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Ex vivo biomechanical comparison of four center of rotation angulation based leveling osteotomy fixation methods

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Ex vivo biomechanical comparison of four center of rotation angulation based leveling osteotomy fixation methods

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Thirty-two canine tibiae with patellae and patellar tendons were harvested from 17 skeletally mature cadavers. Each tibia was randomly allocated to a construct group: plate and pin (Plate), plate with countersink compression screw (HCS), plate with tension band (TB), or plate with HCS and TB (HCSTB). Samples were loaded by distraction until failure. The stiffness, yield load, and ultimate load were compared between each fixation method. No difference in stiffness of the constructs was detected between groups. Yield load and ultimate load for the HCSTB group was greater than the TB group, the HCS group, and the Plate group. CBLO fixation augmented with a TB and HCS provided a stronger construct that withstood a greater yield load and ultimate load than either augmentation strategy alone. Augmenting a CBLO fixation with a TB and a HCS can provide increased construct strength.

DEDICATION

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CHAPTER I

INTRODUCTION

Background

Cranial cruciate ligament (CrCL) disease is the most common cause of pelvic limb lameness in the canine patient.[1] Because of this high incidence of problem, several treatments have been developed to address cruciate ligament disease. These surgical treatments can be broadly sorted into three categories: intraarticular reconstruction, extracapsular stabilization, and osteotomy procedures. Intraarticular reconstruction techniques include use of autografts, allografts, and synthetic materials. Due to marked inflammatory response, poor integration, and overall poor success rates, these techniques are not widely performed in canine clinical cases.[1] Extracapsular techniques include but are not limited to lateral fabellotibial suture, tight rope, and fibular head transposition. Thus far, these techniques have been shown to be inferior to the osteotomy techniques in terms of return to function as assessed by gait analysis; however, the lateral fabellotibial suture remains a common procedure in clinical cases.[1] Osteotomy techniques are currently the most popular for the treatment of canine cranial cruciate disease. This group includes the Tibial Plateau Leveling Osteotomy (TPLO), cranial tibial closing wedge osteotomy, Tibial Tuberosity Advancement (TTA), and Center of Rotation Angulation (CORA)-Based Leveling Osteotomy (CBLO). [1]

The CBLO was developed most recently among the osteotomy procedures to address some of the limitations of the TTA and TPLO. All of these use an osteotomy secured by implants to neutralize the cranial tibial translation encountered in the CrCL-deficient stifle. The main reported advantages of the CBLO come from the preservation of the proximal tibial epiphysis. The creation of a large proximal tibial segment to allow for ancillary stabilization methods and increases bony contact and compression of the entire osteotomy, which in turn facilitates early bone healing.[2] This would also permit additional stabilization techniques for large and giant breed dogs. Additionally, this is the only osteotomy technique to address CrCL disease that preserves the growth plates of the proximal tibia, allowing it to be performed in juvenile dogs.[2]

A recent report also indicated more rapid bony healing with the additional implants permitted by CBLO when compared to previous work evaluating the bone healing in thean TPLO.[3] Following CBLO with the addition of a tension band, serial radiographs were used to score bone healing assessed on a 0-4 scale, where 4 represented 76-100% healed. Bony healing was graded a 4/4 in 38 of 49 stifles by a mean of 35 days (25-40 days) postoperatively. The remaining eleven stifles reached grade 4/4 healing by a mean of 48 days (42-51 days). The rapid healing was attributed to the addition of a k-wire or position screw and tension band.[3] Although there are several options to provide additional fixation, it is unknown which method provides superior resistance to the pull of the patellar tendon. This study aims to compare the strength of four ancillary CBLO fixation methods to resist the quadriceps pull on the patellar tendon.

Anatomy of the Cranial Cruciate Ligament

The cruciate ligaments are intra-articular, extra-synovial ligaments of the stifle joint. These ligaments cross over one another, and their names are derived from the location of their insertion on the tibia: the cranial cruciate ligament (CrCL) and caudal cruciate ligament (CdCL). The origin of the CrCL is the caudomedial aspect of the lateral femoral condyle and the caudolateral part of the intercondyloid fossa of the femur. It runs diagonally in a cranial, medial, and distal direction across the intercondyloid fossa to insert on the cranial intercondyloid area of the tibia. [4-6] This ligament is grossly divided into two bands. A larger caudolateral band attaches at the caudolateral aspect of the tibial attachment site. It is taut in extension but becomes lax in flexion. A smaller craniomedial band attaches at the craniomedial aspect of the tibial attachment site. It is taut throughout all range of motion.[4]

Function of the Cranial Cruciate Ligament

The CrCL functions primarily to prevent cranial tibial translation with respect to the femur (cranial drawer) and hyperextension of the stifle joint.[4,6] The CrCL and the CdCL twist on each other, which helps to limit internal rotation of the tibia relative to the femur. The cruciate ligaments play variable roles in limiting varus and valgus angulation of the stifle joint.[4]

Cranial Cruciate Ligament Disease

The term CrCL disease encompasses several various disorders affecting the CrCL. CrCL disease is the most common cause of canine pelvic limb lameness. Described disorders include traumatic avulsion of the CrCL, acute traumatic rupture of the CrCL secondary to excessive strain, and progressive degeneration of the CrCL due to unknown cause.[1]

Traumatic Cruciate Ligament Avulsion

This type of injury generally occurs in skeletally immature animals because the Sharpey's fibers which attach the ligament to the bone, are stronger than the bone itself. When the ligament is acutely overloaded, an avulsion of the ligament with a small piece of bone may result. Either the femoral or tibial component can be avulsed, although the femoral component is more commonly affected.[1] Because the cruciate ligament itself generally remains intact and because the animal has open growth plates, treatment strategies are unique for this specific category of CrCL disease.[1]

Acute Traumatic Rupture of the Cranial Cruciate Ligament

Acute rupture of the CrCL is a rare injury that occurs secondary to excessive limb loading, traumatic hyperextension of the stifle joint, and/or excessive internal rotation of the tibia leading to acute overload and failure of the ligament. This injury commonly results in a midsubstance tear, giving the cruciate ligament a “mop end” appearance. Affected dogs present with extreme pain, joint effusion, severe lameness, and stifle joint instability. Radiographic findings may include effacement of the infrapatellar fat pad by a soft tissue opacity in the lateral projection (characteristic of edema of the fat pad and/or joint effusion) and the absence of degenerative changes, such as osteophytosis.[1]

