Preoperative Tibial Plateau Leveling Osteotomy Planning Using the Conventional and Common Tangent Methods: A Cadaveric Study

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Academic Abstract

Objective - To compare preoperative tibial plateau leveling osteotomy planning using the common tangent method to the current conventional method and evaluate the effect on tibial translation and patellar ligament angle following rotation of the tibial plateau.

Study Design – Cadaveric study. Seven paired canine pelvic limbs.

Methods- Radiographs of the stifle were taken at 135° of extension prior to and following rotation of the tibial plateau under load (0N and 30N). The tibial plateau of each limb was rotated both according to the common tangent and conventional method. Tibial plateau angle (TPA), tibial translation, and the patellar ligament angles (PLA) were measured radiographically following rotation of the tibial plateau.

Results- There was no significant difference between planning methods with regards to the amount of rotation of the tibial plateau or position of the tibia relative to the femur following rotation. There was no significant association between the postoperative tibial plateau angle and position of the tibia relative to the femur between groups. There was no significant difference between the patellar ligament angles following rotation based on the common tangent or conventional method preoperative TPLO planning.

Conclusion- Both the conventional and common tangent TPLO planning results in adequate proximal tibial rotation to achieve a PLA of approximately 90°, thereby counteracting the compressive shear forces during ambulation. The TPA for both groups following rotation had no significant impact on the amount of cranial or caudal tibial translation relative to the femur.

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Public Abstract

Cranial cruciate ligament disease is one of the most common diseases of the stifle in dogs, and causes great discomfort. The tibial plateau leveling osteotomy (TPLO) procedure is designed to change the geometry of the tibia's articular surface, such that the femur no longer slides in a caudal direction during weight bearing. Conventional methods of planning do not consider the curved anatomical surface of the tibial condyles, but rather treat the condyles like a flat surface. The goal of this study was to compare the current conventional planning methods with a new technique, the common tangent method, and to evaluate if the common tangent method improves accuracy and tibial translation after surgery.

Results of this study show that there was no statistically significant difference in rotation and tibial position between the two planning groups. However, it was found that the common tangent method consistently required less rotation of the tibial articular surface than the conventional method, but still achieved similar postoperative tibial translation. This implies that there may be overcorrection when performing the TPLO under the current conventional method, which could predispose the patients to strain on the caudal cruciate ligament and patellar ligament leading to discomfort. The common tangent method is a feasible way of planning for a TPLO procedure, and shows potential utility in cases where excessive tibial rotation would otherwise cause increased risk for complications or necessitate a more complex procedure.

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TPLO – Tibial plateau leveling osteotomy

CrCL – Cranial cruciate ligament

CdCL – Caudal cruciate ligament

CrCLD – Cranial cruciate ligament disease

GAG – Glycosaminoglycans

TPA – Tibial plateau angle

R-TPA – Radiographic tibial plateau angle; A-TPA – Anatomic tibial plateau angle

BCS – Body condition score

ICN – Intercondylar notch

CT – Computed tomography

EBA – Exam before anesthesia

EDA – Exam during anesthesia

MRI – Magnetic Resonance Imaging

CCR – Correct classification rate

MMR – Medial meniscal release

ECR – Extracapsular repair

PLA – Patellar ligament angle

PLA_{TP} – Patellar ligament angle with respect to tibial plateau

PLA_{CT} – Patellar ligament angle with respect to common tangent

TTA – Tibial tuberosity advancement

ALPS – Advanced locking plate system

Conv. PL – Conventional planning stifle under preload

Conv. AL – Conventional planning stifle under afterload

CTan PL – Common tangent planning stifle under preload

CTan AL – Common tangent planning stifle under afterload

SSI – Surgical site infection

CHAPTER I: LITERATURE REVIEW

1) Cranial Cruciate Ligament

a. Anatomy

The stifle is a complex joint with several significant ligaments that work to stabilize the joint. The most frequently evaluated and studied in dogs is the cranial cruciate ligament (CrCL). The cranial and caudal cruciate ligaments are so named based on the location of their insertion along the proximal tibia. The cruciate ligaments are located centrally in the intercondylar fossa within the joint capsule, but are extrasynovial. The cranial cruciate ligament runs from the caudomedial part of the lateral condyle of the femur, travels diagonally across the intercondylar fossa, and inserts on the cranial intercondyloid area of the tibia, caudal to the transverse ligament of the menisci. The caudal cruciate ligament (CdCL) originates at the lateral surface of the medial femoral condyle and travels across the intercondylar fossa to the lateral edge of the popliteal notch of the tibia. The CdCL is the longer and thicker cruciate, and also lies medial to the CrCL. A detailed evaluation of the fibers of the cranial and caudal cruciate ligaments was performed in over 30 cadaver stifles.[1] The CrCL insertion on the tibia is generally comma shaped with a craniocaudal orientation, and a portion of the ligament may be found attached to the cranial lateral aspect of the medial intercondylar tubercle. The CrCL crosses the stifle between the femur and tibia with fibers oriented such that they exhibit a proximal-to-distal outward spiral of about 90°. The CrCL was also found to have two parts: a craniomedial and caudolateral band. The CdCL femoral attachment exhibits an elliptical shape, where the long axis is horizontal and the cranial most attachment can reach as far as the trochlea. In approximately 63% of cases in this cadaveric study, femoral attachment of the caudal cruciate ligament contains fibers from the femoral ligament of the lateral meniscus. The orientation

of the fibers along the femur and tibia produces a proximal-to-distal inward spiral, opposite of the direction of the CrCL. The CdCL is also divided into two parts, a cranial and caudal band.[1]

The orientation of the fibers, the positioning of the cruciate ligaments in relation to one another, and their respective points of attachment within the stifle all collaborate to provide complex movement and function within the stifle during range of motion. In the 1977 study by Arnoczky, the mobility of the stifle was evaluated, and they found that the components of the cranial and caudal cruciate ligaments work independently of one another throughout flexion and extension of the stifle.[1] The caudolateral part of the CrCL is taut in extension and loose in flexion, while the craniomedial band is taut in extension and flexion. This is because as the stifle is flexed, the origin of the fibers in the caudolateral part are brought closer to the tibial attachment, leading to relaxation. On the other hand, the fibers of the craniomedial band moved caudoventrally rather than cranially, so even with a flexed stifle, the band remains taught. The cranial part of the CdCL is taut in flexion and loose in extension, while the caudal band is loose in flexion and taut in extension. As the stifle is flexed, the cranial band of the CdCL has fibers moving cranially and away from the tibial attachment and thus becomes taut. Conversely, the origin of the caudal band moves ventrally and closer to the tibial attachment during flexion, leading to relaxation.

After evaluating the gross morphology of the ligaments, Arnoczky discovered the functions of each component and the effect on stifle stability if they were transected. With the CrCL intact, no cranial displacement of the tibia relative to the femur was seen. When the craniomedial band was transected, there was 1.5 mm cranial tibial displacement, but with the caudolateral band alone transected, there was no displacement. With the entire cranial cruciate ligament transected, there was cranial subluxation of the tibia of 2 mm in extension, and 9.5 mm in 90°

flexion. Transection of the CdCL did not lead to tibial translation. Under normal intact conditions for both cruciate ligaments, the average internal rotation was 6°, and external rotation was 5° in extension. During flexion of a normal stifle, there was 19° internal rotation, and 8° external rotation. When the CrCL was transected, internal and external rotation increased to an average of 15° and 5°, respectively.[1] With the stifle flexed to 90°, the difference was even more significant with internal rotation of 45° and external rotation of 8°. Finally, CrCL transection resulted in 12° of stifle hyperextension when placed through full range of motion, and the study showed that the CrCL is the first to be damaged with hyperextension. Therefore, this led Arnoczky to conclude that the CrCL is the primary check against cranial drawer motion, and that both cruciate ligaments are especially important in maintaining rotational stability.[1]

Arnoczky's findings are similar to those of other studies that reported hyperextension with cranial cruciate ligament deficiency in dogs.[2–5] Arnoczky's paper, while extremely thorough, is limited in that it only evaluated the ligaments alone, omitting the significant contribution that the surrounding musculature makes to the overall stability of the stifle. Barclay and Theresa Devine Slocum described a more active model that included the influence that weight bearing and the surrounding musculature has on stifle motion.[3] In this model, they stated that cranial tibial thrust, or translation created by weight bearing and muscular compression of the tibial plateau against the femoral condyles, is balanced by the pull of the stifle flexors of the thigh (termed 'active components') and the CrCL and caudal horn of the meniscus ('passive components'). This model was developed to further justify surgical techniques to repair the cruciate deficient stifle described in later sections of this review.[3]

Several studies have since focused on how manipulations of the CrCL affects stifle biomechanics. One experimental study in dogs evaluated the

mechanoreceptors of the CrCL in dogs and cats, and found that tonic activity in the hamstring and quadriceps muscles increased in response to physiological loading on the cruciate ligament.[6] This suggested that the activity of muscles that help stabilize the stifle can be controlled by the load on the CrCL, supporting the active model of Slocum that both the surrounding muscles and the intra-capsular ligaments are vital for maintaining stifle stability.[6] In a study by Korvick et al., attempts to evaluate the kinematics of the stifle in a dynamic state further elaborate on the work done by Arnoczky.[7] This study involved the use of plates surgically attached to the femur and tibia to facilitate attachments for linkages that allowed them to collect kinematic data. They found dogs carried their cranial cruciate deficient ligament (CrCLD) stifle in greater joint flexion (5-14°) during walking, and that internal rotation increased with transection, especially during mid-stance phase of their gait. Cranial displacement of the tibia in relation to the femur occurred in all phases, with the most severe at the beginning of the stance phase with an average displacement of 10 mm. Compression (defined as the femoral condyle subluxating caudally, resulting in a position distal to the surface of the tibial plateau on the vertical axis) was also more abrupt at the beginning of the stance phase.[7]

Cadaveric studies have also evaluated the effect CrCLD had on cranial tibial displacement. A study by Reif et al. demonstrated an average cranial tibial translation of 14 mm post transection, while a study by Warzee et al. reported an average of 18.9 mm, both higher than that reported in Arnoczky's paper.[8,9] This may be due to the differences in measuring translation as well as advancements in biomechanical testing in the 30 year gap between the described studies.

Several in vivo studies were performed to interpret stifle joint kinematics with dogs with CrCLD. One study by Rey et al. evaluated the pattern of sagittal motion of the femur and tibia using fluoroscopic video sequences.[10] The results

suggested that the primary source of instability in the stifle was caudal subluxation of the femur, not cranial tibial subluxation. This theory contrasts with the majority of published literature, and comparison to other studies is difficult given low sample size (n=13) and the subjective nature of the acquired measurements.[10] Alternatively, a recent study from the University of Florida used 3-dimensional fluoroscopic analysis to measure femorotibial kinematics in CrCLD canine stifles.[11] Dogs with CrCLD maintained their joints in greater flexion throughout the gait cycle, and cranial tibial subluxation was present at all points throughout the gait cycle (average 9.7mm), which was similar to the results by Korvick et al.[7] Subluxation was greatest in mid-stance phase, which is consistent with Slocum's claim that the forces of weight bearing contribute to the instability of a CrCLD stifle. This study also found substantial increases in internal rotation in the CrCLD stifle, specifically during the stance phase, compared to control groups.[11]

The CrCL may be part of a complex structure that assist in stabilizing the stifle in dogs, but it is clear from the literature that it plays a significant role independently. Its primary functions are to prevent cranial translation of the tibia, provide rotational stability by preventing internal rotation during weight bearing, and prevent hyperextension of the joint. Severe stifle instability, lameness, and osteoarthritis occur in dogs when these functions are compromised or absent.

b. Pathophysiology

The exact mechanisms by which the cranial cruciate ligament ruptures (to cause CrCLD) have yet to be completely understood, and the process of its development and correlation with osteoarthritis is beyond the scope of this review. Generally, however, studies evaluating histopathological changes in the CrCL of dogs agree that there are significant degenerative changes within the ligament that eventually lead to rupture. In a study from Germany evaluating changes of the

cruciate ligament in healthy versus arthritic stifles in dogs greater than 8 years of age, they found calcium deposits, hyalinization, loss of wavy architecture, and nesting of cartilage cells.[12] The stages of these changes suggest that the midportion and interior layers of the CrCL degenerated before the bony attachments and surface layers. A study by Vasseur et al. performing histopathological analysis on cranial and caudal cruciate ligaments also found changes to be most prominent in the center, and to worsen with age.[13] Primary changes included loss of ligamentocytes, metaplasia of surviving ligamentocytes to chondrocytes, and failure to maintain collagen fibers and primary collagen bundles. Similarly studies by Hayashi et al. showed significant changes within the core of the CrCL, including loss of fibroblast numbers and density, and disruption of the structure of the extracellular matrix with loss of crimping of collagen fibers.[14,15] What exactly causes this degenerative process to occur remains to be determined; however, there are theories suggesting that the relatively poor blood supply to the CrCL leads to poor remodeling capabilities, and only worsens with increases in age and weight.[1,13–16] The resulting degeneration of the CrCL leads to eventual rupture and severe osteoarthritis. Synovium is also recently implicated in the disease process as shown by elevations in matrix-degrading enzymes produced by the synovium in dogs with CrCLD.[17] While efforts are being made to investigate further into the etiology of these pathologic changes, there are still many questions about the development of CrCLD that remain unanswered, making prevention of disease difficult for clients and veterinarians worldwide.

c. Risk Factors

i. Age

With such widespread and significant clinical impact, multiple studies seek to identify risk factors associated with development of CrCLD. An early

prospective study out of Liverpool found that out of 111 CrCLD cases identified, 55 were under 4 years of age and 56 over 4 years of age.[18] For the younger group, the average age at onset was 21.4 months (3 - 47 mo), with 53% classified as having sudden clinical onset. In the older age group, the average age of onset was 6.8 y (4 - 13.5 y) with 64% of cases having sudden clinical onset. This study demonstrated a higher percentage of young dogs affected by CrCLD (46.8% $\leq$ 3 y) compared to an earlier study showing a larger distribution of dogs affected in the 3-7 y age bracket.[19] Alternatively, the largest retrospective study to describe the epidemiology of cranial cruciate ligament rupture (CrCLD) in dogs was by Whitehair et al., with data from 10,769 dogs with CrCLD compared to a control population of 591,548 dogs.[20] The prevalence of CrCLD for each age group was significantly different from one another, but overall the highest occurrence was with greater than seven years of age. They also noted that the higher the body weight of the dog, the younger the mean age was at the time of diagnosis. The authors admitted that they did not account for body condition score (BCS), therefore obesity may be a factor, not just standard weight. They also noted bias toward those dogs that were brought into the clinic for evaluation.[20] To further investigate the prevalence of young dogs, a case-control study by Duval et al. evaluated dogs less than two years of age presenting for signs consistent with hindlimb lameness compared to randomly assigned control dogs.[21] They suggested a strong correlation between age and breed, with larger breeds predisposed to CrCL at a younger age than other dogs, which was consistent with previous studies.[19,21] Alternatively, earlier studies also show an increased hazard of CrCLD in older ages with smaller breeds.[19,22–24] In 2003, Lampman et al. reported similar findings to Whitehair et al., with an average age of 6.6 years at the time of diagnosis.[25] Similar findings were described by Witsberger et al. in a large retrospective study of 1,243,681 dogs that stated age was a significant risk factor

for developing CrCLD.[26] Witsberger et al. found that dogs greater than four years of age were more likely to develop CrCLD; however, they acknowledged that cases were limited to those evaluated by the teaching hospital, and did not include those of various breeds or ages that may have been medically managed by their referring veterinarians.[26] Interestingly, Cabrera et al. investigated age association with bilateral disease and found that dogs with unilateral CrCLD were significantly older than those with bilateral CrCLD, and that dogs less than four years of age at the time of onset were more likely to have bilateral CrCLD.[27] This is similar to conclusions from a previous report of younger dogs more likely to show bilateral CrCLD.[28] Conversely, a study in 2009 determined the age at the time of the first CrCLD was not significantly associated with the development of contralateral rupture later in life.[29] Zeltzman et al. also investigated age in dogs with CrCLD, and found that the average age of 5.4 years was similar to previous reports, but this study did not discuss the time from true onset, just time of diagnosis.[30] Finally, in a retrospective by Guthrie et al. evaluating signalment of dogs presenting for signs of CrCLD, age of dogs ranged from 112 – 4893 days with a median of 1565 days (4.3 y) similar to previous reports; however, the number of young dogs (less than 2 y of age) could not be determined based on provided data by the publication to see if they also found an increase in CrCLD prevalence in young dogs.[31] Regardless of the various methods of data acquisition, there is clear trend towards identifying the associated clinical signs at a younger age than thought previously. Whether this is due to improved client / veterinarian perception or increased prevalence in a young population of dogs remains to be seen, but early client education appears indicated to warn them of the development of disease.

ii. Gender

In the early study by Bennett et al., it was concluded in their recorded population of dogs with CrCLD that the majority were intact (78.5%), and in the

total population, 59% were female and 41% were male.[18] Whitehair et al. found that female dogs and dogs that were neutered had an increased prevalence of CrCLD. They did find the prevalence of CrCLD was not significantly different between dogs that were spayed at a young age and dogs whose age group at the time of ovariohysterectomy was the same as their age group at the time they ruptured their CrCL.[20] Duvall et al. demonstrated similar findings, in that the risk of CrCLD was increased for neutered males and females, but there were no differences between the two genders specifically.[21] Duerr et al. investigated the association of gender status and the slope of the tibial plateau angle (TPA) and found that dogs with a steep TPA (>35°) were three times more likely to be neutered before six months of age compared to dogs with a TPA < 30°.[32] This study attempted to provide a plausible explanation for neutered dogs potentially having increased risk for CrCLD due to altered tibial conformation. However, the exact cause for increased TPA in young spayed/castrated dogs is unknown, but may be due to alterations in growth plate development with maturity.[32] A study by Lampman et al. furthered supported the significance of neutering, as spayed females (58%) and neutered males (38%) were the most represented in their diseased population.[25] A large retrospective study by Witsberger et al. with 1,243,681 dogs found that castrated males (OR 1.68) and spayed females (OR 2.35) were significantly more likely to have CrCLD.[26] Conversely, Guthrie et al. reported that neither sex nor neuter status significantly affected the incidence of developing or presenting with bilateral CrCLD, even though the majority of the population were spayed females (44%) and neutered males (32%).[31] These findings contradict those of Grierson et al., who reported that male dogs have an increased risk of developing bilateral CrCLD.[28] The reason for these differences is uncertain, but may be attributable to geographic distributions and methods of data collection. Alternatively, Buote et al. reported that sex did not affect likelihood or rate of

contralateral CrCLD on presentation of bilateral CrCLD, but did find that females tended to take longer to develop the CrCLD of the contralateral limb.[29]

The distribution of neuter and sex status of a population can be quite variable, especially given specific geographic regions whose cultural influences impact the prevalence of neutering pets. However, despite this, the majority of published literature demonstrates an increased incidence of CrCLD in spayed/neutered pets, thus discussions on the risk for orthopedic disease with clients is warranted, and may impact the decision on timing for an elective neuter procedure.

iii. Weight

Several studies have documented weight distributions among dogs that have developed CrCLD. It should be noted that not all of them explicitly differentiate between body weight as an absolute value and body condition score (BCS) to account for the impact of overall obesity on joint health. One of the earliest studies reporting on cruciate ligament repair by Lewis et al. noted that overweight and obese dogs had an increased rate of CrCLD later in life.[19] In the prospective study by Bennett et al. where dogs were separated into age groups categories A (< 4 y) and B (> 4 y), the average body weight of group A was 34.1 kg (5.5 - 6.2 kg). Of the dogs whose weight was documented, 27/55 were greater than 30 kg, and if the six undocumented weights were included (mixed Rottweilers, St. Bernards, and Bull Mastiffs), the total would be 33/55 dogs greater than 30 kg. For the dogs in group B, the average weight was 25.8 kg (3.3-57 kg) with 15/56 documented greater than 30 kg. Presumptions could not be made regarding patients' weight in group B for those that were documented due to the breed descriptions and the potential for overestimating. Regardless, this study showed that a large percentage of dogs were heavier, and that the heavier dogs who suffered CrCLD tended to be younger.[18] Similarly in the 1993 retrospective study by Whitehair et al., dogs

weighing more than 22 kg had a significantly higher prevalence of CrCLD than dogs less than 22 kg. They also concluded that the difference in prevalence between neutered dogs more than 22 kg and neutered dogs less than 22 kg was statistically greater than the difference between sexually intact dogs weighing greater than 22 kg and sexually intact dogs less than 22 kg.[20] This suggests an important association between weight, spay/neuter status, and development of CrCLD, with larger dogs suffering a greater impact from neutering; however, this study did not account for BCS so the pathophysiology remains difficult to determine with this data. Duval et al. evaluated risk factors for CrCLD in dogs and demonstrated that the mean body weight of affected dogs was 35.4 kg, and was significantly greater than that of the control population, but consistent with previous reports.[21] However, Deval et al. included dogs less than two years of age, potentially showing bias toward larger weight distributions as seen in the study by Bennett et al.[18] It is also difficult to make any numerical comparisons between the demographic of this study and those of previous works as they failed to report the weight of all patients seen.[21] A study by Duerr et al. investigating the risk factors of excessive TPA in large breed dogs (>18.1 kg) showed that the average body weight of dogs with TPA greater than 35° was 37.7 $\pm$ 10.8 kg, and for dogs with a TPA less than 30°, it was 36.3 $\pm$ 9.3 kg.[32] The differences in body weight were not statistically significant. This study had similar body weights to Bennett et al. and Whitehair et al., but both had inherent bias due to the inclusion criteria of dogs less than 18 kg, so statistical comparisons were not feasible.[32] Cabrera et al. found that the mean weight of dogs affected by unilateral versus bilateral CrCLD were 29.5 kg and 37.1 kg respectively, and were not significant. Cabrera et al. included dogs of all weight ranges; therefore, mean weight was slightly decreased from previous reports.[27] Similar findings were noted by Buote et al. evaluating risk factors for bilateral rupture in Labrador Retrievers, who reported that the weight of the dog

had no association with development of contralateral CrCLD or presenting with bilateral CrCLD at first evaluation.[29] Guthrie et al. found no association between weight and age of patients at presentation.[31] These two studies potentially dispute the concept that heavier dogs are at risk for increased incidence of CrCLD, but once again neither recorded the BCS of the dogs, creating inherent bias. There are two major studies that have specifically investigated dogs, both healthy and overweight, and their prevalence of CrCLD. First, Lampman et al. in 2009 reported findings on 758 dogs with 49% of dogs at ideal weight, 40.4% overweight, 8.9% obese, and 2% underweight.[25] They compared two populations, the cases with CrCLD at their referral center, and a general canine population from private general practices as controls, and found that dogs with CrCLD were more likely to be overweight or obese, and that BCS $\geq$ 4/5 was a risk factor for developing CrCLD.[25] Similarly, a study by Grierson et al. with 511 dogs had an overall overweight population of 20%, and showed that overweight dogs were more likely to have bilateral CrCLD.[28] Interestingly, when they categorized the dogs into body weight groups, they showed that dogs less than 22 kg were significantly more likely (1.29x) to develop bilateral CrCLD than dogs greater than 22 kg.[28] The reasoning for this is still unknown, and these results conflict with all previous reports emphasizing a greater prevalence of heavier dogs with CrCLD, whether unilateral or bilaterally affected. It is possible given the short follow up period (<18 mo) that the true number of heavier dogs that experience contralateral CrCLD was underestimated. In contrast, the study by Buote et al. showed no significant association between weight and occurrence of bilateral CrCLD in Labradors, but they acknowledged the lack of BCS definition.[29]

The majority of veterinary literature suggests that those with heavier body weight are more prone to CrCLD, and may be at increased risk for bilateral rupture. The disadvantage of these studies is that a large portion of them do not

distinguish between weight and BCS. The distinction is significant, given the severe impact obesity may have on force distribution across a joint and subsequent development of osteoarthritis. With abnormal force distribution, there is potential for increased strain on intra & extra-synovial support structures, leading to partial and subsequent full tears in the CrCL.

iv. Breed

Much of what is reported on breeds affected by CrCLD often coincides with data on the patients' weights. This is due to the lack of distinction between BCS and the absolute weight of the dog. The earliest studies describing CrCLD in dogs showed surprisingly high prevalence of small breed dogs with particular emphasis on miniature poodles; however, their ages were older than the larger breeds at the time of diagnosis.[19,23,24] The specifics of acquiring the data for these studies were not well documented, therefore it is difficult to directly compare. The increased prevalence in the small breeds like the miniature poodles is contradictory to the predominance of larger breeds more commonly treated in today's practices; however, this could be attributed to the popularity of owning certain breeds at the time and place of these studies. This was demonstrated in the study by Singleton et al., where the most common breeds to own were Boxers and miniature poodles.[24] Several years later, Bennett et al.'s study populations demonstrated that Rottweilers, cross-breeds (weights 12-40 kg), St. Bernards, and Bull Mastiffs were the most common breeds affected by CrCLD.[18] They acknowledged that their reported increase in large breeds (specifically Rottweilers) diagnosed could be influenced by the cultural shift in dog ownership, as they stated over a 10 year span (1974-1984), the number of Rottweilers registered with Kennel Club jumped from 334 to 4690.[18] While this influence is likely, future studies continued to show similar breed prevalence. In a large retrospective by Whitehair et al, Rottweilers, Newfoundlands, and Staffordshire Terriers were most frequently identified in their

population cohort.[20] Whitehair et al. specifically used records from the Veterinary Medical Database (VMDB) to determine characteristics of the general population of dogs, and to then compare the general population of dogs with dogs that had CrCLD. The reasoning for this was to remove the bias from previous studies whose results were affected by local breed popularity. This study showed that Cairn Terriers were more likely to have CrCLD than miniature poodles, which was the breed of interest previously.[20] Similarly, Duval et al. also found a predisposition for CrCLD with Neapolitan Mastiffs, Akitas, St. Bernards, Rottweilers, Newfoundlands, Chesapeake Bay Retrievers, Labrador Retrievers, and American Staffordshire Terriers.[21] Even large breed dogs (German Shepherd, Golden Retriever, and Doberman Pinscher) did not have increased risk of CrCLD, suggesting that predisposition to CrCLD may not just be breed related. To further investigate predisposition in Rottweilers, Wingfield et al. compared biomechanical properties of the CrCL in Rottweilers to that of racing Greyhounds, and demonstrated that ultimate load to failure (related to body mass), linear stiffness, and tensile strength of the CrCL was significantly higher in Greyhounds compared to Rottweilers.[33] Their numbers were limited, and several stifles had large variability during testing; therefore, results should be interpreted cautiously. In addition, this doesn't account for large muscle mass and associated attachments that could impact joint mobility, particularly when Greyhounds have such a large muscle to bone mass ratio compared to Rottweilers.[33]

In the study by Lampman et al. evaluating the prevalence of CrCLD in dogs within referral hospitals versus the general hospital population, the most common breeds affected were mixed breeds, Labrador Retrievers, and Rottweilers. They also stated that breeds of mixed background, Labrador Retrievers, Boxers, and Dobermans represented a risk factor for developing CrCLD in dogs.[25] Likewise, breed was a risk factor in the study by Witsberger et al., with at risk breeds being

Newfoundlands, Rottweilers, Labrador Retrievers, Bulldogs, Boxers, Chow Chows, American Staffordshire Terriers, and St. Bernards. Even though Witsberger's study did not summarize the whole North American population, it did encompass over 27 participating veterinary teaching hospitals. Witsberger et al. suggested that a possible source of bias for this noted predisposition was that many small breeds affected by CrCLD may go undetected, are not evaluated, or are medically managed by their general practitioners without referral to specialty centers.[26] The studies evaluating risk factors for developing bilateral CrCLD have comparable results, showing the three most common breeds represented were Labrador Retrievers, Rottweilers, and Golden Retrievers.[28,31] Grierson and Guthrie et al. both found that Rottweilers had an increased incidence of bilateral rupture compared to other breeds (when compared to the purebred dogs, not the whole population per Grierson et al).

