EFFECTS OF TIBIAL PLATEAU LEVELING OSTEOTOMY AND TIBIAL TUBEROSITY ADVANCEMENT ON STIFLE CONTACT MECHANICS AND KINEMATICS

By

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To my family.
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Tibial plateau leveling osteotomy (TPLO) and tibial tuberosity advancement (TTA) are currently popular surgical treatment options for treating cranial cruciate ligament (CrCL) insufficiency in dogs; however, little is known regarding the biomechanical implications of these procedures. The objectives of this study were to review the literature regarding tibial osteotomies for CrCL insufficiency, and to investigate the effects of TPLO and TTA on femorotibial contact mechanics and three-dimensional stifle kinematics in CrCL-deficient stifles of dogs during weight-bearing.

Contralateral hind limbs from eight large (greater than 25 kg) breed dogs were randomly assigned to receive either TPLO or TTA. Poses of nylon screws implanted in the femur and tibia were digitized using a Microscribe digitizing arm with the limb under an axial load of 30% body weight and stifle angle at 135 degrees. Digital pressure sensors placed subjacent to the menisci were used to measure femorotibial contact force, contact area, peak and mean contact pressure, and peak pressure location. Each specimen was tested under normal, CrCL-deficient, and treatment (TPLO or TTA) conditions. Repeated measures analysis of variance with a Tukey post-hoc test ($P$ less than 0.05) was used for statistical comparison.
Significant disturbances to all measured contact mechanic parameters were evident after CrCL transection, which corresponded to marked cranial tibial subluxation and internal tibial rotation in the CrCL-deficient stifle. No significant differences in three-dimensional femorotibial alignment were observed between normal and TPLO-treated stifles; however, femorotibial contact area remained significantly smaller and peak contact pressures in both medial and lateral stifle compartments were positioned more caudally on the tibial plateau, when compared to normal. No significant differences in any contact mechanic or kinematic parameters were detected between normal and TTA-treated stifles.

We demonstrated that TPLO eliminates craniocaudal stifle instability during simulated weight-bearing; however, the procedure fails to concurrently restore femorotibial contact mechanics to normal. TTA was shown to eliminate craniocaudal stifle instability during simulated weight-bearing and concurrently restore femorotibial contact mechanics to normal.
CHAPTER 1
TIBIAL OSTEOTOMIES FOR CRANIAL CRUCIATE LIGAMENT INSUFFICIENCY

Introduction

Cranial cruciate ligament (CrCL) insufficiency is one of the most common causes of lameness in dogs. Rupture of the CrCL can be caused entirely by trauma; however, in most dogs the rupture is a consequence of mid-substance, progressive, pathologic fatigue. Subsequent instability invariably leads to the development of progressive stifle osteoarthritis (OA) and often results in secondary meniscal damage. This debilitating condition commonly affects young adult large breed dogs and frequently affects both stifles within a year of the initial diagnosis. The economic impact of treating dogs with CrCL insufficiency in the United States was estimated to be just over $1 billion in 2003.

Treatment of CrCL insufficiency aims to resolve lameness caused by joint instability and provide good long-term function of the affected hindlimb. Conservative management of dogs weighing less than 15 kg typically results in acceptable limb function, with reported success rates ranging from 84 to 90%. Surgical intervention is, however, advocated for most dogs with CrCL insufficiency in order to re-establish joint stability, mitigate secondary degenerative joint disease, and address any concurrent meniscal injury. Over the past 50 years, a plethora of surgical techniques have been described to treat this condition. This evolution of surgical procedures reflects the controversy that exists regarding the optimal management of CrCL insufficiency, and to date, no one procedure has consistently demonstrated superior clinical efficacy.

Traditional surgical techniques attempt to impart stability by utilizing an autogenous, allogenic, or synthetic structure placed within or about the stifle that mimics the function of the normal CrCL. Extra-articular techniques utilize peri-articular heavy gauge suture or wires, or
the transposition of soft tissues\textsuperscript{9} to reduce stifle laxity, whereas intra-articular techniques attempt to anatomically reconstruct the CrCL using autogenous tissues\textsuperscript{10}, allografts\textsuperscript{11} or synthetic materials\textsuperscript{12}. Most authors cite good to excellent limb function in most dogs that have undergone extra- or intra-articular procedures.\textsuperscript{13,14} Yet despite these reported satisfactory results, traditional methods are generally considered to yield sub-optimal long-term outcomes, as these techniques fail to consistently maintain stability, arrest the progression of OA, and prevent late meniscal damage.\textsuperscript{15-17}

As surgical techniques continue to evolve, the focus has shifted to the concept of creating dynamic stability in the CrCL-deficient stifle by altering bone geometry. In 1984, Slocum described the cranial tibial wedge osteotomy (CTWO), a surgical procedure that attempts to eliminate cranial subluxation of the tibia during weight-bearing by reducing the caudally directed slope of the tibial plateau.\textsuperscript{18} By establishing dynamic stability of the CrCL-deficient stifle, passive restraint against laxity is not required. Recognition that stabilization could be achieved in this manner led to the development of several proximal tibial osteotomy procedures, such as the tibial plateau leveling osteotomy (TPLO)\textsuperscript{19}, the combined TPLO/CTWO\textsuperscript{20}, the proximal tibial intra-articular osteotomy (PTIO)\textsuperscript{21}, the triple tibial osteotomy (TTO)\textsuperscript{22}, and the chevron wedge osteotomy (CVWO)\textsuperscript{23}. The more recently described tibial tuberosity advancement (TTA) procedure attempts to dynamically neutralize craniocaudal instability by altering the relative alignment of the patella tendon to the tibial plateau.\textsuperscript{24} Though there are few studies evaluating long-term functional outcomes of any of these tibial osteotomy techniques, most have been associated with favorable clinical results.\textsuperscript{18-20,22,24-26}
The purpose of this chapter is to review the biomechanical considerations, experimental investigations and clinical data pertaining to tibial osteotomy procedures for addressing CrCL insufficiency in dogs.

**Cranial Cruciate Ligament Biomechanics**

Due to the high prevalence of CrCL insufficiency, and because CrCL transection in dogs is frequently used as an experimental model to induce OA, the structure and function of the CrCL has been extensively investigated. Cadaver experiments, *in-vivo* kinematic analyses and theoretical models have contributed to the understanding of CrCL biomechanics and subsequently lead to the development of tibial osteotomy techniques.

Using a cadaver model, Arnoczky and Marshall demonstrated that the CrCL contributes to passive restraint specifically limiting cranial translation of the tibia relative to the femur, excessive internal rotation of the tibia, and hyperextension of the stifle. Other structures that provide passive restraint of the canine stifle include the caudal cruciate ligament (CaCL), the collateral ligaments and the menisci. The loss of a passive supporting structure about a joint may increase laxity, but does not necessarily result in clinically relevant instability. During *in-vivo* activity, the joints are subject to other important dynamic restraint mechanisms, such those produced by muscular force. For instance, electromyographic studies have shown that humans with anterior cruciate ligament rupture can inhibit anterior tibial translation by increasing hamstring tone and decreasing quadriceps activity. Further, the magnitude of forces applied to a joint to demonstrate and quantify joint laxity *in-vitro* may be considerably different than the physiologic loads that are sustained *in-vivo*. Therefore results of cadaver experiments such as those reported by Arnoczky and Marshall do not fully define whether or not the CrCL is a primary stabilizer of the canine stifle.
Kinematic studies in dogs, using stereo radiophotogrammetry and/or instrumented spatial linkage, were able to confirm that CrCL transection results in substantial cranial tibial subluxation during the stance phase of gait.\(^{29,31}\) These findings demonstrate that muscular forces are unable to compensate for the loss of restraint provided by the CrCL. In all but one dog, cranial tibial translation did not occur during the swing phase of gait. Thus, the authors concluded that the stability of the stifle during the stance phase of gait is dependent on the CrCL, whereas stability during the swing phase of gait is not dependent on the integrity of the CrCL. The observations are in agreement with findings from a study performed in goats that measured dynamic CrCL strain \textit{in-vivo}, where maximum CrCL force occurred in early stance phase, and dropped to zero during swing phase of gait.\(^{37}\) Conversely, neither kinematic study found significant differences in peak internal rotation magnitude between CrCL-deficient dogs and normal dogs,\(^{29,31}\) suggesting either the CrCL is a secondary stabilizer against internal tibial rotation, or nominal internal tibial torques are generated while walking.

In the clinical setting, the diagnosis of complete CrCL rupture is made with the detection of cranio-caudal joint laxity, which can be elicited by applying a cranially directed load on the proximal tibia. The ‘cranial drawer’ test can be considered a ‘static’ clinical test and is analogous to the cadaver experiment performed by Arnoczky and Marshall, since eliciting cranial drawer relies on displacement of a bone in the direction of an applied force.\(^{35}\) ‘Dynamic’ tests, on the other hand, aim to mimic the forces and dynamic instabilities that normally occur during weight-bearing.\(^{35}\) The ‘tibial compression’ test, described by Henderson and Milton in 1978, attempts to replicate a weight-bearing force on the limb by flexing the hock.\(^{38}\) With the stifle at a standing angle, the tension generated in the gastrocnemius muscle creates strong caudo-distal traction of the femur and consequently a cranio-proximal shear force on the tibia.\(^{38}\) This force is normally
counteracted by the CrCL, so cranio-proximal translation of the tibia will result if the CrCL is ruptured. The tibiofemoral shear force occurring during weight-bearing was termed “cranial tibial thrust” by Slocum in 1983.30

Slocum also presented a theoretical model that proposed the magnitude of cranial tibial thrust was dependent on the degree of the caudodistally directed slope of the tibial plateau.30 Quantification of the tibial plateau slope, the tibial plateau angle (TPA), is defined by the angle formed between the slope of the medial tibial condyle and the perpendicular to the longitudinal axis of the tibia.18 Reported mean TPAs in clinically normal dogs range between 18 - 24°.39-41 According to Slocum, the compressive forces of weight-bearing, assumed to be parallel to the axis of the tibia, can be resolved into a cranially directed component (the cranial tibial thrust) responsible for cranial tibial translation, and a joint compressive force (Figure 1-1).30

A correlation between tibial plateau slope and anterior or cranial tibial thrust has been confirmed in human and animal in-vitro models.42-44 It is, however, important to note that there is no definitive evidence substantiating that dogs with higher than average TPAs are at greater risk for developing CrCL insufficiency.40,41

More recent biomechanical theories argue that the tibia is not axially loaded as proposed by Slocum. Rather, Tepic suggested the total tibiofemoral joint forces in-vivo are directed parallel to the patella tendon.32,45 Cranial tibial thrust, according to this model, is then dependent on the angle between the tibial plateau and the patella tendon (Figure 2).32,45 This model also predicts cranial tibial translation should not occur when a CrCL-deficient stifle is flexed beyond 90°.32

Based on the predominant cranio-caudal instability generated by CrCL transection in-vivo, it is reasonable to conclude that neutralization of cranial tibial thrust is likely the most important
function of the CrCL. Accordingly, current tibial osteotomy techniques primarily aim to address the sagittal plane instability that occurs as a result of weight-bearing. Since these procedures do not provide a passive restraint against internal tibial rotation, excessive internal tibial rotation may still occur (e.g., during certain vigorous activities that involve pivoting on the hind limb), and rotational instability may potentially contribute to the subsequent development of OA and meniscal injury.

**Cranial Tibial Wedge Osteotomy**

The CTWO was the first procedure described that attempted to eliminate cranial tibial thrust by reducing the TPA. Initially recommended as an adjunct to procedures that impart passive stabilization (such as fascial imbrication), the CTWO involves leveling the TPA by resecting a cranially based wedge of bone from the proximal tibia, opposing the margins of the osteotomy, then stabilizing the two bone segments with a medially applied bone plate following standard AO-ASIF principles (Figure 1-3). The ostectomy is performed as proximally as feasible while preserving a large enough proximal bone segment to allow for adequate fixation.

In order to achieve a post-operative TPA of 5°, and thereby neutralize cranial tibial thrust, the angle of the wedge to be excised should equal the measured pre-operative TPA. Intuitively it would seem a wedge angle equal to the TPA would result in a post-operative TPA of 0°. Performing a CTWO, however, induces tibial longitudinal axis shift, which is responsible for inadequate leveling of the tibial plateau slope. Following CTWO, the proximal landmark for defining the tibial longitudinal axis of the tibia, the intercondylar tubercles, is shifted cranially. To compensate for this change in position, ‘over-rotation’ of the tibial plateau is necessary to achieve the expected TPA of 5°. The post-operative TPA will be larger than anticipated if calculations do not account for the shift of the longitudinal axis of the tibia.
Wide discrepancies in the post-operative TPAs have been reported following CTWO.\textsuperscript{18,49,50} For instance, within a single case series reported by Macias \textit{et al}, post-operative TPAs ranged between 7° and 21°.\textsuperscript{49} The difficulty in attaining the target TPA may be attributed to variability in size and position of the ostectomy, and tibial longitudinal axis shift.\textsuperscript{46} Resecting a wedge equal to the TPA, performing the ostectomy as proximal as practical, and aligning the cranial cortices is recommended in order to improve the accuracy of the procedure.\textsuperscript{46,47} Intra-operative calculation of the wedge angle should be precise and methodical to further minimize variability in the post-operative TPA. A trigonometric method,\textsuperscript{20} or a sterilized template of the desired wedge made from radiographic film can be used for this purpose.

