Received: 3 January 2023 | Revised: 21 April 2023 | Accepted: 29 May 2023
DOI: 10.1111/vsu.13981

CLINICAL RESEARCH

WILEY

Morphologic impact of four surgical techniques to correct excessive tibial plateau angle in dogs: A theoretical radiographic analysis

Ashton L. Story DVM, DACVS | **Bryan T. Torres DVM, PhD, DACVS, DACVSMR** | **Derek B. Fox DVM, PhD, DACVS**

Department of Veterinary Medicine and Surgery, University of Missouri, Columbia, Missouri, USA

Correspondence
Derek B. Fox, Veterinary Health Center, University of Missouri, Columbia, MO 65211, USA.
Email: foxdb@missouri.edu

Abstract

Objective: To determine morphologic differences between four tibial osteotomy techniques used to correct excessive tibial plateau angle (eTPA).

Study design: Retrospective radiographic analysis.

Sample population: Sixteen dogs (27 tibias) with eTPA.

Methods: Virtual corrections of eTPA were performed on sagittal plane radiographs of canine tibia using four tibial osteotomy techniques and categorized into respective groups. Group A represented the center of rotation of angulation (CORA)-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO), Group B the tibial plateau leveling osteotomy (TPLO) and CCWO, Group C the modified CCWO (mCCWO), and Group D the proximal tibial neutral wedge osteotomy (PTNWO). Pre- and post-correction TPA, tibial length and mechanical cranial distal tibial angle (mCrDTA) were measured and compared.

Results: Mean TPA prior to correction was $42.67 \pm 6.1°$. Post-correction mean TPAs were $10.47 \pm 2.1°$, $6.77 \pm 1.6°$, $4.76 \pm 1.5°$, and $7.09 \pm 1.3°$ for Groups A, B, C, and D, respectively. TPA correction accuracy in Groups A and D varied least from target TPAs. Tibial shortening was documented in Group B in contrast to other groups. The greatest mechanical axis shift was identified in Group A.

Conclusion: Each technique achieved TPA $< 14°$ despite having different effects on tibial morphology including alteration of tibial length, mechanical axis shift and variation in correctional accuracy.

Clinical significance: Despite all methods being able to correct eTPA, the choice of technique will affect morphology in unique ways and should be considered prior to surgery to consider the implications in a given patient.

Abbreviations: ACA, angulation correction axis; CORA, center of rotation of angulation; CBLO, CORA-based leveling osteotomy; CCWO, cranial closing wedge osteotomy; eTPA, excessive tibial plateau angle; JOL, joint orientation lines; mCCWO, modified cranial closing wedge osteotomy; mCrDTA, mechanical cranial distal tibial angle; PTNWO, proximal tibial neutral wedge osteotomy; TPA, tibial plateau angle; TPLO, tibial plateau leveling osteotomy.

Presented in abstract form at the World Veterinary Orthopaedic Congress and Veterinary Orthopedic Society Conference in Snowmass, Colorado, February 6, 2022.

1 | INTRODUCTION

Tibial plateau leveling osteotomy (TPLO) is the most widely accepted surgical technique performed for the cranial cruciate-deficient stifle in canines.[1,2] The objective of the TPLO is to mitigate cranial tibial subluxation through the performance of a corrective osteotomy that reduces the tibial plateau angle (TPA). A feature of the TPLO is that when the radial osteotomy is centered over the proximal tibial mechanical axis point, cranial tibial thrust is neutralized and tibial length is unaltered.[3,4] While the average TPA for most dogs is ~27°, a small subset of dogs with cranial cruciate ligament disease has an excessive TPA (eTPA) defined as being greater than 34°.[5] Negative ramifications of attempting to treat eTPA with a conventional TPLO have been reported including tibial tuberosity fracture and under-correction of the TPA.[6]

A variety of alternative osteotomy techniques have been described to mitigate tibial subluxation following cranial cruciate ligament injury with concurrent eTPA. These techniques include combination center of rotation of angulation (CORA)-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO),[7] combination TPLO and CCWO,[5] modified CCWO (mCCWO),[8] and proximal tibial neutral wedge osteotomy (PTNWO).[9] Similar to the TPLO, the goal of these techniques is to mitigate cranial tibial subluxation through corrective osteotomy while minimizing morphologic change to the tibia. It is still undetermined which technique best achieves these goals. The purpose of this study was to determine morphologic differences (TPA, tibial length and mechanical axis) between these four reported techniques when performing them virtually using orthopedic planning software. We hypothesized that no differences in post-correction tibial morphologic measurements including TPA, tibial length and mechanical axis shift would exist between techniques.

2 | MATERIALS AND METHODS

Medical records were retrospectively reviewed from 2004 to 2020 searching the terms "excessive tibial slope," "wedge osteotomy", and "wedge ostectomy." Dogs greater than 15 kg in weight, diagnosed with cranial cruciate ligament disease based on physical and radiographic examination findings that possessed a TPA > 34° on preoperative planning radiographs were included in the study. Data collected included signalment, bodyweight, and affected stifle.