Progressive Degeneration of the Cranial Cruciate Ligament

Despite CrCL disease’s initial description in 1926 and almost 100 years of investigation, the exact cause of degeneration remains poorly understood.[1] Several factors believed to cause or contribute to CrCL rupture have been evaluated including abnormal conformation and gait, increased TPA, obesity, age, sex, neuter status, and lack of fitness; however, none of these has proved causative.[7-14] For instance, while the mean TPA was reported to be significantly greater in dogs with CrCL rupture than in dogs with an intact CrCL in one study, further investigations failed to confirm this finding.[12, 15-16] Female dogs have an increased prevalence of CrCL disease compared with male dogs.[17] Although a higher prevalence of CrCL disease has been documented in neutered canines compared to their sexually intact counterparts, age at the time of ovariohysterectomy has not been associated with CrCL disease.[17-19] The CrCL has been shown to be rich in mechanoreceptors and proprioceptors.[20-21] As strain increases on the CrCL, simultaneous contraction of the caudal thigh muscles and relaxation of the quadriceps muscle group occurs; this response is protective of the ligament.[22-23] Thus, obesity and/or lack of fitness may diminish these protective mechanisms, leading to repetitive strain injury of the CrCL and mechanical failure.[23-24] Studies evaluating intact CrCLs have demonstrated a decrease in material properties (modulus of elasticity, maximum stress, strain energy) with aging, with more pronounced changes and earlier onset in dogs weighing more than 15 kg compared with dogs weighing less than 15 kg. These findings are consistent with the observation that CrCL disease often occurs at a younger age in large-breed dogs.[8] Histologic evaluation of the CrCL showed degenerative changes, including loss and metaplasia of ligamentocytes and failure to maintain collagen fibers.[7] In the ruptured CrCL, histology indicated a lack of normal collagen fiber maintenance and loss of fibroblasts from the core region, despite the presence of a normal cell number density in the epiligamentous region. This change in fibroblast numbers was characterized by a shift in the type of fibroblast present, with a decrease in typical fusiform and ovoid fibroblasts, an increased number of cells undergoing chondroid metaplasia, and extensive disruption of the ligamentous matrix.[7,25] Abnormalities in collagen maintenance were demonstrated by decreased birefringence and elongation of crimping in the remaining collagen. This was suggesting progressive mechanical overload was the cause of failure. Interestingly, a proliferative epiligamentous repair response was identified that resulted in the eventual covering of the torn ends of the ligaments, yet no bridging scar was noted between the ends.[25] Immune-mediate degeneration, acquired loss of blood supply in the midportion of the ligament, and a smaller intercondylar notch are factors that likely contribute to this degeneration.[26-27] Ruptured CrCLs have an increased turnover rate of extracellular matrix compared with intact CrCLs, as demonstrated by increased collagen and glycosaminoglycan synthesis.[28] Antibodies to type I and type II collagen have been identified in the sera and synovial fluid of 5 dogs with spontaneous CrCL rupture.[27] While the prevalence of these antibodies has led to speculation that immunologic reactivity may play a role in CrCL disease, their increase is not specific for the type of joint disorder. It is therefore unlikely that anti-collagen antibodies play an active role in the onset of CrCL weakening.[29] Ultimately, it seems that CrCL disease is multifactorial and through a combination of processes the ligament is either too weak to withstand the forces applied to it, or the forces applied are greater than the strength of the ligament.[1]

The material properties of the CrCL have been reported to vary between breeds. The CrCL from the Rottweiler was compared with that of the racing Greyhound. The CrCL from the Rottweiler had a significantly greater cross-sectional area at the tibial attachment. Mechanical testing of these ligaments showed that when normalized to body mass, the ultimate failure load was significantly greater in the extended stifle of the racing Greyhound during loading in cranial tibial subluxation than in the Rottweiler. It was concluded that the Rottweiler ligament is more vulnerable to damage because it required half the load per unit body weight to rupture compared with the Greyhound ligament.[30]

A wide variety of dog breeds are affected by CrCL disease. The highest prevalence has been reported in the Rottweiler, Newfoundland, and Staffordshire Terrier; the lowest prevalence in affected breeds has been reported in the Dachshund, Basset Hound, and Old English Sheepdog.[17] Breeds predisposed to sustain a CrCL rupture before 2 years of age include the Neapolitan Mastiff, Akita, Saint Bernard, Rottweiler, Mastiff, Newfoundland, Chesapeake Bay Retriever, Labrador Retriever, and American Staffordshire Terrier.[31] Dogs weighing less than 22 kg tend to be affected later in life than larger dogs.[8,17,32-33] This data is consistent with the histologic findings that the CrCL of dogs weighing less than 15 kg generally shows less severe degeneration of the ligament than those of larger dogs, and the onset of the degenerative process is often delayed by several years in smaller dogs.[7]

Rupture of the contralateral CrCL is common and is reported to occur in 22% to 54% of dogs, with a median time of 947 days from the diagnosis of first CrCL rupture.[34-39] Increasing age is associated with increased survival of the contralateral CrCL, but breed and body weight have not been found to significantly affect the likelihood of contralateral CrCL rupture.[39] The veterinary literature is conflicted on whether TPA has any influence on contralateral rupture.[35,39] Age, sex, weight, and TPA were found to not be risk factors for bilateral CrCL disease in the Labrador Retriever.[34,36,39]

Patient history often includes pelvic limb lameness that worsens following exercise or periods of rest. Gait evaluation reveals lameness referable to the stifle joint. The severity of lameness reflects the degree of ligament disruption. Dogs with relatively stable partial tears may have a subtle lameness that is detectable only following periods of strenuous activity. Lameness can be severe or non-weight bearing in cases of complete rupture. In these instances, non-weight bearing lameness persists for several days, followed by moderate to severe weight-bearing lameness. Stiffness after rest, particularly following periods of exercise, is often observed.[1]

Cranial Cruciate Ligament-Deficient Stifle Joint

Osteoarthritis of the CrCL-deficient stifle joint likely occurs secondary to abnormal dynamic joint function.[1] Kinematic evaluation using surface markers has demonstrated that the CrCL-deficient stifle joint remains more flexed throughout the gait cycle. In response, the coxofemoral and tarsocrural joints remain more extended during the stance phase than in the normal gait cycle.[40] Kinetic analysis has revealed decreases in peak vertical forces and impulses and braking and propulsion impulses.[40-41] Peak vertical force on the normal pelvic limb has been reported to be 70% of the static body weight of the dog. Peak vertical force was 25%, 32%, and 37% of body weight at 2 weeks, 6 weeks, and 12 weeks following experimental transection of the CrCL, respectively.[42] Full, six degrees of freedom kinematic data were collected in five dogs using an instrumented spatial linkage secured to bone plates. Approximately 8 to 12 mm of cranial tibial subluxation with respect to the femur was observed during the stance phase of the gait. Cranial subluxation of the tibia was unchanged during the swing phase, except in one of the five dogs in which subluxation persisted during the swing phase. This finding was thought to be due to failure of secondary restraints such as the menisci, resulting from chronic, cyclic cranial tibial subluxation and reduction.[43] In a cohort study of 18 dogs, dynamic radiostereometric analysis utilizing dual digital video radiographic capture was used to serially evaluate stifle joint kinematics following CrCL transection. Peak cranial tibial translation increased by an average of 10 mm following CrCL transection. Cranial tibial subluxation was only evident during the stance phase 2 months following ligament transection; however, an average of 5 mm of translation was present at the terminal swing phase 2 years following transection.[44] The medial meniscus was found to be an important secondary stabilizer of the stifle joint, serving as a “return spring” in the CrCL-deficient stifle joint. The intact medial meniscus elastically deforms during periods of cranial subluxation of the tibia and then reduces subluxation once stance phase load is removed.[44-45] Joint capsule fibrosis and meniscal injury secondary to long-term joint instability have been suggested to cause a reduction in static joint laxity and elasticity over time. Significant changes in internal rotation of the tibia relative to the femur were not observed. The range of abduction and adduction of the stifle joint was nearly doubled 2 months following the transection of the CrCL and remained significantly increased at 2 years. In addition, stifle joint flexion increased significantly until 6 months postoperatively. A significant increase in medial translation of the tibia was noted, which persisted 2 years following ligament transection.[44] Interestingly, this study did not identify internal rotation of the tibia relative to the femur observed in some cases of the CrCl deficient stifle, also known as pivot shift. It is likely that this was not observed due to the homogenous population and low number of animals included.