CTWO may be indicated in dogs with certain types of proximal tibial conformation. Though no causal relationship between a high TPA and CrCL insufficiency has been established, abnormally steep tibial plateau slopes have been implicated as the underlying cause of CrCL rupture in several case series.\textsuperscript{20,49-51} Exceedingly steep tibial plateau slopes secondary to alterations in proximal tibial physeal growth may be most amenable to treatment with a CTWO.\textsuperscript{52} Osmond \textit{et al}, attempted to characterize anomalies of the proximal portion of the tibia by correlating the morphometry of the proximal tibia in clinical CrCL insufficiency cases with computer-generated models that mimicked different tibial morphologies.\textsuperscript{52} The authors identified a subset of CrCL-deficient dogs with steep TPAs attributed to proximal shaft deformities, and theorized that the tibia would assume a more anatomically correct alignment after CTWO, as the procedure tilts the distal portion of the tibial shaft in relation to the proximal portion.\textsuperscript{52} Anecdotally, correction of substantial proximal tibial varus or torsion may be more easily addressed with the CTWO compared to other tibial osteotomy techniques (Personal communications, Antonio Pozzi).
Although dynamic stabilization of CrCL-deficient stifles is receiving considerable attention, reports documenting clinical outcomes after CTWO are sparse. In a preliminary study of the CTWO involving 17 dogs, Slocum and Devine reported rapid return to function and clinical union of the osteotomy for the majority of dogs by 6 weeks following surgery.\(^{18}\) All 9 dogs evaluated at 12 months after surgery had limb function that was subjectively considered to be indistinguishable from normal. Radiographic evidence of OA did not progress in any of the stifles; however, objective, quantitative assessment of stifle OA was not performed. The dogs also underwent semitendinosus, gracilis and biceps femoris muscle advancement to reduce laxity, confounding the assessment of the CTWO procedure. In a retrospective analysis of 91 dogs treated with CTWO, 86% of the dogs were considered to have good-to-excellent limb function based on the results of a client survey and physical examination.\(^{26}\) Two case series reported the results of CTWO in small breeds dogs with proximal tibial deformities.\(^{49,50}\) Subjective lameness grading or owner satisfaction was used to gauge the efficacy of the procedure. All dogs (13 overall) in both studies had good-to-excellent limb function within 6 weeks following surgery, and maintained good limb use at an average follow-up period of 1 year. In one of these reports, CTWO was combined with lateral suture stabilization, making it difficult to ascertain the efficacy of CTWO alone in this group of dogs.\(^{50}\)

Reported complications have been principally associated with failure of fixation and non-union.\(^{18,49,50,53}\) In a direct clinical comparison of TPLO and CTWO, the second-surgery rate for CTWO was 11.9%, nearly twice the second-surgery rate for TPLO (4.5%).\(^{53}\) Of the 12 dogs requiring surgical revision after CTWO, 9 were deemed to have catastrophic tibial fractures requiring multiple plating.\(^{53}\)
The CTWO has the advantage of not requiring patented specialized equipment.\textsuperscript{53} Other advantages include the ability to address exceedingly steep tibial plateau slopes, as well as tibial varus and torsion. Because the CTWO causes distal displacement of the patella tendon insertion, the procedure may be used to treat for concurrent patella alta.\textsuperscript{20} Disadvantages include: variability in post-operative TPAs, potential for creating patella baja and limb shortening.\textsuperscript{20,49,50} Also, inducing longitudinal tibial axis shift may result in aesthetically undesirable cranio-caudal angulation of the tibia.\textsuperscript{20} With the growing recognition of proximal tibial angular limb deformities inducing steep TPAs, CTWO may gain wider acceptance in the treatment of CrCL insufficiency.

**Tibial Plateau Leveling Osteotomy**

Like the CTWO, the TPLO aims to provide dynamic cranio-caudal stifle stability during the stance phase of gait by reducing the slope of the tibial plateau. Proposed by Slocum in 1993, the TPLO involves performing a radial osteotomy of the proximal tibia with subsequent rotation of the proximal segment to enable precise manipulation of the tibial plateau slope.\textsuperscript{19} Based on the radius of the osteotomy and the pre-operative TPA, the exact amount of rotation of the proximal segment is calculated in order to achieve a post-operative angle of 5°.\textsuperscript{54} The procedure is performed via a medial approach to the proximal tibia.\textsuperscript{54} A bi-radial sawblade is used to create a crescent shaped osteotomy; compression of the osteotomy results in complete congruency, as the inner and outer edges of the sawblade are of the same diameter.\textsuperscript{54} A custom-jig applied medially maintains alignment of the bone segments while allowing for rotation of the proximal segment.\textsuperscript{54} The osteotomy should be centered over the intercondylar tubercles to ensure accurate rotation and maintain enough bone in the proximal segment for adequate purchase during internal fixation of the osteotomy (Figure 1-4).\textsuperscript{54} Imprecise positioning of the osteotomy may result in an
inaccurate tibial plateau leveling and complications such as angular deformities and tibial

tuberosity fracture.\textsuperscript{55-57}

Biomechanical studies have demonstrated that following tibial plateau rotation, the
tibiofemoral shear force shifts from cranial to caudal when the limb is loaded.\textsuperscript{43,44} Thus it has
been postulated that joint stability is dependent on the CaCL neutralizing caudal tibial translation
following TPLO.\textsuperscript{44} The recommended post-operative TPA was defined as 0° and 5° when the
procedure was first described in 1993 and in the TPLO licensing course, respectively.\textsuperscript{19,54}
Despite these specific guidelines, the optimal TPA is still a contentious subject. \textit{In-vitro} studies
have shown cranial tibial thrust is effectively neutralized at a mean angle of 6.5°.\textsuperscript{43,44} Three-
dimensional computer modeling of the canine stifle, on the other hand, found that rotation to 5°
only marginally decreased the tensile force acting on the CrCL.\textsuperscript{58} Both \textit{in-vitro} analyses and
theoretical modeling, however, can fail to reliably predict clinical outcome.\textsuperscript{59} Limitations
associated with cadaver experiments include the difficulty of replicating naturally occurring
disease and the inability to simulate all the muscular forces acting on the joint. Inaccuracies of
computer modeling can arise from multiple assumptions, such as disregarding muscular
compensation, and simplifying joint geometry. Data from \textit{in-vitro} and computer modeling
investigations should be interpreted and applied to clinical cases with caution because of these
limitations. In a clinical study by Robinson \textit{et al}, there was no statistically significant
relationship between TPA and ground reaction forces after TPLO, where the post-operative
TPAs were between 0° and 14°.\textsuperscript{60} Satisfactory results of under-rotated stifles, which were
indistinguishable from the outcome of dogs having ‘optimal’ post-operative TPAs, may be
indicative of complete elimination of cranial tibial thrust \textit{in-vivo} over a wide range of angles.
Optimal TPAs may vary between breeds, or indeed between individual dogs. Chronically
affected stifles may not require as much rotation as stifles with acute rupture, since periarticular fibrosis can contribute substantially to joint stability. Alternatively, the presence of residual cranial tibial thrust after TPLO may not result in lameness. Precise in-vivo kinematic analyses are required to identify the optimal TPA and further understand the biomechanics of the TPLO.

The results of dogs treated with TPLO have so far been encouraging, although there are no studies documenting objective data with follow-up periods greater than a mean of 17 months. Subjective evaluation of limb function suggests earlier return to weight-bearing after TPLO when compared with the intra- and extra-capsular forms of stabilization. Beyond the initial recovery period, however, convincing proof that the TPLO results in superior limb function currently does not exist. In Slocum’s original study, which included 394 dogs, outcomes at follow-up evaluations greater than 6 months after surgery were reported as excellent for 73%, good for 21% and fair for 3%. Another study with a follow-up period ranging from 6 months to 4 years reported that 93% of owners were satisfied with the outcome after TPLO, which is similar to the proportion of owner satisfaction after other techniques. Good to excellent long-term function, based on owner evaluation, has also been reported in the majority of dogs (25 cases, 50 stifles) treated with single-session bilateral TPLOs.

In an in-vivo experiment by Ballagas et al, experimentally induced CrCL-deficient hind limbs were treated with TPLO and evaluated with force plate analysis pre-operatively, at 8 and at 18 weeks following surgery. By 18 weeks, peak vertical force and vertical impulse were not significantly different when compared with pre-operative values, though a subjective mild lameness was still evident in 4 of 6 dogs. Conzemius et al, performed a prospective clinical study in Labrador Retrievers with CrCL insufficiency to compare limb function after lateral suture stabilization, intra-capsular stabilization and TPLO using force platform gait analysis. Contrary
to the conclusions drawn by some studies that evaluated outcomes subjectively, the investigators found no difference in ground reaction forces or peak vertical impulse between TPLO and lateral suture stabilization treated dogs at 2 months and 6 months after surgery. Moreover, only 10.9% of TPLO treated dogs obtained comparable limb function to clinically normal dogs as compared to 14.9% of dogs with lateral suture stabilization and 15% of dogs with intracapsular stabilization evaluated in the same study.

There are several reports that have investigated the progression of stifle OA after TPLO. A prospective radiographic study of 40 dogs showed a significant overall increase in mean osteophyte scores 6 months following TPLO. Interestingly, progression of osteophytosis was not evident in the majority (57.5%) of dogs, and radiographic parameters of OA were improved in 2 dogs. A comparison of long-term radiographic changes following TPLO and lateral suture stabilization revealed that while the TPLO did not prevent the progression of OA, the rate of progression was approximately 3-fold less than stifles that underwent lateral suture stabilization. Studies assessing the efficacy of the TPLO based on radiographic OA assessment should be interpreted with caution, as soft tissue (e.g., cartilage, synovium, menisci, periarticular tissues) changes are not readily identifiable with this imaging modality, and one study has shown that radiographic OA changes in the stifle are not predictive of limb function.

Numerous intra- and post-operative complications have been reported in dogs undergoing TPLO. The relative high frequency of complications reported for TPLO may be due to the large number of cases that have been evaluated in the literature. The overall complication rate is reported to be 26 to 34%, with tibial tuberosity fracture, implant failure, patellar ligament desmitis, subsequent meniscal tear after TPLO and infection reported most frequently. While most of these are implant or fracture-related complications, others have been attributed
to abnormal stifle biomechanics induced by the TPLO.\textsuperscript{19,62,69-72} Tibial tuberosity fracture is documented to occur in 3 to 7\% of TPLO cases.\textsuperscript{62,70,71} The vast majority of these fractures are non- or minimally displaced and do not require surgical intervention.\textsuperscript{55} Fracture of the tibial tuberosity may be caused by a stress riser effect at the site of Kirschner wire placement used to maintain the rotation of the tibial plateau segment, or at the narrow isthmus of the tibial tuberosity created by a cranially positioned osteotomy.\textsuperscript{62,70} Thermal necrosis, vascular compromise secondary to soft tissue dissection, increased strain in the patellar ligament after TPLO and large rotations of the tibia plateau segment have also been cited as potential predisposing factors.\textsuperscript{20,55,62} A retrospective analysis by Kergiosen \textit{et al}, identified age, weight, single session bilateral TPLO surgery and tibial tuberosity width as potential risk factors for tibial tuberosity fractures.\textsuperscript{55} Prophylactic pin and tension bands have been used in an attempt to decrease the risk of tibial tuberosity fractures.\textsuperscript{63}

Patellar tendonitis is also common, and may cause lameness within the first 2 months following TPLO.\textsuperscript{55,62,69,70} Clinical signs are usually self-limiting. Patellar tendon thickening, visible on radiographs or by ultrasonography, is most commonly noted distally.\textsuperscript{72} Possible causes include trauma to the patella tendon sustained during surgery due to excessive retraction, or thermal damage associated with saw blade contact.\textsuperscript{69,72} Histopathologic changes in the tendon are non-inflammatory and similar to those identified in humans with patella tendon strain, hence excessive loading of patella tendon secondary to altered biomechanics after TPLO has also been implicated as a possible underlying cause.\textsuperscript{56,69} Rotation of the tibial plateau segment may result in a decreased moment arm if the distance between the patella tendon insertion and instant center of rotation of the stifle is reduced; in turn, greater forces in the quadriceps mechanism may be required to generate the same extensor moment about the stifle.\textsuperscript{56,69} This theory is corroborated
by findings from a radiographic study by Mattern et al, where lower post-operative TPAs (< 6°) were associated with more severe ultrasonographic changes in the patella tendon.72

Recurrent lameness after TPLO may indicate subsequent meniscal injuries. Although meniscal tears occurring after stabilization of CrCL-deficient stifles have been reported as a complication associated with several procedures,73,74 it is proposed that there is a high risk of developing meniscal injuries after TPLO because passive joint stability is not restored.19 The caudal pole of the medial meniscus acts as a wedge between the femoral and the tibial condyles and may become crushed during cranial tibial translation.33 TPLO places the stifle joint in a greater angle of flexion during weight bearing, which may be resulting in excessive loading of the caudal pole of the medial meniscus.32 Slocum and others have advocated complete radial transection of the medial meniscus, termed meniscal release, to allow caudal displacement of the caudal pole of the medial meniscus during cranial tibial translation, thereby preventing subsequent meniscal tears.19,62 In-vitro studies have, however, shown that meniscal release impairs load transmission and stability of the stifle.33,75 The adverse consequences of releasing the meniscus were corroborated by a radiographic study demonstrating greater progression of OA in dogs with meniscal release.76 Furthermore there is no evidence to suggest that meniscal release eliminates the risk of subsequent meniscal tears.77 A recent retrospective study reported a 3.5% incidence of subsequent meniscal injury in stifles that underwent arthrotomy with meniscal release.77 Meniscal release did not reduce the rate of subsequent meniscal tearing when compared with cases treated arthroscopically without meniscal release. While traditionally stifle arthrotomy has been considered accurate for diagnosing meniscal pathology78, the data suggests that lack of identification of meniscal tears at the time of TPLO may play an important role in the onset of subsequent meniscal tears.77 Indeed, a recent in-vitro study found meniscal examination
via arthrotomy had significantly lower sensitivity and specificity than arthroscopy for diagnosing meniscal tears.\textsuperscript{79} When meniscal pathology cannot be comprehensively assessed in the CrCL-deficient stifle, releasing the medial meniscus is advocated in order to decrease the incidence of subsequent meniscal tears.\textsuperscript{77,79} If the medial meniscus is thoroughly evaluated at the time of TPLO, and cranial tibial thrust is effectively neutralized, meniscal release may not be warranted.\textsuperscript{77,79} The decision to release an intact meniscus remains controversial, and the issue is further complicated by the apparent nominal impact meniscal release has on limb function.\textsuperscript{77} Further studies are necessary to determine the long term effects of meniscal release on joint function. It is important to note that although meniscal release is most commonly referenced to the TPLO, performing a meniscal release is not restricted to this procedure because passive joint laxity is a consistent feature of all tibial osteotomy techniques.