Very little is published regarding the genetic bases for development of CrCLD, but there are a few reports that have shown support for Newfoundland dogs being affected with certain chromosomal regions of association.[34–36] This significance could potentially be helpful in selective breeding to try and decrease chances of CrCLD in the future, but thorough research in this application is still ongoing.

While early studies may show increased prevalence of CrCLD in smaller breeds, it is apparent through most of the veterinary literature that large breed dogs, particularly Rottweilers, are at increased risk. Whether this is due to anatomical conformation, genetic predispositions for ligament deficiency, or the increased popularity of large breeds across the country is uncertain. Regardless, the prevalence is significant, and owners of large breed dogs should be cautioned and encouraged to keep dogs at lean weight especially at their younger ages.

v. Tibial Conformation

Physical characteristics of the tibia, specifically the tibial plateau, are evaluated in numerous studies to search for a correlation between tibial conformation and predisposition to CrCLD. One of the earliest papers describing tibial conformation was in 1982 by Read et al., in which five dogs were evaluated.[37] In these five dogs, the caudal aspect of the proximal tibial physis displayed retarded growth, resulting in varying degrees of cranial bowing of the tibia. Four of these five dogs developed CrCLD and ligamentous instability, but the exact etiology of these changes was not elucidated. Another study by Aiken et al. described the intercondylar notch (ICN) in dogs, as this structure is suggested to be correlated with anterior cruciate ligament deficiency in people.[38,39] To account for local body size variability, the intercondylar notch index was described and utilized (width of ICN to width of the distal femur).[38,39] Aiken et al. compared 45 clinical dogs to 98 control dogs, and found that dogs with CrCLD had significantly smaller proximal and distal notch window indices compared to control groups. This was not breed specific, as Rottweilers were present in both groups, and the ICN was smaller for those with CrCLD than those without. The belief is that a narrower ICN increases the risk of CrCLD through impingement of the CrCL as it travels from its origin on the femur to cross over the CdCL before inserting on the proximal tibia, as in humans.[39] Morris et al. compared the TPA of a group of dogs with CrCLD and a control group, demonstrating that the mean TPA for the control group was 18° versus 23.8° in those with CrCLD. The breed and body weight distribution was fairly similar between both groups.[40] A study by Selmi et al. focusing on the tibial plateau of small breed dogs (mean body weight 9.3kg) revealed that five dogs with CCLD had excessive prominence of the tibial crest and excessive sloping of the tibial plateau with TPA of 30-32°. Selmi et al. had a small population and did not have a control group representing healthy dogs within the same weight/breed category to show a true association between TPA and

CrCLD.[41] Similarly, another study by Macias et al. looking at eight small breed dogs (7/8 were terriers 5-15 kg) found that all dogs had a caudal deformity of the proximal tibia with a barely distinguishable tibial crest, marked caudal tibial slope, and caudal bowing of the proximal fibula. TPAs in this study ranged from 26-37° with 7/8 being more than 30°. While the Macias et al. study demonstrated variations in tibial conformation in small breed dogs with CrCLD, implications on causation cannot be made without a control group.[42] In effort to compare TPA between breeds known to be predisposed to CrCLD, Wilke et al. evaluated TPA in Greyhounds and Labrador Retrievers with or without CrCLD. Greyhounds had a significantly lower mean TPA (22.5°) than either affected (25.6°) or unaffected (28.0°) Labrador groups. This was contradictory to previous studies suggesting that a steeper TPA had a high association with developing CrCLD, and that it may be both breed and conformation dependent. These results may also be due to the disparity between and small numbers of groups, but the exact reason for this conclusion remains to be seen.[43]

To further characterize the proximal tibia of dogs, Osmond et al. generated computer models mimicking abnormal shapes of the proximal tibia observed in dogs, and used these to describe dogs with a steep TPA and abnormal proximal tibial morphologies.[44] Their two models of proximal limb deformities were based on either premature closure of the caudal tibial physis as a whole, or the medial condyle independently. A total of 67 client owned dogs were considered in this study, and for the dogs with CCLD, the tibial slope ranged from 21.3°-41.2° (mean 31.8°), with 14 dogs in the control group with slopes ranging from 15.7-29.1° (mean 23.6°), and with significant differences noted between the two groups.[44] 67% of dogs with CrCLD had a steep slope greater than 30.4°, and 9% of the 67 dogs with CrCLD had proximal tibial deformities. All dogs with proximal tibial deformities had a steep slope. The significance of their definition of proximal tibial

deformity on the development of CrCLD was unclear, but it supports the complex nature of CrCLD, and its relationship with tibial conformation.[44] The study by Duerr et al. attempted to describe a reason for the development of a steep TPA in dogs, specifically defining control dogs as those with TPA less than or equal to 30°, while excessive TPA was classified as more than 35°.[32] Body weight, gender, and breed were not statistically different. The time of neutering was a significant risk factor for developing steep TPA, with dogs with a TPA of greater than 35° in one or both hindlimbs being three times as likely to have been neutered before six-months of age compared to controls. Dogs with a TPA more than 35° in both hindlimbs were 13.6 times as likely to have been neutered less than six months of age as dogs with a TPA of less than or equal to 30° in both hindlimbs.[32] There is concern over the influence of pre-pubertal gonadectomy on the histologic appearance of the growth plate, potentially predisposing to premature closure, physeal fractures, or angular limb deformities, and the findings in this study are supportive of a hormonal influence.[32] Further evaluation into the conformation of these groups and inclusion of a control group with no CrCLD would be helpful in expressing a specific correlation.[32]

In a study by Guerrero et al., femoral and tibial conformations were compared between dogs with and without CrCLD.[45] There were no significant differences between the two groups with respect to the conformation of the distal portion of the femur. The distance between the tibial tuberosity and center of a circle representing the tibial condyle was shorter in CrCLD affected dogs than the control dogs, suggesting a less developed tibial tuberosity in dogs with CrCLD, potentially increasing shear forces on the stifle joint. The clinical impact of this measurement remains unclear, and all other variables between the groups were not significantly different.[45] Cabrera et al. investigated whether there was any correlation between TPA and developing bilateral CrCLD, and no significant

differences in TPA between those with unilateral CrCLD (median 26°) and those with bilateral CrCLD (27°) disease were appreciated.[27] This is similar to previous reports where there was no difference noted between the right and left TPA in dogs with or without CrCLD. Conversely, another study by Mostafa et al. looking only at Labrador Retrievers and comparing tibial conformation between those with or without CrCLD, showed that cranial angulation of the proximal tibia, excessive steepness of the tibial plateau, and distal femoral torsion appeared more likely to be associated with CrCLD.[46] Inauen et al. also evaluated proximal tibial conformation with the use of specific landmarks, and found that the overall tuberosity width was smaller in dogs with CrCLD and could lead to cranial tibial thrust.[47] They also noted that the TPA did not differ between healthy dogs and those with CrCLD, but more importantly, their method of measuring TPA was unconventional, and relied on the form of the tibial tuberosity, potentially influencing these values and preventing comparison to previous literature.[47] In support of TPA having an association with CrCLD, Ragetly et al. found that TPA and femoral anteversion angle were higher in predisposed limbs versus those that were not predisposed to CrCLD in Labrador Retrievers.[48] Pre-disposed limbs were defined as a contralateral limb in a dog already diagnosed with unilateral CrCLD. They monitored the dogs for an additional five years, and of the predisposed limbs, only 4/9 developed CrCLD, 2/9 were unaffected, and 3/9 were of unknown status (follow up 5 - 54 mo). With such small case numbers and few cases that developed CrCLD, the significance of these findings appears reduced.[48] An ex vivo study by Haynes et al. was performed to evaluate the effect of the steepness of TPA on CrCL strain, and found that an increase in TPA did lead to increased strain on the CrCL. Unfortunately, this study used cadaveric models without support of muscular and soft tissue structures, and was limited to a specific standing angle without accounting for full range of motion of the stifle.[49]

A few studies attempted to evaluate tibial conformation differences in various breeds, and specific anatomical points of variability were discovered, but clinical application of these differences was difficult to describe without prospective studies evaluating the prevalence of CrCLD in these breeds specifically.[50,51] What the veterinary literature collectively supports as a whole is that the etiology of CrCLD is extremely multifactorial, and any effort to pinpoint one specific risk factor to implicate is unrealistic. It appears that increased TPAs with short tibial tuberosities do represent a large proportion of dogs with CrCLD, but it does not conclusively indicate that they will develop the disease.

d. Diagnosis

Since its identification in veterinary medicine, CrCLD can be diagnosed based on physical and orthopedic examination characteristics. Placing a patient in lateral recumbency, the cranial drawer and tibial compression tests are the mainstays of diagnosing CrCLD.[52–54] The cranial drawer test involves stabilizing the femoral condyles with one hand while the other hand grasps the tibial condyles. The tibia is pushed cranially by pressing from the caudal aspect of the proximal tibia, with the thumb firmly holding the fibular head, the index finger on the tibial tuberosity, and the remaining fingers supporting the medial tibial condyle. Cranial translation, if present, is then palpated by movement of the tibial condyle independent of the femoral condyle in the cranial direction. This test is performed both in flexion and extension to evaluate the status of both the craniomedial and caudolateral bands of the CrCL.[55] The tibial compression test is performed by placing the stifle and tarsus in extension such that the limb is approximately in a standing position while in lateral recumbency. The hand supporting the stifle holds the distal femoral condyles, with the index finger gently laying over the patellar ligament and touching the tibial tuberosity. The other hand supporting the tarsus

flexes the tarsus while maintaining stifle extension. The index finger is used to palpate any cranial thrust motion of the tibial tuberosity.[52] While both tests are fairly simple to perform, patient compliance and muscle rigidity/tension can impact the results. One study by Carobbi et al. evaluated the sensitivity of these tests, and found that the sensitivity and specificity for either test were low in awake patients, but improved significantly when placed under full anesthesia.[53] Lower sensitivity and specificity of these tests is suggested to be attributable to varying degrees of osteoarthrosis or experience of the evaluators.[52,53]

i. Imaging

Several studies have focused on radiographic evaluation of stifles with and without CrCLD. In an early study by De Rooster et al., the authors sought to radiographically demonstrate the movement of an unstable stifle in both a neutral position and with tibial compression. In 72 stifles, instability was apparent on stressed radiographic (tibial compression) views in all but two cases, with an overall sensitivity and specificity of 97% and 100%, respectively. With the stressed view (stifle and tarsus placed in approximately 90° flexion or extension), it did not appear to matter if it was a partial or a full CrCL tear.[54] In another study by De Rooster et al. looking at visualizing displacement of bony landmarks in dogs with normal, partial, or complete CrCLD under tibial compression or neutral position, a significant difference was noted between normal dogs and those with full CrCLD.[56] There were discrepancies between anatomic landmarks appreciated between normal and partial CrCLD, and were not as easy to distinguish independently on radiographs.[56] Both of the studies by De Rooster et al. only evaluated displacement of landmarks, and could not specifically identify pathology of the cruciate ligaments, just secondary changes such as osteoarthritis. Furthermore, radiographic evaluation of stifles used to confirm the diagnosis of CrCLD typically rely on the changes seen secondary to instability, including

osteophytosis, effacement of the infrapatellar fat pad, subchondral sclerosis of the tibial plateau, and joint swelling by displacement of the plane between the gastrocnemius and superficial digital flexor muscles.[57–59] The consistency of CrCLD concurrent with degenerative joint disease in the stifle has also led the veterinary community to diagnose CrCLD in patients even without orthopedic examination findings of drawer or thrust if osteoarthritis is present radiographically, particularly in the contralateral limb of a dog who already has unilateral rupture.[57] Cranial tibial translation was also confirmed as a supportive finding of CrCLD in a more recent cadaveric study by Casteneda et al.[60]

Limitations of digital radiography include lack of cross-sectioning to identify the CrCL, and the variability in diagnosing a partial or full cruciate tear; thus, studies were developed to assess the validity and application of computed tomography (CT) and magnetic resonance imaging (MRI) in diagnosis of CrCLD.[61,62] One study by Han et al. out of Korea investigated the use of CT to identify defects in the CrCL that were experimentally transected, and found there was a significant decrease in the cross-sectional area of the CrCL on CT after transection.[61] Whether this would be as easily identifiable with a clinical patient who likely has remodeling, osteoarthrosis, or other secondary changes, remains to be seen. In another study by Samii et al. comparing CT findings with intraoperative findings, radiologists were able to distinguish normal versus torn CrCL with sensitivity and specificities of 96-100% and 75-100%, respectively.[62] There was only one patient with a partial tear, so comparison of sensitivity of partial versus complete could not be made.

Use of MRI has limited discussion with respect to CrCLD, but it recently was used to try and distinguish partial from complete CrCLD. In the study by Fazio et al. to see if MRI could identify complete fiber loss, sensitivity, specificity, and accuracy for MRI was 0.78, 0.5-0.6, and 0.68-0.71, respectively.[63] For

identifying fiber loss in dogs with partial CrCLD, specificity was 1.00, and with a visual analogue scale cut off point of greater than 79, observers had good accuracy distinguishing partial from complete tears. Importantly, they were able to detect significant levels of fiber damage in stifles that were deemed orthopedically stable on examination, showing a possible benefit in predicting likelihood of future rupture in a clinically normal stifle.[63] MRI also was reported to be helpful in detecting the severity of joint changes (synovitis, etc.) correlated with the presence of CrCLD in dogs.[64]

While the presence of such useful and detailed advanced imaging techniques enables a more thorough investigation in assessing the severity of CrCLD in dogs, the practical clinical applications fall short. With the cost of these procedures and the overall support of CrCLD diagnosis based on physical and orthopedic examination combined with radiographs alone, CT and MRI use in the preoperative diagnosis of CrCLD in dogs remains unpopular.

e. Outcomes of Cranial Cruciate Ligament Disease

As evidenced by the number of dogs presenting to the veterinary community for treatment of hindlimb lameness resulting from CrCLD, it is clear this is not a tolerable deficiency. The biomechanical relevance of such a small ligament is remarkable, and deficiency of such a structure can have severe and lasting consequences on limb function. As demonstrated in several cadaveric studies, complete transection of the CrCL results in excessive subluxation of the tibia in relation to the femur, and this results in impingement of the medial meniscus.[1,3] Numerous reports describe degenerative changes and the development of osteoarthritis in dogs after CrCLD, but these are beyond the scope of this review.[55,58,65–68] However, several studies showcase the biomechanical consequences of CrCLD, not only to the limb in question, but the remaining limbs

as well. An early study by Budsberg et al. showed a significant decrease in peak vertical force, associated impulses, and weight distribution of the affected limb compared to the clinically normal limb.[69] In one experimental study by O'Connor et al. evaluating the peak vertical force of adult dogs before and after CrCL transection, the normal peak vertical force (F_z) was 70% of static body weight in the hindlimb and around 115% of static body weight in each forelimb .[70] After transection of the CrCL, the F_z was reduced to 25% for the operated hindlimb, the ipsilateral forelimb dropped to 104% of static body weight, and the contralateral limbs largely remained unchanged two weeks post-op. Over the course of 6-12 weeks, the F_z in the affected limb increased to 32-37% of the patient's body weight, while the remaining limbs returned to preoperative values.[70] There was slight improvement with rest and recovery, but the use of the affected limb was still at best 50% of its normal value, which was a considerable amount for which to compensate. Comparatively, another study by Rumph et al. also looked at changes in peak vertical force after transection of the CrCL.[71] Rumph et al. similarly found the operative limb to have a substantial decrease in ground reaction force compared to the control; at 12 weeks postoperatively, ground reaction force was 61% of the original value. They also noted no significant difference in forelimbs at any of the time points. Conversely, there was an increase in ground reaction force of the contralateral hindlimb, which was 131.7% of the original force at two weeks postoperatively and 113% of the original force at 12 weeks postoperatively. This implied that there is a significant immediate compensatory response in the opposite hindlimb after a unilateral CrCLD.[71] Similarly, when Souza et al. evaluated the force distribution in paw pads of Pitbull terriers with and without CrCLD, they discovered the peak vertical forces were significantly lower in the affected limbs.[72] They specifically noticed a prominent decrease in peak vertical force of the metatarsal pad, with values as low as 30% of values of control limbs.

Unsurprisingly, with decreased weight bearing of the limb, muscle atrophy will follow due to decreased muscle use. Ragetly et al. investigated body size parameters between normal dogs and dogs with CrCLD, and found the thigh and crus weight in CrCLD stifles to be significantly less than their matched contralateral segments, as well as the thigh of normal limbs (matched with dogs of similar BCS and weight).[73] More specifically, one study by Mostafa et al. suggested that the atrophy associated with CrCLD may predominantly affect the gastrocnemius muscle.[74] There was no difference in thigh circumference between normal and affected limbs, but the thigh to crus ratio was increased in diseased limbs on physical exam. On radiographic interpretation, the width of quadriceps and hamstring muscles were decreased in diseased stifles. Mostafa et al. also found the lean mass of the gastrocnemius to be increased in the limbs predisposed to CrCLD compared to normal stifles using densitometry (DEXA).[74] This pattern of muscle atrophy affecting the quadriceps more than the hamstrings implies that dogs with CrCLD tend to carry their hip and stifle in more flexion, while keeping the hock in extension, thereby mobilizing the hamstring muscles to hopefully decrease cranial tibial translation.[74]

Joint mechanics are complex, and disruption of any normal fluid movement can have consequences for other regions of the joint. For example, a study by Guerrero et al. describing the impact of a CrCLD stifle on the femoro-patellar joint through use of a cadaveric model found that CrCLD stifles had altered patellofemoral alignment and contact mechanics.[75] The peak contact location was more proximal than that of intact stifles, and mean pressure acting on the retropatellar area decreased significantly. The findings of this study suggest that these altered biomechanics may predispose to patella-femoral arthritis after CrCLD. This is logical given the prevalence of osteophytosis appreciated along the

trochlear ridge and base of the patella on radiographs of dog stifles affected by chronic CrCL instability.[55,75]

It is evident from the literature and the clinical presentation of these patients that significant changes in limb function and weight distribution occur after CrCLD. Subsequent injuries to other parts of the joint predispose the patients to osteoarthritis, decreased limb use, and muscle atrophy that affects their quality of life. Given the harsh consequences, it is essential that efforts are made to identify and treat patients as early as possible to decrease the severity and, hopefully, progression of these changes.

2) Meniscus

a. Anatomy

The medial and lateral meniscus play an important part in the biomechanics of the stifle joint, and are important to discuss, as they are impacted significantly by CrCL injury. The menisci are semilunar, fibrocartilaginous discs with a convex abaxial surface thicker than the concave axial counterpart.[76] They are thought to form through developments of the fibrous layers of joint capsule, and are covered by synovial membrane.[76] The medial meniscus retains attachment to the joint capsule while the lateral meniscus does not, and cranially the two menisci are connected via a transverse ligament.[76] They are each respectively attached to the tibia via the cranial tibial ligament of the meniscus.[76] Caudally, the lateral meniscus is attached to the femur and tibia via the meniscofemoral ligament and the caudal tibial ligament of the meniscus. The medial meniscus does not attach to the femur caudally, only to the caudal tibia. The medial meniscus is also firmly attached to the medial collateral ligament via the coronary ligament while the lateral is not.[76,77] The microscopic anatomy of the meniscus is also thoroughly described according to Arnoczky et al.[78] In the structure of the matrix, the collagen

fibrils are structured into three layers to allow compressive forces to be distributed into hoop stresses. In the innermost third, the collagen bundles lay in a radial pattern, the outer two-thirds of the deep layer are oriented circumferentially, and the superficial most layer is composed of a random pattern.[55]

The blood supply to the meniscus is complex, with a general description of three main zones: a red-red zone, an intermediate red-white zone, and the avascular white-white zone.[55,78] As described by Arnoczky et al., the vascular supply originates from the medial and lateral genicular arteries that branch to form a perimeniscal capillary plexus within synovial and capsular tissues.[78] This plexus then supplies the peripheral border of the meniscus through attachment to the joint capsule, and forms a circumferential pattern with a few branches that radiate toward the center.[55] These vessels terminate in small capillary loops after they penetrate the meniscal stroma for a brief distance.[78] The presence of the popliteal tendon precludes an attachment of the lateral meniscus to the joint capsule caudolaterally, so as expected, there are no perimeniscal vessels located in this area. There are also small areas of vascular synovial fringe (capillaries proliferating in the synovium) along the articular surface of the meniscus, but these do not penetrate the tissue. There are also endoligamentous vessels originating from the synovial covering that penetrate the meniscal stroma for a short distance and terminate in small capillary loops. Conversely, the axial central zone is primarily avascular.[55,78] Similarly to the vascular pattern within the meniscus, the nerve supply follows a similar course mainly within the periphery of the horns, while the body is mostly devoid of any nerve supply apart from the outermost portion.[79]

b. Function

With the composition of collagen bundles organized in the three layers, the meniscus has the ability to tolerate compressive loads by dissipating them into hoop stresses. It allows smooth low-friction movement between the femur and tibia during stifle motion.[55] In addition to the collagen network, the large amount of proteoglycan content with hydrophilic molecules enables the fibrocartilage to withstand large compressive loads. It is also theorized that meniscal response to load depends on a solid matrix phase and interstitial fluid phase, meaning thatan elastic response occurs from the circumferential collagen bundles during the solid matrix phase, while the fluid phase helps dissipate the compressive load slowly.[55,80] Thus, the complex biomechanical properties could severely impact the protective effects the meniscus has on femoral and tibial surfaces if altered.

c. Pathophysiology and Risk Factors

For optimum function, the meniscus relies on consistent motion and contact between the femoral and tibial condyles during range of motion. As such, it is proposed that with CrCLD, the abnormal cranial tibial subluxation and internal rotation impinges upon the caudal horn of the medial meniscus specifically.[2] Without the CrCL, the wedge shape of the caudal pole acts as a temporary stabilizer trying to prevent further cranial subluxation, thus predisposing it to tears.[55] This resultant damage was investigated, and in a study by Bennett et al. evaluating 87 dogs, it was reported that 49% of these dogs with CrCLD had a meniscal lesion, and all were found in the medial meniscus. The most common lesion was in-folding of the caudal horn between the femoral and tibial condyles.[81] In most cases, the surface of the meniscus was fibrillated, while 30% had normal appearing surfaces.

