THE EFFECT OF TIBIAL TUBEROSITY ADVENCEMENT (TTA) ON CAUDAL CRUCIATE LIGAMENT (CACL) RIGIDITY IN CANINE STIFLE JOINT UNDER CRANIAL FEMORAL DRAWER. COMPARISON BETWEEN INTACT, CRANIAL CRUCIATE LIGAMENT-DEFICIENT (CRCL-DEFICIENT) AND TTA KNEE: AN IAN *IN-VITRO* EXPERIMENTAL STUDY.

EFECTO DEL AVANCE DE LA TUBEROSIDAD TIBIAL (ATT) SOBRE LA RIGIDEZ DEL LIGAMENTO CRUZADO CAUDAL EN ARTICULACIÓN DE RODILLA CANINA BAJO FUERZA FEMORAL CRANIAL. COMPARACIÓN ENTRE RODILLA INTACTA, CON ROTURA DE LIGAMENTO CRUZADO CRANIAL Y CON LA ATT: ESTUDIO EXPERIMENTAL *IN-VITRO*

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ABSTRACT

The tibial tuberosity advancement (TTA) is a surgical technique used to repair cranial cruciate ligament-deficient (CrCL-deficient) canine knees. The aim of this study was to assess the effect of TTA on caudal cruciate ligament (CaCL) under femoral anterior force, in a 135° joint extension angle; and the role of CaCL in an CrCL-deficient knee. Five fresh cadaveric adult canine stifle joints were tested in an apparatus in which muscle forces were simulated. Each knee was tested in three different conditions: intact, CrCL-deficient knee and with TTA surgery. Shear force (Newtons, N) and CaCL deformation (millimetres, mm) were measured using sensors and the ligament rigidity (force divided by deformation, N/mm) was calculated and compared between the three knees. The mean rigiditiy values increased from intact knee, 104.4 N/mm (SD 3.6), to CrCL-deficient knee, 136.5 N/mm (SD 7.5). However, the rigidity was even greater when applying the TTA, 257.2 N/mm (SD 21.1). Since, stress on the CaCL in CrCL-deficient knees was greater than in intact knees, the ligament assumed a more important role. On the other hand, the TTA technique generates an overload on the CaCL until rigidity exceeds its load-bearing capacity. Although the *in-vitro* models are far from reality, these findings suggest the need to further study the effects of TTA on the CaCL.

Key words: Caudal cruciate ligament; cranial cruciate ligament-deficient; canine stifle joint; orthopaedic plates; tibial tuberosity advancement

RESUMEN

El avance de la tuberosidad tibial (ATT) es una técnica quirúrgica usada para reparar la lesion de Ligamento Cruzado Craneal (LCCr) en la rodilla canina. El objetivo de este estudio fue determinar el efecto de la ATT sobre el ligamento cruzado caudal (LCCa) con el efecto de una fuerza femoral cranial, en un ángulo de extension de la articulación de 135º; y el rol del LCCa en rodillas con lesion de LCCr. Cinco articulaciones cadavéricas de rodilla canina se sometieron a pruebas en una bancada, en la cual se simularon las fuerzas musculares. Cada rodilla fué ensayada en tres condiciones diferentes: rodilla intacta, rodilla con rotura de LCCr, y rodilla operada con la ATT. Se midieron con sensores la fuerza cortante (Newtons, N), la deformación del LCCa (milimetros, mm) y se calculó la rigidez del ligamento (fuerza dividida por deformación, N/mm) y se comparó entre las tres rodillas. Los valores promedios de la rigidez se incrementaron desde la rodilla intacta, con 104,4, N/mm (DS 3,6), a la rodilla con lesion de LCCr, con 136,5 N/mm (DS 7,5). Sin embargo, la rigidez aun fué mayor cuando se aplicó la ATT, con 257,2 N/mm (SD 21,1). Debido a que el estrés en el LCCa fué mayor en las rodillas con lesion de LCCr que en rodillas intactas, el ligamento asumió un rol más importante. Por otro lado, la técnica de la ATT genera una sobre carga al LCCa hasta alcanzar una rigidez por encima de su capacidad. Sin embargo, los modelos *in-vitro* siguen estando lejos de la realidad, por lo que estos hallazgos sugieren la necesidad de más estudios de los efectos del ATT sobre el LCCa.