Caudal cruciate ligament injury is cited as a potential complication following TPLO.\textsuperscript{19} As TPLO is postulated to induce caudal tibial thrust, over-rotation increases strain on the CaCL. While increased strain has been demonstrated in cadaver studies,\textsuperscript{44} clinical cases with post-operative lameness definitively attributed to CaCL strain or rupture have not been reported, even in cases in which the TPAs have been as low as -7\degree.\textsuperscript{62}

Neoplasia developing at the TPLO surgical site has been documented; however, a direct causal relationship has not been proven.\textsuperscript{80} Boudrieau \textit{et al} recently described a dog with an histiocytic sarcoma involving the proximal portion of the tibia 5 years after TPLO.\textsuperscript{80} Visual, microscopic, chemical and metallographic analysis of the TPLO plate retrieved from this dog revealed corrosion, and poor corrosion resistance was attributed the casting manufacturing process of the implant. Implant corrosion was implicated as a potential cause of tumor development, and 3 additional dogs were identified that had previously undergone TPLO and
developed osseous neoplasia of the proximal tibia. These findings prompted further investigations; metallurgic analyses of both new and previously implanted Slocum TPLO plates revealed these plates had unusual surface irregularities and porosity.\textsuperscript{81-83} Aluminum and silicon residua and inclusions, which were thought to have originated from the cast molds, were also identified.\textsuperscript{82} Conflicting results exist regarding corrosion of retrieved implants.\textsuperscript{81-83} Although the investigations have focused on corrosion as a potential cause for neoplasia, other causative factors that are not specific to the Slocum TPLO plate, such as the osteotomy itself, have not been eliminated. Moreover, TPLO is almost exclusively recommended to a population of dogs that are at risk for developing primary osseous neoplasia, of which the proximal tibia is a common site of occurrence.\textsuperscript{1} Further work is warranted to determine whether the TPLO procedure, or the specific implants used, increase the risk of tumor development.

Infection, manifesting as septic arthritis, osteomyelitis or superficial wound infection is reported with a rate of 3 to 7\%, which is greater than the infection rate previously reported for other clean surgical procedures.\textsuperscript{62,70,71,84} Septic arthritis is considered one of the most serious complications encountered after TPLO.\textsuperscript{62} The cause of higher infection rate following TPLO is likely multifactorial. Infection after open reduction and internal fixation of proximal tibial fractures in human patients is attributed to poor soft tissue coverage and blood supply.\textsuperscript{85} Poor soft tissue coverage of the surgical site may play a role in migration of bacteria through the surgical wound from the external environment.\textsuperscript{85} Extensive soft tissue dissection around the proximal tibia, poor tissue handling, prolonged surgical time, surface plate characteristics\textsuperscript{86} and thermal necrosis at the osteotomy site may also contribute to infection.

TPLO is currently the most common tibial osteotomy performed, and widely regarded by many veterinary surgeons as the best surgical option for CrCL insufficiency in medium to large
breed dogs. Advantages include geometric precision, maintenance of the original position of the tibial tuberosity and patellofemoral joint. Disadvantages include the technical difficulty and complications of the surgical procedure, including iatrogenic angular and torsional deformities, as well as the potential adverse effects on stifle biomechanics.

**Tibial Tuberosity Advancement**

The TTA, first described by Montavon *et al*, in 2002, attempts to dynamically stabilize the CrCL-deficient stifle without leveling the tibial plateau. As previously discussed, theoretical models of the stifle predict that the total joint forces are approximately parallel to the patella tendon. Thus, if the patella tendon is oriented perpendicular to the tibial plateau, there is no shear component of the total joint force. During the stance phase of gait, where the stifle angle is 135° of extension, the angle between the patella tendon and the tibial plateau is approximately 105°. Accordingly, reducing this angle to 90° should stabilize the CrCL-deficient stifle (Figure 1-2). This anatomic conformation can be achieved by performing a TTA. The procedure involves making a longitudinal osteotomy subjacent to the tibial tuberosity. An appropriately sized spacer-cage is implanted at the proximal extent of the osteotomy to secure the tibial tuberosity in a cranial position. The width of the cage, available in 3 mm, 6 mm, 9 mm and 12 mm sizes, is determined by measurements made from pre-operative lateral hind limb radiographs with the stifle at approximately 135° of extension. A tension-band bone plate is applied to the medial aspect of the tibia, and autogenous or allogenic bone graft is placed in the resulting defect to accelerate bone union (Figure 1-5).

Theoretical reduction of tibiofemoral shear forces by advancing the insertion of the patella tendon has been substantiated in both cadaver and computer modeling studies. The Maquet’s procedure in human patients involves anterior advancement of the tibial tuberosity, which is advocated for treatment of patellofemoral pain. In a cadaver study of the Maquet’s procedure,
the magnitude of tibiofemoral forces in a direction tangential to the joint surfaces consistently 
decreased after incremental advancement, provided the knee angle was at near-to-full 
extension.88 Similarly, finite element analysis of the human knee found that, at near full 
extension, anterior cruciate ligament and tibiofemoral contact forces substantially decreased after 
advancement of the tibial tuberosity.89 A recent in-vitro study performed in canine cadaver hind 
limbs also demonstrated neutralization of tibiofemoral shear forces by advancing the tibial 
tuberosity, where the mean patella tendon-to-TPA required to eliminate cranial tibial thrust was 
90 ± 9°.87

Clinical outcomes after TTA are currently documented in a small number of preliminary 
reports only.24,25,91,92 In a prospective clinical trial of 40 CrCL-deficient stifles treated with TTA, 
mean peak vertical force was 32% of body weight pre-operatively, and doubled to 64% of body 
weight at a final examination that was performed between 4 to 12 months after surgery.92 This 
was still significantly lower than a mean peak vertical force of 74% in clinically normal dogs, 
though the results are comparable to the findings in a similar study evaluating hind limb function 
before and after TPLO.92 In a retrospective report, 38 of 40 owners (95%) were satisfied with the 
long-term outcome of TTA, and the author’s clinical impression was that the post-operative 
recovery with this technique was very rapid.91 Hoffman et al, found that, with a median follow-
up period of 24 weeks, owners assessed the overall outcome of the procedure to be good to 
excellent in 90% of cases.25 These initial results appear promising; however, accurate assessment 
of the outcome after TTA is not possible at this time due the lack of clinical studies currently 
reported.

Reported complications associated with TTA include implant failure, tibial tuberosity 
fracture, medial patella luxation, CaCL injury due to excessive advancement, and subsequent
meniscal injury.\textsuperscript{24,25,91,92} Implant failure, reported to occur in 1 to 5\% of operated limbs, was attributed to either technical error or earlier implant designs that were considered too weak; the implants have been subsequently modified. Excessive post-operative activity has also resulted in complete implant failure.\textsuperscript{25} Partial CaCL rupture that was diagnosed 4 months following surgery in one dog was ascribed to excessive advancement of the tibial tuberosity.\textsuperscript{92} Indeed, in the cadaver study by Apelt \textit{et al}, caudal tibial translation was found to occur when the tibial tuberosity was advanced beyond the defined angle required to neutralize cranial tibial thrust, presumably placing excessive strain on the CaCL.\textsuperscript{87} Post-operative meniscal injuries were frequent in one study, occurring in 7 of 24 cases that had intact medial menisci at surgery.\textsuperscript{91} It is difficult to ascertain whether this was an accurate reflection of the true prevalence of late meniscal injury associated with the TTA, if meniscal lesions were the result of unfavorable biomechanics, if meniscal lesions were missed at the primary surgery, or if meniscal lesions were caused by insufficient advancement of the tibial tuberosity after TTA.

From a biomechanical perspective, the TTA may have two principle advantages over the TPLO. The TTA preserves the natural tibiofemoral articulation because the tibial plateau is not repositioned. In doing so, and provided that the TTA is equally as effective as the TPLO in neutralizing cranial tibial thrust, natural load transmission across the stifle (and menisci) is less likely to be altered. The TTA also increases the extensor moment arm of the stifle and thus the mechanical advantage of the patellar tendon, thereby theoretically reducing the forces acting along the patella tendon.\textsuperscript{32} The TPLO, on the other hand, appears to increase the strain on the extensor mechanisms of the stifle, resulting in clinically relevant complications.\textsuperscript{69,72} At this stage, these potentially advantageous features of the TTA are purely speculative, and future
biomechanical analyses should provide information that allows objective comparisons between the TTA and TPLO.

The purported advantages of TTA include this procedure being less invasive and technically less demanding than other tibial osteotomies, the ability to effectively treat concurrent patella luxation, short operative time and low post-operative morbidity. Disadvantages of TTA include the potential to cause iatrogenic patella luxation, requirement for specialized implants and potentially high rate of late meniscal injuries. Because the technique is a new procedure, the true benefits and complications are yet to be substantiated by sufficient clinical or biomechanical data.

**Other Tibial Osteotomy Techniques**

Several additional tibial plateau leveling techniques have been recently described. While information regarding these procedures currently available in the literature is limited, each procedure presents unique methods developed to circumvent certain limitations of the conventional tibial osteotomies presented above, and may gain further attention in the future.

**Combination Closing Wedge and Tibial Plateau Leveling Osteotomy**

TPLO in conjunction with CTWO is primarily used to treat CrCL-deficient stifles with excessive TPAs (> 34°). Reducing the TPA by using both methods concurrently is purported to diminish the risk of complications encountered when either procedure is performed alone, such as patella baja and tibial tuberosity fracture. The magnitude of rotation and wedge angle is determined by standardizing one measurement (e.g., wedge angle 10°), then calculating the remainder of tibial plateau leveling with the other measurement (e.g., tibial plateau rotation = TPA – 5 – wedge angle) to achieve a post-operative TPA of 5°. The radial osteotomy is positioned in the same location as a standard TPLO, and the cranially based closing wedge ostectomy is placed such that the apex is at the caudal cortical margin of the TPLO. Extensive
rigid internal fixation using interfragmentary Kirschner wires, tension-band wire, and single or double plating is required to stabilize all three bone segments (Figure 1-6).

In a clinical case series of 15 dogs with excessive TPAs, a mean post-operative TPA of 8° was achieved with combination TPLO/CTWO. At a mean final follow-up period of 23 weeks, no lameness was observed in 73%, only a mild lameness was noted in the remaining 27%, and all owners were satisfied with the overall outcome. Postoperative complications were, however, common, occurring in 78% of cases. Most notably, implant failure necessitating a second procedure occurred in over 1 in 4 cases, and the mean time to complete radiographic healing was prolonged at 18 weeks.

CrCL insufficiency due to exceedingly steep TPAs remain challenging orthopaedic cases, and despite a high complication rate, combination TPLO/CTWO may be one of few surgical procedures that result in acceptable outcomes. Dogs with excessive TPAs may also have concurrent hind limb conformational abnormalities, and proponents of combining TPLO with CTWO suggest many of these conditions can be addressed with this technique. It is arguably the most technically demanding procedure of all described tibial osteotomies and should thus be performed by only experienced veterinary orthopaedists.

**Proximal Tibial Intra-Articular Osteotomy**

The PTIO is another tibial plateau leveling technique that involves making a wedge ostectomy with the base of the wedge located between the bursa of the patella tendon and the cranial aspect of the menisci (Figure 1-7). A bi-axial approach is required: the tibial osteotomies are performed from the medial surface; laterally, the craniolateral crus muscles area elevated off the proximal tibia and a fibula ostectomy is made in order to facilitate reduction of the ostectomy site. Both medial and lateral arthrotomies are recommended to inspect the stifle and excise the infrapatellar fat pad for adequate visualization during the procedure. The angle of
the wedge to be excised is determined from pre-operative radiographs, but descriptions of calculating this angle are vague. The margins of the osteotomies are reduced with reduction forceps and stabilization is achieved with lag screws inserted cranio-caudally, with or without augmentation using a medially positioned 6-hole plate applied in buttress fashion. The medial and lateral fascia may be imbricated to reduce passive instability.

In the original description of this procedure, 75 of 87 dogs (86%) were considered to have a sound gait at follow-up assessments 4 months post-operatively, but seven of 87 dogs (8%) were still moderately lame. Slightly better outcomes were reported by Jerram et al, where lameness was not apparent in 54 of 57 (95%) operated limbs when examined 6 months after surgery. The remaining 3 (5%) operated limbs had intermittent, mild, weight-bearing lameness with exercise. Although the overall proportion of dogs with satisfactory results is comparable to other tibial osteotomy procedures, multiple complications may preclude the PTIO from gaining wide spread use. A high rate of subsequent meniscal injuries has been observed. Of 57 stifles with an intact medial meniscus, subsequent meniscal injury requiring surgical intervention was seen in 10 stifles (17.5%). Induced tibial valgus deformity was observed in both reports, occurring in 3 to 12% of operated limbs. Other reported complications included long digital extensor trauma or fibrosis, requiring a second surgery and intensive physical therapy, superficial peroneal nerve injury, laceration of the cranial tibial artery, tibial fracture, osteomyelitis and implant failure.