Active Model of the Stifle

The dynamic nature of instability in the CrCL-deficient stifle joint in the dog wasn't recognized until 1978. The description of the tibial compression test as a method for evaluation of CrCL integrity acknowledged that direct forces of weight bearing and contraction of the gastrocnemius muscle were responsible for the joint compressive force between the tibia and the femur.[46] In 1984, Slocum and Devine defined cranial tibial thrust force as a shear force generated in the stifle during weight bearing that acts to thrust the tibia cranially. Cranial tibial thrust force was concluded to be the result of tibial compression and the slope of the tibial plateau.[47] In 1993, Slocum and Slocum proposed the "active model" of the stifle, in which stifle joint stability is maintained by a synergism between the muscle forces responsible for stifle joint flexion and extension, the cranial tibial thrust force, the pull of the stifle flexor muscles of the thigh, and the passive restraints of the stifle joint including the CrCL and the caudal pole of the medial meniscus.[48] Based on Slocum's model, the magnitude of the cranial tibial thrust force is dependent on the magnitude of the joint compressive force and the slope of the tibial plateau. Cranial tibial thrust force in the normal stifle joint is counteracted by both active (e.g., caudal thigh muscles) and passive (e.g., caudal pole of the medial meniscus) elements. If this force is not neutralized by the pull of the stifle flexors of the thigh, the CrCL ligament begins to rupture or ruptures, resulting in cranial tibial subluxation during the stance phase of the gait. Leveling of the tibial plateau reduces the magnitude of cranial tibial thrust force and restores joint stability during the stance phase.[47-48]

Center of Rotation Angulation Based Leveling Osteotomy (CBLO)

CBLO Concept

A CBLO uses principles of angular deformity correction and center of rotation angulation (CORA) methodology as described by Paley to level the tibial plateau and neutralize cranial tibial subluxation in the CrCL deficient stifle.[49] Because the tibia normally has a procurvatum, it also has a proximal anatomic CORA. This CORA is determined by finding the intersection of the proximal and distal anatomic axes. The magnitude of the CORA dictates the amount of correction needed to achieve the desired postoperative tibial plateau angle (TPA). For CBLO specifically, the desired range of postoperative TPA is 9-12 degrees with the goal of preventing abrasive articular cartilage damage seen with lesser TPAs as described by second-look arthroscopy following TPLO. [2, 50]

A unique feature of the CBLO is that once the tibial plateau is leveled, the epiphysis is centered on the shaft of the tibia. This avoids the complication seen with TPLO in which there is secondary caudal translation of the proximal anatomic axis. This is referred to as the “balcony effect” and has been implicated as a contributor to postoperative loss of rotation or “rock back”.[1,2]

One major advantage of the CBLO is the preservation of the proximal tibial epiphysis which allows for the application of ancillary stabilization methods, increased bone contact and compression of the entire osteotomy facilitating early bone healing, increased bone in the proximal tibial fragment for additional implant application in large and giant breed dogs, preservation of the growth plate in juvenile dogs, and ample room for fixation in small breed dogs. Additionally, treatment of dogs with excessive tibial plateau slope, and concurrent management of patellar luxation are possible with this technique.[2]

Preoperative Planning

Calibrated straight mediolateral and craniocaudal radiographs of the tibia are obtained. From these images, the location and magnitude of the center of rotation angulation (CORA) are determined. On the lateral image, a line is drawn that bisects the marrow cavity at the distal tibial crest and 2 centimeters distal to the tibial crest. This line represents the proximal anatomic axis of the tibia. A second line is drawn to depict the tibial plateau angle (TPA) as previously described.[1] A third line is drawn originating at the cranial extent of the tibial eminence and crosses the TPA line and is the desired postoperative TPA, also called the PPTA. This line is drawn such that the angle between the TPA line and the PPTA is equal to 90 degrees minus the goal postoperative TPA. For example, if the goal is a 10-degree postoperative TPA, the PPTA should be 80 degrees. This angle formed between the anatomic axis of the tibia and the PPTA is the magnitude of the CORA. The location of the CORA is found at the intersection of the mechanical axis of the tibia and the PPTA line. The desired saw blade template is placed centered over the CORA such that it crosses the cranial cortex and is relatively perpendicular to the caudal cortex. Two additional planning measurements are taken, D1, and D2. D1 is the distance from the insertion of the patellar tendon to the site the saw blade crosses the cranial cortex. D2 is measured from the stifle joint line at the level of the medial collateral ligament to the saw blade. The magnitude of the CORA is used with the CBLO rotation chart to determine the required rotation distance to achieve the desired postoperative TPA.[2]

Surgical Technique

After stifle arthrotomy or arthroscopy to evaluate the intraarticular structures is completed, the medial tibia is approached. The measurements D1 and D2 are marked on the bone as in the preoperative plan. The pre-determined size crescentic saw blade is used to make a complete tibial osteotomy intersecting these marks. The proximal tibial fragment is rotated as indicated by the preoperative plan. The osteotomy is temporarily secured with a Kirschner wire driven from the tibial crest in a cranioproximal to caudodistal orientation into the distal tibial fragment. This serves as the anti-rotational pin. The osteotomy is secured with an appropriately sized bone plate. If desired, the anti-rotational pin can either be removed, cut short and allowed to remain, become part of a tension band, or serve as a guide for the placement of a headless compression screw (HCS). Once ancillary stabilization is complete if desired, the medial tibial fascia, subcutaneous tissue, and skin are closed routinely. [2]

Outcome and Complications

Due to the relatively new nature and continued refinement of the CBLO procedure, objective evidence of its clinical outcomes is non-existent. There are however several case series to support its efficacy. A case series of 31 dogs with CrCL disease treated by CBLO and a HCS is described. Dogs were evaluated radiographically for changes in postoperative TPA and evidence of complications. No significant difference in postoperative and final TPA were identified. Two implant-related complications were reported: 1 HCS migration and 1 HCS failure. [51] A second retrospective case series described the outcome of 70 dogs treated with CBLO and HCS and followed for a minimum of 6 months. Radiographic healing was scored on a 5-point scale (0-4) and owners were surveyed about their pet's outcome. The mean final radiographic recheck was 107 days (32-424 days) with 69% of dogs having grade 4/4 healing, 28% having grade 3/4 healing, and 3% having grade 2/4 healing at final recheck. Based on owner survey, 77% of dogs had full function, 19% had acceptable function and 4% had unacceptable function. Complications were reported at 16% and included incisional concerns, late-onset meniscal tears, and 2 implant-related complications.[2]

A case series by Peycke et al. documented 16 stifles of skeletally immature dogs treated with CBLO and a mean follow-up of 23 months. All dogs had full function per the owners. One dog developed a 10-degree proximal tibial recurvatum due to over-rotation intraoperatively to protect a primary repair of a CrCL avulsion. Two dogs developed a valgus deformity secondary to a plate screw interfering with the distolateral aspect of the proximal tibial physis. Although function was reportedly normal in these dogs, owners requested corrective surgery to prevent long-term complications of abnormal weight bearing. [52]

