position distal to the intercondylar eminence resulted in the intercondylar eminence being shifted cranially after TPLO.[21] The shorting of the PLMA in the present DCO group may be caused by the cranial displacement of the intercondylar eminence after TPLO.

During TPLO, the TPA is modified to ~6.5° to neutralize the cranial tibial subluxation.[5,6,22] In the present study, although the TPAs in the ICO and DCO groups after TPLO were 6.1° ± 1.6° and 6.8° ± 0.9° respectively the stifles in both groups showed caudal displacement after TPLO. Another recent study revealed that modification of the TPA to 6°

Table 4 Comparison of the tensile forces of the muscles in the ICO and DCO groups

Tensile force (tensile force/VF)	Quadriceps muscles		Stifle flexor muscles		Gastrocnemius muscle	
	Intact	TPLO	Intact	TPLO	Intact	TPLO
ICO group	3.5 ± 0.3	3.3 ± 0.4	0.4 ± 0.0	0.4 ± 0.0	2.0 ± 0.3	2.2 ± 0.2
DCO group	3.5 ± 0.3	3.9 ± 0.3	0.4 ± 0.0	0.4 ± 0.0	1.9 ± 0.3	2.1 ± 0.4
p-Value	0.671	**0.006**[a]	0.881	0.905	0.624	0.591

Abbreviations: DCO group, cadavers in which distally centred osteotomy TPLO was performed ($n = 10$); ICO group, cadavers in which ideally centred osteotomy TPLO was performed ($n = 9$); SD, standard deviation; TPLO, tibial plateau levelling osteotomy; VF, vertical force.
The reported values are the mean ± SD, and were compared between the ICO and DCO groups. *p* values for post hoc pairwise comparisons are given where analysis of variance testing indicated significant differences. Bold values indicate statistical significance.
[a]Two-sample *t*-test, $p < 0.01$ versus LC group.

during TPLO may not be necessary to neutralize the cranial tibial thrust in accordance with the plateau rotation based on the measurement of the common tangent patellar ligament angle (PLA_{CT}), as a TPA of 12° corresponded to a PLA_{CT} of approximately 90°.[23] Another study that evaluated the currently used osteotomy procedure for CrCL-deficient stifles (i.e. centre of rotation of angulation-based levelling osteotomy) used a target postoperative TPA of 9 to 12°.[24–27] The tensile force of the stifle flexor muscle, which acts as an agonist of the CrCL, was replicated in our model.[14] Therefore, the cranial tibial thrust in *in vitro* models may change to caudal tibial thrust after TPLO, despite a TPA of ~6°. Our results suggest that the cranial tibial thrust may be changed to caudal tibial thrust when the target postoperative TPA is 6°, especially when no conditions associated with a decrease in the tensile force of the stifle flexor muscles are present.

The caudal tibial displacement in the DCO group was significantly greater than that in the ICO group after TPLO. The rotation of the proximal tibial fragment induced by TPLO changes the relationship of the femorotibial articulation, similarly to that in a flexed stifle.[5] An *in vitro* study that investigated the effect of the TPLO position on cranial tibial subluxation showed that when the centre of the osteotomy is located distally, the postoperative TPA was not adequately reduced to the planned postoperative TPA, and there was incomplete neutralization of the cranial tibial thrust force.[7] This suggests that if the centre of TPLO is set caudally, and the postoperative TPA is modified to the preoperative target TPA, the rotation length of the proximal tibial fragment needs to be longer than preoperatively planned.

The DCO group required greater rotation than the ICO group to modify the TPA to 6.5°. Therefore, the femorotibial articulation was more flexed in the stifles of the DCO group compared with the ICO group. Stifle flexion causes relaxation of the lateral collateral ligament and caudal portion of the medial collateral ligament.[28] Hence, differences in the caudal tibial displacement in the ICO and DCO groups may be related to the tensile force at the collateral ligaments.

The present study has some limitations. The model used replicated peak vertical force and joint angles at which the peak vertical force occurred when clinically normal Beagles walked at a velocity of 1.2 m/s.[14] However, the tensile force of the stifle flexion muscles at 22.8% of bodyweight was based on a study that used a walking speed of 0.9 m/s.[17] Additionally, the joint angle and vertical force replicated those at the peak vertical force of walking Beagles. However, the present model was a static model, and so the conditions at peak vertical force were not perfectly reproduced. Another limitation is the centre of the tibiofemoral contact point was defined as the midpoint of the line connecting the cranial and caudal edges of the contact area of the femoral condyle and the tibial intercondylar eminence. However, it is unknown whether this method is the most appropriate method with which to identify the centre of the tibiofemoral contact point. The other limitation is that the TPA in the present study was greater than that reported for clinically normal dogs.[29] The extent of the influence of this high TPA on our results is unclear; however, the cranial tibial thrust disappeared after TPLO in every specimen in the present study.

In summary, this is the first study to investigate the change in the tensile force of the quadriceps in accordance with differences in the centre of osteotomy in TPLO. Additionally, this is the first biomechanical study on TPLO in which the model replicated the tensile force of the stifle flexor muscles. Our results show that the tensile forces of the quadriceps and gastrocnemius do not change after TPLO when the centre of the osteotomy is located on the intercondylar eminence in the population of dogs studied. Conversely, setting the postoperative TPA at 6° may cause excessive rotation in patients with normal tensile force of the stifle flexor muscles.

Conflict of Interest
Dr. Kanno reports grants from SHIMA Laboratories Co., Ltd., and grants from Japan Radio Co., Ltd., outside the submitted work.

Author Contribution
All authors contributed to conception of study, study design, acquisition of data and data analysis and interpretation. All authors also drafted, revised and approved the submitted manuscript.

Acknowledgments
We thank Kelly Zammit, BVSc, from Edanz Group (www.edanzediting.com/ac), for editing a draft of this manuscript.

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