Palabras clave: Ligamento cruzado caudal; ligamento cruzado cranial deficiente; articulación de rodilla canina; prótesis ortopédicas; avance de la tuberosidadtibial

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INTRODUCTION

Anterior displacement of the tibial tubercle was recommended in humans to reduce pressure and pain in the patelofemoral joint in patients with osteoarthritis [15]. Tibial tuberosity advancement (TTA) that was presented in 2002 [17,25] is performed with the premise that it increases the efficiency of the extensor mechanism and decreases quadriceps activation. This technique is adopted in veterinary surgery to neutralize dynamically cranial shear forces in cranial cruciate ligament-deficient (CrCL-deficient) knees lengthening the lever arm of the quadriceps during canine (C*anis lupus familiaris*) gait [2,5]. The tibiofemoral shear force is directed forward when the knee is extended and backwards when flexed and is zero when the patellar tendon angle (PTA) is 90° [19]. If the tuberosity is advanced to the point where the PTA angle is 90° or less in the extended position, the shear force will be neutral or caudally directed. Different studies using *in vitro* models support the theoretical foundations of TTA that measure the cranial tibial thrust (CTT) [1, 8, 12, 16], however, warn that TTA may caudally displace the tibia at 135° of extension, which would cause an excessive load on the caudal cruciate ligament (CaCL) [1, 4, 8, 12]. A finite element simulation model of the forces in the human knee showed that tibial tubercle elevation caused that the CaCL was beginning to tense at lower flexion angles [24], i.e., TTA technique causes an overload on the CaCL from the knee extended position. Although CaCL has a function during gait cycle and, in an CrCL-deficient knee, plays an important role in the extended position, it has received much less attention than the CrCL. Whilst cranial translation in intact and CrCL-deficient knees has been studied, the behaviour of the CaCL submitted to caudal displacement with CrCL-deficient knees and tuberosity advancement has not. (redaccion)

This study analizes the stress on CaCL under tibial caudal translation in canine stifle joints in different conditions: intact, CrCL-deficient and with TTA. After comparing the results, the effect of TTA surgery on CaCL will be assessed. Five unconstrained canine stifle joints were tested *In vitro* in a 135° extension angle. CaCL deformation (in millimeters, mm) was measured using a displacement sensor and a tension load cell measured the tibiofemoral shear force (in Newtons, N). Then, the linear rigidity of the ligament was calculated by means of the linear slope of the resulting load-deformation curve (rigidity is the relation between load and deformation, N/mm). The greater the ligament rigidity, the more tense the ligament is working, and the more stress on it.

MATERIALS AND METHODS

The knee specimens were fixed to a testing bench designed and constructed in the laboratory. The caudal displacement of the tibia relative to the femur is simulated in experimental trials by applying a cranial displacement of the femur on a fixed tibia (FIG. 1). Due to the relative motion that exists between femur and tibia, the cranial femoral displacement on a fixed tibia is equivalent to the caudal displacement of the tibia on a fixed femur. The distal end of the tibia-fibula of each specimen was introduced in a container with a high mechanical strength composite to ensure their embedding. To simulate the position during canine gait, the tibia was bent 30 degrees forward.

An orifice was drilled on the femoral condyles, and a 150 mm horizontal bar with M5 metric threaded was introduced to transmit a shear force on the condyles in order to simulate the movement of the femur relative to the tibia (FIGS. 1 and 2), i.e., the shear force. An u-shaped steel sheet adaptor was fixed on the metal bar. The force sensor[1] was connected to that steel adaptor, which in turn, was connected to metal wire. The metal wire transmitted the shear force through a pulley (FIG. 1). Two inductive displacement sensors of femur motion were placed on the femur bar, which weren't used in this study.