Investigations were performed to assess predisposing factors for developing meniscal tears, with many of them similar to those associations found with CrCLD.

In the study by Guastella et al., they questioned the influence that TPA could have on meniscal injury, and studied outcomes of 218 dogs with CrCLD. They found no correlations between TPA and development of concurrent meniscal injury, even for those with excessive TPA.[82] They acknowledged the limitation of variable means to diagnose meniscal injury, but found no significant impact of TPA on CrCLD or meniscal damage.[82] Similarly, in a retrospective case series by Kalff et al. evaluating prevalence of concurrent meniscal tears in dogs with CrCLD and later onset meniscal tears before and after TPLO in dogs, there was no correlation between TPA and meniscal tears at any time point.[83] Interestingly, they discovered that there was a significant difference in development of meniscal tears with respect to age (mean age with tears 6.2 y $\pm$ 2.7 y versus mean age without tears 4.9 y $\pm$ 2.6 y) and the prevalence of a complete or partial tear. Kalff et al found an increase in meniscal tears for dogs with complete CrCLD, but the protective nature of the few remaining CrCLD fibers on the medial meniscus was questioned, given 8% of the current meniscal tears occurred in palpably stable stifles.[83] As similar findings are reported elsewhere, it is reasonable to suggest that there is a protective effect, and that dogs with meniscal tears are more likely to have complete rather than partial CrCLD.[81,84] In one study by Nečas et al. investigating risk factors for meniscal injury, an association was found between meniscal injury and weight, suggesting that dogs with weights greater than 25 kg were significantly more likely to have a meniscal injury.[85] This is further supported by the amount of cartilage damage seen after transection of the CrCL in an experimental model by Smith et al.[86] In a more recent retrospective study by Hayes et al. investigating risk factors for medial meniscal injury in 443 stifles from 366 dogs, increased body weight, complete CrCLD, duration of lameness, and certain breeds were at increased risk for a meniscal tear.[87] They admitted that selection bias could have influenced the relationship with larger breeds and body weight as they didn't record BCS, and

there was likely a decreased chance lameness in small breed dogs was noticed and/or evaluated.. Their multivariate analysis for complete versus partial CrCLD was impactful, as the presence of complete CrCLD increased the risk for medial meniscal tears by 12.9 times compared to partial tears, which is in agreement with previous reports.[81,83,84,87,88] Hayes et al. also found that for every week of lameness, the risk of medial meniscus tears increased by 2.6%.[87] This is biomechanically logical, as a deficient CrCL will lead to increased cranial subluxation of the tibia and subsequent impingement on the caudal pole of the meniscus. However, this correlation is not universally consistent, as some reports show a significantly increased risk of meniscal tears after several weeks while others found there was no significant association.[84,85,87,89] Newer studies found contradictory results, with one report by Wustefeld-Janssens et al. revealing no association between meniscal injury and CrCL status (complete vs partial), while another study by Neal et al. demonstrated increased risk of acquired meniscal tears with a complete CrCLD, and had higher prevalence of meniscal tears in lighter patients (median 29.6 kg) compared to heavier dogs.[90,91] The explanation for these differences is unknown, but may be due to the methods of acquiring the patients, as well as improvements in diagnostic techniques to identify meniscal injury.

The development of meniscal tears is a multifactorial process, and appears to correlate significantly with the development of CrCLD. Given the overwhelming support of greater incidence of meniscal tears with complete CrCLD, it seems logical to encourage early treatment of CrCLD to help off-load the meniscus during weight-bearing to potentially decrease this risk of injury. The odds of such a protective benefit combined with early surgery was investigated thoroughly, and will be discussed in later sections.

D. Diagnosis

While the medial meniscus plays a major role in the stability of the stifle joint, identifying pathologic changes is difficult without direct visualization. Meniscal injuries can increase the level of discomfort in a patient, but often without a substantial tear or folding, diagnosing a meniscal injury may not be possible on exam. Regardless, a few studies evaluated the ability to detect the presence of meniscal tears on orthopedic examination alone. In a 2014 study by Dillon et al. comparing preoperative physical exam findings with those from arthroscopy, it was concluded that pain on flexion of the stifle and presence of a meniscal click is of significance in detecting meniscal injury.[88] Dogs that had pain on stifle flexion had an increased risk for existing meniscal disease by a factor of 4.3, and dogs with a meniscal click had 11.3 times the risk of a meniscal tear. The presence of stifle flexion pain was 67% accurate,77% sensitive, and 57% specific for diagnosing a meniscal tear, and hearing a meniscal click was 63% accurate, 31% sensitive, and 96% specific in diagnosing meniscal injuries. With the two components simultaneously present accuracy, sensitivity, and specificity increased to 76%, 85%, and 57%, respectively.[88] Comparatively in a study by Neal et al. investigating the significance of a meniscal click, a significant association was found between meniscal click and a meniscal injury both with the exam before anesthesia (EBA) and the exam during anesthesia (EDA) before surgical exploration.[91] For the EBA, the sensitivity was 45.8% and specificity was 94.4% for a meniscal tear. Therefore, the positive predictive values for palpable clicks during an EBA were 84.6% and 87.5% respectively, with diagnostic accuracies of 75% and 80%.[91] To further investigate the diagnostic utility of palpating for meniscal tears, a recent study by Gleason et al. investigated whether there are associations between a meniscal click and specific meniscal pathology in 104 dogs.[92] They had similar findings, in that a meniscal click during EBA was 38% sensitive and 94.5% specific, while during EDA was 38% sensitive and 98.2%

specific for all meniscal tear pathologies. Specifically, a positive meniscal click during the EBA or EDA was associated with a bucket handle meniscal but not with a non-bucket handle meniscal tear.[92] These studies utilized arthroscopic findings to confirm the presence of meniscal injury, but they acknowledged the possibility of missing vertical longitudinal tears, which may or may not cause a meniscal click on orthopedic examination. Regardless, it is safe to say that should a meniscal click be palpated, the likelihood of meniscal pathology is high, and the absence of one does not exclude the possibility.

i. Imaging

Very few studies have specifically evaluated meniscal pathology in relation to radiographs of the stifle. Given the tissue composition of the meniscus and the CrCL, radiographic changes are more likely consistent with degenerative joint disease and stifle effusion occurring concurrently or subsequent to stifle instability. However, one study by Nečas et al. looked at risk factors related to meniscal injury, and found that medial joint cavity collapse was associated with a higher risk of medial meniscal damage.[85] Radiographs were performed under sedation with patients in lateral recumbency at angles approximating a standing position. The sensitivity and specificity of this radiographic sign was relatively poor, at 52% and 71% respectively. The limitation of this correlation is the limbs were radiographed in a non-weight bearing position and with varying degrees of effusion and osteoarthritis, which was associated with meniscal damage as well, thus the clinical utility of such an observation should be interpreted with caution. It would seem more appropriate for radiographs be used as a means of interpreting the severity of osteoarthritic changes rather than attempting to diagnose meniscal pathology.

Sonographic interpretation of the stifle receives little credit, but its utility to diagnose cruciate ligament and meniscal pathology was investigated given its low

cost and relative ease to perform. Two earlier studies examining normal healthy stifles in canines demonstrated identification of the menisci via ultrasound, best seen on a sagittal view as homogenous echogenic triangular structures with the apex of the triangle pointed axially.[93,94] There were limitations in evaluating the entire structure as certain views made it indistinguishable from the infrapatellar fat pad, and if animals were less than 20 kg, the menisci were difficult to identify with a standard transducer due to the narrow joint space and overlapping of artifacts.[94] The determination of a meniscal injury was plausible, with some able to identify certain tear types, but description of the full extent of meniscal injury was difficult.[95] The chronicity of the injury helped with identification, as the structure becomes heterogeneous, has hyperreflective and hyporeflective regions, and appears swollen.[94] A few years later, a small study by Mahn et al. with 10 dogs compared ultrasound assessment of the menisci with arthroscopic interpretation and found the majority of cases had agreement between the two modalities, but one dog suspected of injury in the medial meniscus on ultrasound was normal on arthroscopy (with a tear in the lateral meniscus).[96] They concluded that the sensitivity for ultrasound diagnosis of meniscal tears was 90%, while specificity was 92.9%. Limitations pertaining to the study by Mahn et al. included very small case numbers and lack of control groups. Ultrasound has the benefits of limited cost (if at a specialty facility, as general practitioners would have limited access), and ease of use in attempting to diagnose meniscal pathology; however, the clinical applications and interpretation of this modality needs to be considered. Some of the major limitations include influence of severe fibrosis/osteophytosis, patient size, and variations in meniscal tear conformations that may not be as apparent on sonographic examination.

Cross-sectional imaging, including CT and MRI, has little use in diagnosing meniscal injury, but has the benefits of three-dimensional reconstruction and

evaluating intraarticular structures that are otherwise not visualized on radiographs. The earliest studies by Biard et al. and Soler et al. have shown CT and MRI to be capable of easily distinguishing the menisci as wedge shaped areas of soft tissue.[97,98] Given their entirely different composition, they were much easier to delineate from the infrapatellar fat pad, contrary to using ultrasound. MRI has improved visibility compared to CT for intraarticular structures, but even on MRI, the linear separation where the tendon of the popliteus muscle touches the caudal horn of the lateral meniscus could be misinterpreted as a meniscal tear.[97,98] In a prospective study by Tivers et al. with ten beagles, both medial meniscal injury and CrCLD were experimentally created, and pre/post-CT arthrograms were assessed to test the ability to diagnose the pathology.[99] A blinded radiologist correctly identified all sham operated stifles, but identified one simulated meniscal injury as a sham surgery. Therefore, the sensitivity of CT arthrography for identifying caudal horn meniscal injuries was 90%, and the specificity was 100%. Meanwhile in a study of clinically affected dogs (n = 25) by Samii et al., the overall sensitivity (among 3 reviewers performing separate evaluations) was 64.3%, and the specificity was 73.7%.[62] There were several possible reasons for this significant difference between the two studies, such as the small sample sizes in either study, the uneven distribution of contrast used within the stifles as described by Samii et al., which likely affected the perceived prevalence of fibrosis and osteoarthritis, the lack of CT arthrography experience of the interpreters, and the variability in meniscal injury severity. Regardless, veterinary literature reporting on CT imaging of the canine stifle all agree that a more severe meniscal injury is easier to identify, and CT without contrast makes it difficult to truly distinguish the meniscus from surrounding structures.

MRI is a modality capable of showing greater detail of soft tissues structures of the stifle joint, but low field MRI has the disadvantage of slice thickness being

too wide to accurately differentiate small soft tissue structures (ligaments versus meniscus versus joint capsule, etc.) in the small to toy breed dogs. [100] In a prospective experimental model by Martig et al., they induced stifle instability by transecting the CrCL, and followed up with MRI, arthroscopy, and necropsy to test ability of MRI to identify meniscal injury.[100] MRI could be used to evaluate more severe lesions using a grading scheme adapted from human physicians, but differentiating lower grade lesions from normal was difficult, and there were several false positives and false negatives within the study. There was an increasingly heterogenous signal with meniscal degeneration (similar to a grade 4 lesion). Martig et al. admitted that limitations could be the certain viewing windows preferred by the observers, experience level, or that the nature of the lesions are tough to discern on cross-sectional imaging.[100] To further investigate the value of low field MRI, a prospective double blinded study by Böttcher et al. was conducted with 42 stifles, and the results were compared to arthroscopic findings.[101] The findings concluded that low field MRI had an overall sensitivity of 64% and a specificity of 90% for identifying meniscal tears.. In this same study, low field MRI had considerably inferior results compared to arthroscopic examination, and the severity or degree of CrCLD (complete vs partial tears) did not have any effect on diagnostic accuracy. Böttcher et al. noted that the sample size, the difficulty in differentiating degenerative changes with true tears on MRI, and the possibility of injuries not communicating with meniscal surface as reasons for their data deviating from that of previous reports.[101] As technology improved, high field MRI was used, and a newer study out of NC State University by Blond et al. evaluated 11 dogs with CrCLD for meniscal tears on MRI and compared the results to surgical findings.[102] The global sensitivity and specificity for high field MRI were 100% and 94%, respectively. There was one false positive diagnosis of a tear in the lateral meniscus, which was suggested to be influenced by the

insertion of the popliteal tendon.[102] Similarly in another study by Olive et al. investigating high field MRI in 14 dogs with CrCLD, MRI findings were compared to findings from arthroscopy and arthrotomy. They noted a sensitivity of 75% and a specificity of 100% for diagnosing medial meniscal tears.[103] One limitation of these later studies was the use of surgical findings as the reference point, while more recent studies have suggested that arthroscopy is significantly superior to intraoperative findings.[104–106] To address this, a recent study by Franklin et al. compared findings of ultrasound, MRI, and arthroscopy in dogs with CrCLD to see which modality allowed superior identification of meniscal pathology.[107] Both an unblinded and blinded surgeon performed arthroscopic assessment, and found the following: for the unblinded surgeon group, the MRI sensitivity and specificity were 75% and 100%, whereas the blinded surgeon had a sensitivity and specificity of 68% and 100%. The reason for lower accuracy is uncertain, but it may be attributed to the use of high-field MRI, and the use of arthroscopy as the defined gold standard without necropsy confirmation.

The need to investigate less invasive means of advanced imaging to diagnose meniscal tears stems from the idea of potentially decreasing iatrogenic damage through major arthrotomies to look more closely at intraarticular structures. The advantage is the ability to have a three-dimensional approach to look at all aspects of the meniscus, but still has limitations in differentiating milder degenerative changes from normal tissue. With the added cost and inferior sensitivity compared to arthroscopic examination, the clinical efficacy of MRI evaluation of the stifle in dogs remains in question.

ii. Arthroscopy

As discussed previously, even the cross-sectional imaging studies have limitations when evaluating the full extent of meniscal injury, and some authors suggest superiority in direct visualization of the meniscus itself either with

arthroscopy or arthrotomy.[105] Even so, arthrotomy gives limited access to the meniscus given the constraints of surrounding supportive structures, osteophytosis, and the curvature of the femoral condyles.[105,107] In order to improve visualization and potentially decrease the amount of joint exposure with an open arthrotomy, arthroscopy became a popular means to evaluate meniscal injury and determine if therapeutic action was needed. One of the earliest studies by Kivumbi et al. demonstrated the successful capability of arthroscopy to look at all intra-articular structures with a single infrapatellar approach.[108] Later, Ralphs et al. investigated meniscal injuries in 94 dogs and could identify that 58% of joints examined had medial meniscal tears and 77% of joints examined had lateral meniscal tears.[84] Lateral meniscal injures are uncommonly reported, and they stated that the type seen (small radial tears along the inner horn) would be very difficult to detect via open arthrotomy without magnification or presence of joint fluid in their opinion. Given there was no reference point for comparison, the sensitivity and specificity was notcalculated.[84] In addition, a cadaveric study by Pozzi et al. compared arthroscopy and arthrotomy in diagnosing meniscal pathology.[105] Various injuries were created in the medial meniscus and were then each evaluated by a craniomedial arthrotomy, caudomedial arthrotomy, and arthroscopy in random order. Arthroscopy significantly outperformed arthrotomy, especially with probing of the meniscus rather than with observation alone. Arthroscopy sensitivity and specificity for observation alone were 33% and 83%, while with probing were 80% and 95% with a correct classification rate of 92% for all types of tears grouped into one category. The individual types of tears were not categorized.[105] Meanwhile, sensitivity and specificity with a craniomedial arthrotomy and probing were only 37% and 84% with a correct classification rate of 75%. According to Pozzi et al., it was 21.4 times more likely to misdiagnose a meniscal tear if an arthrotomy was performed with observation alone compared with probing.[105] The main limitations

noted by Pozzi et al. included the use of normal stifles (as diseased meniscus from CrCLD may grossly be easier to identify regardless of the type of tear), as well as the type of meniscal injuries created in this model; these may also provide partial reasoning for a lower than expected sensitivity for either technique. Pozzi et al. included only peripheral detachments and vertical longitudinal tears because these tears can be more difficult to diagnose, which may explain the lower sensitivity.[105] Similarly, a retrospective study of 531 stifles with CrCLD by Plesman et al. found meniscal tears present in 38.8% of cases examined by arthrotomy, and in 48.8% examined by arthroscopy, with the difference being statistically significant.[106] Limitations of the study included its retrospective nature, and the possibility that meniscal tears could still be missed in either group. Comparatively, a prospective cross-sectional study by Ritzo et al. showed that meniscal tears were diagnosed by arthroscopy in 83% of stifles, and in only 44% stifles assessed by arthrotomy.[104] Ritzo et al. found concurrent meniscal tears1.9 times more likely to be diagnosed with arthroscopy compared to arthrotomy in dogs with CrCLD. Unfortunately, these data calculations did not consider that these were two separate groups of dogs with no control group, and did not consider the likelihood of false negatives within either group. Either way, the literature supports that a higher percentage of meniscal tears diagnosed by arthroscopy, supporting the benefits of magnification, and improved visibility.

All of the studies assessing arthroscopy acknowledged that its use was primarily in larger breeds, making the use of arthroscopic equipment typical for observing the joint much more feasible. This practice may be unachievable in certain small breed dogs due to small joint spaces and conformation, such as those seen in terrier breeds and chondrodystrophic dogs.[47] A recent study by Kim et al. was conducted out of Korea to evaluate arthroscopic detection of medial meniscal injury using a stifle distractor.[109] They found that sensitivity for arthroscopy with

and without a joint distractor was 85% and 60%, specificity was 96% and 92%, and correct classification rate (CCR) was 94% and 86%, respectively. A significant improvement in visibility was accomplished using this distractor; however, the authors acknowledged that this was a cadaveric model, so clinical efficacy in severely diseased stifles remains to be examined.[109]

With its magnification, improved visualization, illumination, ability to observe intra-articular structures at multiple joint angles, and its minimally invasive approach, arthroscopy demonstrates its relevance in stifle evaluation. It is the gold standard of diagnosing intra-articular pathology, and allows the surgeon to dictate and facilitate the procedures necessary to address meniscal disease in dogs, while potentially limiting further morbidity.[105,107,110] Potential complications, such as latent meniscal tears, joint swelling, and discomfort should be discussed with the client when using this modality.

e. Treatment and Outcomes

Given its pivotal role in stifle stability, many efforts are made to address meniscal injury in dogs, and considering the lack of adequate blood supply to the majority of the meniscus and its limited healing potential, surgical treatment is advocated to improve healing and limit further morbidity.[78,111–114] Surgical techniques used to address meniscal injury include primary repair, partial meniscectomy, hemimeniscectomy, total meniscectomy, and medial meniscal release.[55,115,116] The choice of treatment greatly depends on severity of injury, location of the lesion, patient clinical status, feasibility, and surgeon's preference and training.

i. Primary Repair

Very little is reported in the veterinary literature on primary repair of meniscal tears, and without sufficient data, little can be concluded regarding its clinical efficacy. The goal is to preserve functional meniscal tissue, while ideally resecting compromised tissue, thus case selection is very important. The location of the tear can preclude healing as blood supply is paramount, and repair is often limited to the red-red vascular zone to achieve the best results.[55,78] Regardless, primary repair is shown to be of benefit with vertical longitudinal and peripheral tears in humans, prompting an interest to explore options to preserve the meniscal integrity in dogs with CrCLD.[117] In a prospective study by Moses et al. evaluating 92 dogs with CrCLD, a modified "inside-out" technique was performed on medial meniscal injuries, which included caudal peripheral detachment (83 dogs), and full thickness longitudinal tears in the abaxial periphery or the vascular region (9 dogs).[118] A horizontal mattress suture was placed through the body of the meniscus and was secured to the joint capsule, and the patients were followed for 8 weeks. At 8 weeks follow-up, there was no pain on palpation in any dog, but function of the limb and longer term follow up was not described and was complicated by pre-existing osteoarthritis and the need for repair of the CrCLD. Moses et al. did note that repeat surgery due to recurrence of meniscal injury was not performed in any of the clients' dogs.[118] This repair subjectively seemed to help for the selected tears described, but as this study pointed out, this type of tear only made up 14% of meniscal injuries in their clinical population, demonstrating the limited use of primary repair for meniscal injury.

Out of concern for poor healing in avascular regions of the meniscus, newer developments are advocated in combination with primary repair.[119] In a study by Cook et al., a bioabsorbable conduit was placed to create and maintain a vascular channel from the synovium to an avascular meniscal tear in conjunction with a horizontal mattress suture over the tear.[111] These tears were experimentally created

in healthy dogs, and at 12 weeks postoperatively, there was complete (2/5) or partial (3/5) integration and/or healing, and within 24 weeks all menisci showed tissue bridging and healing. The menisci with suture alone for tears in the avascular region showed no evidence of histologic healing at any time points. This shows great promise for repair potential of avascular regions; however, practical clinical efficacy is yet to be determined given this study was performed in healthy non-degenerative stifles with no instability from concurrent CrCLD. This technique also requires the ability to insert the conduit, such that it extends from the tear all the way to the meniscal synovial junction, suggesting a steep learning curve for future surgeons to effectively utilize this device.[111] Since the study was performed using intact stifles, it is uncertain how this method would succeed with inappropriate tibial translation in stifles with CrCLD, suggesting future studies should be done evaluating its efficacy in a clinical setting.