The main advantage of the PTIO is that the procedure may be performed without the need for specialized surgical equipment. Disadvantages include a long operative time, apparent necessity for medial meniscal release, and the occurrence of complications, such as valgus deformities and long digital extensor tendon injury, that often require surgical revision. The requirement for extensive arthrotomies is unfavorable when compared to other techniques, as
studies have demonstrated acceleration of OA when a full arthrotomy is performed.\textsuperscript{95,96} At present, the PTIO cannot be advocated as a valid alternative to TPLO.

**Chevron Wedge Tibial Osteotomy**

A cranially-based tibial wedge ostectomy can be performed using chevron kerfs.\textsuperscript{23} The rationale behind utilizing more complex osteotomies stems from the perception that opposed V-shaped osteotomy surfaces resist cranio-caudal shear and torsional forces better than conventional linear osteotomies.\textsuperscript{23} Planning of the CVWO is similar to that of CTWO: tibial longitudinal axis shift should be taken into consideration when calculating the wedge angle, the osteotomies should be positioned as proximally as possible, and the ostectomy site is stabilized with a medially applied bone plate. Accurate execution of the osteotomies may be facilitated with the use of a saw-blade guide jig, and stability of the construct can be enhanced with the placement of a cranially-placed lag screw directed caudad and proximad (Figure 1-8).

Clinical outcomes of CVWO for the treatment of CrCL insufficiency in dogs have not been reported, and thus the complication rate associated with this procedure is also unknown. In an *in-vitro* geometric study of five different tibial osteotomy techniques,\textsuperscript{23} CVWO induced the greatest amount of tibial valgus deformity, and post-operative valgus has also been observed anecdotally in clinical cases (Personal communication, Denis Marcellin-Little, 2007). Due to the paucity of information available on this technique, it is uncertain whether the CVWO has any clinically relevant benefit over other tibial plateau leveling procedures.

**Triple Tibial Osteotomy**

TTO, like TTA, is a procedure that aims to result in a proximal tibial conformation such that the patella tendon is oriented perpendicular to the tibial plateau when the stifle is at a weight-bearing angle.\textsuperscript{22} First, a partial frontal plane osteotomy of the tibial tuberosity is made, leaving the distal cortex intact. A partial wedge ostectomy, with a wedge angle equal to two
thirds of angle between the patella tendon and a line perpendicular to the tibial plateau slope, is then performed caudal to the tibial tuberosity osteotomy. Specialized TTO instrumentation is commercially available to facilitate accurate positioning of the osteotomies. Reduction of the wedge ostectomy site simultaneously reduces the tibial plateau slope and shifts the tibial tuberosity in a cranial direction. Application of a 3.5mm T-plate is recommended to stabilize the wedge ostectomy site (Figure 1-9).

In a prospective clinical study of TTO in 64 dogs with a mean follow-up period of 15 months, no lameness was observed at final examination in the majority of dogs.22 Significant increases in thigh circumference and stifle range of motion were also noted. All owners assessed their dog as being normal or near normal for all physical activities except sitting (2% mildly abnormal) and standing (4% mildly abnormal). Complications were encountered in 36% of cases, including tibial tuberosity fractures, infection, and subsequent meniscal injury. The most common complication was intra-operative tibial tuberosity fracture necessitating tension-band wire fixation, which occurred in 23% of dogs.

The proposed advantages of the TTO include minimal change to the orientation of the tibiofemoral articulating surfaces, a relatively small osteotomy gap caudal to the tibial tuberosity, no loss of limb length, and low technical difficulty when the appropriate instrumentation is used. Potential disadvantages include variability of the post-operative patella tendon-to-tibial plateau angle when using the recommended calculations, and questionable protective effects against medial meniscal injury.

**Conclusion**

By addressing the cranially directed shear force leading to cranio-proximal tibial translation that occurs during weight-bearing, tibial osteotomy techniques have been clinically successful in improving hind limb function in dogs with CrCL insufficiency. Despite their
popularity, differences in long-term outcome between tibial osteotomies and traditional methods of repair are not apparent. As highlighted in a recent meta-analysis evaluating surgical procedures used in dogs with CrCL insufficiency, this may reflect the lack of objective clinical data reported in the literature. Likewise, the current body of information is not sufficient to validate one tibial osteotomy technique over another. Individual and inter-breed differences in morphology, kinematics and kinetics may also influence the final outcome after surgery, and some osteotomy procedures may be more suitable than others in certain breeds of dogs or tibial conformations. Specific indications for each individual technique remain to be determined.

Concerns common to all tibial osteotomies for treating CrCL insufficiency include the sparing effect of on the meniscus, the progression of OA after surgery and the correlation between post-operative TPA and clinical outcome. Future clinical studies need to adopt reliable, validated and standardized outcome measures to permit fair and direct comparisons between the various techniques.

Problems encountered in the surgical management of CrCL insufficiency are undoubtedly a reflection of the complexity of the structure and function of the stifle joint. Future studies should not only focus on the clinical results of different surgical procedures; a clearer understanding of the biomechanics of the canine stifle and the etiopathogenesis of the disease is also required in order to determine whether tibial osteotomy techniques are superior to other treatment modalities for managing CrCL insufficiency in dogs.
Figure 1-1. Slocum theorized that, during weight bearing, the joint reaction force (magenta arrow) is approximately parallel the longitudinal axis of the tibia. In the CrCL-deficient stifle (A), the joint reaction force can be resolved into a cranially directed tibiofemoral shear component (parallel to tibial plateau) and a joint compressive force (perpendicular to tibial plateau). By leveling the tibial plateau (B), the joint reaction force is perpendicular to the tibial plateau, thus can only be resolved into a joint compressive force; cranial tibial thrust is eliminated.
Figure 1-2. An alternate theory, proposed by Tepic, suggests that the joint reaction force (magenta arrow) is approximately parallel to the patella tendon, not the tibial long axis. In the CrCL-deficient stifle, the joint reaction force can be resolved into a cranially directed tibiofemoral shear component and a joint compressive force (A, yellow arrows). By advancing the tibial tuberosity cranially, the patella tendon is perpendicular to the tibial plateau during stance phase of gait (B). The joint reaction force, therefore, becomes perpendicular to the tibial plateau during weight bearing, thus can only be resolved into a joint compressive force; cranial tibial thrust is eliminated.
Figure 1-3. CTWO

Figure 1-4. TPLO
Figure 1-5. TTA

Figure 1-6. CTWO+TPLO
Figure 1-7. PTIO

Figure 1-8. CVWO
Figure 1-9. TTO
CHAPTER 2
EFFECT OF TIBIAL PLATEAU LEVELING OSTEOTOMY ON FEMOROTIBIAL CONTACT MECHANICS AND KINEMATICS

Introduction

TPLO, currently one of the most commonly performed surgical procedures for the treatment of CrCL insufficiency, is purported to eliminate cranial tibial thrust by reducing the caudodistally oriented slope of the tibial plateau. TPLO, therefore, obviates the need for providing passive intra- or peri-articular restraint to cranial tibial thrust. Despite a tremendous rise in popularity of TPLO, relatively little is known regarding the biomechanical implications of this procedure. The majority of research to date has exclusively focused on determining the effects of TPLO on stifle kinematics. In two separate cadaver studies, cranial tibial subluxation was eliminated when TPLO was performed in a hind limb model that simulated CrCL-deficient, weight-bearing conditions. The main techniques employed to assess kinematics, however, precluded the ability to ascertain motion in degrees of freedom other than rotation (stifle flexion) and translation (cranial tibial subluxation) in the sagittal plane. Warzee et al. attempted to quantify axial rotation by tracking a transcondylar tibial Kirschner wire on co-ordinate paper, but the accuracy of their methodology was unclear. The effect of TPLO on axial rotational stability also warrants elucidation: the CrCL in dogs serves as a passive restraint against internal tibial rotation, and yet the procedure aims to address only sagittal plane instability.

The development and progression of OA is intrinsically dependent on the degree of disruption of physiologic load transmission across articular cartilage surfaces. Even minor changes in magnitude or distribution of normal joint contact stresses purportedly induce cartilage wear and degeneration. The optimal treatment for CrCL insufficiency should therefore not only restore stifle stability, but concurrently re-establish normal joint contact mechanics. TPLO may cause undesirable shifts in joint contact stresses because of the resultant changes in the natural
femorotibial joint alignment and stability under loading.\textsuperscript{32} Indeed, recent human cadaver studies report that modifications to the anterior-posterior slope of the tibial plateau adversely influence the distribution of femorotibial contact stresses.\textsuperscript{99,100} As OA can be induced by abnormal joint mechanics,\textsuperscript{98} a better understanding of the effect of sagittal plane alterations caused by TPLO may provide further insight regarding mechanisms for continued progression of osteoarthritic changes consistently observed after TPLO.\textsuperscript{67,101}

The purposes of this cadaver study were to: 1. Evaluate the effects of TPLO on femorotibial contact areas and stresses; and 2. Determine three-dimensional kinematics of the stifle after TPLO. We hypothesized that TPLO would not re-establish normal femorotibial contact mechanics in the CrCL-deficient stifle. We also hypothesized that TPLO would eliminate cranial tibial translation, but only mitigate excessive internal tibial rotation in the CrCL-deficient stifle.

\textbf{Materials and Methods}

\textbf{Specimen Preparation}

Eight hind limbs were harvested by disarticulation of the coxofemoral joint from eight adult dogs weighing between 28 to 35 kg that were euthanatized for reasons unrelated to the study. The contralateral hind limbs from each dog were used for the study detailed in Chapter 3. Craniocaudal and mediolateral view radiographs were taken of each limb to ensure there was no radiographic evidence of stifle pathology. The TPA was measured for each limb on the mediolateral view radiographs, using previously reported methods.\textsuperscript{102} Only limbs with a TPA between 20 to 24° were used to reduce variability between specimens. The level of rotation required to achieve a TPA of 6° was calculated using previously described methods.\textsuperscript{102} After imaging, all musculature was dissected from the limbs while carefully preserving the stifle and
talocrural joint capsules, collateral ligaments, and all soft tissue distal to the talocrural joint. The specimens were wrapped in saline-soaked towels and stored at -20° Celsius until testing.

In preparation for testing, the limbs were thawed to room temperature. Tissues were kept moist throughout the experiment by spraying the specimens with isotonic saline. In each specimen, braided steel cable was passed through a 2.5 mm diameter hole drilled transversely through the widest portion of the patella and secured. A turn-buckle link extending from the femoral neck was attached to the patella cable loop to mimic the quadriceps mechanism. Two 3.5 mm cortical bone screws were inserted at the level of the fabellar articular facets of the femur, and another cable loop was placed through a 2.5 mm diameter hole drilled transversely through the calcaneus. A turnbuckle link that extended from the calcaneus cable loop to a small cable loop anchored to the femoral screws was used to simulate the gastrocnemius muscle. Three nylon screws (McMaster-Carr Supply Company, Cleveland, OH.) were implanted into the femur and tibia as landmarks for determining the three-dimensional, static pose of the stifle during testing.

A radial osteotomy as described by Slocum and Slocum was performed prior to limb testing, and a custom Delrin (DuPont, Wilmington, DE.) plate was applied to the medial aspect of the proximal tibia (Figure 2-1). Using this plate, the tibial plateau segment could be stabilized in its normal anatomic position, then rotated and stabilized at a TPA of 6° (treatment condition) without dismounting the limb from the specimen testing setup. Rotation was centered about a 2.5 mm Steinmann pin implanted 5 mm distal to the surface of the tibial plateau at the level of the medial collateral ligament. Specimens were radiographed at the calculated level of tibial plateau rotation to confirm that appropriate TPAs were attained. With the osteotomy in a sham position (no tibial plateau rotation), the specimen to be tested was linked to a custom femoral jig with two
4 mm threaded rods placed in a lateral-to-medial direction at the neck and the mid-diaphysis of
the femur. The femoral jig, which mounted directly to a servo-hydraulic materials testing
machine (Model 8500, Instron Corp., Canton, MA.), was designed to permit adjustment of ‘hip’
flexion, adduction/abduction and axial rotation angles (Fig 2). During loading, flexion and
adduction/abduction hinges on the femoral jig were constrained, while axial rotation was left
unconstrained.

Instantaneous intra-articular contact area and pressure measurements were obtained using
the I-Scan system (Tekscan Inc. South Boston, MS.), consisting of a custom designed, plastic
laminated, thin-film (0.1 mm) electronic pressure sensor, sensor handle, and data acquisition and
analysis software. The sensors had two sensing areas of 30.9 mm x 12.0 mm, a pressure
sensitivity of 0.01 MPa, and a pressure range of 0.5 to 30.0 MPa. Each sensing area consisted of
a 15 x 6 grid of 1.21 mm² sensing elements. Each new sensor was conditioned and calibrated
according to the manufacturer’s guidelines immediately prior to testing of each specimen.
Following calibration, the sensor was placed subjacent to the menisci by creating cranial and
caudal horizontal capsulotomies in the medial and lateral stifle compartments. Particular
attention was given to minimize sensor crinkling or damage to the sensor and articular cartilage
during insertion. The sensor was then secured in place by gluing and suturing the peripheral tabs,
which were devoid of any sensing elements, to transversely oriented 0.8 mm Kirschner wires
implanted at the cranial aspect of the tibial plateau.