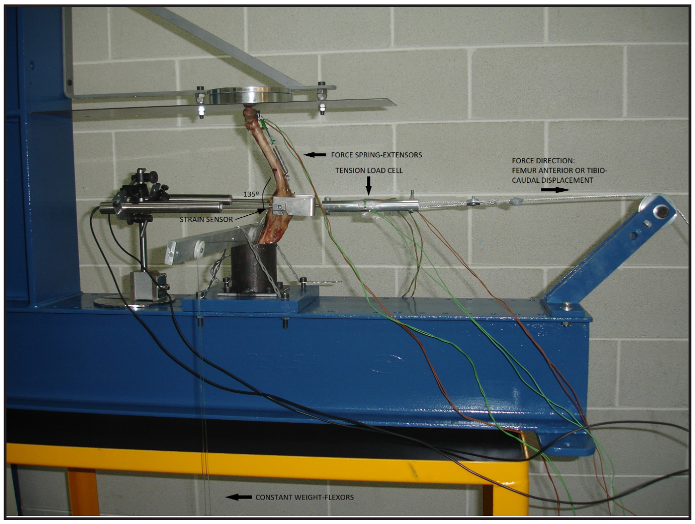

FIGURE 1. TESTING BENCH WITH SPECIMEN, MUSCULATURE SIMULATORS, MEASURING DEVICES AND APPLIED FORCE SYSTEM

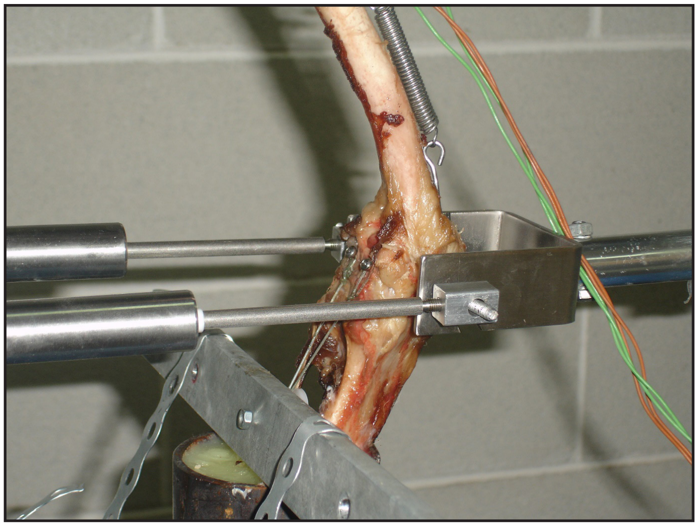

FIGURE 2. FORCE APPLICATION SYSTEMS. A BAR TRANSMITS A SHEAR FORCE ON THE CONDYLES IN ORDER TO SIMULATE THE MOVEMENT OF THE FEMUR RELATIVE TO THE TIBIA. TWO THIN PLASTIC CORDS ANCHORED TO THE SUPRACONDYLAR TUBEROSITIES OF THE FEMUR RECREATED THE FLEXOR MUSCLES

Specimen preparation

Five fresh cadaveric right canine knees from adult dogs between 25 to 35 kilograms (kg) of body weight were used for this study, each of them was tested three times. The specimens were obtained from canine cadavers that were sacrificed by others pathologies with their owner's consent. The bones were disarticulated at the hip joint (articulatio coxae), preserving the femoral head, and the tibia was sectioned distally, on its distal third. All soft tissues were removed except for the patella and patellar tendon and the quadriceps muscle, the stifle joint capsule, the collateral ligaments and the sesamoid bones of the gastrocnemius muscle. The specimens were frozen[2] at -18 °C until it was time to perform the trials.

The mid-stance phase of canine gait when CTT occurs is at 135º [6, 10, 21]. Muscle forces of the canine hind limb during this phase at 135° were simulated in accordance with a mathematical model [22]. A variable force spring attached to the proximal end of the femur and the top of the patella was used to play the role of the extensor muscle. The force of the quadriceps tendon was, according to Shahar and Bank-Sills [22], approximately equal to 48,5% of the animal's weight. The spring was pre-stressed with a force corresponding to 48% of the dog's weight. The spring force helded the limb in extension and an upper stop limited the angle of the limb. To recreate the flexor muscles, mostly attached to the Achilles tendon, it was used a constant weight provided by thin plastic cords that were anchored to the supracondylar tuberosities of the femur with two 3.5 mm threaded screws, and run parallel to the tibia towards the heel. According to Shahar and Bank-Sills [22], the total strength of the muscles that is attached to the calcaneal tendon was 29.09% of the dog's weight (FIGS. 1 and 2). Since the trials were performed on specimens free of muscles and tissues a reduction factor was applied to quadriceps and Achilles tendon force.

Specimen preparation with the TTA system

A longitudinal osteotomy was performed from the proximal cranial portion of the tibia, at the extensor sulcus level, to the distal area of the tibial crest, where a 3.5 mm orifice was made, as described in the TTA technique by Montavon et al. [18]. To perform the TTA, the tibial cranial fragment was progressively advanced, and a 9 mm box introduced and anchored in position with a 2 mm cortical screw. The plate was fixed with 2 mm cortical screws in its cranial portion and 2.7 mm screws in its caudal portion.

Measuring systems

The devices measuring tibiofemoral shear force and CaCL deformation were electromechanical transducers. The force sensor was a tension load cell[3]. And the displacement sensor was an inductive sensor, Linear Variable Differential Transformer (LVDT)[4], which measured the CaCL deformation in millimetres. The superficial CaCL was exposed in the back of the knee, and the DVRT for displacement was securely sutured to the ligament.