Meniscal repair is advocated to help alleviate pain, preserve meniscal function, and provide stability and fluid motion within the stifles. Some of the more common tears (bucket-handle, and flap) are shown in cadaver models to have significant effects on contact mechanics, leading to increasing peak contact pressure along the condyles, and that repair of these simpler tears in the red-red zone may have benefit in contact mechanics before they progress to complex tears requiring meniscectomy.[120] A cadaveric study by Thieman et al. evaluating three meniscal repair techniques (horizontal mattress, vertical mattress, cruciate) on contact mechanics demonstrated that there was no significant difference between stifles with repaired menisci and control stifles.[113] There was no difference in contact area, mean contact pressure, or peak contact pressure between the three techniques. All of these techniques restored normal load bearing function, and were superior to the results of contact mechanics of a partial meniscectomy.[113] The meniscus plays an important role in joint mobility of the stifle, and the possibility

of restoring function in injured menisci is promising. While most of these studies are conducted in cadaveric or experimentally created models, the capacity of the meniscus to heal is evident and potentially should be considered more in future CrCLD patients, but efficacy in unstable stifles is yet to be determined.

ii. Partial Meniscectomy

When a region of the meniscus is severely damaged, has crushing injuries, has degenerative changes, or the injury is present within the avascular portion of the meniscus, conventional standard of care is to perform a type of meniscectomy. A partial meniscectomy involves excising only the devitalized region of the meniscus while attempting to preserve as much of healthy meniscus as possible, and is performed frequently by veterinary surgeons.[55,113,114,119,121] With a partial meniscectomy, variations in regenerative and healing capabilities are demonstrated in several studies in which meniscal lesions were experimentally induced, a partial meniscectomy performed, and follow up with histological and gross analysis of cartilage degeneration was performed (time points vary between 4 weeks and 12 months).[112,119,121–128] Regeneration of new tissue within the defects was variable, starting with dull thin friable tissue which then progressed to a dull, non-glossy tissue with fair to poor integration.[112,121,125,126,128] The prevalence of any regenerated tissue was dependent on the extent of resection, as those within strictly avascular regions showed no pseudo-fibrocartilage development, and if any tissue was present, it consisted of avascular tissue composed of fibroblasts and synovial-like cells on the surface, with unorganized scarce collagen fibers developing over 15 months postoperatively. Those closer to the vascular region demonstrated increased tissue regeneration with vascularization along the periphery, and showed maturation with more fibrochondrocyte formation.[112,121,122,125,128] While the regenerative capacity appeared relatively minimal with smaller partial meniscectomies of only the affected region, several studies showed benefits of

minimal excision to limit articular cartilage damage and improve stifle joint biomechanics.[113,122,124,129] The general consensus of the veterinary literature is that the smaller the meniscal defect from the partial meniscectomy, the less severe the chondromalacia and/or articular cartilage damage along the femoral and tibial condyles.[121,122,124,126,127] These findings correlated with the changes seen biomechanically, as the meniscus is a major supportive structure of the stifle. For example, in an unpublished study by Malcolm and Daniel, changes in pressure transmitted to the articular cartilage after removing portions of the lateral meniscus were evaluated, and they noted that with a partial meniscectomy (25% of the entire medial meniscus), the percent load increased from 29% to 45%.[130] In an ex vivo biomechanical study by Pozzi et al. out of Florida, it was concluded that a meniscectomy of 30% radial width had no significant effect on contact mechanics, while removing 75% radial width caused a 60.9% increase in peak contact pressures.[129] Thieman at al. found similar increases in peak contact pressures with partial meniscectomies of approximately 66-75% radial width, which resulted in 55% higher peak contact pressures compared to stifles that received primary repair of the meniscus.[113] However, Thieman et al. reported that the change in peak contact pressures with partial meniscectomies was significantly less than reported with hemi-meniscectomies or total meniscectomies, implying there is stability maintained by preserving the outer rim of the meniscus. The amount of cartilage degeneration supports this finding, as there was less degeneration with partial meniscectomies than the hemi- or total meniscectomies.[113,122,129] Clinical consequences of these pressure increases and cartilage degeneration is demonstrated in studies with variable responses.[81,121,127] In an early study by Bennett et al. evaluating the outcome of 87 dogs with CrCLD, they found improvement with no crepitus on palpation for those with meniscectomy, and no difference in postoperative recovery or return to limb function between dogs that

did or did not have a partial meniscectomy.[81] Unfortunately, the authors had no further criteria described to ascertain function, but they did state that data was obtained at eight weeks post-op for treatment of cruciate and meniscal injury. Alternatively, in the studies by Cook et al. evaluating outcomes of partial meniscectomy with or without small intestinal submucosal graft, they consistently found that the meniscectomy group had significant persistent lameness (median 2-3/4 grades) at 6 and 12 months follow-up despite having opportunity for meniscal healing.[121,127,131] These meniscal injuries were all experimentally induced in otherwise healthy stifles with an intact CrCL. Alternatively, a more recent study by Case et al. evaluated meniscal tears post-surgical stabilization for CrCLD, and it was found that after partial meniscectomy, there was improvement or resolution of lameness in 96.2% of cases at a median of 10 days.[132] While this was a retrospective study, the authors were confident that the sole cause of residual lameness was meniscal injury, as cases were excluded if meniscal injury occurred with other pathology (infection, fracture, implant failure, etc.) that could account for the lameness, and arthrotomy, arthroscopy, and/or orthopedic examination ruled out any other apparent causes.[132] Apart from lameness, a newer retrospective study by Gatineau et al. investigated potential risk factors for complications after TPLO, and found that a medial meniscectomy was a risk factor for the occurrence of the pivot shift phenomenon, where 12/14 dogs with pivot shift had received a medial meniscectomy at the time of TPLO surgery.[133] The limitation of this retrospective study was that the amount of meniscus removed in each case was not specified, making clinical interpretation difficult as the degree of joint pathology and altered biomechanics was dependent on the amount of meniscus removed.[125,129,134,135]

iii. Hemimeniscectomy

Hemimeniscectomy, also known as segmental meniscectomy, begins at the midbody of the meniscus, immediately caudal to the medial collateral ligament, and extends caudally to the caudal menisco-tibial ligament. This technique is recommended for complex and degenerative tears, peripheral detachments with macerated or friable tissue, severe fibrillation of the caudal pole, and other peripheral detachments, where no benefit from primary repair or partial meniscectomy is possible.[55,116] As described previously with a partial meniscectomy, the amount of impact on the stifle either histologically or biomechanically depends on the amount of tissue resected, yet the hemi-meniscectomy has resulted in a surprisingly increased regenerative process.[112,122,134] In the early study by King et al., all dogs with segmental meniscectomies (cranial, midbody, and caudal pole) had defects completely replaced with pseudo-cartilage which grossly resembled fibrocartilage, but histologically consisted solely of fibrous connective tissue with no cartilage cells.[122] Similarly, in a study by Cook et al. comparing grafted and ungrafted hemimeniscectomy lesions, within 12 weeks grossly fibrous tissue replaced the majority of the defect (71.3% of the surface area was filled), and was composed of well vascularized, loose dense connective tissue with no evidence of chondroid differentiation.[112] Johnson et al. noted incomplete regeneration of meniscal tissue, but what grew was connected smoothly to the remaining cranial pole of the medial meniscus with associated remodeling of the native tissues at their junction.[134] The composition of replacement tissue had significantly decreased type II collagen as well as glycosaminoglycans (GAG), which would ultimately compromise the ability of the meniscus to distribute load across the joint under hoop tension.[112] This supports the finding that despite the remarkable formation of fibrous tissue, there is still evidence of moderate to severe articular cartilage degeneration, osteophytosis, and osteoarthritis within these studies. This was demonstrated

further with studies by Pozzi et al., which concluded that dogs with hemimeniscectomies showed an 87.4% increase in peak contact pressure compared to intact stifles, and that even in dogs with a TPLO, stifles with a caudal pole meniscectomy had a 1.7-fold increase in the percent of surface area with peak pressure.[114,129,136] They found that caudal pole hemimeniscectomy resulted in tibial translation greater in CrCLD than in intact stifles, supporting its significant role in stifle stability.[114,129,136] This was supported further by Kim et al., who reported that after a caudal pole meniscectomy, there was significantly more persistent cranial tibial translation after TPLO compared to dog stifles with an intact meniscus.[137] Additionally, as previously discussed, dogs that had meniscectomies performed were more likely to show pivot-shift phenomenon.[133] While there are likely multiple factors contributing to the success of stifles after segmental meniscectomy, the available literature is limited, and often confounded by presence of CrCLD and osteoarthritis, which could impact clinical presentations of those patients after surgery.

iv. Total Meniscectomy

Total meniscectomy is defined as excision of the entire meniscus by removing it from the peripheral synovial membrane as well as transecting the cranial and caudal meniscotibial ligaments to facilitate removal. Total meniscectomy is rarely performed given most meniscal tears or types of pathology involve the caudal horn.[55,115,138] This technique is typically reserved for severe complex meniscal tears that extend to the peripheral rim with or without disruptions of ligamentous attachments, for severely deranged stifle injuries, or lesions present within both horns.[55,116] Advantages of the total meniscectomy over other techniques include removing latent meniscal tears and improving regenerative capacity by exposing and thus providing access to the vascular capsular attachments and synovium.[55,78,116] The majority of studies using

experimental models of total meniscectomy showed a significant amount of regeneration, with a full semi-lunar shaped false cartilage developing as a meniscus replacement.[122,123,139,140] The composition of this fibrocartilage varied from irregularly organized connective tissue consisting solely of fibroblasts to areas of comparable composition to normal cartilage.[122,140] Specifically, in the study by DeYoung et al., they noticed that seven months post total meniscectomy the tissue towards the abaxial margins looked to be of similar composition to a normal meniscus, whereas the axial margins had collagen with less well defined bundles merged with a pale blue matrix containing chondrocyte-like cells.[140] Collagen bundles were mainly oriented to the long axis of the meniscus, and were not as orderly as in the normal meniscus.[140] In one study by Johnson et al. evaluating 14 large breed dogs with an experimental meniscectomy performed, the authors found considerably less regeneration; however, their follow-up gross examination was only four months following surgery, and the previous studies with marked regeneration ranged from 7 - 12 months.[134] The benefit of this regenerated cartilage has yet to be seen, since the majority of these studies demonstrate that with increased meniscal tissue resection, there is considerably more development of osteoarthritis, intraarticular synovitis, articular cartilage degeneration, and increased instability.[122–124,134,141] The study by DeYoung et al. lacked any gross evidence of articular cartilage erosions, had a much lower incidence of osteophytic changes than reported elsewhere, and had an improvement in lameness seven months postoperatively.[140] The exact reason for this discrepancy is undetermined, although these dogs received surgical stabilization for CrCLD, which may have limited any instability that could have led to articular trauma and damage. Flo et al. had similar findings, in that none of the dogs had returned for lameness after total meniscectomy, but neither the exact timeline of their follow-up nor any objective descriptions of their follow-up

examination were available, which may have underestimated true meniscus induced lamenesses.[141] It is possible that in the short-term period, lameness is reduced with total meniscectomy versus partial meniscectomy as there is no discrepancy between the surface of the cranial and caudal tibial condyles, therefore motion may be less disruptive. However, based on the histopathologic changes seen in the articular cartilage and the false cartilages that form, there is great disruption in the biomechanics of stifles with total meniscectomies, and it is recommended to preserve as much tissue as possible with meniscal lesions.[55]

v. Meniscal Release

Prophylactic measures have been suggested to decrease the chances of meniscal tears and/or pathology in the future. Barclay and Theresa Devine Slocum originally advocated for performing a meniscal release concurrently with a TPLO out of concern that the resultant decreased caudal joint space postoperatively would predispose the caudal horn to tearing, leading to residual pain, lameness, and progressive osteoarthritis.[115] The meniscal release is performed by either radial transection at the caudal meniscotibial ligament or at the midbody of the medial meniscus. The release theoretically allows the caudal horn of the medial meniscus to move caudally and decreases impingement when cranial drawer occurs in CrCLD stifles.[55,115] This theory is supported within the literature by Kennedy et al. using cadavers treated with either of the two release techniques, which reported that medial meniscal release (MMR) spared the caudal pole of the meniscus from meniscofemoral entrapment.[142] The authors found based on MRI images that the femorotibial contact increased axially with axial release, but the axially located remnant of the caudal pole still experienced compression between the femoral condyle and the tibial plateau with the abaxial midbody release.[142] The importance of the meniscal remnant being compressed is yet to be determined. A study by Kennedy et al. suggested that either type of meniscal release could provide stifle

congruency as a spacer, could be an additional source of pain, or lead to a more severe meniscal injury requiring repair.[142] The act of MMR resulted in increased femoro-tibial contact since the hoop stress capabilities in dispersing compressive load were reduced or absent, and as such, also led to increased peak pressures on the femoro-tibial condylar surfaces.[114] Meniscal release alone without CrCLD induces significant instability as well as increased development of osteoarthritis, articular cartilage damage, and lameness. This is rarely a clinical scenario, however, and this procedure is typically done in conjunction with the TPLO.[136,143]

There is a large debate if MMR should be done at the time of TPLO in the absence of meniscal injury. Several studies have suggested that MMR is unnecessary, and does not decrease the rate of subsequent meniscal tears post-TPLO surgery.[55,133,144] Specifically in a study by Thiemen et al., the overall rate of subsequent meniscal tears was similar between those that had a MMR and those that did not. When the data were divided based on arthrotomy vs. arthroscopy, those canines that received an arthrotomy and no meniscal release were 3.8 times more likely to be diagnosed with a subsequent meniscal tear than canines that had an arthrotomy with a MMR or arthroscopy with no MMR.[144] Additionally, it is demonstrated that the pressure and contact mechanics are significantly affected by the MMR in stifles that received a TPLO, and were in fact statistically similar to those following a caudal pole hemimeniscectomy, suggesting that MMR is not a benign procedure, and may worsen the progression of arthritis without providing any benefit.[114,136,143,145] Conversely, an early study by Rayward et al. evaluating dogs treated with a TPLO procedure found no change in osteophyte score between those with or without a MMR performed.[146] The osteoarthritis progressed regardless of therapy, which could relate to the severity of the CrCLD, but it was not possible to isolate any the association with meniscal release. A more recent prospective study by Ritzo et al. suggested there is benefit to MMR as they noted

that 0% of dogs with MMR had subsequent tears, while dogs without MMR performed had a subsequent tear rate of 11%.[104] The discrepancy between these studies is possibly confounded by the inability to determine the presence of a meniscal tear with 100% certainty at the time of surgery, as well as the study designs. It is concerning that studies repeatedly show that even stifles with MMR performed develop subsequent meniscal tears, which calls the validity of performing such treatment into question.[144,147]

The choice of meniscal treatment depends historically on the severity of the lesion, the current clinical status, and surgeon's preference. Isolated meniscal injury without concurrent CrCLD is extremely rare, and thus treatment is often indicated at the same time that the underlying CrCLD is addressed.[148] The principle agreed upon by the majority of the veterinary community is to preserve as much meniscal tissue as possible in the hope of conserving biomechanical advantages, and to decrease the severity of osteoarthritis.[55] Based on the available reported findings, the decision to perform a MMR is highly controversial, and comes down to the surgeon's decision at the time of surgery. A surgeon must take into consideration the pros and cons of performing this procedure, and the potential clinical impact it has on each patient individually, particularly with several studies showing that performing MMR does not confer a significant difference in development of subsequent meniscal tears.

3) Cranial Cruciate Ligament Disease: Therapeutic Options

As a result of CrCL instability, there is cranial translation of the tibia in relationship to the femoral condyles during weight bearing, causing significant pain, and leading to the development of osteoarthritis. The purpose of surgical treatment for CrCLD is to decrease this motion, and provide a means of returning the patient to normal activity.[55,115] There are many procedures developed to address

CrCLD, typically divided into the following categories: intraarticular reconstruction, extracapsular repair (ECR), and osteotomy procedures. Intra-articular procedures involve the use of grafts (autogenous, cadaveric, and synthetic) from various sources to replace and simulate the actions of the native CrCL, and their use was advocated for quite some time given their popularity in the human field.[55] Since their introduction, the use of such techniques is uncommon, and more surgeons prefer extracapsular techniques or osteotomy procedures.[55] Extracapsular techniques focus on providing stability around the joint to allow periarticular fibrosis to generate long-standing stability, and these include the lateral fabellotibial suture, the fibular head transposition, and the Ruby procedure.[55,149–153] Early on, some authors preferred extracapsular repair due to such advantages as lower cost, fewer foreign implants, and that some of the procedures did simulate all functions of the CrCL (including preventing internal rotation of the proximal tibia), but newer studies suggest that osteotomy procedures such as the TPLO and TTA are superior for longer term function.[154–160] An early study by Lazar et al. evaluated and compared development of osteoarthritis after the TPLO procedure and extracapsular repair techniques, and the authors showed that dogs that had an ECR were 5.78 times more likely to have greater differences in their pre and postoperative osteoarthritis score compared to dogs that had a TPLO procedure performed.[154] Limitations included its retrospective nature, and that a greater percentage of the ECR group had meniscal tears, which has been shown to significantly increase osteoarthritis development in CrCLD stifles, potentially impacting the severity in that group. There are a few studies showing no remarkable differences between ECR and TPLO in terms of function, peak vertical force, and radiographic changes.[155–157] The criticisms of these studies have included lack of treatment randomization, non-standardized meniscal treatment between groups, use of observational subjective evaluation

rather than blinded objective measurements, non-standardized postoperative rehabilitation protocols, and only evaluating patients at a walk.[155] More recent studies tried to address some of these flaws with randomized groups, and evaluating both gait analysis and ground reaction forces at a walk and trot.[158–160] All three of the more recent studies found that TPLO patients returned to normal function faster, had improved or close to normal reaction forces and symmetry index compared to ECR patients, and had significantly more favorable owner-perceived outcome.[158–160] Despite these findings, the choice between osteotomy procedures and ECR remains dependent on factors such as financial restrictions, owner preference, size of patient, and ultimately, surgeon's preference.

a. Osteotomy Procedures

Numerous osteotomy procedures are utilized, and have been evaluated in the veterinary literature to address canine CrCLD, but a detailed description of each procedure is beyond the scope of this review.[55,105,115,136,161–167] Osteotomy procedures were developed to address various issues, including conformational deformities, tibial plateau angles deemed too steep for conventional osteotomies, and to further improve upon the presumed faults of other techniques.[55,167–169] For the purpose of this review, the primary osteotomy discussed will be the TPLO.[3,55,115]

b. TPLO Technique

The TPLO was developed by Barclay and Theresa Devine Slocum with the theory that in addition to passive actions that led to stifle stability, there was also active stability maintained by muscle groups during weight bearing.[3] The purpose of this procedure was explicitly stated to neutralize the effects of uncontrollable cranial tibial thrust, not to reconstruct passive forces such as those exhibited by the

CrCL and medial meniscus.[3] In the simplest terms, the procedure is performed by making a semicircular osteotomy starting at the cranial tibial plateau, and extending to the caudal cortex of the proximal tibia. This facilitates caudal rotation of the proximal fragment containing the tibial plateau, thus reducing the TPA.[3] The original description suggested that the ideal TPA post rotation was approximately 0°; however, later the written recommendation stated to strive for 5°.[115] This 5° was considered ideal to provide adequate stifle stability, and hopefully prevent strain on the CdCL. By decreasing the tibial plateau angle, there would be little to no cranial tibial translation during weight bearing, but the tibia could translate cranially during the swing phase of motion, or during flexion of the stifle. The osteotomy site is typically secured with a specialized plate, and the patient is rested for a minimum of eight weeks.[115]

c. Complications

The TPLO is reported to have excellent outcomes, in terms of both gait analysis and client satisfaction, and restores dogs to near normal function several months postoperatively.[155,158,160,170–172] While the overall success rate continues to improve since it was first described by Barclay Slocum, there are still several reported complications worth mentioning. The veterinary literature reports overall complication rates between 9.7% - 28%, and the most recent retrospective studies reported less than half of the complication rates in earlier studies.[133,147,172–174] Intraoperative complications included tibial fracture, intra-articular screw placement, hemorrhage/laceration of the cranial tibial artery, broken drill bits, screws or holding pins, fibular fracture, intra-articular pin placement, bone screw(s) in the osteotomy, and a retained surgical sponge.[55] Many of these intraoperative complications are the result of poor technique or surgeon error, and have gradually improved with TPLO experience as well as improvements in TPLO

planning, implant advancements, and refinement in surgical technique over the last decade. The reported rates of these complications are listed in Table 1. One retrospective study by Kowaleski et al. reported that fibular fractures were associated with previous synostosis of the tibia and fibula, which fractured upon rotation of the proximal segment.[175] The development of pre-contoured locking plates led to adjustments in techniques, as using a curved plate with the proximal screws fixed in a position angled away from the articular surface potentially decreases the risk of inappropriate intra-articular screw placement.[55] Strategies to prevent hemorrhage via laceration of the cranial tibial artery have included packing gauze cranially and caudally deep to the popliteus muscle, and distraction of the osteotomy site to ligate the vessel after a tear has occurred.[55]

Postoperative complications (short or long-term) include surgical site infection (SSI)/implant-associated infection, incisional complications, implant failure, tibial fracture, patellar ligament thickening, tibial tuberosity fracture, diaphyseal fracture of the tibia, osteomyelitis, postliminary meniscal tears, draining tracts, fibular fractures, patellar fractures, septic arthritis, formation of a ring sequestrum (around distal jig pin site), pivot shift, internal torsion, patellar luxation, and joint capsule swelling; rates of these complications reported in the literature are listed in Table 2.[55] Development of SSI is thought to be multifactorial, with several proposed reasons, including the following: excessive soft tissue dissection, increased anesthetic times, use of propofol for induction, implant surface properties, increased body weight, and intact male status.[55,147,173,176–178] Minimal soft tissue manipulation and adequate closure of multiple layers are advocated to help prevent SSI as much as possible. Decreasing the rate of tibial tuberosity fractures was thoroughly evaluated, and has been successful with technique adjustments in the tuberosity width, placement of the osteotomy, anti-rotational K-wire placement, and identification of a safe corridor

for tibial rotation.[168,179–182] As previously discussed, the factors affecting subsequent meniscal tears are difficult to delineate as some studies suggest the number of tears that are missed at the time of surgery remains unknown.[55,116,144] Thorough examination of the meniscus and addressing any damaged tissue is recommended to decrease the risk of injury later. The introduction of locking plates is beneficial, as it provides a direct guide for the screws and drill bit to hopefully decrease risk of breakage, as well as decreasing the change in TPA that can occur after TPLO, termed "rock back".[55,183] With regards to patellar ligament thickening, there is concern that the TPLO procedure places additional stress on the patellar ligament, leading to inflammation.[55] One retrospective study by Mattern et al. found that a TPA less than 6° and greater body weight (absolute weight, not BCS) were risk factors for patellar ligament thickening.[184] Additionally, both saw blade kerf and the position of the osteotomy have been demonstrated to have an effect on the distance between the patellar ligament insertion on the tibial tuberosity and the intercondylar eminence; decreasing this distance can increase strain on the patellar ligament resulting in thickening.[179,180,185]

Lastly, there are a few studies reporting the incidence of osteosarcoma following the TPLO procedure, with the proposed source being a specific cast bone plate.[186] A direct causation between the plate and/or procedure and development of neoplasia was debated, with implant corrosion, the specific metal alloy used, electrolysis between dissimilar metals, tissue damage at time of trauma or surgical repair, and altered cellular activity related to delayed union, nonunion or infection as the proposed factors involved.[178,186,187] A direct association between the incidence of osteosarcoma and the TPLO surgery is uncertain, but the prevalence of osteosarcoma developing at the TPLO site in recent studies suggests that osteosarcoma should still be listed as a differential diagnosis for pain and/or lameness months to years after the initial surgery.[188–190] Many of the reported

complication rates continue to improve, and the hope is that as surgical experience continues to increase and techniques evolve, the rates will continue to decline.

4) Preoperative Planning for CCLD

a. Benefits and Rationale

The ability of orthopedic procedures to result in successful outcomes greatly relies on surgical execution, surgeon experience, patient health and/or condition, but also in the consistency with which the procedure can be performed.[55] Preoperative planning is a major component of orthopedic surgery as it can provide objective step-by-step measurements and instruction, and allows adaptation to dogs of variable body conformation and conditions. The same exact measurements may not work for every patient, as there are many variations to the anatomy of the tibia that could impact the technical aspect of a TPLO. One retrospective study by Guastella et al. evaluated 275 client owned dogs that received a TPLO, and showed that German Shepherds had a significantly higher TPA than other breeds, and suggested that German Shepherds may require significantly more rotation to achieve adequate stability of the stifle.[82] The clinical consequences of increased rotation, however, were unable to be determined given the retrospective nature, but with excessive rotation of the tibial condyles, altering the surgical planning in order to reduce the risk of fractures may be required.[55] The ability to utilize preoperative planning in cases with anatomic variation is paramount as shown in a prospective study by Mossman et al., which evaluated the accuracy of three measurement techniques for TPLO.[191] In this study, the proximal tibial conformation of Bulldogs made preoperative planning difficult using the standardized methods and were disregarded in favor of intraoperative observation and adjustment. Rather than dismissing this as a means to discredit preoperative planning, it demonstrates that the anatomy of the tibia can vary and the more

prepared the surgeon is prior to surgery, the higher likelihood of decreasing the risk of intraoperative and postoperative complications.

Another proposed benefit of preoperative planning is to improve the accuracy during surgery, as the presence of soft tissues, periosteal proliferation, and osteophytosis can make consistent anatomic markers difficult to appreciate intraoperatively. The consequences of inaccuracy can be severe, and impact the patient outcome, as well as predispose the procedure to failure. A study by Kowaleski et al. investigated the effect of the position of the tibial osteotomy on the resultant tibial plateau angle and found that alterations in the center of the osteotomy led to shifts of the tibial long axis, as well as the postoperative TPA.[180] Clinical consequences of these separate positions were not assessed given this was a cadaveric model, but if the TPA is too steep postoperatively, there is concern that the stifle could remain unstable, nullifying the original purpose of surgery.[180] The concerns of over or undercorrection are centered on the strain placed on the caudal cruciate ligament or persistent instability of the stifle, so ideally, preoperative planning would reduce the chances of instability in the postoperative period. In a cadaveric study by Windolf et al. the benefit of preoperative planning was evaluated, and it was discovered that even within a controlled environment, there were noticeable variations between radiographically planned and achieved rotations.[192] Theories to explain the disparity included position of the blade and thus angle of the osteotomy, and any movement that may occur during application of the plate. Windolf et al. also identified that increased amount of rotation led to reduced biomechanical stability of the stifle.[192] This study measured the TPA using conventional Slocum planning charts, rather than using additional radiographic markers that could assist with positioning of both the osteotomy and plate for each stifle, which could in turn impact the amount of rotation. It emphasizes the need for precise surgical technique in combination with adequate preoperative

planning.[192] A large retrospective study by Collins et al. evaluating 468 TPLO procedures compared the outcomes between the groups with pre and intraoperative planning to those that had free-hand osteotomy only.[193] The group with preoperative planning had significantly improved reproducibility of the centered osteotomy placement and was associated with a significantly lower rate of tibial tuberosity fractures.[193] This is important as tibial tuberosity fractures are reported to occur more commonly than expected, and are associated with implant placement and osteotomy position.[173,181] Therefore, any planning that could help decrease the morbidity associated with this complication is strongly encouraged.[173,181] A prospective study by Mossman et al. evaluating 59 dogs that had a TPLO procedure, three preoperative planning techniques were assessed by comparing postoperative radiographic measurements to the planned preoperative radiographic measurements.[191] Mossman et al. found two of the methods to be significantly more accurate, with consistent comparative post and preoperative measurements.[191] The authors described the disadvantage of anatomic variation, and particularly with Bulldogs, intraoperative planning was vital to adjust the osteotomy position to accommodate the appropriately sized plate for the patient's weight, which could not be appreciated fully on radiographs alone. Regardless, it emphasizes that free-handing without preoperative planning resulted in poorer clinical outcomes and increased surgical complications. Lastly, one of the other advantages of preoperative planning is the ability to accommodate angular deformities that may require correction concurrently with the TPLO procedure. Such utility was demonstrated in a study by Weh et al. describing the technique of combining a TPLO and a transverse corrective osteotomy of the proximal tibia for treating tibial deformities in dogs.[169] Overall outcomes were excellent, and while it is presumptuous to associate that success entirely with preoperative planning, there is

no denying that performing such procedures without thorough preoperative planning would be difficult, and likely should be discouraged.