**Testing Protocol**

With the specimen mounted to the materials testing machine in an unloaded state, the
locations of the cranial and caudal margins of the medial and lateral tibial condyles on the
contact maps were identified by applying gentle pressure to the overlying sensing elements with
a probe (Figure 2-3). The turnbuckles were adjusted to attain a stifle and hock angle of 135 ± 5°,
corresponding to the mid-point of stance phase of gait during walking.\textsuperscript{103} The joint angles during loading were measured with a plastic goniometer, with each arm aligned to the tibial and femoral diaphyses. The paw of the specimen was in contact with, but was not fixed to, the Instron actuator table during loading (Figure 2-2). To reproduce \textit{in-vivo} conditions, a static axial load of 30\% body weight was applied by the materials testing machine.\textsuperscript{44} Prior to data acquisition, the limb was initially loaded with the adduction/abduction hinge of the femoral jig unconstrained. By monitoring the real-time contact patterns, the adduction/abduction hinge was then locked in a position that resulted in a 50:50 to 60:40 medial-to-lateral force distribution across the normal (CrCL-intact, sham TPLO) stifle.

Loading of each specimen was performed in the following sequence: 1) Normal (CrCL-intact, sham TPLO); 2) CrCL-deficient, (CrCL-deficient, sham TPLO); 3) TPLO-treated (CrCL-deficient, TPLO-treated). For testing conditions 2) and 3), the CrCL was transected at its origin via a caudal approach to the stifle. Turnbuckles were adjusted throughout the experiment to maintain stifle and hock angles of 135 ± 5°. For each condition, the contact area and pressure measurements were acquired after maintaining peak force for 5 seconds. While the specimen was loaded, the static, three-dimensional pose of the tibial and femoral nylon screws were digitized using a Microscribe 3DX digitizing arm (Immersion Corp., San Jose, CA.), which possesses an accuracy of 0.23 mm.\textsuperscript{104}

Following testing, CT images of the femurs and tibiae, with the nylon screws in place, were acquired. Bone segmentation was performed on the Slicomatic software package (Tomovision, Montreal, Quebec, Canada.), and three-dimensional bone models for the tibiae and femurs of each specimen were created using Geomagic software (Geomagic Inc., Research Triangle Park, NC.).
Data Analysis

The digital pressure sensing data acquisition software was used to generate a contact map and measure the contact area, mean contact pressure and peak contact pressure in the medial, lateral, and total (medial+lateral) stifle compartments (Figure 2-3).

Contact area was defined as the area of contact between the tibial plateau, the femoral condyle, and the portion of the meniscus loaded by the femur. Peak contact pressure was defined as the highest pressure measured in the contact area, whereas mean contact pressure represented the average of the pressures across the contact area. Pressure distribution was described according to the location of the peak pressure in each stifle compartment: the relative location of peak pressure for each condition was defined as the distance from the peak pressure sensel to the caudal margin of the tibial condyle (medial or lateral) in the sagittal plane, divided by the entire length of the tibial condyle in the sagittal plane (Figure 2-3).

Locations of anatomical landmarks and nylon screw markers for the femur (center of the lateral and medial condyles, center of the femoral head, and origin of CrCL) and the tibia (outermost edge of the lateral and medial condyles, center of the distal end of the tibia, insertion of CrCL) were identified in the three-dimensional bone models. Hence, the orientation of the anatomical landmarks relative to the nylon screw markers with respect to the CT volume was known. Rotations of the tibia relative to the femur were calculated using body-fixed axes in the order (flexion/extension, adduction/abduction, internal/external rotation), corresponding to the rotational component of the Joint Coordinate System described by Grood and Suntay. Translations of the tibia relative to the femur were measured from CrCL origin to insertion, and expressed in an orthogonal anatomic coordinate system fixed to the tibia. Calculations were performed on a custom written computer program using Matlab (The MathWorks Inc., Natick, MA.).
**Statistical Analysis**

A one-way repeated measures analysis of variance was used to evaluate differences in contact area, mean contact pressure, and peak contact pressure, and pressure distribution in the total and individual (medial and lateral) stifle compartments, among the three different conditions (normal, CrCL-deficient, TPLO-treated). A one-way repeated measures analysis of variance was also used to evaluate differences in internal-external tibial rotation, cranial-caudal tibial translation, proximal-distal tibial translation, and stifle flexion angle among the three conditions. Where significant differences were indicated, paired comparisons were made using the Tukey method. For all statistical analyses performed, $P < 0.05$ was considered statistically significant. A statistical analysis software package (SPSS 16.0, SPSS Inc., Chicago, IL.) was used to perform all statistical analyses.

**Results**

Mean body weight of the dogs was $32 \pm 3$ kg. The mean TPA was $23 \pm 1^\circ$. As determined by the kinematic analysis, stifle angles did not vary between the normal ($141 \pm 2^\circ$), CrCL-deficient ($141 \pm 5^\circ$), and TPLO-treated ($142 \pm 4^\circ$) conditions ($P = 0.422$).

**Contact Mechanics**

CrCL transection resulted in significant changes to all parameters for the total and medial stifle compartments, while differences were less apparent in the lateral compartment. Treatment with TPLO was unable to restore all abnormalities induced by CrCL transection to control values. CrCL transection resulted in a decrease in total contact area, from $316 \pm 43$ mm$^2$ to $178 \pm 27$ mm$^2$ ($P < 0.001$); total contact area increased to $277 \pm 42$ mm$^2$ after TPLO ($P < 0.001$), which was significantly lower than normal ($P = 0.018$). In the medial stifle compartment, contact area decreased from $179 \pm 16$ mm$^2$ to $79 \pm 15$ mm$^2$ after CrCL transection ($P < 0.001$). Medial
contact area after TPLO, 150 ± 18 mm², was also significantly lower than normal ($P < 0.001$). Peak pressure magnitude in the medial compartment increased by approximately 1.8-fold from $2.7 ± 0.3$ MPa to $4.9 ± 1.0$ MPa after CrCL transection ($P < 0.001$), then decreased to $2.8 ± 0.5$ MPa after treatment with TPLO ($P < 0.001$); there was no significant difference between medial compartment peak pressure magnitude of normal and TPLO-treated conditions ($P = 0.981$). A similar pattern of changes in peak pressure magnitude was evident in the lateral compartment. Total and medial mean pressure magnitudes also significantly increased after CrCL transection, and returned to normal after TPLO.

In the normal stifle, the medial peak pressure was located at 48 ± 9% of the medial tibial condyle length from the caudal margin of the medial compartment. Peak pressure in the medial compartment shifted caudally to 13 ± 3% ($P < 0.001$). Treatment with TPLO shifted the peak pressure location in the medial compartment cranially to 35 ± 9% ($P = 0.001$), although there was still a significant difference in medial peak pressure location between normal and TPLO-treated conditions ($P = 0.012$). Similarly in the lateral compartment, there was a caudal shift in peak pressure location after CrCL transection, from 64 ± 7%, to 20 ± 8% of the lateral tibial condyle length from the caudal margin of the lateral tibial condyle ($P < 0.001$). Peak pressure shifted cranially to 53 ± 11% after TPLO, which was significantly different from both CrCL-deficient ($P < 0.001$) and normal ($P = 0.018$) conditions (Table 2-1).

**Stifle Kinematics**

In the normal condition, the tibial insertion of the CrCL was located 6.6 ± 2.2 mm cranial to the femoral origin of the CrCL; this distance increased to 21.9 ± 3.1 mm following CrCL transection ($P < 0.001$), indicating cranial translation of the tibia. Cranial tibial subluxation was eliminated after TPLO, where the sagittal distance between the CrCL origin and insertion was 4.6 ± 2.3 mm; this distance was not significantly different from normal ($P = 0.146$).
In the normal condition, the medio-lateral axis of the tibia was axially aligned 5.4 ± 5.3° (external axial rotational alignment) relative to the medio-lateral axis of the femur. In CrCL-deficient condition, the axial position of the tibia was -8.9 ± 6.3° (internal axial rotational alignment), indicating 14.3 ± 2.9° of internal tibial rotation after CrCL transection ($P < 0.001$). Following TPLO, the tibia returned to a slight externally rotated position of 4.6 ± 7.3°. Axial rotational alignment in the TPLO-treated condition was significantly different from the CrCL-deficient condition ($P < 0.001$), but not significantly different from normal ($P = 0.757$) (Table 2-2).

**Discussion**

The results of this investigation demonstrate that altering the orientation of the proximal tibial articular surface by performing TPLO may restore appropriate joint alignment during weight-bearing, but is unable to restore the normal pattern of load distribution across the femorotibial joint. While the pathomechanics of OA involve a complex interaction between biological and mechanical pathways, it is well established that abnormal joint contact mechanics will result in progressive damage to articular cartilage.\textsuperscript{98} TPLO improves limb function in most dogs with CrCL insufficiency;\textsuperscript{64,65} however, progression of OA is frequently observed in stifles treated with TPLO.\textsuperscript{67,101} The abnormal mechanical environment within the stifle, generated by reduction of the tibial plateau slope, may be at least partly responsible for continued joint degeneration in the face of adequate functional stability.

**Limitations**

Our findings should be carefully interpreted in light of the following limitations. This study was restricted to an analysis of stance phase of walking because we used a static model of the dog’s hind limb. Medial meniscal release, a procedure commonly performed in conjunction
with TPLO to prevent subsequent meniscal injury, has been shown to markedly alter stifle contact mechanics, and was not performed in our specimens. We did not assess contact or kinematic patterns under loading conditions of other common daily activities, such as stair-climbing, turning, pivoting, or running. The testing methodology and our instrumentation also precluded the ability to gauge femorotibial contact shear forces, which are thought to contribute substantially to the development and progression of OA.

In-vivo forces cannot be accurately reproduced in this cadaver hind limb model. For instance, we noted a mean of 15.2 mm of cranial tibial translation after CrCL transection, approximately 50% greater than the equivalent in-vivo results obtained by Korvick et al. Powerful co-contraction of the hip extensors that occur during stance phase were not simulated in this study; inclusion of a hamstrings mechanism may have increased stifle stability as well as femorotibial joint contact forces. Development of more accurate cadaver models of the dogs’ hind limb should be beneficial for future research into CrCL insufficiency.

Other limitations of our study directly stem from the use of I-scan pressure sensors. Most of the stifle joint capsule and the coronal attachments of the menisci to the tibial plateau were incised to allow for insertion of the sensors within the joint. Similar to the meniscotibial ligaments, such structures may function to improve load transmission across the stifle. The contact maps often extended to the border of the sensing pad, thus the true contact area may not have been entirely captured by the sensors. The sensors were, however, carefully positioned to attempt to acquire data from the entire tibial plateau. A further limitation is that the physical presence of a sensor within a joint space affects peak pressure magnitude measurements. The accuracy of our custom sensors may have been lower than commercially available sensors (such as those developed for the human knee), since each sensing pad had a proportionally small
number of sensing elements (sensor discretization).\textsuperscript{109} As we were primarily interested in the relative changes in outcome measures, and because the only sources of variation between testing conditions were controlled (CrCL status and tibial plateau position), we consider it unlikely that these factors would have substantially influenced the pertinent findings in our study.

**Methodological Issues**

Stifle biomechanics are complex in nature and therefore difficult to replicate in an \textit{ex-vivo} testing environment. Pressure-sensing tools to ascertain joint contact mechanics, however, cannot be used \textit{in-vivo} in a practical manner.\textsuperscript{110} A slightly modified hind limb model, first described by Warzee \textit{et al.} was chosen because it appeared to adequately simulate weight-bearing conditions during stance phase of a walking gait cycle.\textsuperscript{44,87} The medial-to-lateral ratio load distribution in normal stifles was controlled between specimens to mimic \textit{in-vivo} measurements from the human knee, since equivalent data for dogs does not currently exist.\textsuperscript{111} Slight preferential loading of the medial compartment, between 50:50 to 60:40 medial:lateral load split, was achieved in all specimens with minimal manual adjustment of the adduction/abduction hinge on the femoral jig, suggesting that the natural conformation of the normal dog’s hind limb favors slightly asymmetric load transmission across the stifle. With axial rotational freedom of the femur and an unconstrained paw, the specimen set-up allowed for motion of the tibia in relation to the femur in five degrees of freedom; all kinematic variables (excluding the fixed flexion/extension angle) were thus exclusively determined by the respective joint characteristics. Hence, while the model was a gross simplification of the dog’s hind limb, we believe that stifle biomechanics were sufficiently replicated to allow for relevant study of the effects of TPLO on femorotibial contact mechanics and kinematics during stance phase of a walking gait in dogs.
No significant difference between standing stifle flexion angle was detected between the
different conditions, as it was a controlled variable purposely kept consistent. We did not attempt
to replicate adaptive gait pattern changes, such as decreased weight-bearing and increasing stifle
flexion, known to occur in CrCL-deficient stifles in-vivo. Our methodology also presumes that
flexion angle during stance-phase of gait after TPLO does not differ from normal. This
assumption is supported by findings from a recent in-vivo kinematic study, where experimental
CrCl transection combined with TPLO did not significantly alter normal gait patterns.

The I-scan system was selected over other contact mapping modalities for the advantages
of reproducibility, accuracy, simplicity, and ability to acquire pressure profiles in real-time. When compared to Fujifilm pressure sensitive film, which is commonly regarded as the standard orthopaedic research tool for measuring joint contact stresses, the I-scan was shown to have
superior accuracy and repeatability for measuring contact area, pressure, and force, obtaining
accuracies to within ± 5% of a known value. Though the I-scan sensors have a finite
lifespan, each sensor can be used for multiple measurements whereas pressure sensitive film is
single-use only. This particular feature of digital pressure sensing devices was critical to our
investigation. Peak pressure locations for all three testing conditions of each specimen were
calculated according to the same anatomic reference points defined at the commencement of
testing. Using pressure-sensitive film would have required re-establishing anatomic reference in
each individual contact map, which may have introduced a significant source of variability and
bias.