The two sensors were connected to a multiplexer[5] to treat and amplify the signal. The multiplexer captured the analogue inputs from the measuring devices in reading channels, which used the Wheatstone bridge as a connection circuit. A data acquisition card converted the analogue signal into a digital signal, which was treated by a software designed using the *Laboratory Virtual Instrument Engineering Workbench* (LabView)[6] Management Program. This program was responsible for the reading management of all channels on the acquisition card, and for displaying and saving all the generated data in files.

Each of the five specimens were tested three times and the values corresponding to the applied force and the CaCL deformation were recorded for the three cases: intact knee, CrCL-deficient knee, and after applying the TTA technique with surgical instruments in the laboratory. In order to produce a standard force versus deformation curve that could be used for biomechanical comparison, all the tests were performed with repeated loads and a constant rate of loading, thus minimizing side effects.

Statistical analysis

One way analysis of variance, ANOVA calculated with an excel sheet, with five specimens, was used to compare changes in ligament rigidity between intact knee, CrCL-deficient and TTA surgery. The confidence limits were 95%. Significant differences between three groups was observed ($P < 0.001$). Normality of residuals was met by all values on the displacements, and variability of residuals were similar in the three groups (assumption of homoscedasticity); there were no residuals outliers.

RESULTS AND DISCUSSION

The shear force and CaCL deformation curves are shown in a figure in which specimen 4 is represented in different conditions: intact, CrCL-deficient and TTA knee (FIG. 3). All the specimens had similar behaviors. Because the high sensitivity sensors measurements, large amounts of data per second were gathered and highly accurate curves were developed

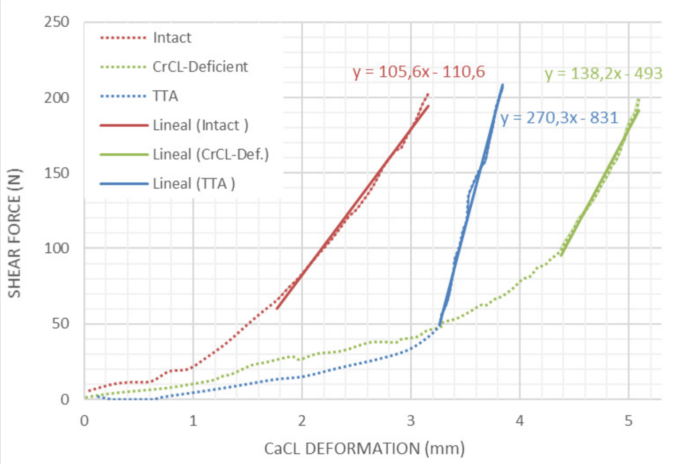

FIGURE 3. FORCE-STRAIN CURVE IN INTACT, CrCL-DEFICIENT AND TTA KNEE IN 135º EXTENSION, IN A CAUDAL DISPLACEMENT OF THE TIBIA (KNEE 4). The linear regression of the linear part of the curves are shown

The rigidity of each ligament was calculated in the linear region of the graphs by divinding the shear force, in Newtons, by CaCL deformation in millimetres (N/mm), i.e., the rigidity is the slope of the linear regression. The linear ligament rigidity calculation of five specimens for each type of knee is summarized in a Table (TABLE I).

TABLE I

DATA ON LIGAMENT LINEAR RIGIDITY (N/mm) IN CADAVER KNEES (n=5) IN 135° EXTENSION. ANOVA ANALYSIS

	Intact Knee	R-sq[1]	**CrCL deficient**	R-sq[1]	**TTA**	R-sq[1]
knee 1	100.2	0.99	125.6	0.99	231.3	0.98
knee 2	106.1	0.99	143.3	0.99	261.5	0.98
knee 3	108.9	0.99	140.4	0.99	245.8	0.99
knee 4	105.6	0.99	138.2	0.98	270.3	0.99
knee 5	101.1	0.99	135.1	0.99	276.9	0.97
Mean	**104.4**		**136.5**		**257.2**	
Standard Deviation (SD)	3.6		7,5		18.1	

P = 0.000 ; R-sq = 96.81%

[1] R-sq of the linear regression

All curves of the ligaments showed the same behaviour pattern with a nonlinear and a linear phase (FIG. 3). In the initial nonlinear part of the curves wavy collagen fibres are not maximally stretched [20]. In the linear region, the CaCL is tensed and wavy collagen fibres that compose it, are maximally stretched.