Second-look arthroscopy has produced some insights into the outcome of the CBLO. On the evaluation of intra-articular structures by second-look arthroscopy of 41 stifles at a minimum of 9-12 months following CBLO 6 of 7 stable partial CrCL tears remained intact. Minimal to no change was noted in the articular cartilage at a median of 14 months following surgery. However, a late meniscal tear rate of 47% was reported and discussed as a common reason for postoperative lameness.[53]

Supplemental Fixation Methods for CBLO

Tension band

A tension band (TB) is an internal fixation device that is constructed from a segment of orthopedic wire wrapped in a figure-of-eight pattern and applied to the tension surface of a fracture or osteotomy. Generally, it is anchored around two small pins that align the bone fragments and counter rotation on one side of the fracture or osteotomy and through a bone tunnel on the other side. TBs work to oppose the eccentric loading of a muscle or tendon on a bone fragment, such as the pull of the quadriceps muscle and patellar tendon on the tibial tuberosity. Theoretically, the summation of the vectors created by the tension band and the muscular contraction should result in compression of the osteotomy or fracture site spanned by the TB.[1]

Headless compression screw

The headless compression screw (HCS), also known as the countersink compression screw, was designed to allow compression of an osteotomy or fracture while sitting below the chondral surface of the bone to minimize soft tissue irritation and allow application from articular surfaces. There are several types of HCS including conical and shaft screws. HCS are designed such that the thread pitch is greater at the leading edge of the screw than at the trailing end of the screw. Due to the variable pitch, when the screw is advanced it moves through the distal bone fragment faster than the proximal bone fragment thus compression is generated across the gap between the bone fragments.[54]

Challenging the Status Quo

Although the CBLO is still in early stages of clinical use, it potentially offers some unique advantages over the TPLO, which is considered the current gold standard surgical treatment of canine CrCl disease. Some theoretical advantages of CBLO include a larger proximal tibial segment that could allow for improved bone stock for fixation in toy and giant breeds, ability to correct patellar luxation’s concurrently, and ability to use intraarticular grafts concurrently. Research investigating these claims is currently underway, but results of such research efforts are not currently available. Other advantages of CBLO compared to TPLO are described in the literature detailed in the above "outcomes" section and include compression of the osteotomy for early bone healing, no secondary translation of the proximal tibial anatomic axis, avoidance of the proximal tibial physis in skeletally immature dogs, ability to manage excessive TPA, and lack of observed cartilage degeneration at second-look arthroscopy.[2, 3, 49-53]

A case series by Johnson et al. describing early bone healing with CBLO as compared to TPLO generated the clinical question we sought to answer with this study. Johnson's report described bone healing in CBLOs stabilized with the addition of a TB and HCS. Serial radiographs were used to score bone healing assessed on a 0-4 scale, where 4 = 76-100% osseous bridging, grade 3 = 51-75% osseous bridging, grade 2 = 26-50% osseous bridging, grade 1 = 1–25% osseous bridging, and 0 = no osseous bridging. Bony healing was graded as 4/4 in 38 of 49 stifles by a mean of 35 days (25-40 days) postoperatively. The remaining eleven stifles reached grade 4/4 healing by a mean of 48 days (42-51 days).[3] This can be loosely compared to previous work by Conkling et. al. that evaluated the rate of healing following TPLOs with locking plate technology. This study evaluated 64 dogs at 8 weeks postoperatively and showed that 34/64 (53%) had grade 4 healing, 25/64 (39%) had grade 3 healing, and 5/64 (8%) had grade 2 healing.[55]

Increased speed of bony healing would decrease the duration required for postoperative activity restriction, decrease the duration needed for radiographic follow up, and decrease the time that implants are relied on to maintain stability of the osteotomy to prevent loss of reduction or postoperative shift in TPA. The rapid healing in Johnson's report was attributed to the increased construct strength afforded by the addition of a Kirschner wire or position screw w/ tension band and HCS. Each additional implant placed requires additional surgical and anesthetic duration, different surgical skills and instrumentation, and increased implant costs. The exact combination of fixation methods required to achieve this early healing is unknown. The goal of our study was to determine the additional strength afforded by each ancillary fixation method to the overall construct and help determine which, if any, additional fixations would be recommended in a clinical case.

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CHAPTER II

EX VIVO BIOMECHANICAL COMPARISON OF FOUR CENTER OF ROTATION ANGULATION BASED LEVELING OSTEOTOMY (CBLO) FIXATION METHODS

Introduction

Center of rotation and angulation (CORA)-based leveling osteotomy (CBLO) is one of the available osteotomy procedures performed to address cranial cruciate ligament rupture.[1] A benefit to the CBLO compared to a tibial plateau leveling osteotomy (TPLO), is a larger proximal tibial segment that allows for ancillary stifle stabilization methods. Current recommendations for CBLO fixation involve the use of a bone plate and a headless compression screw (HCS). Recently, the suggestion has been made to further augment the fixation with the addition of a tension band (TB) in conjunction with the bone plate and HCS.[2] There have been no previous biomechanical evaluations of the stability of the CBLO fixation methods. It is unknown if similar biomechanical stability could be achieved in a CBLO construct secured by a plate alone, or a plate and tension band. This information would be valuable to aid the surgeon in limiting the number of implants used to only those required to achieve similar stability to avoid excess surgical implant cost, minimize surgical time, and minimize surgical trauma.

The objective of this study was to compare the biomechanical properties (stiffness, ultimate load, and yield load) of four constructs used to secure an osteotomy following a CBLO in an ex vivo model and identify the mode of failure for each fixation method. We hypothesized that the CBLO plate with a headless compression screw and tension band would provide the strongest construct.

Materials and Methods

Cadaveric Samples

Tibiae with patella and patellar tendons were collected from canines euthanized at a local humane society for reasons unrelated to this study. Study inclusion criteria were a body weight of 18–35 kg and radiographically confirmed skeletal maturity. Tibiae with open physes or osseous abnormalities noted on preoperative planning radiographs were excluded. An alphabetic label was assigned to each limb as each sample became available. Prior to completing any procedures, each alphabetic label was randomized to a construct group (Figure 2.1); CBLO plate and pin (Plate), CBLO plate with headless compression screw (HCS), CBLO plate with tension band (TB), or CBLO plate with HCS and TB (HCSTB) using a computer-generated randomization program (randomizer.org). Cadavers were frozen at -20°C until they were ready to be tested. Cadavers were thawed at room temperature for 6-24 hours, and tibiae were harvested, stripped of soft tissues other than the patellar ligament and patella, and tested within 48 hours of being removed from the freezer. When samples were not actively being prepared or tested, they were wrapped in saline-moistened towels at 4°C.