The benefits of preoperative planning are evident, and with little cost and minimal delay in the surgical process, the investment is worth it. Future studies investigating preoperative planning techniques, which account for anatomic variation, and acknowledging the necessity of astute intraoperative surgical technique will help lead to more positive and consistent clinical outcomes.

b. Conventional Planning Method: Tibial Plateau Angle (TPA)

Traditionally, TPLO planning begins by first measuring the TPA. A lateral radiograph of the stifle and tarsus with both held in about 90° of flexion is typically obtained for this measurement (although this angle is not required).[55] A line centered at the trochlea of the talus is drawn to intersect with the tips of the intercondylar eminences on the tibial plateau. A line tangential to the tibial plateau is then drawn to intersect at the approximate attachments of the cranial and caudal cruciate ligaments. The tibial plateau angle is measured at the intersection of the tibial plateau line and the tibial long axis lines with reference to a line perpendicular to the tibial long axis (Figure 1). For example, a tibial plateau axis perpendicular to the tibial long axis would be assigned a TPA of zero. While many surgeons use this technique, there are some who feel that it may underestimate the true tibial slope at the point of interest (the femorotibial contact point), and instead incorporate too much of the non-articulating surfaces of the tibial condyle.[194] To evaluate this, a cadaveric study by Baroni et al. was performed using 16 limbs to compare TPA calculated from the conventional method as well as an alternative method to those obtained from anatomic evaluation of the limb without soft tissue components present.[194] The alternative method measured the TPA by finding the angle between a line tangential to the linear portion of the medial tibial condyle

and the line representing the mechanical axis of the tibia (Figure 2). Baroni et al. reported that the mean TPA using conventional methods was significantly lower than anatomic measurements, while the anatomic TPA and the TPA measured using the alternative method were not significantly different.[194] One concern with this study was the variable experience in radiograph interpretation as well as the difference in clarity between digital measurements and those made on printed radiographs. The implications of these variations for clinical patients remains unknown. To further provide standardization of radiographic positioning for measurement of the TPA, a study by Reif et al. was performed using five canine cadaver limbs.[195] Two methods of measuring the TPA, the conventional method and a tangential method, were utilized to determine the radiographic TPA (R-TPA). The R-TPA was then compared to the anatomic TPA (A-TPA), which was determined using Kirschner wires inserted at the caudal and cranial extent of the tibial plateau after dissection of peri-articular soft tissues. The stifle with the Kirschner wires was photographed, and the photo was printed. Measurements were made to determine the A-TPA utilizing the photograph. Various radiographs were obtained with the hind limb specimens relocated in proximal, distal, caudal, and cranial directions with respect to the radiographic beam. In a true lateral position with superimposition of the femoral condyles, there was no significant difference between R-TPA and A-TPA; however, with both methods, the difference between R-TPAs increased as specimens were moved to extreme positions. This emphasizes the importance of maintaining a true lateral view of the stifle (or the tibia) to improve accuracy and consistent TPA measurements.[195]

To investigate the question of whether or not observation from a radiograph was sufficiently accurate for planning a TPLO, a study was conducted by Grierson et al. with 12 cadaver limbs for which the R-TPA and the A-TPA were compared.[196] They found that for shallow A-TPAs, the R-TPA tended to be an

overestimation by the observers, but for steep A-TPAs, the observers tended to underestimate the actual value. Specifically, the difference between the anatomic and radiographically observed TPA was significant for the limbs for which the A-TPA was less than or equal to the median angle (23.3°), and not significant when the A-TPA was greater than the median. Overall, the mean and median discrepancies were negative and very small (-0.64° and 0°); therefore, it was concluded that measurements made using radiographs are suitable for planning a TPLO.[196] Given that the A-TPA is unachievable in a live patient, there is little choice but to rely on radiographic assessment for calculating the TPA.

Consistency in measuring the TPA is difficult, particularly when the landmarks are not easily identified, such as cases with severe osteophytosis.[55] In a study by Ritter et al. using 31 mongrel dogs, TPA measurements were obtained using a novel technique to identify the caudal medial tibial plateau landmark in cases with osteophytosis induced by experimental transection of the CrCL.[197] Two lines were drawn with one following the distal to proximal margin of the caudal cortex of the medial tibial ridge, while the other followed the articular surface of the medial tibial plateau until it intersected with the first line (Figure 3). With this method, severity of osteophytosis did not have a significant effect on differences between TPAs.[197] There was no significant difference between the TPA of the right hindlimb before and after induction of osteophytosis. Ritter et al. also compared the TPA of the right and left stifles to see if the contralateral limb is useful as a measurement tool in cases of severe osteophytosis. They found no significant difference between the TPA of the right and left limb, and that there was tibial plateau symmetry (difference $\leq$ 2°) in 90% of dogs. This study did not compare these values to the anatomic TPA given the in vivo nature of this study, so the definitive accuracy of these measurements is questionable. This study also provides support for utilizing the unaffected limb for TPLO planning cases with

severe osteoarthritis; however, the potential for over or underestimation needs to be considered.[197]

Tibial plateau angles vary, and can range from as low as 12° to greater than 50°.[55] Multitudes of ranges are reported, with a large representative sample listed in Table 3 with their respective categories. Many of these studies were conducted to investigate factors associated with the TPA and development of CrCLD as described earlier in this review. With such wide ranges and the questions regarding modalities used to measure TPAs, efforts were made to assess inter- and intra-observer variability to investigate the accuracy of TPA measurements for TPLO planning. One study by Baroni et al. compared radiographic assessment of the tibial plateau slope in dogs among three examiners using radiographs, and compared the results to the A-TPA. It was concluded that, for printed films, the mean interobserver variance was 8.6°, and the mean absolute deviation from the mean for alternative TPA measuring techniques was 2.0°.[194] For digital films centered over the stifles, variance and mean absolute deviation from the mean were 6.8° and 1.5°, respectively.[194] Baroni et al. did not assess interobserver variability, but found no difference between radiographic technique and anatomic measurements. In a study by Caylor et al., the TPA was measured by three observers of various experience (very experienced, six months experience, and one-two days experience) using lateral radiographs of the tibia.[198] There was an overall intraobserver variability of $\pm$ 3.4°, and an interobserver variability of $\pm$ 4.8°, with no significant differences seen for intraobserver measurements. There was a significant difference between the inexperienced observer and the two experienced observers.[198] Another study by Fettig et al. evaluated variability among observers and specifically compared their measurement points on the radiograph to see if there was any correlation between the landmarks used and the resultant TPA (Figure 4).[199] Interobserver variability for each dog was 0.8°, while

the intraobserver variability was 1.5°. The TPA by all 11 observers differed significantly from each other, but there was no significant difference between the measured TPA among the different groups of observers. The greatest source of interobserver variability was attributed to variations in the caudal point for both the horizontal and vertical measurements. Specifically, significant correlations were shown between the TPA and the amount of degenerative joint disease present at the caudal point.[199] In contrast, a study out of Kansas State University by Lister et al. comparing two digital software systems and plain films among three observers showed significantly more variability among TPA for images with the least amount of osteoarthritis.[200] The explanation for the disparity is unknown, but there was a difference between software programs. The authors suggested validating the programs against film radiographs to assess the magnitude of this difference in the future.[200] Interestingly, in a recent study by Unis et al. comparing two computer-based programs and standard films, there was no significant difference in the average variability with each method for all but one observer (the least experienced).[201] Experience level had no effect on measurement variability, but interobserver variability was significantly lower using the computer programs rather than standard films, suggesting there may be improvements in digital calibration and/or program diagnostics.[201] Unis et al. did not compare these findings to anatomic TPA, so the validity of these program measurements is unclear.[201] Similar to the study by Baroni et al., another study by Grierson et al. looking at anatomic versus observer TPA measurements found an interobserver variance of 11.69°, and mean absolute deviation from the mean of 2.88°.[196] Grierson et al. found that the reliability for any single observer measurement was low, and the reliability of the average measurement was moderate using the intra-class correlation coefficient. They theorized that this could be due to having a homogenous population and low sample size. They stated that clinical focus should

be placed on the similarity between the average observed TPA and A-TPA, and suggested that these measurements were suitable for TPLO planning.[196] A study by Glassman et al. alternatively found there to be strong intraobserver and interobserver agreement for measuring TPAs on radiographs and other measuring modalities for caudal tibial angulation.[202]

The ideal TPA recommended following a TPLO procedure remains elusive, but conventional methods began with striving for 0°, and Barclay Slocum later adjusted this to 5° to stabilize the stifle, but to also prevent strain on the CdCL.[3,115] With that, efforts were made to investigate optimum postoperative TPAs, and their impact on tibial femoral contact. A study by Warzee et al. using a cadaver model discovered that cranial tibial thrust was eliminated when the postoperative TPA was 6.5°, suggesting that patients may be overrotated clinically if calculating measurements were based on an end-goal of 5°.[9] In support of these findings, another cadaver study by Reif et al. found that when the proximal tibial rotation resulted in a 5° TPA, there was a caudal tibial translation of two millimeters (± 2.9 mm), supporting the concern for over-rotation in clinical patients.[8] The limitations of these studies included factors inherent to their cadaveric nature. However, they sparked concerns that without evidence-based confirmation of a fixed TPA for alleviating stifle instability, the variability of preoperative TPA measurements could have significant clinical impact on postoperative outcome of TPLO in dogs. Thankfully, reported ranges of TPA continue to narrow in recent literature, but without standardized methods for calculating the margin of error possible in intra and postoperative TPAs, the need for improvement in TPLO planning is still evident.

c. Alternative Technique – Patellar Ligament Angle

Apart from the tibial plateau angle, an additional anatomic measurement that has been evaluated and compared between dogs with and without CrCLD is the patellar ligament angle (PLA). A newer school of thought by Tepic et al. suggests that the overall relationship between the patellar ligament and the tibial plateau, in terms of the angle between a line tangential to the tibial plateau surface and a line parallel to the patellar ligament, could have a significant impact on stifle stability.[203] A cadaveric study by Dennler et al. was conducted to evaluate how the PLA changes throughout stifle range of motion and concluded that the patellar ligament was perpendicular to the tibial plateau at a stifle flexion angle of 90° in a healthy patient (Figure 5). The purpose of the study was to establish a baseline for future consideration for surgical planning for treatment of stifle disease.[5] Similar findings were reported in another study by Schwandt et al., which compared the PLA in healthy dogs to that of dogs with CrCLD. The crossover point (the point at which the patellar ligament is perpendicular to the tibial plateau) for the flexion angle was 90° for healthy dogs, while for dogs with CrCLD, the crossover point was 110° of flexion, meaning that their stifles had to be carried at greater flexion to resist shearing forces.[204] The PLA was statistically significantly greater in dogs with CrCLD compared to that of dogs with an intact CrCL. The consistency of this measurement demonstrated repeatability in this study, but another study by Bismuth et al. compared a radiographically measured PLA with the anatomic PTA, and suggested poor validity for the radiographic PLA, which was consistently higher than anatomic measurements.[205] Regardless, the investigation of the role of the patellar ligament angle in stifle stability led to development of surgical procedures, such as the tibial tuberosity advancement (TTA), which utilizes the spatial relationship between the patellar ligament and the tibial plateau to alter the PLA to reduce cranial tibial thrust.[203,206] The role of PLA with respect to the TPLO has limited mention, although one study by Drygas et al. did investigate the effect

of TPLO on the PLA.[207] They reported that after rotating the proximal tibial segment to an end TPA of 6°, the mean PLA (94.1°) was reduced to values similar to those recommended when performing a TTA to reduce tibial thrust.[207] Stifle mechanics are complex, but these studies demonstrate that the patellar ligament plays an important role in stifle stability.

d. Alternative Technique – Common Tangent Method

The common tangent method is a newer method of evaluating stifle conformation for preoperative planning. A common tangent is defined as a line that is tangent to 2 circles, and in this context, the common tangent of interest is also perpendicular to a line connecting the centers of the two circles. In the application of this to the stifle, the circles are superimposed over the of the femoral and tibial condyles, such that their articular surfaces align as an arc of each circle. The common tangent is then compared geometrically to the position of the patellar ligament and the tibial plateau. The common tangent method is rarely reported in the veterinary literature, apart from its use in evaluating the PLA, and its association with planning for the tibial tuberosity advancement (TTA).[203] The same studies by Dennler and Schwandt previously compared the PLA between the tibial plateau (PLA_{TP}) and the common tangent (PLA_{CT}).[5,204] Dennler et al. concluded that the point of flexion at which the patellar ligament is perpendicular to the common tangent was at 110°, 20° greater than that for the tibial plateau.[5] Schwandt et al. found similar values, where the patellar ligament is perpendicular to the common tangent at a joint flexion angle of 110°. With partial CrCLD and a fixed stifle flexion angle, the PLA was significantly larger (2°) compared to the PLA of a normal stifle.[204] Both of these studies showed high consistency with low interobserver variability in measuring the common tangent. While the clinical application of this baseline data is not completely known, the potential benefit of

this method is to improve accuracy by treating the joint as two cylindrical surfaces rolling against one another, rather than assuming that movement is like that of a cylinder on a flat tibial plateau. The measurement capabilities of the common tangent method were called into question in two studies (Bismuth et al. and Millet et al.) that both demonstrated a relatively poor interobserver reliability, and only moderate intraobserver reliability.[205,208] Furthermore, the PLA_{CT} on radiographs was found to be statistically significantly less than the anatomic PLA and the PLA_{TP} in the study by Bismuth et al.[205] Similarly, Millet et al. demonstrated that the PLA_{CT} was less than the PLA_{TP}; however, it should be noted that the angle in this study was labeled differently than in all previous reports. Typically, the PLA would be labeled as a value of 'x,' whereas in Millet's study, the angle labeled as the PLA is actually '180°-x', thus comparisons of common tangent measurements with this study are irrelevant as its terminology has a different definition.[208] The conflicting results in measuring the common tangent may not necessarily represent invalidity of the design, but rather a steep learning curve, and future studies assessing its utility are warranted. One study by Drygas et al. used the PLA measurement with the common tangent to assess the effects of tibial plateau rotation in a TPLO.[207] In this study, to achieve a PLA_{CT} of 90° required an end TPA of 12°, indicating that using the common tangent method may require less rotation of the proximal tibia to achieve stability. This is significant given the potential strain that over-rotation could place on the CdCL, as well as complications associated with the tibial tuberosity.[207] Logically, the concept of planning a TPLO by treating the proximal tibial plateau as a convex surface appears valid, but more studies are required to assess the repeatability of the common tangent method, and to demonstrate its clinical efficacy in achieving stifle stability.

e. Miscellaneous TPLO Planning Methods

There are some other described methods of TPLO planning besides the above mentioned. Two recent studies evaluated whether certain intraoperative techniques could be used to improve the accuracy of rotating the tibial plateau. Woodbridge et al. evaluated a two wire technique in 72 cases.[209] In this study, the authors measured 3 preoperative markers: A_1 (the point where the intended osteotomy contacted the proximal tibial surface), B_1 (measured from most cranioproximal point of the tibial tuberosity and ending at the osteotomy site, while remaining perpendicular to the cranial straight edge of the tibial crest), and C_1 (the point where intended osteotomy contacts the caudal tibial cortex) (Figure 6). The points A_1 and C_1 were located and measured with calipers intraoperatively, and Kirschner wires were inserted (medial to lateral) against which the TPLO blade rested. Unfortunately, the position of the osteotomy varied significantly (based on postoperative radiographic assessment) from preoperative measurements, with variation ranging from 5-13%.[209] Potential reasons included the irregular surface of the medial proximal tibial metaphysis, the possibility of soft tissue disruption (particularly in measuring C_1), and the positioning of the blade in relation to the Kirschner wires. In a different study by Restle et al., cadaveric limbs were used to assess the utility of a novel jig (ROMA) device to accurately predict the intraoperative change in TPA.[210] They placed the novel jig arm on a standard Slocum jig, and measured the TPA after rotation by using the chord length method.[115] They found that the ROMA provided similar accuracy in determining postoperative TPA compared to the chord method, and served as an alternative way to evaluate TPA intraoperatively.[210] Its utility in clinical cases is still being investigated.

Although there are multiple tools of measurements for preoperative TPLO planning, variability still exists, and is most likely multifactorial. As continued

improvements are made with the surgical techniques, and as understanding of stifle mechanics evolves, TPLO planning should improve in accuracy and consistency.

5) Significance of Preoperative Planning and Surgical Outcomes

a. Implications on Cranial/Caudal Tibial Translation

Preoperative planning techniques are critically evaluated because of the variability associated with planning, which ultimately has significant clinical impact. As previously discussed, earlier cadaveric studies looking at the effect of rotation to specific goal TPAs on cranial translation showed that a TPA angle of 6-6.5° would effectively stabilize the stifle, and rotating the tibial plateau to 5° would in turn result in caudal subluxation, which directly places significant strain on the CdCL.[8,9] This finding is significant because there is concern that the recommended conventional measuring techniques may lead to over-rotation, which gives all the more reason to refine the techniques in planning TPLO surgery. Alternatively, a study by Shahar et al. utilizing a computer based model to simulate stifle biomechanics found that cranial tibial thrust is converted to caudal tibial thrust when the end TPA is 0°, and that rotating to a TPA of 5° does not eliminate cranial tibial thrust.[211] However, when the tibia was rotated to achieve either an end TPA of 0° or 5°, the result is an increased load placed on the CdCL of up to 25-35% compared to an unoperated stifle.[211] Another study by Kowaleski et al. demonstrated how alterations in blade positioning could alter tibial translation.[179] They used six cadaver limbs, and a TPLO was performed with either a centered TPLO osteotomy (centered on the proximal tibial long axis point dividing the intercondylar tubercles) or a distally positioned osteotomy (centered as distal on the tibial long axis as possible without altering the integrity of the tibial plateau). They found that the centered osteotomy resulted in significantly lower cranial tibial translation compared to the distal osteotomy, and was biomechanically more

effective. In fact, Kowaleski et al. found that residual subluxation after a distal osteotomy to be near equivalent to an untreated stifle with CrCLD.[179] It is uncertain why these studies show inconsistent results; it may be that both cadaveric and computer based models have omitted the impact of local soft tissue structures, and the restrictions they impose upon stifle motility. Regardless, these conflicting results demonstrate the need for improved standardized preoperative planning techniques. To evaluate cranial translation on live patients undergoing a TPLO procedure, a study was performed by Kim et al., and it was found that a TPLO procedure did not consistently resolve cranial tibial translation during standing. In this clinical study, 33% of cases still had evidence of cranial tibial translation at six months following the procedure.[137] The majority of these cases had a hemimeniscectomy performed and had a postoperative TPA less than 8°; however, it is uncertain if these factors alone were the reasons for the continued stifle instability. Although the same surgeon performed all the procedures using the conventional planning standards, 33% is an alarmingly high rate of persistent cranial tibial translation in the TPLO treated stifle. This warrants further investigation into the technique of TPLO planning both preoperatively and intraoperatively.

b. Alterations to the Tibial Plateau Angle

Since postoperative TPA is a major component influencing preoperative planning, it is no surprise that adjustments to this value could have significant impact on limb function. In the same cadaveric study by Kowaleski et al. where adjustments to the position of the TPLO blade affected resultant cranial tibial translation, they also discovered that the resultant TPA was affected as well (Figure 7). Specifically, the end TPA of the centered TPLO (mean 5.5°) was significantly lower than that of the distally located TPLO (mean 7.92°).[179] The end

TPA may change due positioning of the blade, secondary to unknown factors. A change in end TPA was also shown in a retrospective study of 149 TPLO treated stifles by Moeller et al.[212] In this study, follow-up radiographic evaluation revealed a significant increase in end TPA after the osteotomy had healed.[212] While the authors could not associate this change with any specific factors or surgical application, the knowledge that this occurs is important as the idea of perfect preoperative planning may not be achievable given inherent biological changes after surgery. In addition, a study by Windolf et al. used 10 cadavers to compare the planned tibial rotation with that of the postoperative stifles, and evaluated how the rotation and/or positioning affected construct stability.[192] There was a statistically significant deviation (up to 4.7°) between the radiographically planned and achieved rotation of the tibial plateau, as well as location of plate application, which all resulted in significant distal translation of the tibial plateau fragment. They also reported a positive correlation between the amount of rotation and the biomechanical stability of the construct, with lower rotations (higher TPAs) appearing more beneficial when considering cyclic loading.[192] An important point concerning this study is that Windolf et al. only evaluated the use of nonlocking screws, and the tightening of nonlocking screws can induce a change in rotation and resultant TPA. This is secondary to compression along the osteotomy generated when tightening nonlocking screws. This was also a cadaveric study that inherently lacked consideration of the surrounding soft tissue structures, and the effect they could have on stability.[192] Another study by Vecchio et al. investigated changes in TPA postoperatively with respect to various plate types and healing.[213] All stifles evaluated in this study showed a trend of having an increased TPA at follow up compared to the immediate postoperative measurements, and the type of plate used was significantly associated with changes in TPA. Specifically, the plates with a statistically significantly increased TPA were the Slocum and

Olmstead TPLO plates. However, Vecchio et al. also discovered that use of any plate other than the Slocum plate decreased the odds of achieving a clinically recommended angle of 4-6° postoperatively by 48%.[213] Lastly, leaving a cranial pin in place did not prevent loss of reduction (or the "rock back" effect), and the presence of one decreased the odds of obtaining a TPA between 4-14° by 27%. There are no clear conclusions drawn from these findings; however, the mentioned limitations were small sample size for the Cobra and TPLO plates, the use of conventional screws (as using these was shown to alter the postoperative TPA), and the lack of reported consistent osteotomy positioning.[213] To address the question of how use of nonlocking or locking screws affects TPLO healing and postoperative TPA, a prospective study by Conkling et al. was performed using 118 dogs with CrCLD.[183] In this study, both methods resulted in a slight increase in TPA at follow-up, but the mean change in TPA using locking screws (1.29° $\pm$ 0.22, range -2 - 5°) was significantly less than the change in TPA using nonlocking screws (2.59° $\pm$ 0.31°, range -1 – 8.67°).[183] When evaluating radiographic healing using a medio-lateral radiograph, locking screw constructs had significantly more healing than nonlocking screw constructs. Limitations included using only one view to assess healing (the cranio-caudal view would potentially lead to bias as the screws were easily identifiable), and the use of two different plate sizes.[183]

c. Clinical Outcome of TPLO based on Planning

While studies have analyzed and modified the recommended postoperative TPA needed to achieve stifle stability, the clinical relevance of such suggestions remains uncertain.[55] In a recent retrospective study by Robinson et al. evaluating 32 Labrador Retrievers with CrCLD, ground reaction forces were assessed four months after TPLO surgery.[214] Despite a varied range in postoperative TPA (0-14°), there was no significant association between postoperative TPA, amount of

rotation, and the peak vertical force or vertical impulse. When patients were grouped according to rotation (over-rotation, appropriate, and under-rotation), there was no significant difference between the groups.[214] There are several limitations with this study, namely the overall sample size was low (32), the follow up times and the number of surgeons that performed the TPLOs varied, there was no control group, and there was no standardized postoperative exercise or physical rehabilitation protocol.[214]

Other studies, both in vitro and vivo, were conducted to describe the changes that the tibial rotation had on the contact mechanics and biomechanics of the stifle.[137,215] A study by Kim et al. looking at stifle kinematics in unpaired cadaver limbs found that in a postoperative TPLO stifle, the mean contact area was significantly lower than normal and the contact point between the tibial and femoral condyles was displaced to a more caudal location.[215] The TPLO failed to restore femorotibial contacts to normal, and this is a concern as development of osteoarthritis can result from abnormal contact and uneven loads along the articular surface.[215] Kim et al. also developed a study in live patients to assess the femoro-tibial spatial relationship following a TPLO procedure utilizing standing radiographs.[137] In this study, 5/15 (33%) dogs had persistent cranial tibial translation at two or more postoperative evaluations. Kim et al. suspected, given the high number of hemimeniscectomies within that group, that the meniscus played a major role in stifle instability.[137]

6) Conclusion

CrCLD is a complex disease that ultimately results in instability of the stifle, causing meniscal injury, pain, and the development of osteoarthritis. Multiple factors are implicated in its occurrence, including the influence of genetics, bone

development, and conformation, as well as gender, breed, and age, although data over time is inconsistent apart from medium to large breed young dogs being most often affected. Meniscal injury is a common concurrent condition, and the evidence suggests that the meniscus must be considered an important stabilizer of the stifle. This lends support to why preoperative planning is vital for a successful clinical outcome of the TPLO procedure, with an aim to improve stability as well as potentially protect the meniscus. Multiple therapeutic options exist, with the TPLO being the most commonly used procedure despite the existing disparities between preoperative planning methods. With the concerns of severe osteoarthritis, subsequent meniscal injury, strain on the caudal cruciate ligament, and cases where conventional rotation may lead to postoperative complications, the need for improved standardized planning techniques is evident. The project outlined below in this thesis is a proposed method to address this concern.

CHAPTER II: Preoperative Tibial Plateau Leveling Osteotomy Planning Using the Conventional and Common Tangent Methods: A Cadaveric Study.

