Anatomy and Biomechanics of the Posterolateral Aspect of the Canine Knee

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ABSTRACT: The purpose of this study was to describe the anatomy and characterize the biomechanics of the posterolateral aspect of the canine knee. Ten adult canine knees were each used for anatomy and biomechanical testing. Distances and motion limits were measured using a 6 degree-of-freedom electromagnetic tracking system. Canine knee dissection reproducibly identified structures present in the human posterolateral knee. The course and attachment sites of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon were similar to human anatomy. Sequential sectioning of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon all significantly increased varus translation at full extension, 60°, and 90° of knee flexion. Sectioning of the fibular collateral ligament significantly increased external rotation at flexion angles near full extension, while popliteus tendon sectioning also significantly increased external rotation at 90° of knee flexion. Based on the fact that the anatomy of the fibular collateral ligament, popliteus tendon, popliteofibular ligament, and the biomechanical properties of the canine posterolateral knee are similar to the human knee, we believe the canine knee is a suitable model to study the natural history of posterolateral knee injuries. The canine model will also prove valuable in the validation of reconstruction techniques and studying the potential development of medial compartment osteoarthritis following posterolateral knee injuries. © 2007 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 25:1231–1242, 2007

Keywords: canine knee; fibular collateral ligament; popliteofibular ligament; popliteus tendon; posterolateral knee

INTRODUCTION

The understanding of the posterolateral aspect of the human knee has significantly increased in recent years.[1–9] However, in vivo animal studies addressing the natural history of injuries to the posterolateral knee have only been reported in rabbit models.[10,11] Anatomic studies on human knees have documented that the fibular collateral ligament, popliteus tendon, and popliteofibular ligament are the primary stabilizers against abnormal varus, external, and coupled posterolateral rotations.[1,3,12] An extensive search of the veterinary literature yielded documentation of only the fibular collateral ligament and popliteus tendon as the primary stabilizers against the same abnormal movement in the canine knee (stifle) joint.[13–16] Moreover, to our knowledge, the popliteofibular ligament has not been previously described in the canine knee. Due to the paucity of detailed information about the posterolateral aspect of the canine knee, the purpose of this study was to perform qualitative and quantitative anatomic dissections and measurements, and to characterize the biomechanics of the posterolateral aspect of the canine knee, similar to previous studies on rabbits,[17] goats,[18] and humans.[4,5,9,10] Furthermore, increased medial compartment stress, degenerative arthritis, and medial meniscal tears have been reported to develop over time as sequelae of untreated or unrecognized chronic posterolateral injuries.[6,19–21] This study will determine if the canine knee is a functional model to further examine the natural history of injuries to the posterolateral aspect of the knee, validate posterolateral reconstruction techniques, and study the potential development and progression of medial compartment osteoarthritis.

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MATERIALS AND METHODS

Canine Knee Specimen Preparation

Ten paired, fresh-frozen, adult cadaveric canine knees (stifles), with an approximate weight of 30 kg, were utilized in this study. The knees were stored at -20°C and thawed out overnight prior to anatomical dissection or biomechanical testing. The specimens were severed at the mid-femur and mid-tibia, and both the proximal and distal ends of the specimens were prepared by removing all soft tissues, followed by potting in polymethylmethacrylate. One limb from each pair was randomly selected for detailed anatomical dissection ($n = 10$: seven left limbs and three right limbs) and the contralateral limb was utilized for biomechanical testing ($n = 10$: three left limbs and seven right limbs).

Measurements

Measurements of anatomical relationships, areas of bony attachments, and biomechanical motion were taken using the Polhemus Fastrak system (Polhemus Incorporated, Colchester, VT). The Fastrak is a 6 degree-of-freedom electromagnetic tracking device that uses a global positioning transmitter and a receiver, either a digitizing stylus or sensors, to capture three-dimensional coordinate locations. The global positioning transmitter consists of three coils on orthogonal axes, which act as solenoids. The receiver has a similar set of three coils (solenoids) on orthogonal axes. An alternating current (AC) current is passed through each coil in the transmitter, which produces a magnetic field. The magnetic field created by the transmitter acts on the solenoids in the receiver to create an electrical current. The difference between the amperage passed through the transmitter and the amperage created in the receiver reports information about the distance of the receiver from the transmitter. Using time multiplexing, the Polhemus system is able to isolate the magnetic fields created by the current passing through the three orthogonal coils on the transmitter. Simultaneous collection of information about the distance of the receiver from the transmitter and isolated magnetic fields in the x, y, and z planes yields the location of the receiver in three-dimensional space for each data point collected.

All of the anatomical measurements and biomechanical data points were collected on a plastic cart and Plexiglas mounting table to minimize the distorting effect that metal has on electromagnetic fields. A distance of approximately 300 mm between the stylus and transmitter was maintained, which was within the previously reported range of 100 to 700 mm for suggested optimal accuracy.[22,23] The accuracy of AC tracking devices has been previously reported to be in the range of 0.3–0.9 mm and $0.3–1^{\circ}$.[23]

Gross Anatomical Dissection

The potted ends of each specimen were mounted into a stabilization device that maintained the knees at 40° of knee flexion, which is within the normal range of motion for canine knees, for dissection and collection of three-dimensional data points. The biceps femoris muscle was reflected anteriorly by separating the broad aponeurotic sheath attachment from the underlying vastus lateralis muscle, separating the calcaneal attachment of the biceps femoris muscle from the calcaneal tendon, and severing the femoral and intermuscular septal attachments of the biceps femoris muscle. Subsequently, the attachment of the biceps femoris muscle to the lateral tubercle of the tibia was severed and outlined with a methylene blue pen; data points were then collected at roughly equidistant intervals around the perimeter of its attachment site. Following the dissection and retraction of the biceps femoris muscle, the calcaneal tendon was severed and the lateral gastrocnemius and flexor digitorum superficialis muscles were reflected proximally.