Application of Fixation Method

Preoperative radiographs were taken to determine the CORA, appropriate blade size, tibial plateau angle, and appropriate location for the osteotomy as previously described.[3] The primary author planned and performed all procedures. All implants used in this study were manufactured by the same company (Veterinary Orthopedic Implants, St. Augustine, Florida, USA). A CBLO was performed, and a fixation was applied according to the assigned treatment group. An oscillating saw with a crescentic blade was used to create a bi-radial osteotomy in the proximal tibia centered on the CORA. The proximal tibia was rotated to decrease the TPA to 9-12° and align the proximal and distal weight-bearing axis of the tibia as described by Raske et. al.[3] A 1.6 mm (0.062”) anti-rotational pin was placed at the level of insertion of the patellar tendon to maintain reduction while the osteotomy was secured via one of the four previously listed methods.

The CBLO plates were secured with five 3.5 mm locking screws and one 3.5 mm cortical screw placed in compression. In the indicated treatment groups, a 4.5 mm cannulated HCS was placed across the osteotomy at the level of the insertion of the patellar tendon in a cranioproximal to caudodistal orientation such that it exited the caudomedial cortex of the tibia, as described by Raske et al.[3] When a TB was a component of the fixation, it was placed after the plate and HCS were secured.

The anti-rotational pin was cut flush with the tibia after the construct was completed in the Plate group. In the HCS group, this pin was used as the guide pin for placement of the HCS. In the TB group, an additional 1.6 mm (0.062”) pin was driven parallel to the anti-rotational pin, and both pins served as the proximal fixation point of the TB. In the HCSTB group, the anti-rotation pin served as the guide for the HCS, and two separate 1.6 mm pins were placed parallel to and approximately 5 mm distal to the HCS. The distal anchor point of the TB was a bone tunnel created by driving a 1.6 mm pin in a medial to lateral fashion, immediately cranial to the CBLO plate, and approximately equidistant to the osteotomy compared to the proximal fixation points. Tension bands were constructed from 18-gauge orthopedic wire with a twist knot on each side of the figure eight, twisted until palpably tight as would occur in a clinical scenario (Figure 2.1).

Biomechanical Testing

The distal tibiae were potted in a 1.5” diameter PCV pipe with poly methyl methacrylate (PMMA) to facilitate placement in a jig. A clamp was used to secure the patella and patellar tendon, such that the apex of the patella was included in the clamp. The jig was configured to hold the tibia and patellar tendon at 135° to simulate the mid-stance weight-bearing angle of the patellar ligament in dogs (Figure 2.2).[4]

Vertical distraction force was applied to the patella and patellar tendon via a universal testing machine (Model MTI K2, Measurement Technology Inc., Marietta, GA). A preload of 20 N was applied, and the construct was then loaded at a displacement rate of 20 mm/min until failure of the construct was observed. Stiffness (N/mm) was defined as the slope of the linear portion of the load-displacement curve. Yield load was defined using an offset method of 1.5 mm displacement for samples that had plastic deformation prior to failure.[5,6] For samples with no plastic deformation prior to failure (those that underwent acute failure), the yield load was defined as the ultimate load. Ultimate load (N) was the maximum load applied during a test (Figure 2.4).

The mode of failure was recorded for each specimen. Data was inadvertently lost for two samples by accidentally overwriting the information collected from these samples. These samples were replaced in alphabetic order by the next available sample that had not already been assigned a treatment group.

Statistical Analysis

Using data from a similar biomechanical study,[4] it was determined that 8 samples per group would be adequate to achieve a power of 0.80 and alpha of 0.05. To calculate the sample size, an estimate of the standard deviation of the mean load at failure for the phase I TPLO group using G*Power 3.1 software (Faul F, Erdfelder E, Lang AG, et al. 2007. G*Power 3: A flexible statistical power analysis for the social, behavioral, and biomedical sciences. Behav Res Meth 39:175-191).[7] Assuming an alpha level of 0.05, power of 0.80, and a two-tail test, it was estimated a sample size of 8 tibias per treatment group would allow the detection of a difference of 500 N or greater between groups.

The effect of construct on stiffness, yield load, and ultimate load were assessed separately by linear models using the mixed procedure of SAS for Windows v9.4 (SAS Institute Inc., Cary, NC). Tibias were considered independent when randomly allocating constructs rather than blocking by dog. Body weight was considered the most important dog-specific factor and was, therefore, included as a covariate in the models. If the construct by weight interaction was not significant, the interaction was dropped from the model and re-assessed with construct and weight as explanatory variables. Differences in least squares means were used to make pairwise comparisons between constructs using a Tukey adjustment to account for multiple comparisons. Visual assessment of the residuals was used to determine whether the assumptions of normality and homoscedasticity were met. The level of significance was set at an alpha of 0.05.

Results

Data were collected from 32 tibiae from 17 mixed-breed dogs (Table 1, Figure 2.5). Yield load was higher for the HCSTB group when compared to the HCS group (p=0.0311), and the HCSTB group compared to the Plate group (p=0.0042). Ultimate load was also higher when comparing the HCSTB group to the HCS group (p=0.0025), the HCSTB group to the Plate group (p=0.0002), and the HCSTB group to the TB group (p=0.0456).

There were no differences in yield load for: HCS vs. plate, HCS vs. TB, HCSTB vs. TB, and Plate vs. TB (p = 0.6004, p = 0.6869, p = 0.2334, p = 0.1459 respectively). There were no differences in ultimate load for: HCS vs. Plate, HCS vs. TB, and Plate vs. TB (p = 0.4952, p = 0.5351, p = 0.0661 respectively). Body weight of the dog did not influence construct stiffness (p = 0.6681), ultimate load (p = 0.6793), and yield load (p = 0.9991). There was no difference detected in construct stiffness between fixation methods (p = 0.6937).

All HCS constructs failed by fracture through the HCS hole. All Plate constructs failed by displacement of the tibial tuberosity followed by fracture through the most cranial screw hole in the proximal tibia. All TB constructs failed by progressive stretching of the TB, widening of the osteotomy cranially, and subsequent fracture through the most cranial screw hole in the proximal tibia. All HCSTB constructs failed by progressive stretching of the TB, widening of the osteotomy cranially, and subsequent fracture through the HCS hole.

Discussion

In this study, the ultimate load of the HCSTB was greater than those of the HCS, TB, and Plate groups, while the yield load of the HCSTB was greater than the HCS, and Plate groups, but not different than the TB group. The stiffness was not different among groups. The body weight of the animal was accounted for in our statistical model and did not differ between groups. Stiffness is defined as the extent to which an object resists deformation in response to an applied force. Interestingly, there was no difference in stiffness between the construct groups. The load displacement curve for each sample has a variable “toe region” (Figure 2.3). The “toe region” of the curve likely reflects the elongation of the patellar tendon as the load was applied by the testing apparatus. A preload of 20 N was applied to each sample. The time between preload and application of our testing forces was not measured as a part of the study but is estimated to be less than 1 minute in each case. This time may have allowed a variable degree of stress relaxation of each tendon prior to the test force being applied. The patellar tendon and patella were included in the jig's clamp to the level of the patellar apex for each sample. However, the working length of the patellar tendon (between the clamp and the tibial tuberosity) subjectively varied between samples, and likely corresponded to the body weight of the dog. Longer patellar tendons may allow for greater displacement before becoming fully stretched and transmitting the load to the bone. Although not objectively measured by our study, subjective real-time observations indicated that the tibial tuberosity did not undergo significant displacement during the "toe region" of the curve. This suggests that displacement on the curves accounts for both the displacement that occurs at the level of the patellar tendon as it is stretched, as well as changes occurring at the level of the bone and implants. Given this information, displacement from these curves alone should not be used to determine a point of clinical failure. This could be considered a limitation of this study, however measuring displacement at the level of the osteotomy, or determining a point of clinical failure was not an outcome established at the outset of the study. The following data points were not radiographically documented on every specimen and may be considered a limitation of this study: actual postoperative TPA, and size of tibial crest available for implants. Given that the CBLO procedures performed were consistent with that of clinical cases the authors' feel that the TPA values are not relevant to the outcomes measured in this study.