Stifle poses were assessed with a three-dimensional digitizing arm. There were several
key benefits of our methodology over previously utilized techniques for ascertaining in-vitro
stifle kinematics, which include linear measurements from lateral-view radiographs and dial
indicators. The accuracy of the digitizing arm has been validated and is regarded as an instrument of high precision. This is in contrast with calculations obtained from fiduciary markers on single view radiographs, where presence of unaccounted distortion and magnification can significantly alter final measurements. We were able to determine the position of the tibia relative to the femur in all six degrees of freedom because the fiduciary marker positions in this study were in a three-dimensional coordinate system. In contrast, most geometric descriptions in previous studies were uniplanar, where only two stifle motion components, flexion and cranial tibial translation, could be measured. Finally, stifle motion was described according to a universally accepted kinematic representation of the femorotibial joint, a prerequisite for accurate assessment and communication of kinematic data.

A 5 to 7° difference was noted between the stifle flexion angles estimated by goniometry during testing and our kinematic results. In hindsight, this minor discrepancy was ascribed to differences in the method for defining the longitudinal axis of the femur: the femoral diaphysis was used in goniometric measurements, whereas the plane passing through the center of the head of the femur and the mid-point of the femoral condyles was used in the kinematic measurements. Due to the normal caudal bow of the distal femur in dogs, the femoral longitudinal axis was more ‘vertical’ when the femoral condyles were used as landmarks rather than the diaphysis; hence, our goniometric measurements slightly differed from the final flexion angle results.

Our pilot studies demonstrated highly reproducible measurements from both the I-scan system and Microscribe tool. Repeated measurements of a given specimen for each testing condition resulted in standard deviations of less than 5% and 1% for I-scan and Microscribe measurements, respectively. Thus only one measurement was taken under each testing condition to limit the effects of repetitive testing and wear on the specimens and sensors.
Contact Mechanics

Despite improving contact area in both medial and lateral stifle compartments relative to the CrCL-deficient condition, contact area after TPLO was still significantly lower than normal. Peak pressures were concurrently redistributed more caudally in TPLO-treated conditions when compared to normal. The differences may be explained by the relative change in position of the femoral and tibial articular surfaces (Figure 2-5). As a result of the more flexed alignment of the femorotibial joint with a lower tibial plateau slope, the area of contact on the femur shifted from the flattened central region of the femoral condyles in the normal joint, to the more convex caudal surface femoral condyles in the TPLO-treated joint. Contact stresses were therefore distributed predominately over the caudal tibial plateau, as reflected by the significant differences in medial and lateral peak pressure locations between TPLO-treated and normal stifle conditions.

These findings indicate that TPLO may be inducing mild impingement of the caudal aspect of the stifle during weight-bearing. This observation is corroborated by recent clinical reports of focal cartilaginous defects in the caudomedial compartment on second-look arthroscopy after TPLO. Furthermore, our contact mechanics data are in agreement with femorotibial biomechanics observed in humans. In a recent human cadaver study, increasing the tibial plateau slope by performing a high tibial flexion osteotomy was shown to shift the femorotibial contact regions anteriorly. The authors concluded that high tibial flexion osteotomies could benefit patients with posterior gonioarthrosis by alleviating pressure over posterior aspect of the tibial plateau. TPLO in dogs appears to produce the opposite effect, where decreasing the tibial plateau slope may be subjecting the caudal aspect of the tibial plateau to increased loads during weight-bearing.
Stifle Kinematics

Marked cranial tibial translation (15.2 mm) in CrCL-deficient stifles was completely eliminated after TPLO. This data is in agreement with the results of in-vitro studies of TPLO by Warzee et al. and Reif et al., and supports the biomechanical theory proposed by Slocum.\textsuperscript{43,44} Whether sagittal translation of the tibia occurs during swing phase in TPLO-treated stifles remains unknown, as the model used in our study simulated stance phase only. Swing phase changes, however, are minimal following CrCL loss.\textsuperscript{29} Accordingly, it could be argued that craniocaudal motion of the tibia relative to the femur in TPLO-treated joints, during the entire gait cycle, is normal. In-vivo dynamic analyses are required to substantiate this claim.

We found that excessive internal tibial rotation in CrCL-deficient stifles was eliminated by TPLO. With loss of the CrCL, soft tissue structures such as the collateral ligaments become the primary restraints against further cranial subluxation.\textsuperscript{29} Internal tibial rotation occurs because the lateral collateral ligament is not as taut as the medial collateral ligament when the stifle is in extension,\textsuperscript{34,119} and thus the lateral aspect of the tibia translates further cranially than the medial side. With the TPLO-treated femorotibial joint remaining completely ‘reduced’ during limb loading, the collateral ligaments were no longer primary restraints against cranial translation. Accordingly, tension in the collateral ligaments, and therefore axial rotational alignment of the stifle, was likely comparable to normal. In the cadaver study by Warzee et al., TPLO only mitigated excessive internal tibial rotation, because laxity in the lateral collateral ligament increases when the femorotibial articulation is at a relatively greater degree of flexion.\textsuperscript{34} Similar results may not have been apparent in our study because the tibial plateau segment was only rotated by a mean of 17°, approximately 10° less than the amount of rotation performed by
Warzee et al. The risk of inducing disturbance to normal axial rotational alignment may be increased with higher degrees of tibial plateau rotation.

The anterior cruciate ligament (ACL)-deficient human knee may have very similar kinematic patterns to the TPLO-treated, CrCL-deficient dog stifle: tibial plateau slopes are comparable (between 5 to 12°), sagittal plane translations are minimal, and, as supported by our data, maintenance of normal axial rotational motion during low-demand activities such as walking does not appear to be dependent on the integrity of the ACL/CrCL. Rotational instability in ACL-deficient knees, however, becomes immediately apparent with slightly more complex actions. In a recent in-vivo kinematic study of ACL-deficient patients, common activities such as running and cutting were shown to produce fundamentally different kinematic patterns to walking, characterized by poor control of femorotibial coronal translation and axial rotation.120 Similar patterns of instability may be occurring in CrCL-deficient stifles treated by TPLO. The specimens in our study were not subjected to axial torques that are experienced during various activities other than straight-line walking, hence we were unable to reproduce potential kinematic abnormalities relevant to axial stability in TPLO-treated joints. Similar to the current focus in ACL biomechanics,120 we believe future research into CrCL insufficiency should aim to further elucidate the clinical significance of rotational instability after TPLO along with other surgical methods of treatment.

**Conclusion**

Performing TPLO in CrCL-deficient stifles will redistribute femorotibial contact pressures caudally on the tibial plateau. Further studies characterizing degenerative changes after TPLO are warranted to determine if abnormal contact mechanics contribute significantly to the progression of OA. TPLO appears to restore normal sagittal and axial rotational alignment
during stance phase of a walking gait; due to the limitations of this investigation, however, we could not ascertain if the procedure imparts adequate stability during activities other than walking. Additional analyses are required to elucidate other kinematic effects of TPLO in CrCL deficient stifles.
Figure 2-1. Cadaver limb preparation. A) Before. B) After tibial plateau leveling osteotomy. Stabilization was achieved with a custom-made Delrin plate. The tibial plateau segment was rigidly secured to the disc portion of the plate; controlled rotation of the disc therefore enabled precise manipulation of the TPA.
Figure 2-2. Prepared hind limb specimen mounted to the Instron and positioned on the actuator table. The digital pressure sensor can be seen entering the femorotibial joint caudally, which is linked to a computer via the sensor handle.
Figure 2-3. Contact map obtained from the Tekscan software, depicted over an axial view of a tibial plateau. The software is able to define the peak pressure location (white boxes) in each stifle compartment; the cranial and caudal margins of the medial and lateral stifle compartments (green boxes) were identified prior to data acquisition. Peak pressure location was defined as the distance from the peak pressure sensel to the caudal margin of the tibial condyle (medial or lateral; white arrow), divided by the entire length of the tibial condyle in the sagittal plane (green arrow). Left = lateral, top = cranial.
Figure 2-4. Axial view of left bone models depicting three-dimensional poses of normal, CrCL-deficient, and TPLO-treated stifles, with corresponding contact maps representative of each testing condition. The tibia (light gray) is cranially displaced and internally rotated relative to the femur (dark gray) after CrCL transection; femorotibial pose of normal and TPLO-treated stifles are similar. CrCL transection resulted in caudal shift, reduced area and increased pressure of femorotibial contact; TPLO contact patterns also differ from normal. Left = lateral, top = cranial.
Figure 2-5. Femorotibial contact regions in the normal (A) and TPLO-treated (B) stifle. There is a large area of contact in the normal stifle, as the tibial plateau apposes the flat, central portion of the femoral condyles. By decreasing the tibial plateau slope with TPLO, the femorotibial joint is in a relatively more flexed position during weight-bearing, shifting the region of contact to the more convex, caudal region of the femoral condyles. Consequently, the contact area in TPLO-treated stifles is smaller than in normal joints.
Table 2-1. Contact mechanics data for the normal, CrCL-deficient, and TPLO treated conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal (1)</th>
<th>CrCL-deficient (2)</th>
<th>TPLO-treated (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Force (N)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>395 ± 72</td>
<td>276 ± 55 (P₁₂&lt;0.001)</td>
<td>315 ± 44 (P₁₃=0.017, P₂₃=0.280)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>179 ± 16</td>
<td>79 ± 15 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>137 ± 35</td>
<td>100 ± 18 (P₁₂=0.013)</td>
</tr>
<tr>
<td>Contact Area (mm²)</td>
<td>Total</td>
<td>316 ± 43</td>
<td>178 ± 27 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>179 ± 16</td>
<td>79 ± 15 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>137 ± 35</td>
<td>100 ± 18 (P₁₂=0.013)</td>
</tr>
<tr>
<td>Peak Pressure Magnitude (MPa)</td>
<td>Medial</td>
<td>2.7 ± 0.3</td>
<td>4.9 ± 1.0 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>2.4 ± 0.3</td>
<td>4.4 ± 0.6 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1.3 ± 0.2</td>
<td>1.6 ± 0.3 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td>Mean Pressure (MPa)</td>
<td>Medial</td>
<td>1.3 ± 0.2</td>
<td>1.8 ± 0.4 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>1.2 ± 0.2</td>
<td>1.4 ± 0.2 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td>Peak Pressure Location (%)*</td>
<td>Medial</td>
<td>48 ± 9</td>
<td>13 ± 5 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>64 ± 7</td>
<td>20 ± 8 (P₁₂&lt;0.001)</td>
</tr>
</tbody>
</table>

*Peak pressure location was defined as the distance from the peak pressure sensel to the caudal margin of the tibial condyle (medial or lateral) in the sagittal plane, divided by the entire length of the tibial condyle in the sagittal plane. P-values for post-hoc pairwise comparisons are given where significant differences were found on analysis of variance.

Table 2-2. Static three-dimensional femorotibial poses for normal, CrCL-deficient, and TPLO-treated conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal (1)</th>
<th>CrCL-deficient (2)</th>
<th>TPLO-treated (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translations (mm)</td>
<td>Craniocaudal</td>
<td>6.6 ± 2.1</td>
<td>21.9 ± 3.1 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Mediolateral</td>
<td>5.6 ± 4.9</td>
<td>6.6 ± 4.8 (P₁₂=0.072)</td>
</tr>
<tr>
<td></td>
<td>Proximodistal</td>
<td>7.9 ± 2.3</td>
<td>0.8 ± 2.2 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td>Rotations (deg)</td>
<td>Flexion-extension</td>
<td>140.6 ± 2.3</td>
<td>140.9 ± 4.8</td>
</tr>
<tr>
<td></td>
<td>Internal-external</td>
<td>5.4 ± 5.3</td>
<td>-8.9 ± 6.3 (P₁₂&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Varus-valgus</td>
<td>7.6 ± 3.3</td>
<td>4.8 ± 3.2 (P₁₂=0.022)</td>
</tr>
</tbody>
</table>

For the translational parameters, positive values indicate cranial, distracted and medial positions of the tibia relative to the femur. For the rotational parameters, positive values indicate greater stifle extension, external tibial rotation, and varus. P-values for post-hoc pairwise comparisons are given where significant differences were found on analysis of variance.
CHAPTER 3
EFFECT OF TIBIAL TUBEROSITY ADVANCEMENT ON FEMOROTIBIAL CONTACT MECHANICS AND KINEMATICS

Introduction

TTA was developed to neutralize cranially directed stifle shear forces (cranial tibial thrust) responsible for cranial tibial subluxation occurring during stance phase of gait. Based on a biomechanical theory that assumes the total femorotibial joint reaction force parallels the patellar tendon during ambulation, TTA attempts to eliminate cranial tibial thrust by aligning the patellar tendon perpendicular to the tibial plateau when the stifle is in a weight-bearing stifle angle.

Initial clinical studies report very promising results, with 90 to 95% of owners indicating excellent functional outcome after TTA. The perceived clinical success with TTA implies the procedure is generating adequate stifle stability; however, there are very few studies aiming to validate the biomechanical theories of TTA, or determine the potential biomechanical advantages or disadvantages of this novel technique. Two cadaver experiments demonstrated that TTA appears to neutralize cranial tibial thrust under CrCL-deficient, weight-bearing conditions, but measurements in these studies were made exclusively from either lateral-view radiographs or dial indicators, and the effect of TTA on axial tibial rotation could not be assessed. Concerns have been raised over the ability of tibial osteotomy procedures, including TTA, to prevent excessive internal tibial rotation associated with a CrCL-deficient stifle. Considering that the biomechanical model of TTA is uniplanar, loss of passive restraint against excessive internal tibial rotation associated with CrCL insufficiency may not have been addressed. Hence the effect of TTA on internal tibial rotation clearly warrants investigation.