The lateral patellofemoral ligament (LPFL) was carefully dissected out. The widths of the LPFL at its attachment to the lateral fabella, at its mid-section, and at its attachment to the vastus lateralis tendon were measured. The length of the patella was also measured. The patellar tendon was detached from the tibial tuberosity and the perimeter of its attachment site perimeter was measured.

The combined lateral gastrocnemius/flexor digitorum superficialis muscle attachments to the supracondylar tubercle on the femur were exposed by removing the LPFL. The fabellofemoral ligament was then identified by its location proximomedial to the lateral fabella. The common origin of the lateral gastrocnemius and flexor digitorum superficialis muscles on the supracondylar tubercle of the femur was detached and its outline measured.

A band of tissue stretching from the lateral fabellar capsule to the peroneus longus fascia, corresponding to a fabelloperoneal ligament, also previously identified as the superficial component of the fibular collateral ligament (FCL),[17,18] was isolated and excised. The deeper (medial) FCL was then isolated and width measurements were taken 5 mm distal to its femoral origin near the lateral epicondyle, directly over the lateral meniscus, and 5 mm proximal to its fibular insertion. Data points were also collected along the perimeter of each attachment site. Once the FCL had been detached from the femur, the lateral epicondyle was exposed and its perimeter was measured.

The popliteus tendon (PLT) was identified and isolated next. A data point for the location of the musculotendinous border of the PLT was obtained before the popliteus complex was released from any attachments. The lateral capsular ligament and popliteomeniscal fascicles were qualitatively observed. The popliteofibular ligament (PFL) was dissected out and the widths of its attachments at the fibular styloid process and at the musculotendinous border of the PLT were taken. The PLT was then detached from its femoral attachment and both its attachment site and the bony confines of the popliteal sulcus were outlined. The lengths of the medial tibial attachment of the popliteus muscle and the distance from the proximal border of the popliteus muscle to the tibial plateau were measured next.

The posterior joint capsule was opened and the Ligament of Wrisberg (posterior meniscofemoral ligament), the posterior cruciate ligament (PCL), and caudal meniscotibial ligament were isolated. The caudal meniscotibial ligament was qualitatively observed for its attachment site, spatial relationship to other structures, and cross-sectional shape. The width and length of the Ligament of Wrisberg were measured. The PCL was dissected away from its tibial attachment and its attachment site outlined.

The extensor digitorum longus (EDL) tendon was dissected off of its femoral attachment and outlined. A data point for the location of the medial epicondyle was obtained next to determine interepicondylar width. Finally, the fibula was disarticulated from its tibial attachment to verify that the tibia and fibula were not fused.

Length Calculation

Lengths were calculated using the distance formula:

$$\text{Dist} = \sqrt{(\Delta x^2 + \Delta y^2 + \Delta z^2)}$$

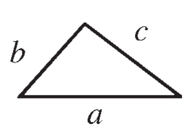
The center of each attachment site was used as the edge of a structure, which was determined by averaging the x-, y-, and z-coordinates. In structures where the area of the attachment site was not measured, the electromagnetic stylus of the Polhemus Fastrak was placed at the center of the attachment site for length calculations.

Attachment Site Area Calculation

The perimeter position of eight sites along each attachment site was outlined using the Polhemus Fastrak system. These Cartesian coordinates were used to calculate the attachment site area. First, the mid-point of the attachment site was determined by averaging the x-, y-, and z-coordinates. Then, the distance from the mid-point to each of the data points was calculated using the distance formula. Next, the distance between a data point and the next data point in sequence was calculated. Thus, by calculating these distances, the attachment site was broken up into a series of triangles. From the calculated distances, the area of each triangle was calculated using Heron's formula:

$$\text{Area} = \sqrt{\frac{(2 * (a^2b^2 + b^2c^2 + c^2a^2) - (a^4 + b^4 + c^4))}{4}}$$

for the following triangle



Finally, the areas of the individual triangles were summed to yield the overall area of the attachment site.

Biomechanical Testing

Specimen preparation for biomechanical testing was previously described in the canine knee specimen preparation section. In addition to the previously described specimen preparation procedure, a hexagonal bolt was potted in the distal polymethylmethacrylate parallel to the long axis of the tibia and fibula. A lock nut was placed on the end of the hexagonal bolt for application of external forces. The knees were tested in a specially designed knee testing apparatus, which consisted of an aluminum clamp and carbon fiber rods. The aluminum clamp secured the femur at a horizontal angle, while the carbon fiber rods, which were attached directly to the aluminum clamp, supported the tibia and fibula at defined testing angles. The testing apparatus was designed to restrict motion of the femur while allowing uninhibited motion of the tibia/fibula within the defined testing angle. In addition, the testing apparatus contained minimal metal parts to minimize interference with the Polhemus testing device. Sensors from the Polhemus Fastrak system were attached to K-wires placed into the anterior cortex of the femur and tibia to measure movement of the tibia with respect to the femur. Coordinate systems were set up for both the femur and tibia using the Polhemus electromagnetic stylus.