The CaCL deformation in intact knees curves were increasing uniformly, and the average ligament rigiditiy was 104.4 N/mm (SD 3.6) (TABLE I). Only the CrCL linear stiffness is reported in a ligament tensile test with Femur-CrCL-Tibia system [26]. The stiffness was 265 N/mm at an extension angle of 150°; and, in a test with a cranial movement of the tibia, the stiffness obtained was 224.6 N/mm [26]. In the intact knee the mean value of 104.4 N/mm, far below 224.6 N/mm, indicates less CaCL deformation, and that the ligament was working below its load-bearing capacity due to the involvement of other stabilizers - collateral ligaments, menisci and cartilage.

Instead, CaCL linear rigidity increased in CrCL-deficient knees in response to the shear force, and the values ranged from 125.6 to 143.3 N/mm (SD 7.5) (FIG. 3 and TABLE I). The CrCL consists of a cranio-medial band and a caudo-lateral band, so it acts in both directions. When the CrCL is missing, the force in the CaCL increases. A biomechanical model of the canine knee during gait found that when the CrCL was sectioned, the CaCL tensed for most of the gait cycle, reaching a magnitude equal to 11% of body weight [23].

On the other hand, the ligament deformation in CrCL-deficient knees greatly increased versus the intact knee, and rigidity only did so by a 24.7% on average. So, CrCL-deficient curves show that there is no direct correlation between the increase in CaCL deformation and the rigidity. This could be explained because the total CaCL deformation can vary, as it can be found initially relaxed or taut depending on whether the knee is intact, CrCL-deficient or operated. In the absence of the CrCL, the tibia adopts a more cranial position, since the CrCL is the primary restraint to tibial anterior translation [3], so a CrCL injury causes an anterior shift. DeFrate measured approximately 3 mm translation [7]. This distance is travelled by the CaCL in the caudal movement of the tibia, so the curves show a longer deformation.

Rigidity values for kness with TTA surgery were higher still, with 257.2 N/mm (SD 18.1) on average, similar to that value obtained in a ligament tensile test of 265 N/mm [26]. This high value means that the ligament was very taut and was offering resistance being deformed. Because the linear region is not entirely linear for heterogeneous natural materials, stiffness increases in the last stretch before the beginning of the fibres rupture [20]. It appears that the TTA led the ligament to this limit, above the physiological range. Since this high value in a TTA surgery knee is reached repeatedly while walking, fibres might rupture.

TTA varies the position of the patellar tendon to neutralize the CTT or make it caudal during walking. The high CaCL rigidity shows that tibial advancement promotes a caudal force at 135°, which is absorbed mainly by CaCL during walking. Apelt also observed a caudal displacement of the tibia when the advancement was higher than 10 mm [1]. Shirazi's finite element model of the human knee showed that tibial tubercle elevation in full extension reduces the force on the CrCL from 143 N without advancement to 32 N with a 2.5 centimetre advancement [24]. Therefore, if TTA stops the CTT in extension, this implies greater caudal forces in any other flexion position, where they occur naturally. Shirazi's model shows that the CaCL begins to tense only at a flexion of 20°, and at a flexion of 40° the force goes from 0 without advancement to 100 N with 2.5 cm advancement. However, the caudal shift in direction of the tibia of a healthy knee happens from an angle of 60° [9, 13, 14]. In this canine study the CaCL is tensed from extension position.

On the other hand, the behaviour of the CaCL was somewhat different from the intact and CrCL-deficient knees. At the beginning of the curve the ligament was deformed by applying little force, but the distance travelled was smaller than in the CrCL-deficient (FIG. 3). This effect can be explained because the drawer between the advanced portion of the tuberosity and the tibia tends to displace the latter in the caudal direction. This would imply a permanent pre-tension on the CaCL and a change in the relative position between the joint surfaces. This could have consequences in the normal knee kinematic patterns. Several studies warn that an increase in caudal tibial translation and external rotation is accompanied by an increase in contact pressure in the patellofemoral joint [11, 14, 24].

CONCLUSIONS

CaCL takes a leading role in the caudal movements in CrCL-deficient knees from the extended position. The TTA surgery in canine CrCL-deficient knees causes an unstable behaviour and an overload on the CaCL. Based on mean values of TABLE I, CaCL rigidity under anterior femoral force in a 135° angle extension, increases with TTA 246.4% versus the intact knee, and 188.4% versus CrCL-deficient. Current results further emphasize the need for an integral view of the entire joint in management of disorders. However, experimental models have large limitations to simulate actual conditions within the joint. To reach conclusive results on the effects of TTA on the CaCL, long-term follow-up clinical studies are needed.

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