The true magnitude of the force created by the quadriceps mechanism on the tibial tuberosity in a normal dog is unknown. However, using three-dimensional biomechanical modeling of the canine pelvic limb, Shahar and Banks-Sills estimated the force of the quadriceps muscles during the stance phase of the walk as up to 94.8% of body weight.[8] Our samples were from dogs weighing 18 to 35 kg. Applying this model, our samples would be expected to experience approximately between 170 and 325 N from the quadriceps muscles. All samples in our study withstood at least 542 N. This suggests that all four construct types would adequately resist the peak distractive forces generated by the quadriceps mechanism on the tibial tuberosity postoperatively; however, clinical cases suggest that fixation by CBLO plate alone risks catastrophic failure. It has been assumed that an HCS is required to oppose the forces of the quadriceps muscles and avoid catastrophic failure in a CBLO construct. Interestingly, the HCS was not different than the TB, or Plate constructs in terms of yield load or ultimate load. The HCSTB construct was superior in terms of both yield and ultimate load. The definition of clinical failure for these implants has not been established and data regarding the frequency or mode of failure of each fixation method in clinical cases are not available. This study suggests that the HSCTB construct would provide the strongest construct.

Postoperative TPA shift is a reported complication of the CBLO.[3,9,10,11,12] This complication is attributed to the pull of the quadriceps mechanism on the tibial tuberosity during muscle contraction. However, Johnson et al. reported no change in TPA in 49 cases of CBLO fixation with HCS and TB.[2] It is possible that the early bony healing observed in that study led to a shorter window of vulnerability to this complication. In vivo, the pull of the quadriceps mechanism is cyclic, and that cyclic force would cause cyclic fatigue of the implants used to secure the osteotomy. Pin and wire constructs, such as a tension band, would be expected to be more susceptible to plastic deformation from this dynamic loading than screws or plates would.[13]

The ex vivo nature of our model did not allow us to capture and compare TPA shift among the fixation groups.

Mode of failure was consistent within groups but varied between each group. Ultimately, all constructs failed by fracture of the bone through the most cranial screw hole in the proximal tibial segment. In cases of the constructs that included a HCS (HCSTB and HCS groups), this was through the HCS hole, and for those without an HCS (TB and Plate groups) failure was through the most cranial and proximal screw associated with the plate. This seems logical as both types of screw implants represent a relatively large defect in a small section of bone. The Plate group showed progressive proximal displacement of the tibial tuberosity and subsequently fractured at the most cranial screw in the proximal tibia. Similarly, the TB group showed progressive stretching of the TB and displacement of the tibial tuberosity until subsequent fracture at the most cranial screw in the proximal tibia. These modes of failure are also logical, as the pins are much smaller and smooth, which allowed the bone to slide along the pins as the tibial tuberosity became progressively displaced. No construct failed at the level of the patellar tendon, indicating that the limiting factor to resisting the distractive pull on the patellar tendon was the construct, not the tendon itself.

A limitation of this ex vivo model may be that it does not account for all forces experienced by the postoperative patient in the convalescent period, such as cyclic fatigue or physiologic loading. However, the authors believe the model replicates the pull of the quadriceps mechanism on the patellar tendon and effectively tests the ability of the implants to resist the load on the proximal tibia generated by the quadriceps.

Tables and Figures

Table 2.1 Least squares mean (95% confidence interval) for stiffness, yield load, and ultimate load for each construct group.

Biomechanical Properties by Construct Group			
Construct	**Stiffness, N/mm**	**Yield Load, N**	**Ultimate Load, N**
Plate	117[a] (98.1-136.4)	788[a] (639.5-936.0)	774[a] (608.4-940.3)
HCS	117[a] (99.9-135.5)	907[a] (769.6-1044.9)	927[a] (772.6-1080.7)
TB	109[a] (90.8-128.6)	1016[ab] (870.2-1162.6)	1076[a] (912.8-1240.0)
HCSTB	125[a] (105.7-145.0)	1212[b] (1059.9-1363.3)	1388[b] (1218.1-1557.6)

HCS, headless compression screw group; HCSTB, headless compression screw and tension band group; Plate, bone plate; TB, tension band group. Means within a column that share the same letter superscript are not significantly different ($p>0.05$).

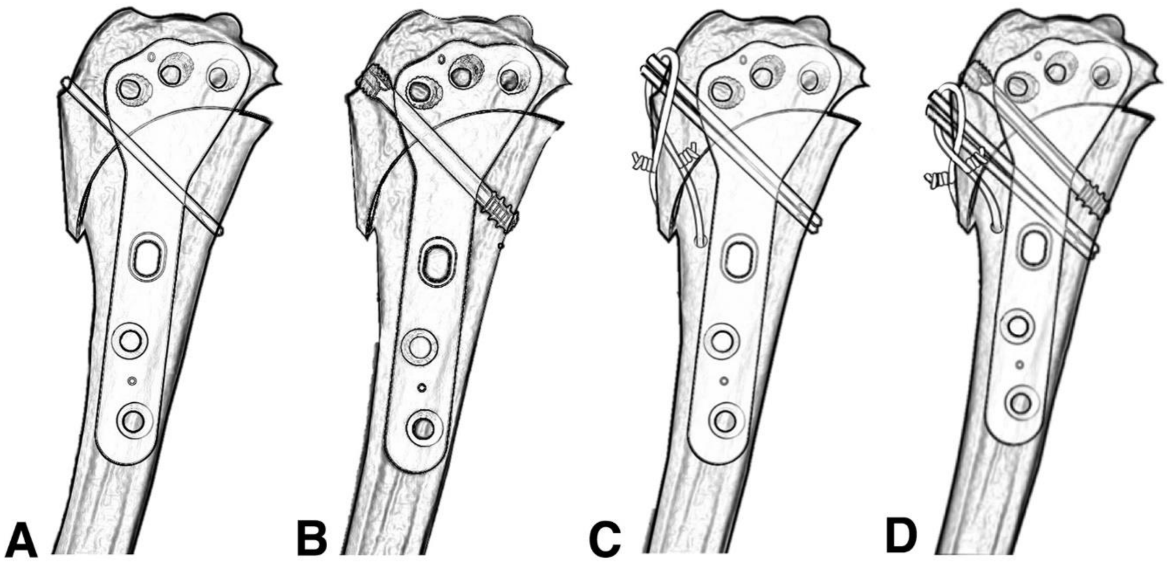

Figure 2.1 Digital sketches of each construct group.

A. Plate construct. B. Headless compression screw (HCS) construct. C. Tension band (TB) construct. D. Headless compression screw with tension band (HCSTB) construct.