Each knee was tested at full extension for that particular knee (mean: 24.4°, range: 18–32°, 60°, and 90°). According to previously reported sequential posterolateral structure sectioning studies by Gollehon et al.[1] and LaPrade et al.,[8] the knees were tested in the intact state and with sequential sectioning of: (1) the FCL at the joint line, (2) the PFL from the fibular head, and (3) the PLT at its femoral attachment. The following loads were applied at all flexion angles and for each testing state: 3.25 Nm of varus torque and 1.25 Nm of internal and external rotation moments. Varus torque was measured by a load cell (Interface Force, Scottsdale, AZ). Internal and external rotational moments were measured by a 17 kg cm Torqometer (Snap-on Tools Corporation, Kenosha, WI) with a manufacturer's reported accuracy of ±2%. Each knee was tested three times at each flexion angle and the results averaged. As loads were applied to the knee, the Polhemus Fastrak system detected the change in angulation between the coordinate systems previously defined for the tibia and femur. Motion Monitor Software (Innovative Sports Training, Chicago, IL) used the Polhemus Fastrak system output to characterize the rotational motion of the tibia with respect to the femur.

Biomechanics Data Analysis

To standardize the starting position, the mean angulation prior to any application of load in the intact state was calculated and used as the origin for tests in all states at that flexion angle. The mean difference between the origin and the endpoint angulation was calculated for the three tests performed for each flexion angle and sectioned state. The mean and standard deviation were then calculated for the 10 knees at each flexion angle and sectioned state. The amount of rotational change with an applied force was indicative of the amount of knee stability. Subsequently, a

Student's t-test was performed at the $p < 0.05$ significance level to evaluate statistically significant changes in angulation between the different sectioned states at each flexion angle.

RESULTS

All distances and areas are reported as mean values. Distances between structures are reported to the calculated midpoint of their attachment sites based on the average of the x-, y-, and z-coordinates of the perimeter of the attachment sites.

Overview of Bony Anatomy

The canine knee consisted of tibiofibular, tibiofemoral, fabellofemoral, and patellofemoral articulations. The femur had a deep trochlear groove with prominent medial and lateral ridges that allowed the elliptically shaped patella to articulate within it. The mean length of the patella was 23.2 mm (Table 1). The posterosuperior borders of the medial and lateral femoral condyles were flat to allow articulation with the medial and lateral fabellae. Directly on the femur, superior to the lateral fabellar articulation, was the supracondylar tubercle. The extensor fossa was located on the anterior portion of the lateral femoral condyle and surrounded the origin of the EDL tendon on three sides. The popliteal sulcus followed the curvature of the lateral condyle along the distal edge of the femur. The average area of the popliteal sulcus was 40.5 mm^2 (Table 2). The lateral epicondyle was a broad elevated area with a smaller, more

Table 1. Quantitative Measurements of the Posterolateral Canine Knee

Distances[a]	Mean (mm)	SD	Range (mm)
FCL width 5 mm distal to femoral attachment	6.0	1.1	3.9–7.6
FCL width over joint line	5.6	0.9	4.3–6.9
FCL width 5 mm proximal to fibular attachment	5.8	1.1	4.0–7.7
FCL length	37.1	5.5	28.5–48.5
Femoral origin of FCL to lateral epicondyle	6.8	2.3	3.4–10.7
Femoral origin of FCL to femoral attachment of PLT	11.1	3.3	5.4–15.7
Femoral origin of FCL to femoral attachment of lateral gastrocnemius	20.7	6.0	9.7–28.3
Femoral origin of FCL to femoral attachment of LPFL	18.6	4.6	11.0–27.4
Fibular insertion of FCL to anterior border of fibula	6.8	3.5	2.9–13.4
Fibular insertion of FCL to posterior border of fibula	11.6	3.8	5.4–17.5
Fibular insertion of FCL to proximal border of fibula (in line with FCL insertion)	10.7	2.8	6.6–15.0
Fibular insertion of FCL to proximal border tip of the fibular styloid process	13.7	3.2	9.1–19.9
PLT length	12.6	2.3	8.9–15.7
PLT femoral attachment to lateral epicondyle	11.0	4.1	5.4–16.6
PFL width at fibular attachment	7.0	2.6	3.9–11.9
PFL width at attachment to PLT	5.9	2.4	2.8–10.4
PFL length	5.1	1.6	2.5–7.2
Tibial attachment of popliteus muscle to proximal border of tibial plateau	14.3	5.0	7.1–20.7
Popliteus muscle medial tibial attachment length	57.1	9.0	40.7–72.6
Ligament of Wrisberg length	20.6	5.9	11.2–30.5
Ligament of Wrisberg midportion width	4.9	1.2	2.6–7.2
LPFL length	21.2	3.5	16.2–25.5
LPFL width at vastus lateralis attachment	9.8	2.4	5.2–13.4
LPFL midportion width	7.5	1.4	5.0–9.6
LPFL width at lateral gastrocnemius attachment	12.0	3.7	6.5–16.5
Femoral attachment of LPFL to lateral epicondyle	19.6	5.8	9.9–25.9
Patella length	23.2	4.6	16.2–29.9
Femoral lateral gastrocnemius attachment to lateral epicondyle	30.6	7.2	19.8–40.1
Epicondyle width	33.3	3.2	29.7–38.9

FCL = fibular collateral ligament; PLT = popliteus tendon; PFL = popliteofibular ligament; LPFL = lateral patellofemoral ligament; SD = standard deviation.

[a]Distances calculated from the midpoint of attachment site.

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Table 2. Attachment Areas of Posterolateral Canine Knee Structures

Area	Measurement (mm^2)	SD	Range (mm^2)
Biceps femoris attachment to lateral tibial tubercle	28.9	8.8	15.6–48.1
FCL femoral attachment	38.0	12.3	17.6–55.2
FCL fibular attachment	25.4	12.1	15.4–52.7
Popliteus tendon femoral attachment	24.4	4.6	18.5–33.0
PCL tibial attachment	34.2	9.7	20.8–51.9
Patellar tendon tibial attachment	59.7	11.0	43.6–74.8
EDL tendon femoral attachment	21.5	7.1	10.9–34.5
Popliteal sulcus	40.5	7.6	28.2–55.3

FCL = fibular collateral ligament; PCL = posterior cruciate ligament; EDL = extensor digitorum longus; SD = standard deviation.

distinct elevated peak. The width between the medial and lateral epicondyles on the femur was 33.3 mm (Table 1).