1) Introduction

Cranial cruciate ligament disease is the most common musculoskeletal disorder to affect dogs.[1,2,216,217] With a ruptured cranial cruciate ligament there is cranial tibial translation in relation to the femoral condyles during weight bearing resulting from shear and compressive forces exerted across the stifle through the femoro-tibial interface.[1–3] There are numerous surgical procedures described to address this translation, the most common of which is the tibial plateau leveling osteotomy (TPLO) procedure originally described by Barclay and Divine Slocum. The theory behind the procedure is in rotating the proximal tibial segment, where the surface of the tibial plateau is perpendicular to the compressive force exerted across the stifle, neutralizing the shear forces in the stifle and cranial translation is disrupted during weight bearing.[3,161]

Proper preoperative planning is essential and is shown to significantly impact postoperative complications and functional outcomes of the TPLO procedure.[181,193] Traditionally planning a TPLO procedure involves utilizing the tibial plateau angle (TPA).[3] Slocum originally described the ideal postoperative TPA as 5°[115] in order to sufficiently prevent cranial tibial translation; however, later studies showed conflicting results. In one cadaver study the required TPA to achieve stability was 6.5°, where anything less resulted in caudal translation of the tibia relative to the femur.[9] In a similar study standard rotation of the proximal tibia segment resulted in an average of 2.5 mm caudal translation of the tibia relative to the femur.[8] Interestingly, in one retrospective study evaluating ground reaction forces among Labrador retrievers, there was no significant difference in ground reaction forces among dogs whose postoperative TPAs ranged from 0-14°.[214]

Alternatively, one computer model showed 5° did not adequately prevent cranial translation.[211] Therefore, the perfect postoperative TPA that correlates with excellent functional outcome is yet to be determined.

Despite the reported success of the TPLO procedure, alternative theories evaluating the forces acting across the stifle emerged, most notably with the development of the tibial tuberosity advancement (TTA) procedure.[203,218] In this model attention is made to the quadriceps musculature and emphasizes the forces exerted on the patella and subsequently on the cranial tibial tuberosity to assist in stabilizing the stifle joint. The sum of the forces results in a direction parallel with the patellar ligament, rather than the mechanical axis of the tibia. The amount of cranial tibial translation relative to the femur relies upon the patellar ligament angle (PLA), where in theory, if the patellar ligament is 90° to the tibial plateau. then the femoro-tibial shear force is neutralized.[203,218]

PLA initially was measured in respect to the tibial plateau, but in order to acknowledge the curvature of the tibial condyles and the femoro-tibial contact point, the common tangent method was introduced. This method is stated as the more accurate method for preoperative planning. A tangential line is created perpendicular to the axis between two concentric circles, representing the femoral and tibial condyles. The theory behind the common tangent method is that the tibial surface should be treated as convex, rather than straight in relation to how it moves with respect to the femoral condyle during ambulation. Studies comparing the PLA to both the traditional and common tangent methods are published; however, they did not conclude that one method was superior to the other. [5,204,208]

One cadaveric study evaluated TPA at various degrees of rotation and its relation to the PLA (traditional method or common tangent method) following a TPLO procedure;[207] however, to the authors knowledge, no study has evaluated the functional outcome (cranial or caudal translation of the tibia relative to the femur)

of the common tangent method following the TPLO procedure. Therefore, our purpose was to compare preoperative tibial plateau osteotomy planning using either the common tangent method and the conventional method and evaluate their effects on tibial translation relative to the femur following rotation of the tibial plateau. We hypothesize that the common tangent method will improve the accuracy, resulting in a tibial position relative to the femur that mimics an intact stifle conformation.

2) Material and Methods:

a. Specimen Collection / Preparation

Eight pairs of cadaveric pelvic limbs, from young to middle aged large breed dogs were used in this study. All dogs were euthanized for reasons unrelated to the study. Initial examination included baseline radiographs with all soft tissues still present of the stifle to evaluate for any orthopedic disease.

Once initial radiographic examination was conducted, the soft tissue and surrounding musculature were removed from the limbs, leaving the quadriceps tendon insertion along the patella (to allow attachment of the necessary testing construct), the patellar ligament, collateral ligaments, cruciate ligaments, menisci, and all tissues distal to the talocrural joint intact. All limbs were moistened with saline and frozen at -20°C until testing. The day prior to testing the limbs were thawed and kept moist with saline soaked towels.

To prepare the limbs for testing, implants were applied to the hindlimb to represent the gastrocnemius and quadriceps mechanisms. A 10-hole ALPS plate was applied to the plantar aspect of the third metatarsal and secured to the calcaneus in the caudal to cranial direction with two cortical screws to serve as the distal attachment of the gastrocnemius. A hole was then drilled in the patella and the proximal femur in a cranial to caudal direction. A threaded bolt was inserted into the proximal femur to serve as the proximal attachment of the quadriceps mechanism. Two screws were inserted into the distal femur each just proximal to the location where the fabella articulate with the femur to serve as the proximal attachment of the gastrocnemius. The gastrocnemius and quadriceps mechanisms were represented with adjustable rigid links of turnbuckles and Dyneema cording as depicted in Figure 1. The turnbuckles were adjusted as needed to provide an approximate 135° stifle extension and hock angle of 145° for testing.

b. Testing Protocol

Once implants were applied, the limb was placed in a loading apparatus made of carbon fiber and aluminum to simulate load bearing in a mid-stance phase (Figure 8). Turnbuckles were adjusted as needed to maintain the stifle extension angle at approximately 135°, hock extension angle at 145° and femoral longitudinal axis at 70° with the horizontal plane.

Radiographs of the stifle were obtained at approximately 135° extension angle in the following order: intact cranial cruciate ligament, transected cranial cruciate ligament, repaired with TPLO plate using the conventional method, and TPLO plate using the common tangent method. For each preoperative planning method, images were taken with 30% body weight applied and labeled "afterload" for all analysis. All measurements were performed utilizing a computer software (Footnote 1 Horos).

i. Evaluating TPA and Common Tangent

Using the lateral radiograph of the tibia with the stifle and tarsus in 90°, measurements were taken to calculate the tibial plateau angle, using the mechanical axis of the tibia and the line tangential to the tibial plateau connecting the cranial and caudal margins of the tibial plateau (Figure 8A). Using the lateral 135° stifle extended stifle view, the common tangent method was performed. Two concentric circles were placed over the femoral and tibial condyles with the center of the two marked "A" and "B" respectively. (See Figure 8B). An axis line between the two centers was then drawn. A line was drawn over the patellar ligament "pl" and a line parallel to this line ("pp") was made and positioned to intersect over the center of the circle representing the femoral condyle A. A circle centered over the site of the proximal jig pin in the proximal tibia (approximately 5 mm distal to the base of the intercondylar eminences) was made to represent the

center of the rotation of the TPLO, designated by “C” and was drawn so it intersected with center B.” The intersection between the line pp and circle C was labeled “B’”, which represents the center of the circle of the desired tibia position that correlates with the common tangent perpendicular to the patellar ligament. The angle BCB’ is drawn and measured to represent the correct amount needed to rotate the tibial plateau (Figure 8B). With the common tangent method, the desired TPA would be approximately 0°; however, Slocum’s TPLO charts calculates the rotation to result in a TPA of 5°. In order to utilize this chart, the following conversion was used: Angle θ = BCB’ + 5°. After identifying the converted angle, the final rotation in millimeters (mm) was calculated according to the saw blade used with each specimen.

ii. Performing the TPLO

Measurements were made on the lateral tibial radiograph with the stifle and tarsus flexed to 90° to predict placement of the saw blade intraoperatively and to approximate the appropriate size plate as demonstrated in Figure 8A. The osteotomy line was centered approximately 5 mm distal to the intercondylar eminences to accommodate and limit interference of the proximal jig pin intraoperatively. D1 is the measurement in the horizontal plane between the cranial most aspect of the tibial tuberosity and the osteotomy line. D2 is the distance from the tibial tuberosity to the proximal osteotomy line. D3 is the measurement between the proximal tibial articular surface caudal to the intercondylar eminences and the osteotomy line along the caudal surface of the tibia. Prior to performing the osteotomy, two jig pins were inserted (one caudo-proximal to the insertion of the medial collateral ligament, and one in the center of the distal diaphysis of the tibia) to stabilize the tibia segments after the osteotomy. Marks were made using an osteotome at the points representing D1, D2, and D3 prior to making the osteotomy cut. After the osteotomy was performed the proximal segment was rotated first

according to the conventional planning method with a properly sized TPLO locking plate (KYON, Zurich, Switzerland). With the same limb, the proximal segment was adjusted to the rotation calculated using the common tangent method stabilized with the same TPLO plate.

c. Outcome Assessment

All radiographic images were evaluated following the tibial plateau osteotomy using a computer software (Footnote 1 Horos). Stifle extension angles were calculated according to the methods described previously using the long axis of the femur and tibia. The TPA was calculated for each image in the intact, transected cranial cruciate ligament, conventional method pre-load (Conv. PL) and afterload (Conv. AL), and common tangent method pre-load (CTan PL) and afterload (CTan AL) following the tibial plateau osteotomy. For consistency, landmarks were used along the cranial and caudal tibial plateau corresponding to a TPA (on the intact stifle) within 3 degrees of the original TPA recorded in the first part of the study. These landmarks were then used to measure the TPA for all views following the tibial plateau osteotomy. Once obtained, these independent values were combined into groups for statistical analysis: “underrotated” (TPA > 7°), “normal” (TPA $7 \geq x \geq 3°$), and “overrotated” (TPA < 3°).

i. Evaluating Tibial Translation

Tibial translation was calculated measuring the relationship between the femoral and tibial condyles (Figure 9). Best-fit circles were placed over the femoral condyles and the center was marked with a dot (or the average of the two centers in specimens with imperfectly aligned femoral condyles) to serve as the femur marker. A tangential line was drawn to the tibial plateau and a line perpendicular to the tibial plateau was made intersecting at the level of the intercondylar eminences of the tibia. In specimens where there was imperfect

overlap, the perpendicular line was placed in the center between the apex of both eminences. The distance between the femur marker and the perpendicular line in the horizontal plane represented tibial translation. These measurements were obtained for intact, transected cranial cruciate ligament, Conv. AL, and CTan AL stifles. The position of the tibia following the tibial plateau osteotomy was compared to the intact position, with positive values indicating cranial to the intact stifle, and negative values indicating caudal displacement of the tibial relative to the femur.

ii. Patellar-ligament angle (PLA)

The relationship between the patellar ligament and the tibial plateau (PLA_{TP}) and the patellar ligament and the common tangent (PLA_{CT}) of the femoral and tibial condyles were evaluated for intact, transected cranial cruciate ligament, Conv. AL, and CTan AL stifles (Figure 10). These measurements were made while 30% bodyweight load was still applied to each specimen. Starting with best-fit concentric circles of the femur and tibia the centers were marked and an axis was drawn between the two as shown in Figure 4. A line was drawn over the patellar ligament ("pl") and a tangential line was drawn to the tibial plateau "tp." The common tangent to the axis between the two circles was drawn and labeled "ct". The angle "γ" represents the PLA_{TP} and the angle "α" represents the PLA_{CT}. With the desired goal of a post-osteotomy PLA of 90°, we also compared the difference between these two PLA measurement methods and their variability for each preoperative TPLO planning group.

d. Statistical Analysis

Normal probability plots showed that all measurements were normally distributed. However, an outlier was observed among paired differences between position Conv. AL adjusted and position CTan AL. To accommodate the outlier,

nonparametric methods were used for comparisons between the Conv and the CTan methods while parametric methods were used for all the other analyses. The comparative analysis (Conv vs. CTan) of the tibial translation, tibial rotation, TPA, were evaluated using Wilcoxon signed rank test. All TPAs were categorized for each treatment group into underrotated, over rotated, and normal and were evaluated for association with tibial translation using Kruskal Wallis test. Stifle extension angles were compared between the conditions and preoperative planning methods using mixed model ANOVA. Association between extension angles and TPA, extension angles and tibia translation, was tested using scatter plots and correlation analysis. PLA_{TP} and PLA_{CT} were compared within each condition (intact, transected cruciate, Conv. AL, and CTan AL) and conditions within each method using a mixed model ANOVA followed by Tukey-Kramer's procedure for multiple comparisons. Distance from the desired 90° was tested (if significantly different from 0) within each combination method and condition using a mixed model ANOVA. All mixed ANOVA models specified specimen and limb within specimen as random effects. All p values ≤ 0.05 were deemed statistically significant. Statistical analysis was performed using SAS version 9.4 (Cary, NC, USA).

3) Results:

Eight pairs of limbs of medium to large breed dogs were used in the study (weight 28.4 kg ± 2.5). One pair of limbs was used as a test pair for adjusting the testing construct so a total of seven pairs of limbs were used for the statistical analysis. Breeds included: Pitbull mix (n=3), Labrador retriever mix (n=2), German shepherd mix (n=1), and Rottweiler mix (n=1).

a. Extension angles.

Stifle extension angles ranged from 104-144.6° and mean extension angles for each condition: intact, Conv. AL, and CTan AL were 133.1 ± 7.2°, 120.2 ± 7.2°, 120.3 ± 8.8° respectively. There was a significant difference between the intact stifle and the CTan AL ($p < 0.0001$), and Conv. AL ($p < 0.0001$). All remaining stifle extension angle comparisons were not significantly different. There was a significant correlation between extension angle CTan AL and TPA CTan AL ($p = 0.037$) with TPA decreasing as extension angle increased ($r = -0.56$).

b. Tibial rotation

Median proximal tibial rotation required for the conventional planning method and the common tangent method were 9.25 (7.25-10.25) mm and 8.5 (4.3 – 12.75) mm respectively. There were no statistically significant differences between rotation of the two preoperative planning methods ($p=0.464$); however, 6/14 (42.9%) limbs showed the common tangent method required more rotation and 8/14 (57.1%) limbs required less rotation than the conventional method.

c. Tibial plateau angle

Median tibial plateau angle in intact stifles was 28° (23-30°). Median postoperative tibial plateau angle in Conv. AL, and CTan AL were 8.4° (2.6 – 11.4), and 8.4° (-2.2 – 12.9°) respectively. TPAs within each condition were divided into normal, underrotated, and overrotated and summarized in Table 1. In all four radiographed conditions the majority of proximal tibia segments were underrotated with the percent of underrotated TPAs varying from 57.1 – 64.3% of the total limbs under each category.

d. Tibial translation

Tibial translation was reported as the amount of translation in comparison to the position of the tibia in the intact stifle, where positive variables denoted cranial translation and negative variables denoted caudal translation. Median translation in intact stifles was -3.35mm (-5.7 – 1.5) tibial translation following transection of the cranial cruciate ligament was 13.1mm (10.5 – 19.8mm). Median tibial translation of the conditions Conv. AL, and CTan AL were 2.05 mm (-2.6 – 11.6 mm), and 2.3mm (-2.5 – 10.4mm) respectively. There was no significant difference in tibial translation between Conv. AL and CTan AL ($p = 0.404$). With the conventional preoperative planning method, 1/14 (7.2%) resulted in caudal tibial translation, while in the common tangent method, 3/14 (21.4%) resulted in caudal tibial translation. One limb had caudal translation with both planning methods and resulted in an underrotated TPA. The other two limbs for the common tangent method had an underrotated TPA as well. All three limbs that resulted in caudal translation of the tibia relative to the femur that were underrotated had decreased stifle extension angles (104-111°).

There was no significant correlation between the extension angle and the amount of tibial translation of intact stifles. There was a significant positive correlation between stifle extension angle and tibial translation for Conv. AL (p =

0.0005, r = 0.779), and CTan AL (p = 0.042, r = 0.546). As stifle extension angle increased, the amount of tibial translation increases cranially following rotation.

The amount of rotation following osteotomy of the tibial plateau (defined as normal (5 ± 2°), overrotated (<3°) or underrotated (>8°)) was not significantly associated with tibial translation for any of the stifle conditions following rotation: Conv. AL (p = 0.758), or CTan AL (p = 0.504) respectively.

e. Patellar Ligament Angle

All patellar ligament angles are summarized in Figure 11. Mean angle between the patellar ligament and the tibial plateau (PLA_{TP}) for intact, transected cranial cruciate ligament, Conv. AL, and CTan AL were 109.8 ± 3.2°, 92.8 ± 4.2°, 89.3 ± 3.9°, 90.1 ± 4.2° respectively. Mean angle between the patellar ligament and the common tangent (PLA_{CT}) for intact, transected cranial cruciate ligament, ConvAL, and CTan AL stifles were 104.4 ± 2.6°, 111.4 ± 2.9°, 88.9 ± 6.6°, 88.8 ± 6.4° respectively. With intact stifles, there was a significant difference (p = 0.001) between PLA_{TP} (109.8 ±3.2°) and PLA_{CT} (104.4 ± 2.6°). Following transection of the cranial cruciate ligament there was a significant difference (p < 0.001) between PLA_{TP} (92.8 ± 4.2°) and PLA_{CT} (111.4 ± 2.9°). There was no significant difference between PLA methods within Conv. AL or CTan AL stifles.

In comparing the PLA_{TP} for the intact stifle to the remaining three stifle conditions, there was a significant difference between intact stifle and transected cranial cruciate ligament (p < 0.0001), Conv. AL (p < 0.0001), and CTan AL (p < 0.0001) stifles. For PLA_{CT}, there was a significant difference between intact stifle and transected cranial cruciate ligament (p = 0.0002), Conv. AL (p < 0.0001), and CTan AL (p < 0.0001) stifles. In addition, the PLA_{CT} was significantly different between ruptured and Conv. AL (p < 0.0001) and CTan AL (p < 0.0001) stifles. The last test was to evaluate the accuracy between the two methods and measure

their proximity to the desired goal of 90°. There was no significant difference between PLA_{CT} and PLA_{TP} and their distance from 90° in the post-osteotomy radiographs using either the conventional ($p = 0.82$) or common tangent ($p = 0.387$) TPLO planning methods.

4) Discussion:

This study aimed to compare the translation of the tibia relative to the femur following rotation of the tibial plateau based on the conventional and common tangent planning methods in experimentally induced cranial cruciate ligament deficient stifles. The common tangent method takes into account the convexity of the tibial plateau in relation to the curvature of the femoral condyles, as well as acknowledging the impact of the quadriceps mechanism along the stifle during the stance phase to prevent cranial translation.[203,204,207,218] The resulting direction of the force across the stifle is parallel to the patellar ligament, rather than the caudally directed from the mechanical axis of the tibia. This suggests that the conventional method of TPLO planning may result in significant deviated rotation to achieve stability.[3,203] The theory that the direction of the force across the stifle is parallel to the patellar ligament is utilized in procedures such as the tibial tuberosity advancement, and is successful in decreasing or eliminating cranial tibial translation.[219,220] The common tangent and its association with the patellar ligament with preoperative TPLO planning was previously investigated, but no study has evaluated how using the common tangent method would impact tibial translation with a TPLO procedure.[185,207,221]

Tibial translation was evaluated using methods previously described with stifles extended at approximately 135°.[8,9] There was no significant difference between the two methods with respect to tibial translation under physiologic load (30% body weight) and therefore our null hypothesis was rejected. Both methods resulted in reduction of cranial tibial translation in stifles with the cranial cruciate ligament transected, leading to a median translation within 3 mm of the intact stifle for both methods. Important to note is the median tibial translation in relation to the femur in the intact stifle was not 0 mm but rather -3.35 mm, and this is because

no radiograph truly showed the center of the femoral condyles directly over the center of the tibial condyle in a stance position. Therefore, all specimen stifles required a baseline measurement to calculate the position of the tibia after transection of the cranial cruciate ligament and osteotomy relative to the position it was in the intact state. The median translation for both methods following transection of the cranial cruciate ligament revealed an increased cranial translation compared to previous studies. One study revealed that a resultant tibial plateau rotation of TPA < 6.5°, resulted in significant caudal subluxation (-6.3 $\pm$ 1.8mm) while another showed a mean caudal tibial translation (-2 $\pm$ 2.9mm) post tibial plateau leveling osteotomy.[8,9] No direct statistical comparison can be made between these studies and this study given the lack of a common tangent group. With the conventional method used in this study, the differences in tibial translation relative to the femur may be attributed to the center of rotation for our tibial osteotomy compared to previous studies. In the present study, the center of rotation was approximately 5 mm distal to the base of the intercondylar eminences to not interfere with placement of the proximal jig pin which this adjustment of osteotomy can alter tibial translation as previously reported.[179,180] While translation of the tibia is evaluated postoperatively with respect to the position of an intact stifle, there is no specific distance found to significantly correlate with clinical outcome in the current veterinary literature and future studies evaluating the position of the tibia in relation to postoperative outcome are warranted to develop guidelines for future TPLO planning.[8,9]

In the current study postoperative TPA was evaluated between the two preoperative planning methods and categorized into normal, underrotated, and over rotated, to evaluate association with tibial translation relative to the femur. Median preoperative TPA was 28° which is consistent with previous reports.[29,32,40,44,133,202,222,223] Median TPA following rotation was 7.9 – 9° (-2.2 –

12.9°) among both planning groups, which correlates that the majority of limbs in both groups were categorized into the "underrotated" category. The negative lower boundary TPA value indicates the rotation leads to caudal tibial thrust. This TPA range fits within previously reported ranges (-6.5 – 24°), but is still higher than the recommended 5-6° for cranial-caudal stability.[8,9,131,133,172,183,212] This slight increase in the TPA may be explained by the mild distal centering of the TPLO in our study, which is shown to increase the TPA to be greater than expected following rotation of the tibial plateau.[179,180] Care should be made in these suggestions; however, given there could be variability between the radiographic osteotomy center and anatomic center executed during the procedure.

There was no significant difference in postoperative TPA between either TPLO planning methods, since the amount of tibial rotation (mm), was also not significantly different between the two methods. There was no significant impact of postoperative TPA on the resulting translation of the tibia relative to the femur, which may indicate a larger window of acceptable TPA following rotation of the tibial plateau that can result in adequate stabilization or function following a TPLO procedure. This is consistent with a previous study that revealed no significant influence of postoperative TPA on functional outcome where the range of the TPA was 0-14°.[214] Several factors can impact measuring TPA on radiographs, and considerable attention should be made to how the limbs are positioned and how much is lost during the osteotomy procedure itself.[195,214] It is possible that in this current study the TPA following rotation of the tibial plateau was underestimated due to implant fixation causing a loss of planned TPA. Since, the limbs were each used for both planning methods, the proximal tibia fragment was manipulated more for the common tangent method than the conventional method.[180] Inter- and intra-observer variability is also a factor to consider and was evaluated in numerous reports ranging 0.8-4.8° and 1.5-3.4° respectively.[195,198,199] Two pairs of

observers together calculated the preoperative TPA, while a third observer performed all measurements following rotation of tibial plateau. To help keep measurements consistent the third observer used landmarks associated with the TPA measured prior to rotation to limit the impact of interobserver variability. Repetitive measures and direct comparisons between the third and first two observers were not recorded; therefore, statistical variability could not be obtained within this study.

Extension angles were also recorded for intact, Conv. AL, and CTan AL stifles as previously described using long axis of the femur and tibia.[5,224] We evaluated for association between angle of stifle extension and the tibial translation, patellar ligament angle, and tibial plateau angle post-osteotomy. There was a significant correlation between extension angle and TPA for the common tangent preoperative planning method, where TPA decreased as the extension angle increased. The significance of this is uncertain since the angle of the stifle does not impact the proximal or distal landmarks for measuring the tibial plateau angle or the mechanical axis of the tibia. Extension angles significantly correlated with tibial translation measurements for both the conventional and the common tangent method following rotation of the tibial plateau. As extension angle increased the cranial translation of the tibia increased. This is consistent with other studies describing, that as the extension angle of the stifle increases, the femoro-tibial shear force is directed cranially. This force leads to cranial translation in a cranial cruciate ligament deficient stifle, and is in agreement with a previous study showing dogs with cranial cruciate ligament deficient stifles, hold their stifles in greater flexion to reduce strain cranially.[5,7,204,224] However, the relationship in this current study contradicts the outcome of previous studies, where extension angles of the stifle were greater and reported median caudal tibial translation.[8,9] Factors such as proper sagittal radiographic alignment and methods of measuring angles

(radiographic measurement[224] vs goniometer) may have played a role in this discrepancy.

Inclination of the patellar ligament in relation to the tibial plateau and common tangent were both evaluated for intact, transected CCL stifles, Conv. AL, and CTan AL stifles as previously described.[5,204,207] PLA_{TP} was significantly greater than PLA_{CT} for the intact stifle and is consistent with a recent study (PLA_{TP} mean 119.9 $\pm$ 2.0°, PLA_{CT} 97.3 $\pm$ 2.1°).[207] This is because on lateral radiographs with a stifle extension of 135°, the common tangent line is less steep than the tibial plateau in this study and in the study by Drygas et al and is demonstrated in Figure 4. In another recent study; however, PTA_{TP} in a normal healthy group of dogs was lower at 97.4 $\pm$ 7.7°,[225] which may be due to observer variability or positioning of the stifle. The direct comparisons cannot be made for the common tangent method, as they only used the tibial plateau-patellar ligament inclination angle.