While other tibial osteotomy procedures, such as TPLO, impart functional stability by decreasing caudodistal tibial plateau slope, TTA does not alter with the alignment of the normal femorotibial articulating surfaces. This is a potentially significant biomechanical
advantage over other tibial osteotomy procedures because restoring normal joint contact mechanics is an important consideration in articular surgery, particularly for weight-bearing joints. Indeed, minor disturbances to the distribution of contact pressures on articular cartilage may induce progressive OA of an affected joint. To the authors’ knowledge, the effects of TTA on femorotibial contact mechanics have not been investigated.

The purposes of this cadaver study were to: 1. Evaluate the effects of TTA on femorotibial contact areas and stresses; and 2. Determine three-dimensional kinematics of the stifle after TTA. We hypothesized TTA would restore normal femorotibial contact mechanics in the CrCL-deficient stifle. We also hypothesized that TTA would eliminate cranial tibial translation, but only mitigate excessive internal tibial rotation in the CrCL-deficient stifle.

Material and Methods

Specimen Preparation

Eight hind limbs were harvested by disarticulation of the coxofemoral joint from eight adult dogs weighing between 28 to 35 kg that were euthanatized for reasons unrelated to the study. Contralateral hind limbs from each dog were used for the study described in Chapter 2. Limbs were evaluated for pathology, stored, and prepared for testing as described in Chapter 2, with differences as detailed below.

A longitudinal tibial osteotomy as described by Montavon et al.24 was performed before testing. A modified type-II external fixator was applied to the proximal tibial metaphysis and tibial tuberosity using positive profile centrally-threaded fixation pins and threaded rods that spanned the osteotomy site (Figure 3-1). The external fixator served to initially stabilize the tibial tuberosity in its normal, non-advanced position, then advance and stabilize the osteotomy at the planned amount of distraction that resulted in a patellar tendon-tibial plateau angle of 90° (treatment condition), without dismounting the specimen from the testing setup. This allowed for
valid comparisons of all contact data collected for one limb, where any major disturbance to the test setup may have resulted in discrepancies in contact map orientation due to shifting of the sensors. Limbs were radiographed at the calculated level of advancement at a stifle angle of 135° to verify appropriate patellar tendon-to-tibial plateau angles were attained.

Instantaneous intra-articular contact area and pressure measurements were obtained using a digital pressure sensing (I-Scan) system (Tekscan Inc. South Boston, MA), which included custom designed, plastic laminated, thin-film electronic pressure sensors. Sensors were calibrated, inserted subjacent to the menisci, and secured to the tibial plateau as described in Chapter 2.

Testing Protocol

Specimens were mounted to a materials testing machine (Model 8500, Instron Corp., Canton, MA), and loaded to replicate the stance phase of a walking gait, as described in Chapter 2. Loading and data acquisition were performed in the following sequence: 1) Normal (CrCL-intact, sham-TTA); 2) CrCL-deficient, (CrCL-deficient, sham TTA); 3) TTA-treated (CrCL-deficient, TTA-treated). For testing conditions 2) and 3), the CrCL was transected at its origin via a caudal approach to the stifle. For each condition, the contact area and pressure measurements were acquired after 5 seconds of holding peak force. The static, three-dimensional poses of tibial and femoral nylon screws implanted during specimen preparation were digitized using a Microscribe 3DX digitizing arm while the limb was loaded (Immersion Corp., San Jose, CA).

Data Analysis

Total contact force, contact area, mean contact pressure and peak contact pressure measurements in the entire, medial and lateral stifle compartments were acquired with the digital pressure sensing system. Total contact force was defined as the magnitude of load transmitted
across the femorotibial articulating surfaces. Contact area was defined as the area of contact between the tibial plateau, the femoral condyle, and the portion of the meniscus loaded by the femur. Peak contact pressure was defined as the highest pressure measured in the contact area, whereas mean contact pressure represented the average of the pressures across the contact area. Pressure distribution was described according to the location of the peak pressure; the relative location of peak pressure for each condition was defined as the distance from the peak pressure sensel to the caudal margin on the tibial plateau in the sagittal plane, divided by the entire length of the tibial plateau in the sagittal plane. Following testing, CT images of the femurs and tibiae, with nylon screws in place, were acquired. Creation of three-dimensional bone models, identification of anatomical landmarks and fiducial marker locations, and calculations of translations and rotations of the tibia relative to the femur, were performed as detailed in Chapter 2.

**Statistical Analysis**

A one-way repeated measures analysis of variance was used to evaluate differences in total contact force, contact area, mean contact pressure, peak contact pressure, and pressure distribution in the medial, lateral, and total (medial + lateral) stifle compartments, among the three different conditions (normal, CrCL-deficient, TTA-treated). A one-way repeated measures analysis of variance was also used to evaluate differences in internal-external tibial rotation, cranial-caudal tibial translation, proximal-distal tibial translation, and stifle flexion angle among the 3 conditions. Where significant differences were indicated, paired comparisons were made using the Tukey method. For all statistical analyses performed, $P < 0.05$ was considered statistically significant. A statistical analysis software package (SPSS 16.0, SPSS Inc., Chicago, IL) was used to perform all statistical analyses.
Results

Mean preoperative patellar tendon-tibial plateau angle was $109 \pm 4^\circ$; mean advancement of the tibial tuberosity required to obtain patellar tendon-tibial plateau angle of $90^\circ$ was $13.5 \pm 1$ mm. As determined by the kinematic analysis, mean stifle angles did not vary between the normal ($141 \pm 3^\circ$), CrCL-deficient ($142 \pm 4^\circ$), and TTA-treated ($143 \pm 3^\circ$) conditions ($P = 0.371$).

Contact Mechanics

Mean values for the contact mechanics parameters are shown in Table 3-1 (Figure 3-2). CrCL transection resulted in significant changes to all parameters for the total and medial stifle compartments, while differences were less apparent in the lateral compartment. Treatment with TTA was able to restore all abnormalities induced by CrCL transection to control values. Total contact force decreased from $365 \pm 71$ N to $284 \pm 53$ N after CrCL transection ($P = 0.004$); contact force increased to $322 \pm 53$ N after TTA, which was not significantly different from normal ($P = 0.129$). CrCL transection also resulted in a decrease in total contact area, from $306 \pm 42$ mm$^2$ to $182 \pm 19$ mm$^2$ ($P < 0.001$); total contact area increased to $293 \pm 30$ mm$^2$ after TTA ($P < 0.001$), which was not significantly different from normal ($P = 0.459$). In the medial stifle compartment, contact area decreased from $173 \pm 28$ mm$^2$ to $75 \pm 16$ mm$^2$ after CrCL transection ($P < 0.001$). Medial contact area after TTA, $160 \pm 16$ mm$^2$, was also not significantly different from normal ($P < 0.156$). Peak pressure magnitude in the medial compartment increased by approximately 2-fold from $2.6 \pm 0.3$ MPa to $5.1 \pm 0.7$ MPa after CrCL transection ($P < 0.001$), then decreased to $2.7 \pm 0.3$ MPa after treatment with TTA ($P < 0.001$); there was no significant difference between medial compartment peak pressure magnitude of normal and TTA-treated conditions ($P = 0.841$). A similar pattern of changes in peak pressure magnitude was evident in
the lateral compartment. Total and medial mean pressure magnitudes also significantly increased after CrCL transection, and returned to normal after TTA.

In the normal stifle, the medial peak pressure was located at 47 ± 9% of the medial tibial condyle length from the caudal margin of the medial compartment. Peak pressure in the medial compartment shifted caudally to 9 ± 4% (P < 0.001) after CrCL transection. Treatment with TTA shifted the peak pressure location in the medial compartment cranially to 44 ± 12% (P = 0.001), and there was no significant difference in medial peak pressure location between normal and TTA-treated conditions (P = 0.544). In the lateral compartment, there was a caudal shift in peak pressure location after CrCL transection, from 56 ± 9%, to 19 ± 7% of the tibial plateau length from the caudal margin of the lateral tibial condyle (P < 0.001). There was a significant cranial shift in peak pressure to 51 ± 12% after TTA (P < 0.001). There was no significant difference in lateral peak pressure location between normal and TTA-treated conditions (P = 0.398).

**Stifle Kinematics**

Mean values for kinematic parameters are provided in Table 3-2 and depicted in Figure 3-2. In the normal condition, the tibial insertion of the CrCL was located 8.9 ± 1.6 mm cranial to the femoral origin of the CrCL; this distance increased to 24.5 ± 2.2 mm following CrCL transection (P < 0.001), indicating cranial translation of the tibia. Cranial tibial subluxation was eliminated after TTA, where the sagittal distance between the CrCL origin and insertion was 9.7 ± 3.0 mm; this distance was not significantly different from normal (P = 0.449).

In the normal condition, the medio-lateral axis of the tibia was axially aligned 5.0 ± 2.9° (external axial rotational alignment) relative to the medio-lateral axis of the femur. In CrCL-deficient condition, the axial position of the tibia was -9.3 ± 4.4° (internal axial rotational alignment), indicating 14.2 ± 4.1° of internal tibial rotation after CrCL transection (P < 0.001).
Following TTA, the tibia returned to a slight externally rotated position of $1.7 \pm 5.3^\circ$. Axial rotational alignment in the TTA-treated condition was significantly different from the CrCL-deficient condition ($P < 0.001$), but not significantly different from normal ($P = 0.135$).

**Discussion**

In support of our hypotheses, we found TTA effectively restored the three-dimensional alignment and femorotibial joint contact mechanics of CrCL-deficient stifles to normal. Chapter 2 shows that decreasing the tibial plateau slope by performing TPLO imparted appropriate joint stability, but at the cost of significant disruption to the normal pattern of load distribution across the weight-bearing stifle. The results of the current study corroborate that maintenance of the normal orientation of the femorotibial articulating surfaces is an advantageous biomechanical feature of TTA.\textsuperscript{32}

As with all *in-vitro* biomechanical studies, there were numerous limitations associated with our methodology, and our findings cannot be directly extrapolated to the clinical setting. Chapter 2 thoroughly explores the assumptions and limitations of the hind limb model, and the techniques and instrumentation used to acquire kinematic and contact data.

Tibial tuberosity was advanced a mean of $13.5 \pm 1$ mm to achieve a patellar tendon-to-tibial plateau angle of $90^\circ$, which is beyond the maximum magnitude of advancement attainable with the current commercially available equipment (Kyon, Zurich, Switzerland).\textsuperscript{24} Recently, it has been suggested that the tangent to the femorotibial contact point, rather than conventional landmarks (cranial and caudal margins of the medial tibial condyle) should be used to define the slope of the tibial plateau.\textsuperscript{45} Adopting the tangential method for defining the patellar tendon-to-tibial plateau angle would have likely resulted in a lower degree of advancement required, thereby becoming more consistent with what is performed clinically to equivalent sized dogs. As
the cadaver model used in our study can only be regarded as a very basic representation of true hind limb biomechanics, we believe the significance of the effect of slight ‘over-advancement’ performed in our specimens is negligible.

TTA restored femorotibial contact patterns to those obtained prior to CrCL transection. This is in contrast to our TPLO contact data, where contact stresses were distributed caudally and overall contact area was smaller than normal. The shift in the major load-bearing regions was proposed as a potential mechanism for on-going articular surface damage and progression of OA commonly observed after treatment with TPLO. TTA, on the other hand, appears to re-establish normal contact mechanics within CrCL-deficient stifles. Whether OA post-TTA progresses at a similar rate to that documented after TPLO is unknown. Surgery for CrCL insufficiency is inevitably performed in stifles with some degree of degenerative joint disease, and abnormal articular cartilage is less tolerant of even physiologic compressive forces.98 Nevertheless, our data suggests that the articular cartilage and menisci would be subjected to more normal contact stresses during weight-bearing in TTA treated stifles than after TPLO.

A major caveat, however, exists with the above interpretation of our contact data. The model assumes the stifle is out of drawer immediately prior to paw-strike. In limbs with complete CrCL rupture treated with tibial osteotomy procedures, there is still opportunity for the stifle to be loaded in a subluxated position.19 If this were to occur, femorotibial contact patterns are likely to resemble the contact maps generated in untreated, CrCL-deficient stifles, regardless of the treatment applied. We observed abnormal femorotibial alignment (i.e. cranial tibial subluxation) corresponded with severe disruption to contact patterns in all tested specimens. Thus, the ability for TPLO or TTA to consistently eliminate cranial tibial thrust becomes a far more important consideration than the relatively minor differences in contact mechanics found
between the TTA- and TPLO-treatment conditions. A high incidence of subsequent meniscal injury has been documented in dogs following TTA if meniscal release is not performed, which may indicate that TTA may not be as reliable as TPLO in preventing subluxation. While TTA seems biomechanically superior to TPLO in this static cadaver model, *in-vivo* analyses are required to properly validate our results.