The surface of the lateral tibial plateau was convex both in the coronal and sagittal planes with a more exaggerated posterior downslope. The posterior mid-portion of the proximal tibia had a prominent indentation between the medial and lateral plateaus (popliteal notch).[14–16] The PCL attached to the medial aspect and the caudal meniscotibial ligament inserted on the lateral aspect of the popliteal notch. The posterolateral surface of the proximal tibia had an oblique facing facet that articulated with the fibular head. On the anterior border of the lateral tibial plateau, the EDL tendon coursed through the extensor groove. The tibial crest was long and located along the anterior border of the tibia. It served as the distal attachment site for the gracilus, sartorius, and semitendinosus muscles as well part of the biceps femoris aponeurosis.[14] The tibial tuberosity was located at the proximal edge of the tibial crest and served as the insertion site of the patellar tendon (Table 2). Located proximolateral to the tibial tuberosity was the lateral tubercle of the tibia, which served as a significant distal attachment of the biceps femoris.

The fibula articulated proximally with a small medial facet on the posterolateral aspect of the tibia. It was closely associated with the tibia distally, but they were not fused.

Due to the number of ligaments surrounding the lateral fabella, it appeared to have its own capsule. On the medial edge of the lateral fabella, there was a fabellofemoral ligament, which coursed proximally and anteriorly from the fabella to the femur.

A cyamella (popliteal sesamoid) was located within the popliteus muscle on the posterior side of the musculotendinous border in all specimens. It articulated with the posterolateral aspect of the lateral tibial plateau.

Overview of Soft Tissue Anatomy

Biceps Femoris Muscle

The biceps femoris muscle was superficial and covered almost the entire lateral aspect of the thigh and leg. Six distal insertions were noted, including the following: (1) a broad attachment to the fascia lata superficial to the vastus lateralis muscle; (2) a fibrous connection to the femur just lateral to the vastus lateralis; (3) a fibrous connection to the lateral intermuscular septum; (4) a strong tendinous attachment to the lateral tubercle of the tibia (Fig. 1); (5) a broad distal aponeurotic sheet that extended from the patella distally over two-thirds of the tibia; (6) a thick tendinous band with a common insertion to the calcaneal tendon.

Fabelloperoneal and Fibular Collateral Ligaments (FCL Complex)

The FCL complex was consistently composed of the FCL and the more laterally located fabelloperoneal ligament that could be individually distinguished by their shape, course, and attachment sites. The fabelloperoneal ligament coursed lateral to the FCL and was a wide, ribbon-like structure that could be identified by its anterodistal course from the lateral fabella to its broad, diffuse attachment to the fascia posterolateral to the peroneus longus muscle. The deeper located FCL was a stout cord-like structure that coursed distal from its femoral attachment near the lateral epicondyle to the fibular head. The FCL was 37.1 mm in length, and had widths of 6.0 mm near its femoral origin to 5.6 mm over the joint line to 5.8 mm in width near its fibular insertion (Table 1). The femoral attachment of the FCL (Table 2) was located 6.8 mm posteroproximally to the lateral epicondyle (Table 1). The FCL fibular attachment was: (1) 6.8 mm posterior to the

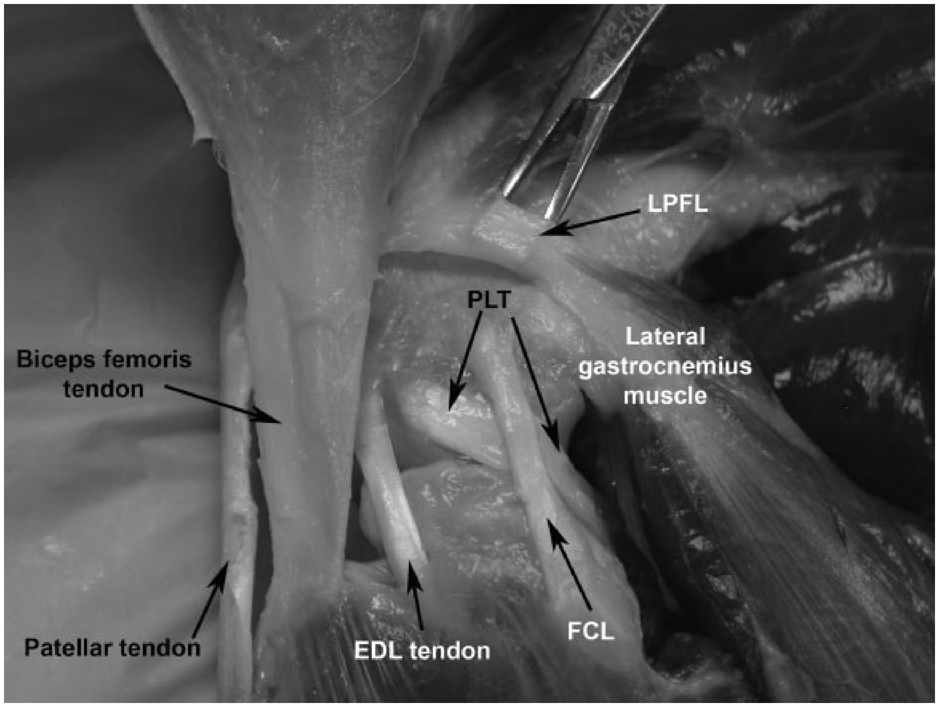

Figure 1. Photograph of a canine knee displaying the soft tissue structures of the lateral aspect of the posterolateral knee. The muscle belly and femoral attachment of the flexor digitorum superficialis muscle (not shown) lies anterior to and is completely covered by the muscle belly of the lateral gastrocnemius muscle[15] (lateral view, left knee). Legend: EDL = extensor digitorum longus; PLT = popliteus tendon; FCL = fibular collateral ligament; LPFL = lateral patellofemoral ligament.

anterior border of the fibula; (2) 11.6 mm anterior to the posterior border of the fibula; (3) 10.7 mm distal to the proximal border of the fibula; and (4) 13.7 mm distal to the tip of the fibular styloid (Table 1 and Figs. 1 and 2).