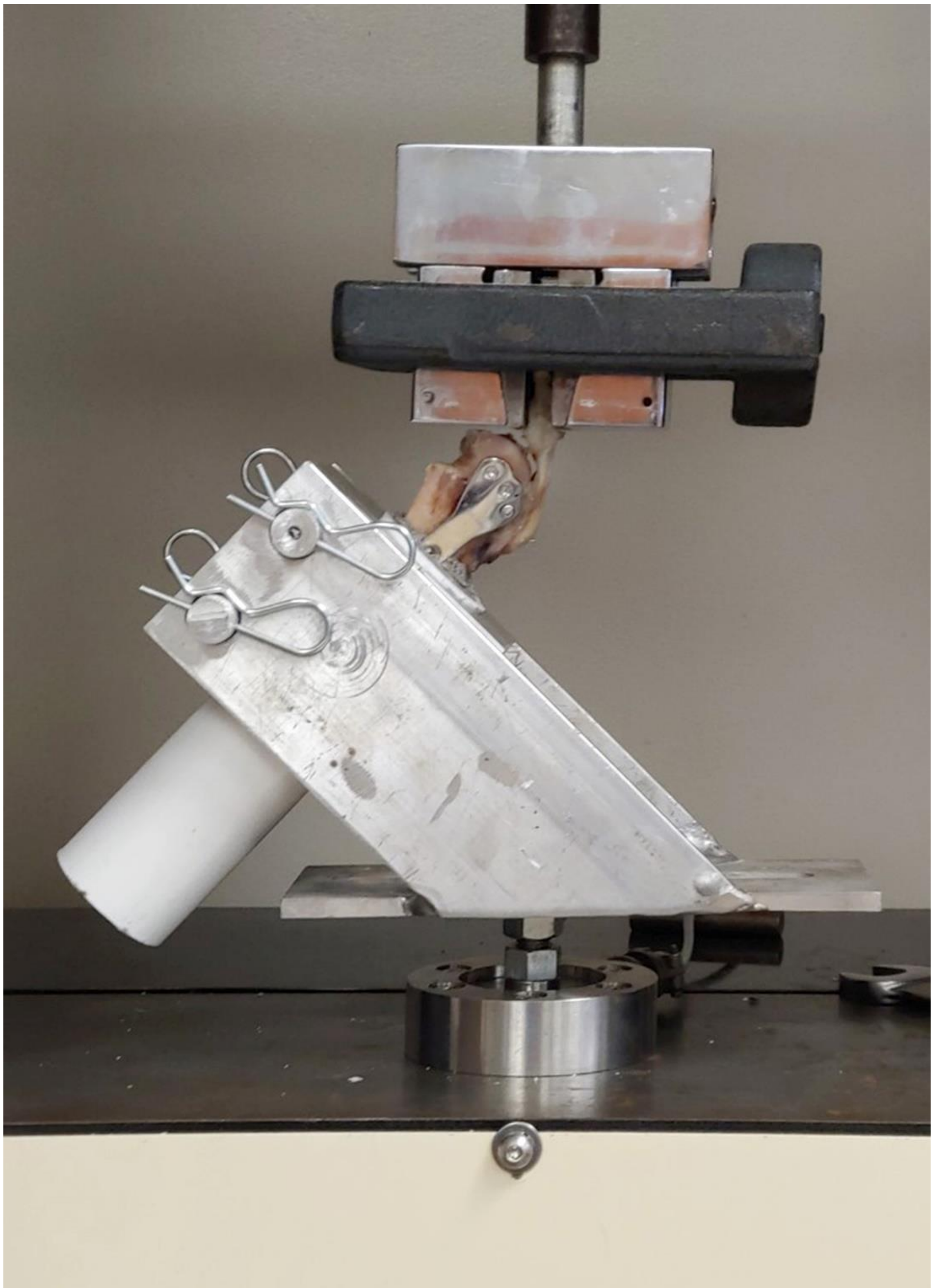

Figure 2.2 Testing apparatus, including the potted tibia loaded in jig, attached to the load cell prior to testing.

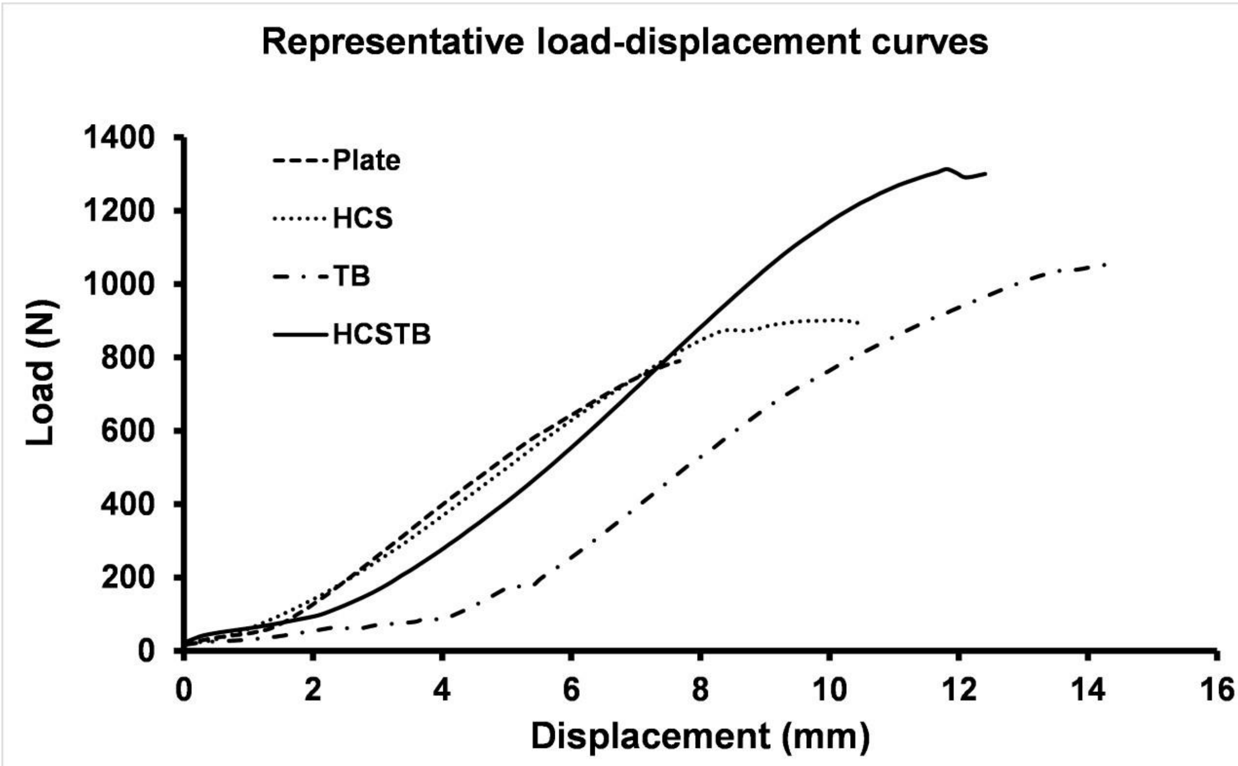

Figure 2.3 Typical load deformation curves of each construct group.