In the current study, the PLA_{CT} was significantly greater than PLA_{TP}, once the cranial cruciate ligament was transected. This difference is greater than previously reported, where mean PLA_{TP} (96, 70-116°) and PLA_{CT} (96.5, 86-108°) were similar; however, in that study all dogs had partial cranial cruciate ligament ruptures, and therefore the instability may be too mild to show statistical significance.[204] Since in the intact stifle the common tangent is significantly less steep than the slope of the tibial plateau, cranial translation of the tibia would have a greater impact on the steeper slope of the tibial plateau in relation to the common tangent, making the resulting PLA_{TP} less than PLA_{CT}. However, with cranial translation of the tibia, the mean PLA_{CT} with cruciate ligament rupture, should also decrease compared to its intact stifle value, but instead it increased in our study; the reason for this finding remains unclear.

For PLA_{TP} and PLA_{CT}, there was a significant difference between the intact stifle and stifle following transection of the CCL and, Conv. AL, and CTan AL

stifles. The decrease in PLA of both methods with the TPLO procedure occurs because the purpose of proximal tibial rotation is to decrease the inclination of the patellar ligament with respect to either the tibial plateau or common tangent to 90° to neutralize the cranio-caudal shear force in the cruciate ligament deficient stifle.[203,207] Importantly, there was no significant difference between the two patellar ligament angles following rotation of the tibial plateau for either the conventional or common tangent preoperative TPLO planning methods. This finding supports the application of the common tangent preoperative TPLO planning method since both preoperative planning methods (conventional or common tangent) achieve similar cranial caudal stability resulting in PLAs close to 90°.

Limitations of this study are inherent to its cadaveric study model and are similar to previous reports.[8,9,207] While the turnbuckles served to mimic the action/tension of the gastrocnemius and quadriceps muscles, it does not equate to the entire soft tissue structures that fully support the stifle in vivo. Load applied was also unidirectional and static with compressive force used at approximately 30% of the patient's body weight at a moderately extended stifle mimicking the stance phase, similar to previous studies and does not take into account torsional stability within the stifle.[9,207] This becomes significant as for some of the limb specimens upon increase in load there was a moderate deviation within the distal femur resulting in imperfect femoral condyle superimposition on the radiographs. Interobserver and intra-observer variability is another limitation, with reports showing ranges 0.8 – 4.8°, and 1.5 – 3.4° respectively.[196,198,199] To improve consistency, all postoperative measurements were obtained by one observer, who used landmarks consistent with measurements taken prior to performing the TPLO by the first two observers. Despite these limitations, the resulting postoperative radiographs for either conventional or common tangent method both showed

significant translation after transection of the cranial cruciate ligament and improvement in the PLA and tibial translation after performing the tibial plateau leveling osteotomy.

CHAPTER III: CONCLUSIONS

Current methods of preoperative planning consider the tibial plateau as a flat surface and utilize the mechanical axis; however, novel approaches suggest that the overall forces across the stifle are parallel to the patellar ligament rather than the mechanical axis of the tibia. This new approach suggests using the common tangent method may be a more accurate means to plan stifle stability, as it treats the proximal tibia as a cylindrical surface and accounts for the joint force in line with the patellar ligament. The results from this study show utilizing the common tangent provides similar outcomes to the conventional methods both in resulting tibial translation as well as adjusting the inclination angle of the patella. Superiority of the common tangent method remains to be determined, but future in vivo studies evaluating clinical outcome utilizing the common tangent method is warranted.

FIGURES

Figure 1. A. Tibial plateau angle (TPA) is determined at the intersection of the tibial plateau axis (white line) and the tibial long axis (black line). B. A reference line perpendicular to the tibial long axis (white line) can be used to facilitate measurement of the tibial plateau angle. (From: Kowaleski MP, Boudrieau RJ, Pozzi A. Stifle Joint. In: *Veterinary Surgery Small Animal*. Vol 1. Second. St. Louis Missouri: Elsevier SAUNDERS; 2018:1071-1168.)

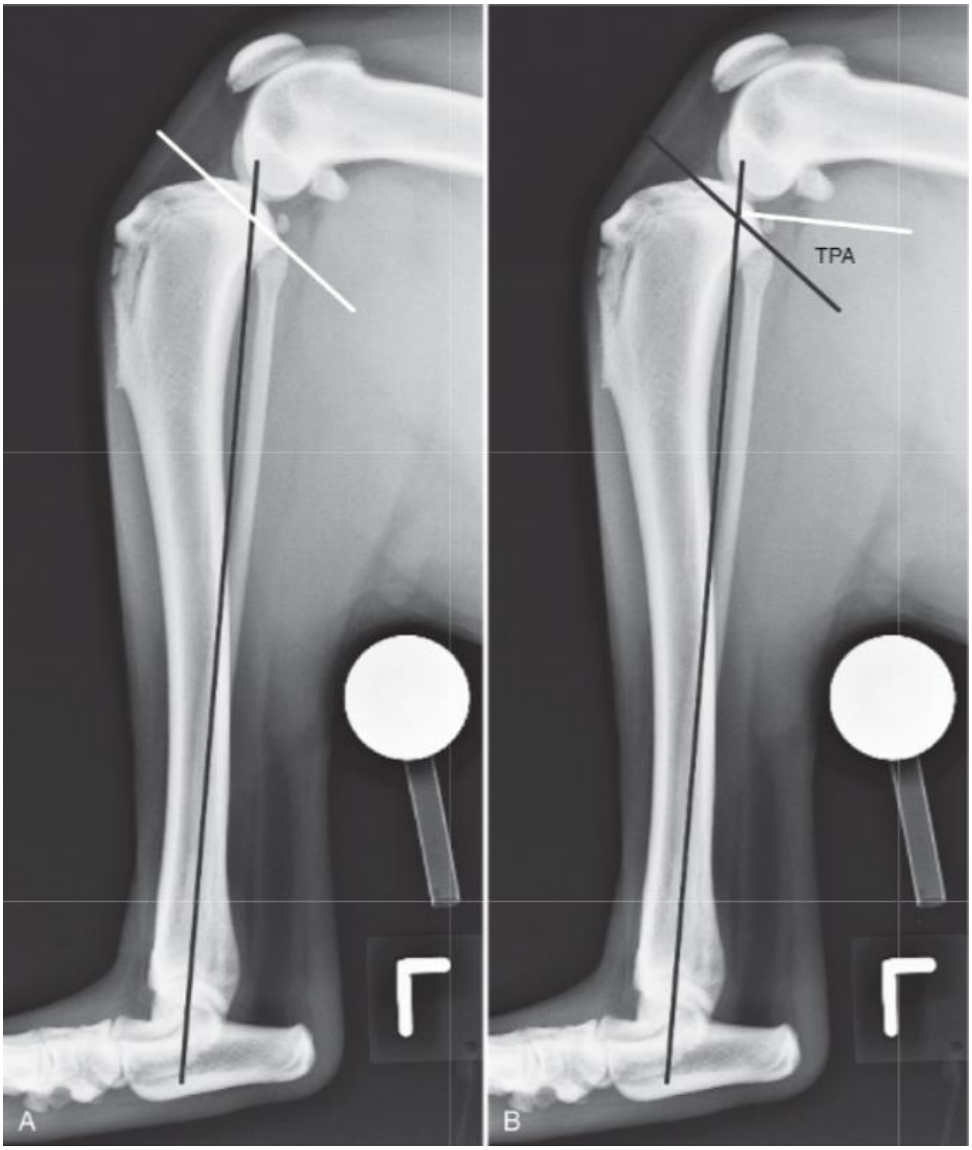


Figure 2. Mediolateral radiographic view (A), illustrations (B, C, D), and photograph (E) of a tibia and stifle joint in a dog. Femoral condyles are superimposed. Tibial plateau slope (TPS) is conventionally measured by comparing orientation of the functional axis of the tibia defined as the line joining the intercondylar eminence and a point equidistant to the cranial and caudal aspects of the trochlea of the talus (B) and the axis of the medial tibial condyle defined as the line joining the small, discreet cranial margin of the tibial plateau and the point of insertion of the caudal cruciate ligament (C). Alternatively, the axis of the medial tibial condyle may be defined as a line tangential to the cranial linear portion of the medial tibial condyle at the femorotibial contact point (D). The latter measurement more closely approximates the anatomic slope of the medial tibial condyle (E). (From: Baroni E, Matthias RR, Marcellin-Little DJ, Vezzoni A, Stebbins ME. Comparison of radiographic assessments of the tibial plateau slope in dogs. *Am J Vet Res*. 2003;64(5):586-589.)

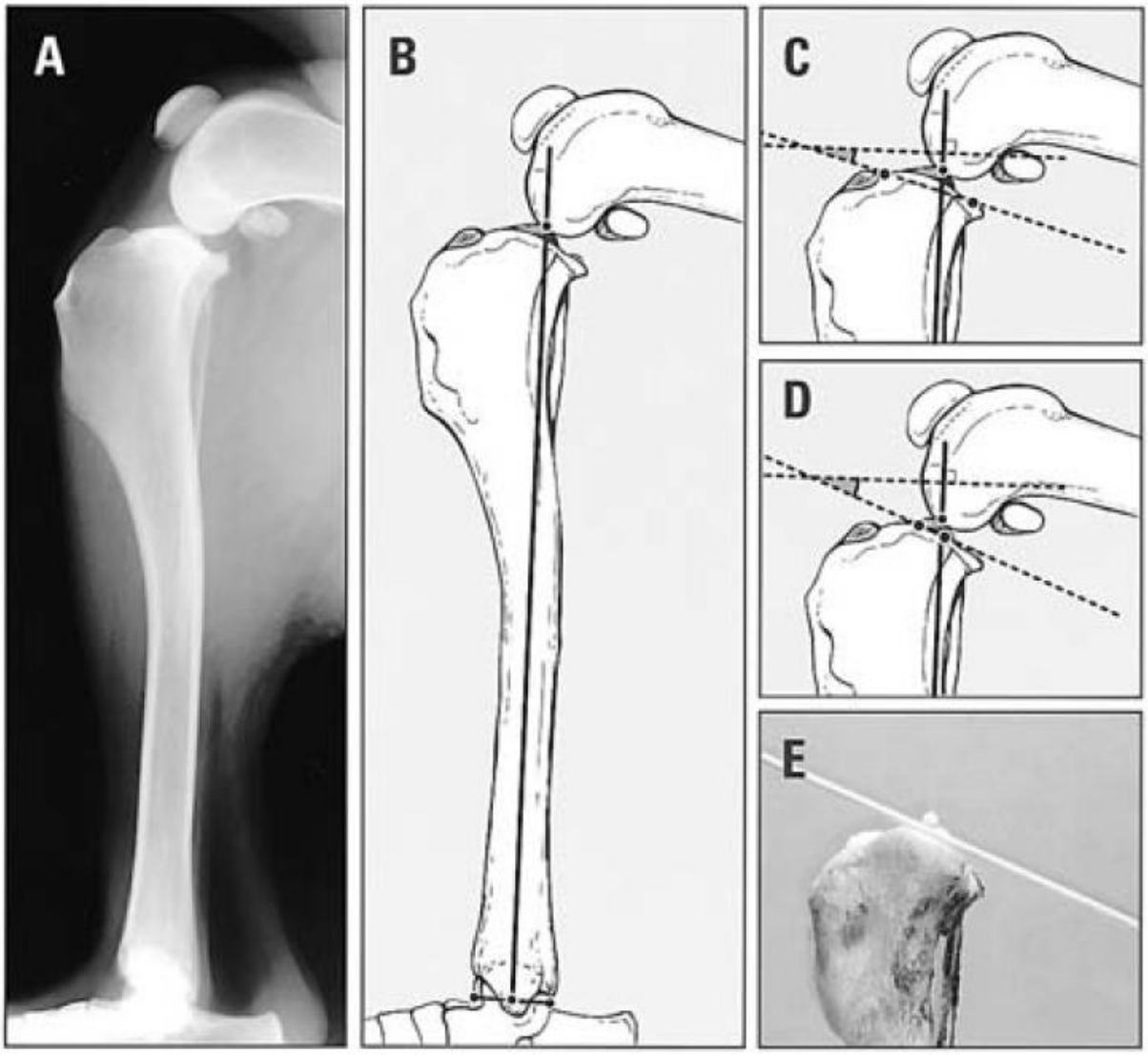


Figure 3. Illustration of the extension technique used to estimate the caudal landmark on the medial tibial plateau. This point is located at the intersection (white circle and dot) of a line drawn from the caudomedial tibial cortex, extending proximally beyond the articular surface (vertical curvilinear black line), and a line drawn from the articular surface of the medial tibial plateau and extending beyond the caudomedial tibial cortex (horizontal curvilinear black line). (From: Ritter MJ, Perry RL, Olivier NB, Kim SY, Dejardin LM. Tibial Plateau Symmetry and the Effect of Osteophytosis on Tibial Plateau Angle Measurements. *J Am Anim Hosp Assoc*. 2007;43(2):93-98.)

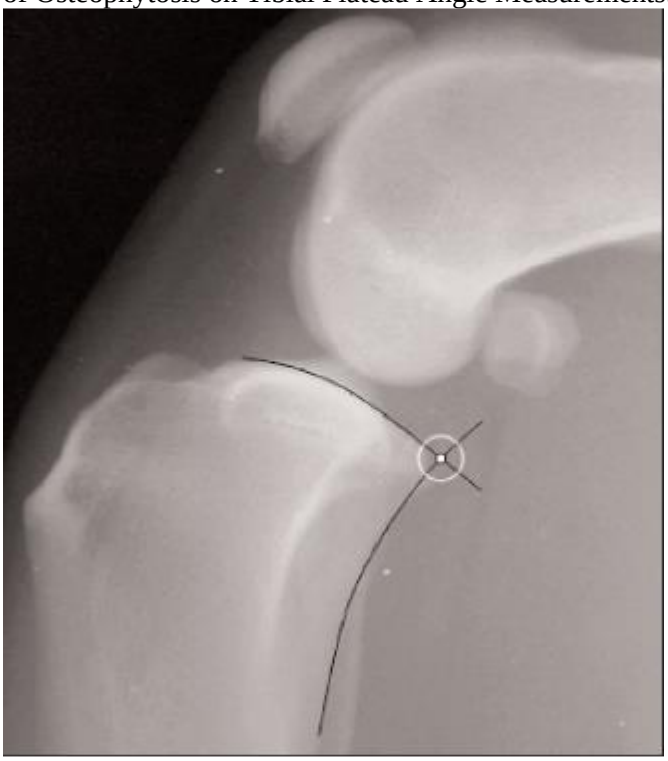


Figure 4. The functional axis line of the tibia (a) is used as the first reference line (normalized between dogs with the distance D). A second reference line ® is drawn perpendicular to the functional axis line of the tibia at the intersection of the tibial intercondylar eminences along line a. From these reference lines, the horizontal and vertical distances (x and y displacements) of the cranial (hCr and vCr) and caudal (hCd and vCd) points of the tibial plateau line (b) are measured. (From: Fettig AA, Rand WM, Sato AF, Solano M, McCarthy RJ, Boudrieau RJ. Observer variability of tibial plateau slope measurement in 40 dogs with cranial cruciate ligament-deficient stifle joints. *Vet Surg*. 2003;32(5):471-478.)

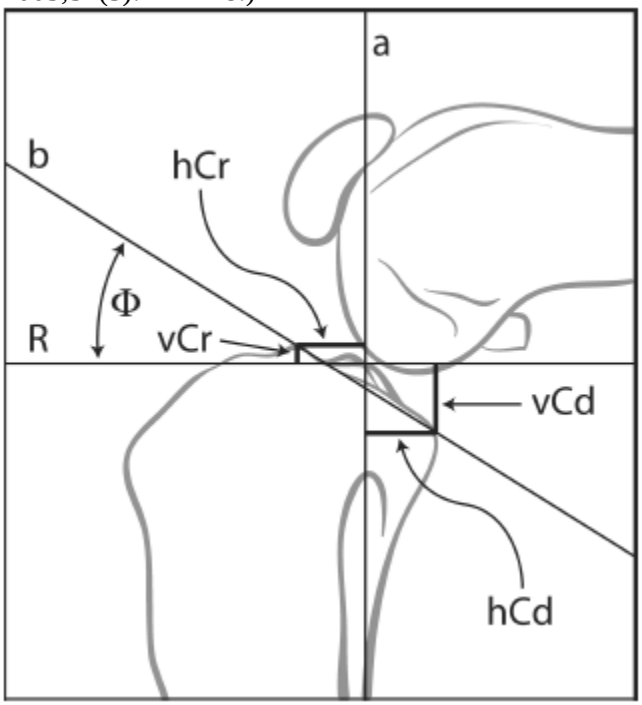


Figure 5. Illustration of the features of the mediolateral radiographic views of stifle joints of cadaveric dogs (without degenerative joint disease) used to assess the inclination of the patellar ligament in relation to flexion angle. Femur, patella, 1 sesamoid bone of the gastrocnemius muscle, and tibia are outlined. The femoral (af) and tibial (at) long axes were defined as the lines between the 2 shaft midpoints at one third and two thirds of the femoral and tibial lengths from the TFCP. Angle β is representative of joint flexion. Line p was drawn along the tibial plateau from the CrCL insertion point to the CdCL insertion point. Angle γ was measured between the cranial border of the patellar ligament (pl) and the tibial plateau (p). The TFCP was defined by drawing a circle representing the joint surface of the femoral condyles in the articulating area and another circle outlining the area of contact on the tibial plateau. Line c was drawn between the midpoints of these 2 circles, and a second line (t) was drawn perpendicular to the former within the tibiofemoral joint space (representing the common tangent of the 2 circles); line t was perpendicular to line c at the TFCP. Angle α was measured between the cranial border of the patellar ligament (pl) and the common tangent (t) at the TFCP. (From: Dennler R, Kipfer NM, Tepic S, Hassig M, Montavon PM. Inclination of the patellar ligament in relation to flexion angle in stifle joints of dogs without degenerative joint disease. *Am J Vet Res*. 2006;67(11):1849-1854.)

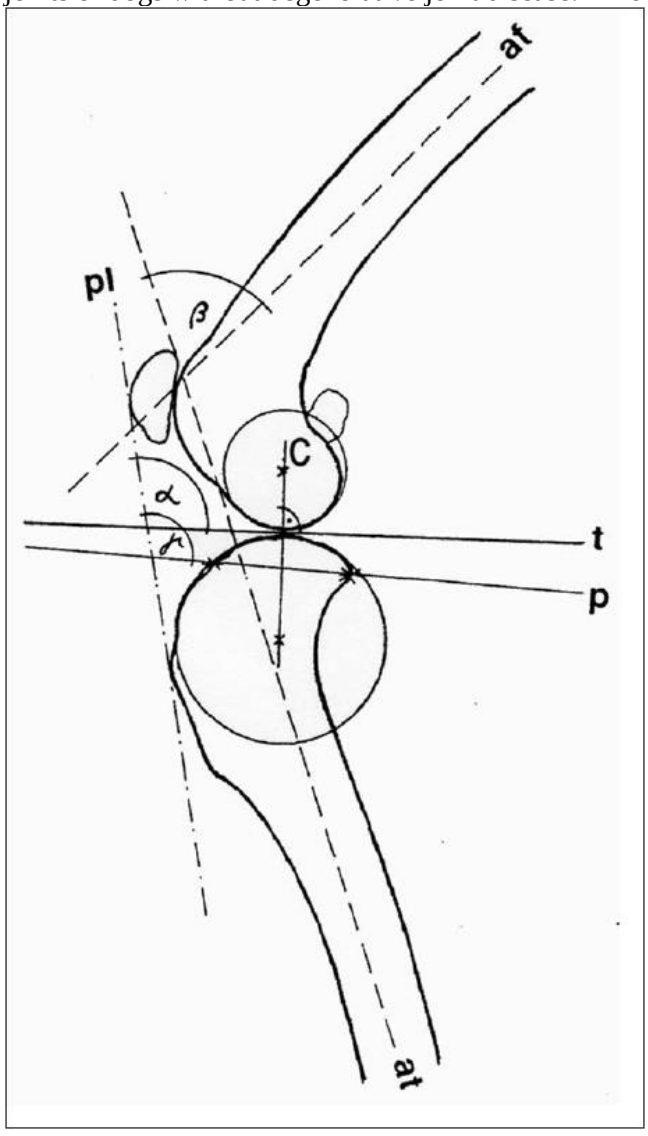


Figure 6. A. A line drawing, not drawn to scale, of the preoperative planning. The circle represents the most cranioproximal point of the tibial tuberosity. The curved line represents the planned tibial osteotomy. The solid line represents measurement A1. The large dashed line represents B1, the measurement made perpendicular to the cranial straight edge of the tibial crest. The small dashed line represents measurement C1. B. Line drawing, not drawn to scale, of the postoperative analysis. The circle represents the most cranioproximal point of the tibial tuberosity. The solid line represents measurement A2. The large dashed line represents B2, the measurement made perpendicular to the cranial straight edge of the tibial crest. The small dashed line represents measurement C2. (From: Woodbridge N, Knuchel-Takano A, Brissot H, Nelissen P, Bush M, Owen M. Accuracy evaluation of a two-wire technique for osteotomy positioning in the tibial plateau levelling procedure. *Vet Comp Orthop Traumatol*. 2014;27(01):08-13.)

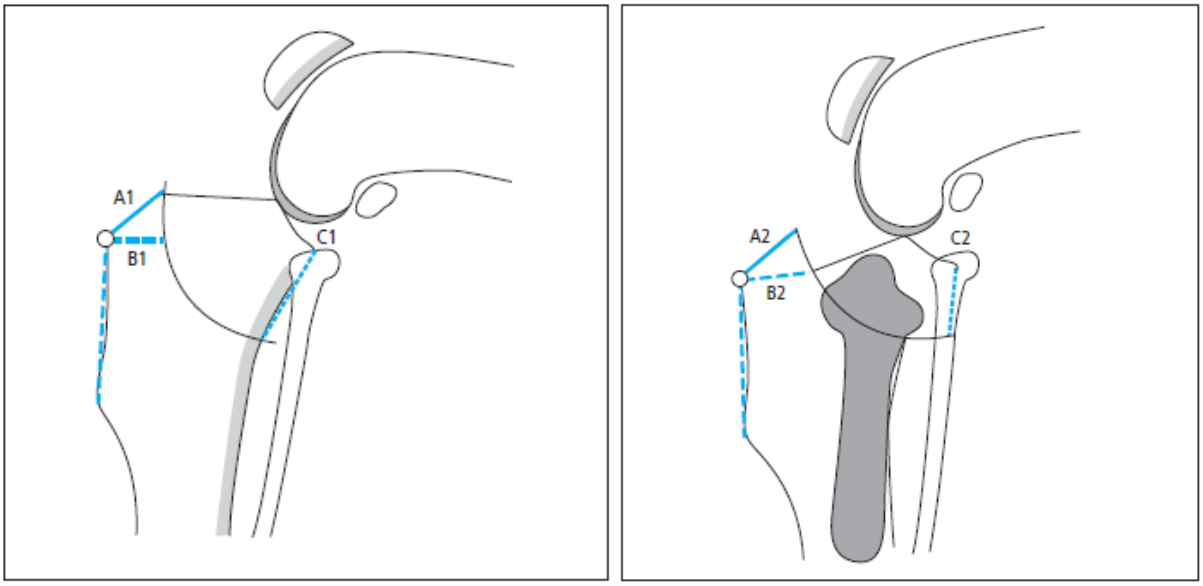


Figure 7. Diagrammatic representation of a tibia with a centered TPLO (A) and a distally positioned TPLO (B). (From: Kowaleski MP, Apelt D, Mattoon JS, Litsky AS. The Effect of Tibial Plateau Leveling Osteotomy Position on Cranial Tibial Subluxation: An In Vitro Study. *Vet Surg*. 2005;34(4):332-336.)

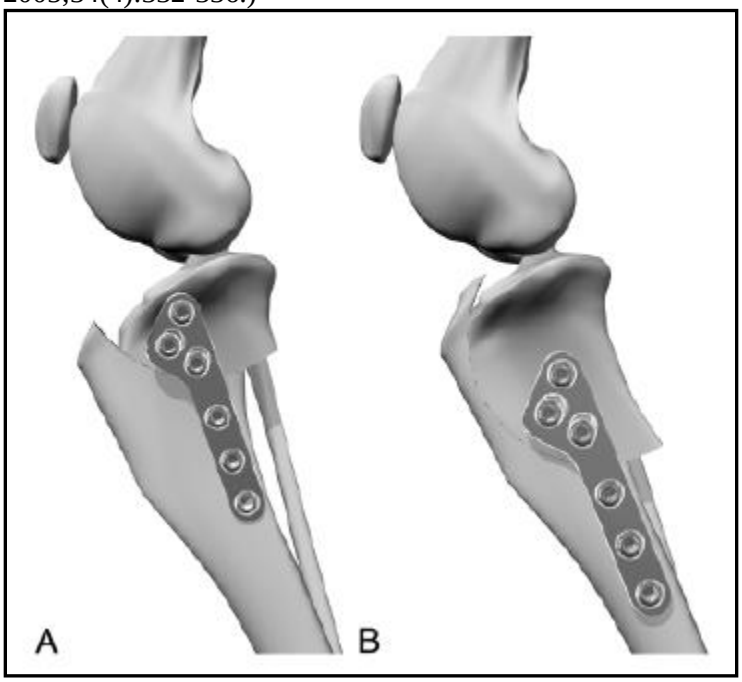


Figure 8. Photograph of the specimen limb position within the carbon fiber jig under load. Approximate stifle extension angle 135° and hock angle 145°. Turnbuckles were used to mimic the gastrocnemius and quadriceps muscles and adjusted throughout the experiment to maintain the stifle and hock angles accordingly.