Lateral Patellofemoral Ligament

The lateral patellofemoral ligament (LPFL) originated from the lateral fabella and coursed anteriorly with a close association with the vastus lateralis tendon (Table 2 and Fig. 1). It passed deep to the vastus lateralis tendon and inserted onto the lateral border of the patella. The LPFL was a wide, sheet-like structure with widths of 12.0 mm at its fabellar attachment, 7.5 mm at its mid-portion, and 9.8 mm at its association with the vastus lateralis tendon (Table 1). Its length was 21.2 mm (Table 1). Fibers from the lateral gastrocnemius muscle ran parallel to the LPFL and eventually joined into a common insertion on the lateral border of the patella (Fig. 1).

Popliteus Complex

The components of the popliteus complex included the popliteus muscle and its tendon, the popliteofibular ligament (PFL), and popliteomeniscal fascicles. The medial attachment of the triangularly shaped popliteus muscle was on the posterior aspect of the medial tibia, 14.3 mm distal to the medial tibial plateau (Table 1), and was 57.1 mm (Table 1) long on the medial tibia. The muscle then narrowed as it traveled superior and anterolaterally until its distinct musculotendinous border where it became a ribbon-like tendon (Fig. 2). The PFL was located at the popliteus musculotendinous junction and was 5.9 mm wide at this attachment, 6.0 mm wide at its fibular attachment, and 5.1 mm in length (Table 1 and Fig. 2). The PLT became intraarticular, passed medial to the FCL and lateral to the lateral meniscus, and coursed to its femoral attachment on the popliteus sulcus, located 11.0 mm (Table 1) from the lateral epicondyle (Fig. 1). The length of the PLT was 12.6 mm (Table 1). Intraarticularly, there were three distinct popliteomeniscal fascicles attaching the PLT to the lateral meniscus. The posterosuperior popliteomeniscal fascicle attached the superior border of the PLT to the superior border of the lateral meniscus along the posterior aspect of the popliteal hiatus. The anteroinferior and the posteroinferior popliteomeniscal fascicles coursed

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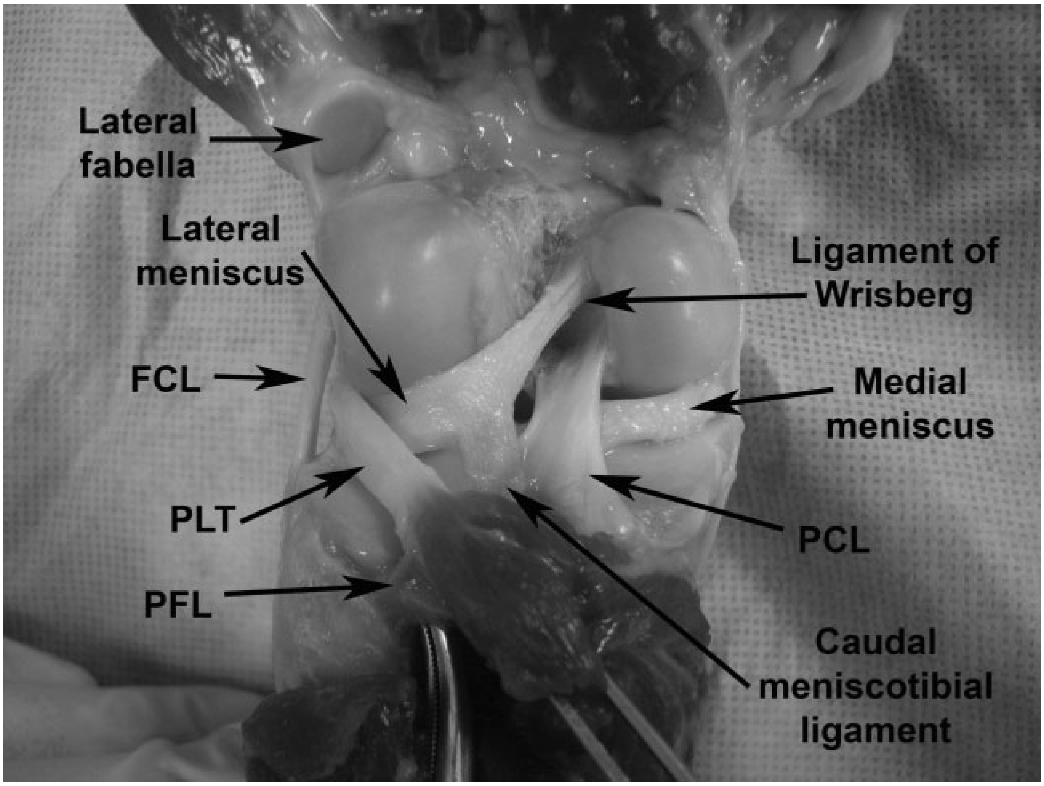


Figure 2. Photograph of the posterior anatomy of the canine knee (left knee, joint capsule removed). Legend: FCL = fibular collateral ligament; PLT = popliteus tendon; PFL = popliteofibular ligament; PCL = posterior cruciate ligament.

distally together along the anterior aspect of the popliteal hiatus to blend with the proximal portion of the PFL. The anteroinferior popliteomeniscal fascicle attached the anterolateral portion of the lateral meniscus to the inferior border of the PLT. The posteroinferior popliteomeniscal fascicle attached the posterior horn of the lateral meniscus to the distal medial border of the PLT. Further lateral and anterior than the popliteomeniscal fascicles, the lateral capsular ligament was a wide and stout thickening of the lateral capsule that appeared to limit the ability of the PLT to move out of the popliteus sulcus. Upon severing the lateral capsular ligament, the PLT was qualitatively noted to have increased mobility to move proximally and distally out of the popliteal sulcus.