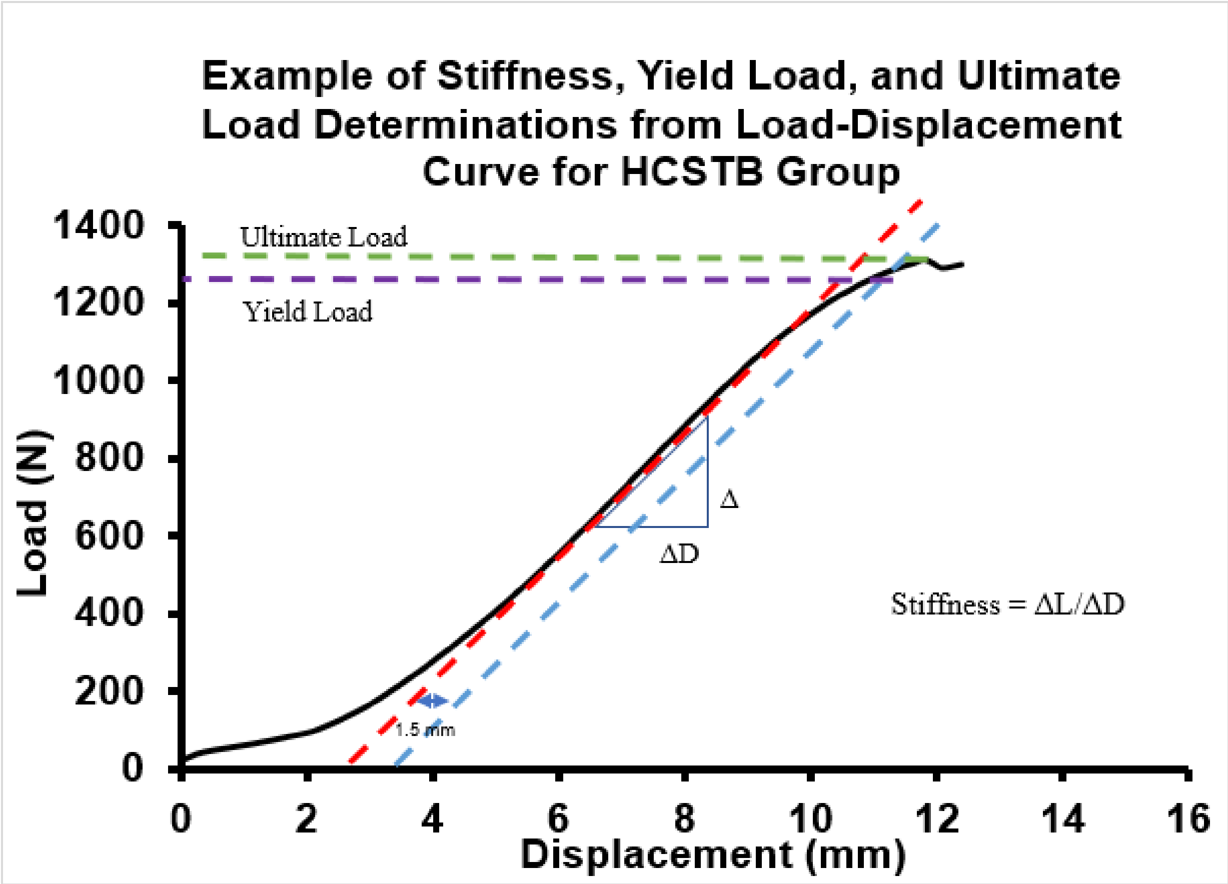

Figure 2.4 Sample stiffness calculation.

This is a visual representation of the stiffness calculations used. The green dashed line represents the ultimate load. The purple dashed line represents the yield load. The red dashed line represents the slope of the flat portion of the load displacement curve. The blue dashed line represents the 1.5 mm offset line used to determine yield load in cases with plastic deformation. Stiffness (N/mm) was defined as the slope of the linear portion of the load-displacement curve and is calculated as the change in load divided by the change in displacement.

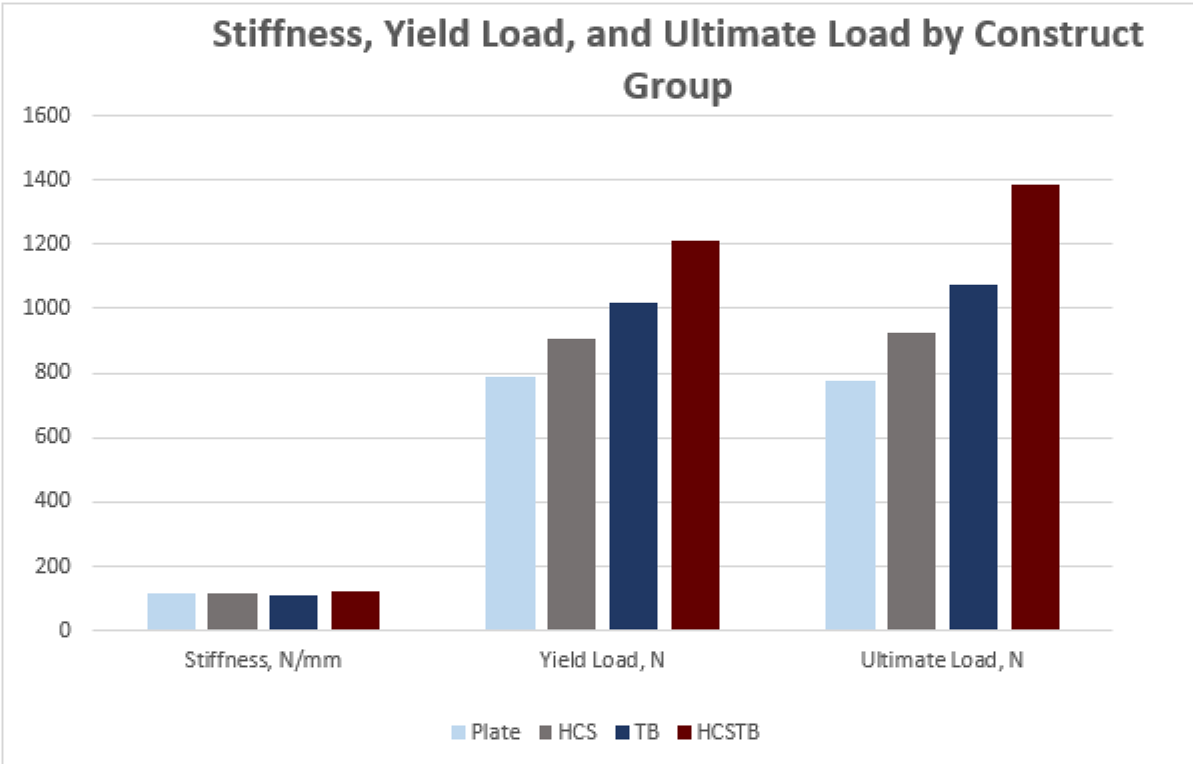

Figure 2.5 Stiffness, Yield Load, and Ultimate Load by Construct Group

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CHAPTER III

CONCLUSION

In conclusion, the HCSTB fixation method confers a clear biomechanical advantage in terms of yield load and ultimate load. Future studies could consider evaluating the frequency and mode of implant failure in clinical CBLO cases, the degree of compression achieved with each fixation method, and the surgical time required for the application of each fixation method.