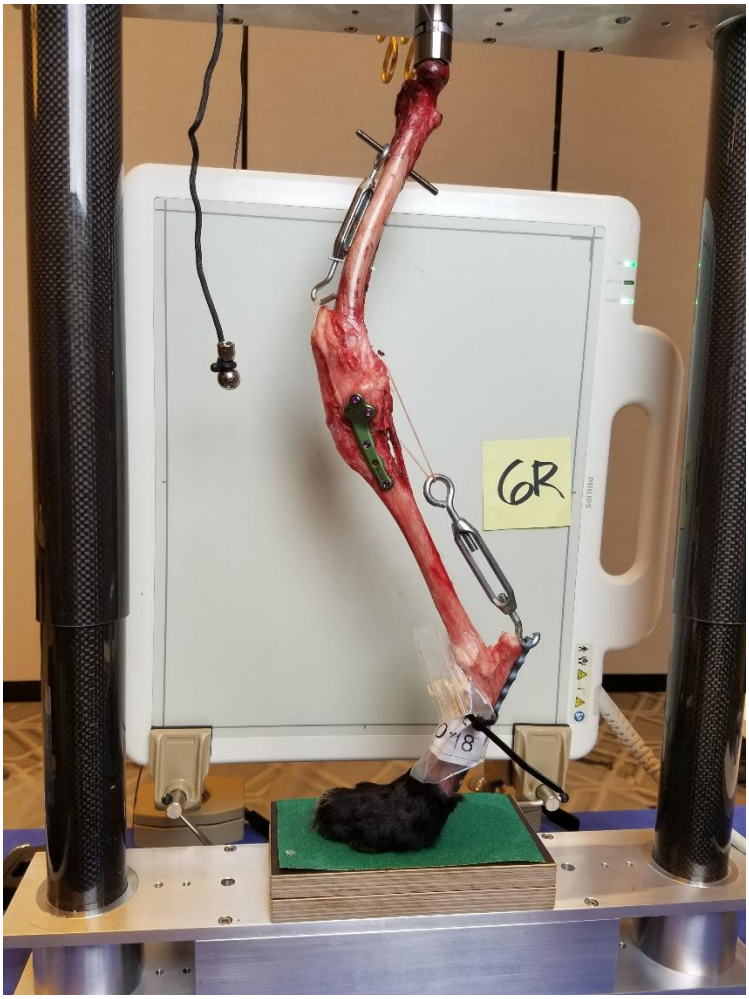


Figure 9. 9A: Radiographic image depicting conventional preoperative TPLO planning utilizing the mechanical axis of the tibia (M) and line tangent to the tibial plateau (TP). Tibial plateau angle corresponds to 90° - α. D1 and D3 correspond to measurements used intraoperatively to mark the osteotomy line. 9B: TPLO planning using the common tangent method: two circles used to represent the curvature of the femur and tibia (A and B) and a line is drawn connecting their two centers. A line drawn parallel to the patellar ligament (pl) is placed intersecting center of circle A to denote where the new center of B (B') should be after proximal tibial rotation. A circle representing the osteotomy line (C) is drawn to show the distance required for B to rotate to B'. The angle BCB' is the angle representing correct osteotomy rotation.

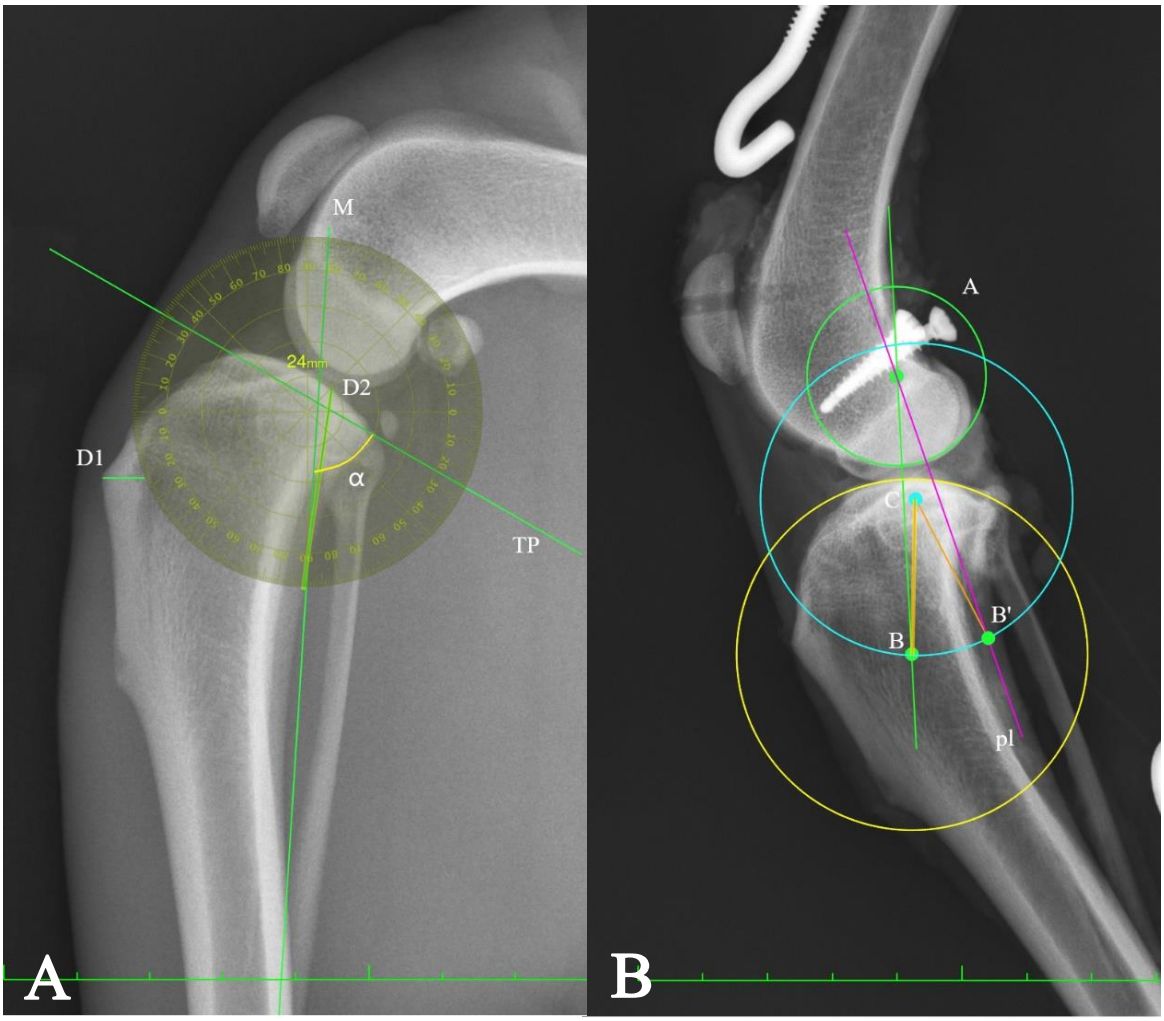


Figure 10. Radiographs show evaluation of tibial translation for intact (A), ruptured cranial cruciate (B), conventional afterload (C), and common tangent afterload (D) stifles. Circles are placed to represent the curvature of the femoral condyles and averaged to mark the center. A line tangent to the tibial plateau is placed (TP) and then a line perpendicular to the tibial plateau is drawn (pink line) and is placed to intersect the apex of the intercondylar eminences. The distance between the femoral marker and the pink line is measured (x). For the ruptured, Conv. AL, and CTan AL images, the final tibial translation (X_T) is measured with respect to the intact stifle with the equation $X_T = X – X_I$ where X_I is the distance measured in the intact stifle. Note the significant increase in distance with the ruptured stifle, while both the conventional and common tangent planning result in minimal cranial tibial translation post-osteotomy.

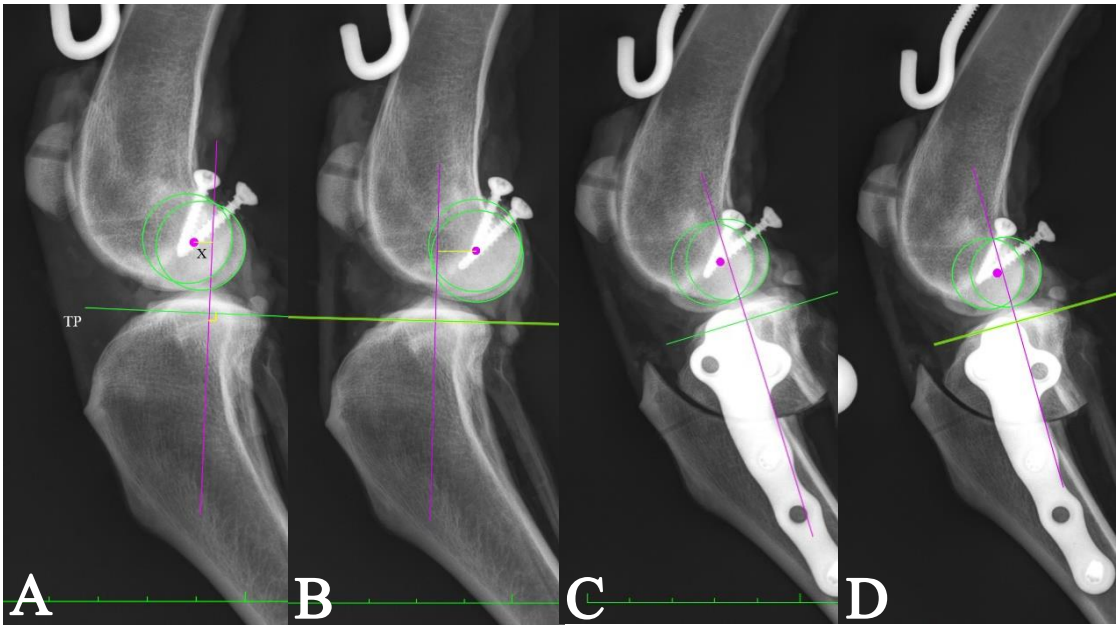


Figure 11. A radiographic image depicting measurements to record the patellar ligament angle (PLA) in the stifle. This image is using the common tangent method for preoperative TPLO planning denoted with the missing screw in the caudal aspect of the proximal TPLO plate. For the PLA_{TP} method (represented by γ), a line tangent to the tibial plateau (tp) is drawn and intersects the line representing the patellar ligament (pl). For the common tangent, circles are drawn to represent the articular surfaces of the femur and tibia as shown. With imperfect laterality two circles are drawn and the center is averaged between them. A line is drawn between the two centers and a line perpendicular to this axis is the common tangent (ct). The angle α represents the PLA_{CT}. Note the similarity between the angles using the two different methods to measure the PLA postoperatively.

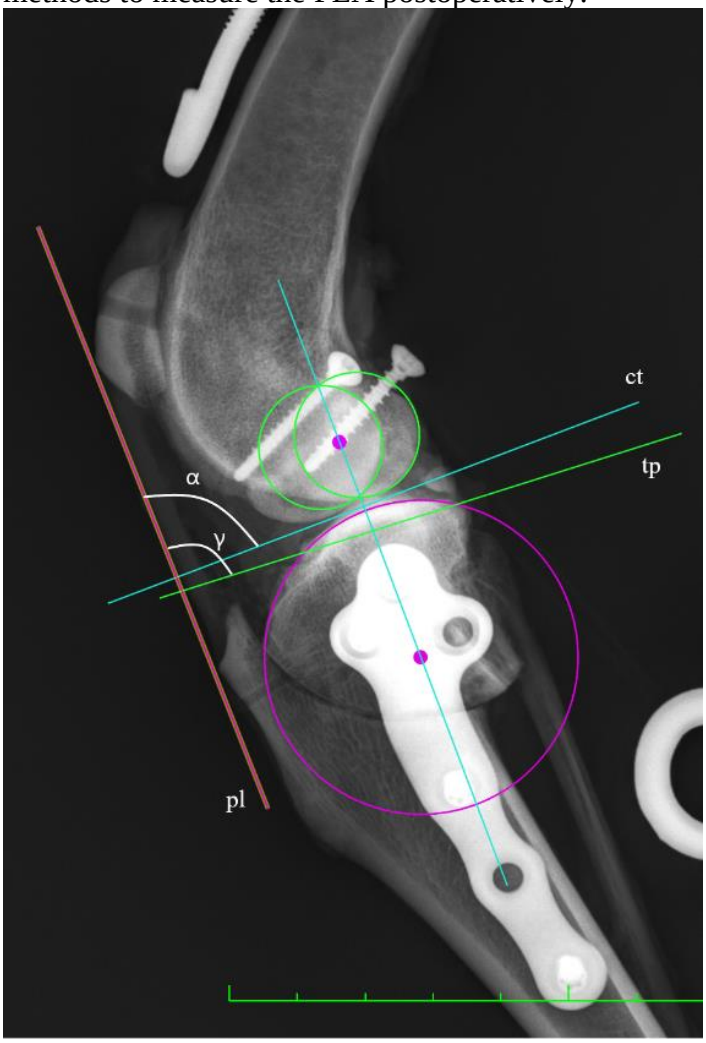
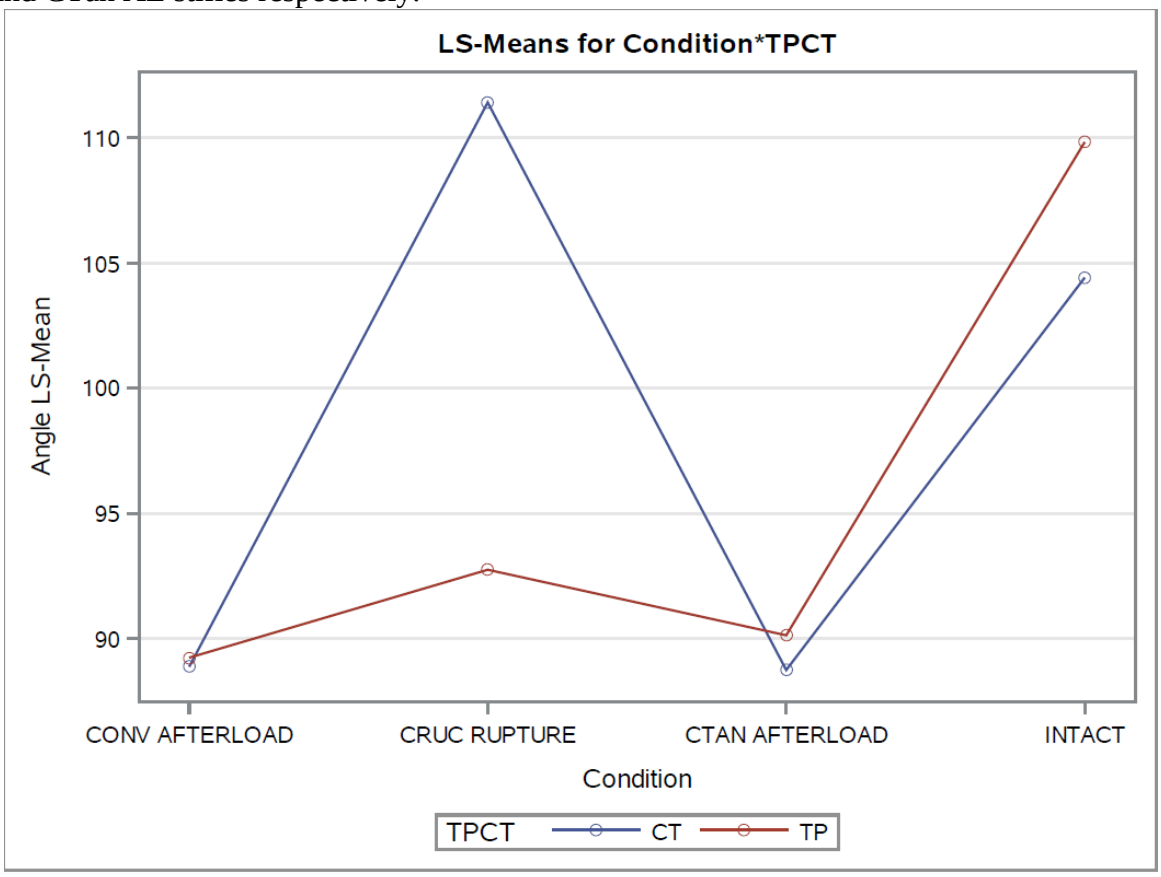


Figure 12. A line plot representing the variations of patellar ligament angle with respect to the tibial plateau (PLATP) and the common tangent of the femoral and tibial condyles (PLACT). Comparisons are represented between the intact, transected cranial cruciate ligament, Conv. AL and CTan AL stifles respectively.



TABLES

Table 1. Summary of intraoperative complications during a tibial plateau leveling osteotomy (TPLO) procedures in dogs. The larger prospective and retrospective studies reporting multiple complications are included.

	Priddy et al.[172]	Pacchiana et al.[174]	Stauffer et al.[226]	Gatineau et al.[133]	Kowaleski et al.[175]
Number of TPLOs performed	**253**	**397**	**696**	**476**	**56**
Tibial fracture	**3 (1.2%)**	**3 (0.8%)**	**1 (0.1%)**		
Intra-articular screw placement	**2 (0.8%)**	**2 (0.5%)**		**2 (0.4%)**	**2 (3.6%)**
Significant hemorrhage	**3 (1.2%)**	**1 (0.3%)**	**4 (0.6%)**		
Broken drill bits	**7 (2.8%)**				
Fibular fracture	**6 (2.4%)**		**1 (0.1%)**		**1 (1.8%)**
Intra-articular pin placement	**2 (0.8%)**				
Bone screws in osteotomy	**1 (0.4%)**				
Retained surgical sponge	**1 (0.4%)**				
Broken holding pin	**1 (0.4%)**				
Broken screw			**1 (0.1%)**	**1 (0.2%)**	

Table 2. Summary of postoperative complications from a tibial plateau levelling osteotomy (TPLO) procedure in dogs in chronological order of publication from earliest to most recent studies.

	Slocum et al.[3]	Priddy et al.[172]	Pacchiana et al.[174]	Carey et al.[227]	Stauffer et al.[226]	Corr, Brown[163]	Bergh et al.[181]	Duerr et al.[228]	Tuttle et al.[229]
Number of TPLOs performed	**394**	**253**	**397**	**94**	**696**	**21**	**213**	**146**	**168**
SSI or implant infection		**9 (3.6%)**	**3 (0.8%)**			**3 (14.3%)**			
Implant failure		**6 (2.4%)**	**6 (1.5%)**		**7 (1%)**	**2 (9.5%)**		**4 (2.7%)**	
Tibial fracture					**3 (0.4%)**	**1 (4.8%)**		**1 (0.7%)**	
Patellar ligament thickening			**2 (0.5%)**	**24 (25.5%)**	**19 (2.7%)**				
Tibial tuberosity fracture		**6 (2.4%)**	**14 (3.5%)**	**4 (4.3%)**	**28 (4%)**		**9 (4.2%)**	**7 (4.8%)**	
Osteomyelitis		**14 (5.5%)**	**7 (1.8%)**					**4 (2.7%)**	
Postliminary meniscal tear	**16 (4%)**		**4 (1%)**	**2 (2.1%)**				**1 (0.7%)**	
Draining tract		**1 (0.4%)**	**1 (0.3%)**						
Fibular fracture		**6 (2.4%)**	**2 (0.4%)**		**3 (0.4%)**	**1 (4.8%)**		**4 (2.7%)**	**9 (5.4%)**
Patellar fracture			**1 (0.3%)**	**1 (1.1%)**					
Septic arthritis		**4 (1.6%)**							
Ring Sequestrum		**1 (0.4%)**							
Pin migration									
Pivot shift									
Incision swelling/ inflammation			**17 (4.3%)**		**50 (7.2%)**	**1 (4.8%)**		**1 (0.7%)**	
Patellar luxation	**5 (1.3%)**								
Joint capsule swelling					**1 (<1%)**				
Internal rotation	**8 (2%)**			**12 (12.8%)**					

Table 2 (Continued). Summary of postoperative complications from a tibial plateau levelling osteotomy (TPLO) procedure in dogs in chronological order of publication from earliest to most recent studies.

	Conkling et al.[183]	Cook et al.[155]	Fitzpatrick et al.[147]	Gatineau et al.[133]	Rutherford et al.[230]	Kowaleski et al.[175]	Oxley et al.[231]	Olive et al.[232]	Coletti et al.[233]
Number of TPLO performed	**118**	**23**	**1146**	**476**	**305**	**56**	**97**	**87**	**1519**
SSI or implant infection	**1 (0.8%)**	**1 (4.3%)**	**66 (5.8%)**	**14 (2.9%)**			**1 (1%)**	**4 (4.6%)**	
Implant failure	**1 (0.8%)**		**3 (0.2%)**	**9 (1.9%)**			**1 (1%)**	**1 (1.1%)**	**9 (0.6%)**
Tibial fracture		**2 (8.6%)**		**1 (0.2%)**					**9 (0.6%)**
Patellar ligament thickening	**1 (0.8%)**	**1 (4.3%)**	**3 (0.3%)**						**4 (0.3%)**
Tibial tuberosity fracture	**2 (1.7%)**		**5 (0.4%)**					**1 (1.1%)**	**44 (2.9%)**
Osteomyelitis									
Postliminary meniscal tear		**1 (4.3%)**	**28 (2.4%)**	**10 (2.1%)**		**1 (1.8%)**	**4 (4.1%)**		**12 (0.8%)**
Draining tract									
Fibular fracture	**1 (0.8%)**		**1 (0.09%)**	**2 (0.4%)**				**6 (7%)**	**3 (0.2%)**
Patellar fracture			**1 (0.09%)**	**1 (0.2%)**	**6 (2%)**				**44 (2.9%)**
Septic arthritis				**3 (0.6%)**			**1 (1%)**		**9 (0.6%)**
Ring Sequestrum									
Pin migration	**2 (0.2%)**								**27 (1.8%)**
Pivot shift	**1 (0.8%)**		**3 (0.3%)**	**15 (3.2%)**					
Incision swelling/ inflammation		**1 (4.3%)**				**2 (3.6%)**			
Patellar luxation			**3 (0.3%)**	**5 (1.1%)**			**1 (1%)**		**13 (0.9%)**
Joint capsule swelling									
Internal rotation									

Table 3. Summary of the mean tibial plateau angles (TPA) measured in dogs in the veterinary literature listed in chronological order from earliest to most recent of the larger prospective and retrospective studies.

Caylor et al.[198]		**Morris et al.**[40]		**Selmi et al.**[41]	**Macias et al.**[42]	**Fettig et al.**[199]	**Reif et al.**[222]		**Venzin et al.**[234]		**Grierson et al.**[196]	
23.5°		With CrCL Without CrCL	23.8° 18.1°	32.5°	32.7°	24.1°	With CrCL Without CrCL	23.5° 23.6°	With CrCL Without CrCL	24.7° 24.3°	24.4°	
Fujita et al.[235]		**Duerr et al.**[32]		**Guastella et al.** [82]		**Glassman et al.**[202]	**Ragetley et al.**[48]		**Sabanci et al.**[236]*		**Su et al.**[223]**	
With CrCL Without CrCL	25.3° 23.9°	TPA > 35° TPA < 35°	41.7° 24.7	All dogs Labrador Retriever Rottweiler Boxer German Shepherd	26.6° 25.9° 26.2° 25.9° 28.2°	27.9°	Predisposed Not Pre-disposed	28.4° 25.2°	Medial TPA-R Medial TPA-P Lateral TPA-P	24.1° 24° 25.5°	Small Large	29.2° 26.1°

*TPA-R, TPA recorded from radiographs TPA; TPA-P, TPA recorded from photographs

**Study refers to differences between small and large breed dogs and their recorded TPAs.

Table 4. The number of limbs within the conventional and common tangent preoperative TPLO planning groups corresponding to a tibial plateau angle categorized accordingly: “under-rotated” (TPA > 7°), “normal” (TPA 7° $\geq$ x $\geq$ 3°), and “over-rotated” (TPA < 3°). Conv. = Conventional method planning. CTan = Common tangent method planning. PL = Preload. AL = Afterload.

Condition	Normal	Overrotated	Underrotated
TPA Conv. PL	**5**	**1**	**8**
TPA Conv. AL	**4**	**1**	**9**
TPA CTan AL	**2**	**4**	**8**
TPA CTan AL	**2**	**4**	**8**

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