Extensor Digitorum Longus Tendon

The femoral attachment of the EDL tendon had an area of 21.5 mm^2 (Table 2 and Fig. 1). After crossing the joint line, the EDL tendon coursed within a thick fascial compartment between the peroneus longus and tibialis anterior muscles. As previously described, the EDL tendon coursed through the extensor groove on the anterior surface of the tibia. The tendon was held in this bony channel by a thick overlying transverse ligament.

Lateral Gastrocnemius Muscle/Flexor Digitorum Superficialis Muscle Complex

The common origin of the lateral gastrocnemius and flexor digitorum superficialis muscles on the supercondylar tubercle of the femur was in the shape of a "shepherd's hook" with the long section of the hook anterior and the curved edge proximal (Fig. 1). The flexor digitorum superficialis muscle, analogous to the human plantaris muscle was distinguished from the lateral gastrocnemius muscle proximally by its posterior position, where it only attached to the supracondylar tubercle on the femur, versus the lateral gastrocnemius muscle, which attached to both the supracondylar tubercle on the femur and the LPFL. Distally, the flexor digitorum superficialis muscle was anterior to the lateral gastrocnemius muscle. Both of these muscles inserted distally onto the calcaneal tendon.

Ligament of Wrisberg (Posterior Meniscofemoral Ligament)

The Ligament of Wrisberg was a stout ligamentous attachment between the lateral meniscus and the medial edge of the femoral portion of the intercondylar notch proximal to the posterior cruciate ligament (PCL) attachment. From its femoral attachment, it traveled distolaterally and posterior to the PCL until it attached directly to the posterior horn of the lateral meniscus (Fig. 2). The Ligament of Wrisberg was 20.6 mm in length and 4.9 mm in width at its mid-portion (Table 1).

Caudal Meniscotibial Ligament

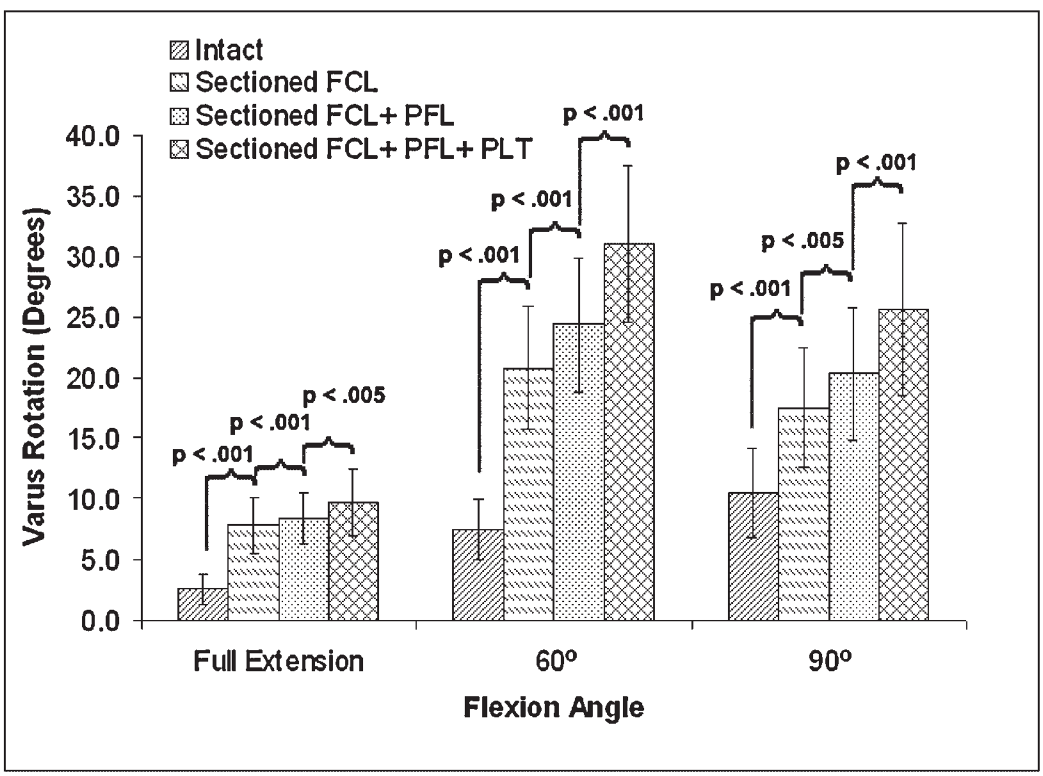
The caudal meniscotibial ligament was a stout ligament with a thickened ribbon shape. It originated on and coursed posterior to the superior border of the junction between the posterior horn of the lateral meniscus and the Ligament of Wrisberg and inserted at the base of the lateral tibial plateau on the lateral aspect of the popliteal fossa on the tibia (Fig. 2).