As discussed in Chapter 1, the influence of anterior translocation of the tibial tuberosity on femorotibial contact forces has been studied in humans. The Maquet’s procedure, which involves advancement of the tibial tuberosity, has been shown to affect femorotibial biomechanics. One cadaver study demonstrated a progressive decrease in the forces normal to the surface of the femorotibial joint as the tibial tuberosity was advanced anteriorly. These findings were corroborated by a recent three-dimensional finite element analysis study, which revealed the amount of load transmitted across the femorotibial joint decreased by 15% when the tibial tuberosity was advanced by 2.5cm. Increasing the moment arm of the patellar tendon by advancing the tibial tuberosity appears to improve the mechanical efficiency of the knee extensor mechanism and thereby reduce the joint compressive forces experienced within the knee during ambulation. A similar phenomenon may be occurring in dogs’ stifles treated by TTA; however, we were unable to demonstrate a significant difference in the total contact force between normal and TTA-treated stifles. The limitations of the pressure sensing equipment and/or the hind limb model utilized in our study may have restricted our ability to detect such trends.

Cranial tibial translation detected in CrCL-deficient conditions was eliminated after TTA. Our results are consistent with two previous biomechanical studies which found TTA has the ability to neutralize cranial tibial thrust. While it appears the procedure restores normal
sagittal plane alignment of the stifle, it is prudent to re-emphasize that appropriate functional
stability in TTA-treated stifles relies on correct limb alignment and muscle activity throughout
the gait cycle. Our test set-up, being static in design, precluded the ability to assess whether
cranial tibial subluxation is neutralized under a variety of loading conditions. Thus, it remains
uncertain whether stifles afflicted with CrCL insufficiency treated by TTA remain consistently
out of drawer during a range of different activities.

To the authors’ knowledge, this experimental study is the first to examine the effects of
TTA on rotational stability. We were not able to identify a significant difference in the axial
rotational alignment of stifles between normal and TTA-treated conditions. This lack of
significance may have been due to a type II error (i.e. low statistical power), as TTA-treated
conditions were still 6 to 8° internally rotated relative to normal in 3 of 8 limbs tested.
Conversely, there was a difference of less than 3° between normal and treatment conditions in all
except one TPLO specimen. The cause of the persistent internal rotation in these few TTA-
treated limbs was unclear. TTA, like the Maquet procedure, is purported to decrease
patellofemoral contact pressures, which may result in increased mobility of the patella in a
mediolateral direction and, consequently, alter the coronal alignment of the patellar tendon.
Excessive internal tibial rotation may be contributing to the development of post-operative
medial patellar luxation documented in clinical cases of dogs undergoing TTA.

In summary, altering the alignment of the patella tendon by performing a TTA in CrCL
deficient stifles of dogs eliminates cranial tibial subluxation and excessive internal tibial rotation
occurring during weight-bearing. Unlike TPLO, dynamic stabilization with TTA does not induce
significant alterations to femorotibial contact areas and stresses and thereby provides a more
normal mechanical environment to the stifles afflicted with CrCL insufficiency.
Figure 3-1. Cadaver limb preparation. A) Before, B) After TTA. Stabilization was achieved with a modified type-II external fixator. The threaded rods of the external fixator facilitated precise distraction of the osteotomy without the need to disrupt the specimen testing set-up.
Figure 3-2. Axial view of left bone models depicting three-dimensional poses of normal, CrCL-deficient, and TTA-treated stifles, with corresponding contact maps representative of each testing condition. The tibia (light gray) is cranially displaced and internally rotated relative to the femur (dark gray) after CrCL transection; femorotibial pose of normal and TTA-treated stifles are similar. CrCL transection resulted in caudal shift, reduced area and increased pressure of femorotibial contact; TTA contact patterns are similar to normal. Left = lateral, top = cranial.
Table 3-1. Femorotibial contact mechanics for normal, CrCL-deficient, and TTA-treated conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal (1)</th>
<th>CrCL-deficient (2)</th>
<th>TTA-treated (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Force (N)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>365 ± 71</td>
<td>284 ± 53 (P&lt;0.004)</td>
<td>322 ± 53 (P&lt;0.001, P&lt;0.185)</td>
</tr>
<tr>
<td>Contact Area (mm²)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>306 ± 42</td>
<td>182 ± 19 (P&lt;0.001)</td>
<td>293 ± 30 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>173 ± 28</td>
<td>160 ± 16 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>134 ± 20</td>
<td>134 ± 22 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td>Peak Pressure Magnitude (MPa)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.6 ± 0.3</td>
<td>5.1 ± 0.7 (P&lt;0.001)</td>
<td>2.7 ± 0.3 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>2.2 ± 0.4</td>
<td>2.2 ± 0.4 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Pressure (MPa)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2 ± 0.1</td>
<td>1.6 ± 0.2 (P&lt;0.001)</td>
<td>1.1 ± 0.2 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>1.3 ± 0.1</td>
<td>1.4 ± 0.4 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>1.1 ± 0.2</td>
<td>1.3 ± 0.2 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td>Peak Pressure Location (%)</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>47 ± 9</td>
<td>9 ± 4 (P&lt;0.001)</td>
<td>44 ± 12 (P&lt;0.001, P&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>Medial</td>
<td>56 ± 9</td>
<td>51 ± 12 (P&lt;0.001, P&lt;0.001)</td>
</tr>
</tbody>
</table>

*The relative location of peak pressure for each condition was defined as the distance from the peak pressure sensel to the caudal margin on the tibial plateau in the sagittal plane, expressed as a percentage of the tibial plateau length. P-values for post-hoc pairwise comparisons are given where significant differences were found on analysis of variance.

Table 3-2. Static three-dimensional femorotibial poses for normal, CrCL-deficient, and TTA-treated conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal (1)</th>
<th>CrCL-deficient (2)</th>
<th>TTA-treated (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translations (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Craniocaudal</td>
<td>9.0 ± 1.6</td>
<td>24.5 ± 2.2 (P&lt;0.001)</td>
<td>9.7 ± 3.0 (P&lt;0.04, P&lt;0.001)</td>
</tr>
<tr>
<td>Mediolateral</td>
<td>5.5 ± 1.4</td>
<td>5.9 ± 2.1</td>
<td>5.8 ± 1.6</td>
</tr>
<tr>
<td>Proximodistal</td>
<td>7.0 ± 0.8</td>
<td>-0.6 ± 0.9 (P&lt;0.001)</td>
<td>6.9 ± 1.3 (P&lt;0.052, P&lt;0.001)</td>
</tr>
<tr>
<td>Rotations (deg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion-extension</td>
<td>140.9 ± 2.7</td>
<td>142.4 ± 4.0</td>
<td>142.8 ± 2.7</td>
</tr>
<tr>
<td>Internal-external</td>
<td>5.0 ± 2.9</td>
<td>-9.3 ± 4.4 (P&lt;0.001)</td>
<td>1.8 ± 5.3 (P&lt;0.013, P&lt;0.001)</td>
</tr>
<tr>
<td>Varus-valgus</td>
<td>8.6 ± 4.2</td>
<td>5.9 ± 5.3 (P&lt;0.001)</td>
<td>8.1 ± 4.9 (P&lt;0.001, P&lt;0.003)</td>
</tr>
</tbody>
</table>

For the translational parameters, positive values indicate cranial, distracted and medial positions of the tibia relative to the femur. For the rotational parameters, positive values indicate greater stifle extension, external tibial rotation, and varus. P-values for post-hoc pairwise comparisons are given where significant differences were found on analysis of variance.
CHAPTER 4
CONCLUSION

The concept of altering tibial geometry to impart functional stability in the stifles of dogs afflicted with CrCL insufficiency has gained immense popularity. All described tibial osteotomy procedures were designed to eliminate cranial tibial thrust by either decreasing the tibial plateau slope or altering the alignment of the stifle extensor mechanism. Chapter 1 outlined the biomechanical concepts and evolution of tibial osteotomies for the treatment of CrCL insufficiency. It was summarized that each procedure is associated with its own inherent advantages and limitations, and certain osteotomy techniques may be more appropriate in dogs with specific conformational abnormalities. We also highlighted the technical difficulties and invasive nature of all tibial osteotomies, as well as numerous common concerns such as persistent progression of OA and subsequent meniscal injury. While we were able to conclude that all the reported procedures can improve limb function, this literature review highlighted the lack of available data precluding accurate comparisons between different tibial osteotomy techniques, and with other more traditional methods of stabilizing the CrCL-deficient stifle.

Our in-vitro investigations have provided valuable data regarding the joint mechanics of TPLO and TTA. Using a digital pressure sensing system and high-precision three-dimensional digitizing instrumentation in a cadaver hind limb model, we were able to accurately estimate the effects of TPLO and TTA treatment on femorotibial joint contact mechanics and kinematics.

In Chapter 2, it was shown that whereas TPLO eliminates craniocaudal stifle instability during simulated weight-bearing, the procedure fails to concurrently restore femorotibial contact mechanics to normal. We demonstrated normal three-dimensional femorotibial alignment in CrCL-deficient stifles treated by TPLO, however a caudal distribution of contact stresses over the tibial plateau and concurrent decrease in overall contact area was consistently observed. This
finding was suggestive of mild caudal impingement of the stifle caused by decreasing the tibial plateau slope to 6°. Progression of stifle OA in dogs treated with TPLO may thus be partly the result of abnormal stifle contact mechanics during weight-bearing induced by altering the orientation of the proximal tibial articular surface.

As detailed in Chapter 3, TTA was found to be more effective in restoring a more normal mechanical environment within the weight-bearing CrCL-deficient stifle than TPLO. No significant differences in femorotibial contact mechanics or kinematics were found between normal and TTA-treated, CrCL-deficient stifles. It was concluded that TTA may be superior to TPLO as it imparts dynamic stability without the need to alter the orientation of the femorotibial articulating surfaces.

The results of our cadaver studies should be interpreted with caution. In-vitro research is crucial to the understanding of fundamental biomechanical concepts and aids in validating theory; however, in-vitro studies are categorized as having the least clinical relevance on the evidence-based hierarchy. We adopted a popular cadaver model of the dog’s hind limb for evaluating the biomechanics of CrCL insufficiency and the currently available treatment options, which is associated with several limitations. In this model, muscular forces were crudely represented, with only two muscle groups, the quadriceps and gastrocnemius muscles, being simulated. Acute transection of the CrCL does not accurately replicate the degree of instability observed in dogs with naturally occurring disease. Further, loading conditions were used to attempt to mimic only the stance phase of a walking gait; thus, no inferences can be made to other activities such as running, jumping, turning, or rising.

The clinical significance of our contact mechanics data also remains disputable for several additional reasons. Firstly, the specimens were tested with an intact, normal medial meniscus.
Medial meniscal release, caudal pole hemimeniscectomy and partial meniscectomy are frequently performed in conjunction with both TPLO and TTA. Any disturbance to this important structure, due to secondary damage, resection or excision, has been shown to impair normal load transmission across the stifle. Secondly, the occurrence of subsequent medial meniscal injury following either TPLO or TTA in clinical subjects is highly suggestive of persistent craniocaudal or rotational instability. Our results do not provide any insight into whether one procedure reliably eliminates cranial tibial subluxation or abnormal rotational motion better than the other in vivo. Finally, although the magnitude of difference between normal and TPLO-treated femorotibial contact patterns may be statistically significant, the biologic significance of the abnormalities remains unknown. Andriacchi postulates even a minor shift in the regular pattern of load distribution may initiate OA progression, however whether or not the observed contact shift induced by TPLO alone is truly detrimental to the CrCL-deficient stifle has yet to be determined.

Our emphasis on the limitations of in vitro biomechanical testing underscores the importance of in vivo studies to validate or refute our findings. To date, all investigations on stifle stability following tibial osteotomies have been bench-top studies. We believe the next crucial step towards understanding the effects of TPLO and TTA should be directed towards obtaining high-precision, three-dimensional, in vivo kinematic analyses of CrCL-deficient stifles before and after treatment. The feasibility of performing such studies has been demonstrated. The information obtained would help definitively determine whether improvement in limb function is due to elimination of cranial tibial subluxation occurring during weight-bearing.

Despite the heavy focus on CrCL insufficiency in the current veterinary literature, much also remains unknown regarding the clinical efficacy, and superiority of the currently described
tibial osteotomy techniques. Indeed, there may not be one universal ‘optimal’ procedure, as CrCL insufficiency presents with a wide clinical spectrum of severity and secondary joint adaptive change. Future investigations need to also consider different hind limb conformations, levels of activity and even client expectations between individual dogs when attempting to define an ‘optimal’ procedure selection.

But perhaps the most significant advancement in the study of CrCL insufficiency lies not in evaluating the ever-evolving treatment options developed for the condition, but rather, uncovering the aetiopathogenesis of the ligamentous degeneration. While multiple theories exist, ranging from the purely biologic\textsuperscript{121} to the purely biomechanic\textsuperscript{30}, the definitive cause of rupture remains uncertain. The ideal treatment option, and ultimately, prevention, of CrCL insufficiency will also remain elusive without a greater focus on identifying the underlying disease process itself.

Our results suggest that TTA is superior to TPLO during walking; however, it is clear that further research is required to substantiate these findings. Carefully designed long-term clinical studies, further biomechanical analyses, and perhaps most importantly, a better understanding of the pathomechanics of CrCL insufficiency, are required to determine the optimal surgical treatment for this common cause of hind limb lameness in dogs.
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BIOGRAPHICAL SKETCH

Stanley E. Kim was born and raised in Australia, and graduated from the University of Sydney with a Bachelor of Veterinary Science degree in 2003. After a year-and-a-half of small animal private practice in Sydney and the United Kingdom, Stanley completed a clinical internship in small animal medicine and surgery at the Ontario Veterinary College, University of Guelph, Guelph, Ontario, Canada, between 2005 and 2006. After completing the internship, Stanley moved to Gainesville, Florida, in 2006, where he entered the Master of Science degree program at the University of Florida’s College of Veterinary Medicine. In combination with the master’s degree, Stanley is also completing a residency in small animal surgery, and is scheduled to be board eligible in summer 2010.