Posterior (Caudal) Cruciate Ligament (PCL)

The PCL had a stout femoral attachment that originated inferior to the Ligament of Wrisberg on the medial edge of the intercondylar notch of the femur. It widened as it coursed distolaterally and inserted onto the medial aspect of the popliteal fossa on the tibia (Fig. 2). The area of its tibial insertion was 34.2 mm^2 (Table 2).

Biomechanical Results

Sequential sectioning of the FCL, PFL, and PLT significantly increased varus angulation with an applied varus torque with each sequentially sectioned structure at full extension, 60°, and 90° of knee flexion for each sectioned state ($p < 0.005$) (Fig. 3). Internal rotation was significantly



Degrees of Varus Opening to a 3.25 Nm Moment

Degrees of flexion	Intact		Sectioned FCL		Sectioned FCL+ PFL		Sectioned FCL+ PFL+ PLT	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Full Extension	2.5	1.2	7.8	2.2	8.4	2.1	9.7	2.8
60°	7.4	2.5	20.8	5.1	24.3	5.5	31.0	6.5
90°	10.5	3.7	17.5	5.0	20.3	5.5	25.6	7.1

Figure 3. Graph of change in varus rotation as a result of a 3.25 Nm applied varus moment with sequential sectioning of the FCL, PFL, and PLT. Legend: FCL = fibular collateral ligament; PFL = popliteofibular ligament; PLT = popliteus tendon; SD = standard deviation.

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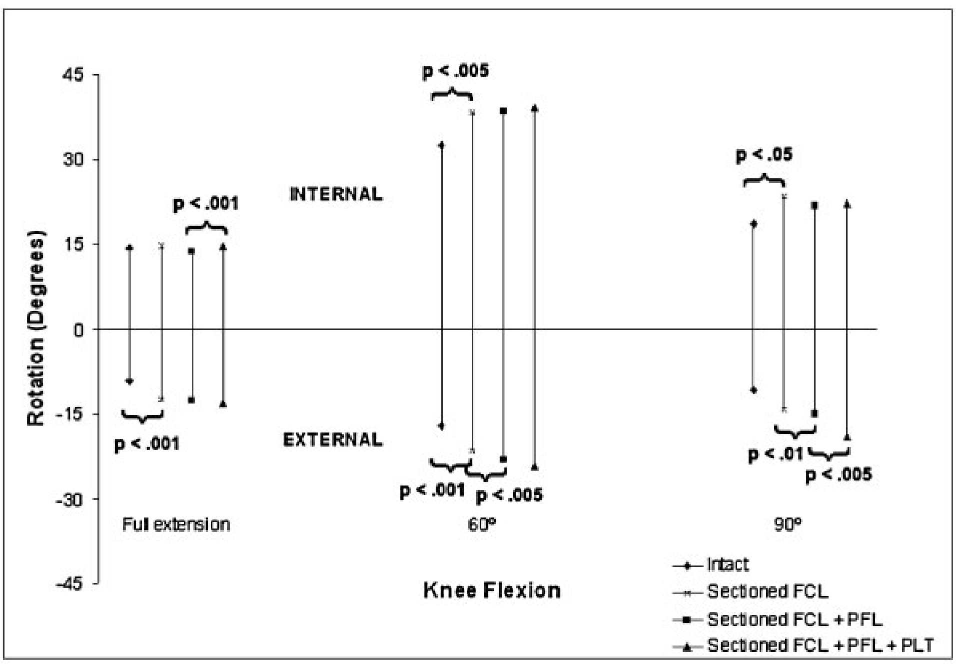
increased at 60° and 90° of knee flexion as a result of FCL sectioning ($p < 0.05$) (Fig. 4). Internal rotation was also significantly increased at full extension as a result of PLT sectioning ($p < 0.001$) (Fig. 4). At full extension, sectioning of the FCL significantly increased external rotation ($p < 0.0005$) (Fig. 4). At 60° of knee flexion, combined sectioning of both the FCL and the PFL significantly increased external rotation ($p < 0.005$) (Fig. 4). Moreover, combined sectioning of the PFL and the PLT increased external rotation at 90° of knee flexion ($p < 0.01$) (Fig. 4).

DISCUSSION

Injuries to the posterolateral aspect of the knee have been shown to cause rotational and varus instability as well as increased forces on the cruciate ligaments of the knee.[8,24–26] Studies have documented that the most important posterolateral structures in the human knee are the FCL, PLT, and PFL, which are the primary stabilizers against abnormal varus angulation and tibial internal and external rotation.[1,3,12,27,28] The posterolateral structures also serve an important secondary role in the prevention of anterior and posterior translation of the knee with cruciate ligament deficiency.[1,3,26–28] Until this study, the anatomy of the individual structures of the canine posterolateral knee and the roles of individual posterolateral structures in preventing abnormal joint motion in the canine knee had not been previously established in the literature.

The anatomy of the posterolateral aspect of the canine knee exhibits considerable resemblance to the human knee. The courses and attachment sites of the FCL, PLT, and PFL are almost identical between the human and the canine knees.[5,12,29]



Degrees of Internal Rotation to a 1.25 Nm Moment

Degrees of flexion	Intact		Sectioned FCL		Sectioned FCL+ PFL		Sectioned FCL+ PFL+ PLT	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Full Extension	13.7	5.4	15.3	7.4	15.3	6.5	16.2	6.5
60°	30.1	11.9	35.8	14.5	36.8	13.7	37.5	13.9
90°	19.5	7.6	24.5	11.5	25.4	11.1	27.0	11.1

Degrees of External Rotation to a 1.25 Nm Moment

Degrees of flexion	Intact		Sectioned FCL		Sectioned FCL+ PFL		Sectioned FCL+ PFL+ PLT	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Full Extension	8.5	2.7	11.7	2.7	12.7	2.6	13.4	2.9
60°	20.1	7.5	24.8	8.2	26.7	8.6	31.5	13.1
90°	14.1	5.9	16.7	9.5	18.0	10.0	24.4	13.3

Figure 4. Graph of change in internal and external rotation as a result of a 1.25 Nm applied internal or external applied moment with sequential sectioning of the FCL, PFL, and PLT. Legend: FCL = fibular collateral ligament; PFL = popliteofibular ligament; PLT = popliteus tendon; SD = standard deviation.

The bony anatomy of the canine knee is also very similar to the human knee with the convex shaped lateral tibial plateau articulating with a convex-shaped lateral femoral condyle.[30] In addition, the canine fibula is a separate structure, and is not fused to the tibia as it is in the rabbit or goat knees.[17,18]

The largest differences between the canine knee and the previously studied animal posterolateral knee models involved their bony anatomy and the presence of the PFL. We theorize that the differences in the bony anatomy of canine versus goat knees contributed to the greater amount of abnormal motion limits found in the canine knee with sequential sectioning of the posterolateral structures. The fibular head in the fused tibia and fibula of the rabbit knee was distal to the lateral tibial plateau surface and had an overall bony architecture similar to the shape of the human knee,[17] while the fibular head in the fused tibiofibula of the goat knee was fused to the proximal edge of the lateral tibial plateau and formed a bony prominence, which functioned as a buttress against lateral motion.[18] This bony prominence formed a concave shape in the coronal plane of the lateral tibial plateau of the goat knee, which produced more bony stability than the two opposing convex surfaces of the lateral femoral condyle and lateral tibial plateau in canine and human knees.[11,17,18] In addition, the well-defined PFL present in the canine knee was not found in previous work on rabbit and goat posterolateral knee anatomy.[17,18]

There were differences in the musculature between the canine and human knees. Anteriorly, the origin of the EDL muscle in the canine knee was proximal to the joint line, whereas the analogous structure in the human knee originated distal to the joint line. Posteriorly, the FDS muscle in the canine knee was located at the medal aspect of the lateral gastrocnemius muscle, similar to the location of the plantaris muscle in the human knee.

The significant and dramatic increase in varus rotation as a result of sectioning of the FCL in the canine knee indicates that it is the primary restraint to varus rotation at all flexion angles, which has already been shown in biomechanical studies on human knees.[1,3,31] The canine posterolateral knee biomechanics are also similar to the human knee in that sectioning of the PLT and PFL further significantly increased varus rotation.[1,3,27] Moreover, the canine knee also displayed greater varus rotation than was seen in previous experiments involving rabbit and goat knees.[17,18]

Sectioning the posterolateral structures in the canine knee had a limited effect on internal rotation, similar to findings in human knees.[27,32] Popliteus tendon sectioning resulted in significant increases in internal rotation near full extension, while FCL sectioning resulted in significant increases in internal rotation at greater degrees of knee flexion, which is similar to the findings in human knees.[32] Nielsen et al.[32] showed that sectioning of the FCL and the posterolateral knee structures resulted in a significant increase in internal rotation in a knee with flexion $>50^\circ$, while Veltri et al.[27] found small, but significant, increases in internal rotation at 30°, 60°, and 90° with posterolateral structure sectioning compared to intact knees.[27]

Sectioning of the posterolateral structures had a significant effect on external tibial rotation in both the canine and human knees.[1,3,32] Previous experiments in human knees have shown that sectioning of the FCL, as well as the popliteus complex, resulted in a significant increase in external tibial rotation at all knee flexion angles compared to intact knees.[1,3] These findings are consistent with the findings in the present study, where external tibial rotation was significantly increased in joints near full extension following FCL sectioning and at higher flexion angles, closer to 90° of knee flexion, following sectioning of the PFL and PLT.

To the best of our knowledge, the tendinous attachment of the biceps femoris to the lateral tubercle of the tibia had not been previously described in the canine literature, but this attachment was as stout as any other tendon attachment to bone in the canine posterolateral knee (Fig. 1). In human anatomy, this bony structure is the attachment site for the superficial layer of the iliotibial band and is also referred to as Gerdy's tubercle.[5]

Although in vivo study of the rabbit knee 6 months following surgical creation of posterolateral instability demonstrated a progression toward the development of medial compartment arthritis, the overall instability of the rabbit knee was less than that in the canine knee following the sectioning of the posterolateral structures.[11] Due to this increased instability in the canine knee and the fact that laboratory canines exercise their knees more than rabbits, we theorize that the canine knee will develop medial compartment arthritis subsequent to sectioning of the posterolateral structures. The human literature has reported that the long term sequelae of chronic isolated and combined posterolateral knee injuries are medial meniscal tears and degenerative arthritis, primarily of the medial compartment.[6,19–21] Development of a posterolateral knee instability model in animals would allow for the initiation of intervention studies to determine if the natural history of untreated posterolateral knee injuries can be altered. This information would help to determine if a more assiduous clinical recognition of this instability pattern, as well as a more universal treatment plan, would lead to improved outcomes and less knee osteoarthritis over time.

To account for the differences in canine body size, epicondyle width was assessed to determine if size normalization was necessary. However, with a low standard deviation in epicondyle width (Table 1), we believe no normalization was necessary.

In conclusion, the FCL, PLT, and PFL of the canine knee have very similar morphology as in the human knee. In addition, there was a significant increase in the varus, internal, and external rotation of the canine knee following the sectioning of these structures. We believe that the canine model will prove valuable to the in vivo study of the natural history of posterolateral knee injuries and provide validation of reconstruction techniques. Furthermore, the canine model displays potential for the validation of posterolateral knee injury involvement in the development and subsequent progression of medial compartment osteoarthritis.

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