Measurements and virtual corrections were performed on standardly positioned pre-TPLO mediolateral radiographs of the tibia with the stifle and tarsal joints positioned at 90° of flexion. Dedicated orthopedic planning software (vPOP-pro, version 2.4.3[158], VetSOS Education Ltd., veterinary preoperative orthopedic planning software) was used to perform the virtual corrections on each tibia following four previously described surgical techniques: Group A: combination CBLO and CCWO,[7] Group B: combination TPLO and CCWO,[5] Group C: mCCWO,[8] and Group D: PTNWO.[9]

Images were calibrated to either a 25 or 30 mm marker ball depending on the year the radiograph was obtained. The mechanical axis of the tibia in the sagittal plane was measured from the midpoint of the intercondylar eminences proximally to the center of the talus distally.[10] Tibial length was measured from the mechanical axis as the distal intermediate ridge utilized in other studies is often obscured by the trochlear ridges of the talus.[11–13] Joint orientation lines (JOL) were determined for the proximal and distal tibia in the sagittal plane using previously described landmarks.[10] The mechanical cranial distal tibial angle (mCrDTA) was measured as the cranioproximal angle between the mechanical axis and the distal JOL in the sagittal plane.[10] TPA was measured between the proximal tibial JOL and a line perpendicular to the mechanical axis.[14] Tibial length, mCrDTA, and TPA were measured before and after each virtual correction by a single investigator (A.L.S.).

2.1 | Brief description of corrective techniques

All techniques described in their respective original source documentation (abstract, manuscript or textbook chapter) including procedure-specific post-correction target TPAs.[5,7–9]

2.1.1 | CBLO + CCWO[7]

The proximal JOL was drawn (Group A, Figure 1). A proximal caudal tibial angle (PCdTA) signifying the desired post-correction TPA of 11°, was utilized to determine the position of a proximal mid-diaphyseal anatomic axis.[15,16] A distal, mid-diaphyseal anatomic axis was drawn.[15,16] The intersection of the proximal and distal anatomic axes determined the location and magnitude of the CORA. A radial saw blade template with a diameter slightly larger than that of the bone was chosen and centered over the CORA.[15] A second radial saw blade template was drawn and translated slightly caudodistal from the first, converging at the caudal tibial cortex. The cranial aspect of the distal radial osteotomy was adjusted until a 15° cranial wedge was achieved. A 15° coplanar

CCWO was performed in the proximal tibial metaphysis, and the proximal segment was reduced by the software. The remaining correction (CORA-15°) was performed along the double radial osteotomies with the objective of achieving a post-correction TPA of 11°.

FIGURE 1 Group A-combination center of rotation of angulation (CORA)-based leveling osteotomy and coplanar cranial closing wedge ostectomy. Radial saw blade templates are centered at the CORA with a resultant 15° cranial wedge. Group A was planned to a target tibial plateau angle of 11°. Image created using vPOP-pro.

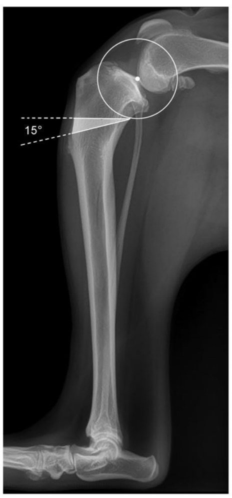

FIGURE 2 Group B-combination tibial plateau leveling osteotomy (TPLO) and cranial closing wedge osteotomy. A TPLO template is centered at the intercondylar eminence. A 15° cranial closing wedge was positioned at the base of the TPLO cut with the proximal arm oriented perpendicular to the tibial crest and the apex of the triangle at the caudal tibial cortex. Group B was planned to a target tibial plateau angle of 5°. Image created using vPOP-pro.

2.1.2 | TPLO + CCWO[5]

A radial saw blade template was chosen per traditional methods: one sized to accommodate the desired plate and large enough to avoid offending the articular surface while maintaining a tibial tuberosity width of at least 10 mm at its narrowest point (Group B, Figure 2).[17,18] The radial saw blade template was then centered over the intercondylar eminences. A 15° cranial closing wedge ostectomy was positioned at the base of the TPLO cut with the proximal arm oriented perpendicular to the tibial crest and the apex at the caudal tibial cortex and executed. The remaining correction ([TPA-15°]−5°) was performed by cranial rotation of the tibial plateau segment along the radial osteotomy with the objective of achieving a target TPA of 5°.

2.1.3 | mCCWO[8]

The distal arm of a closing wedge ostectomy was oriented perpendicular to the mechanical axis of the tibia in the sagittal plane (Group C, Figure 3). The proximal osteotomy was positioned 3 mm distal to the patellar ligament insertion on the cranial cortex, intersecting with the distal osteotomy at a wedge angle equal to the preoperative TPA. The distal osteotomy line was transposed until it intersected the proximal osteotomy

FIGURE 3 Group C-modified cranial closing wedge osteotomy. The distal arm of the wedge osteotomy was oriented perpendicular to the mechanical axis of the tibia in the sagittal plane. The proximal osteotomy was positioned just distal to the patellar ligament insertion, intersecting the distal osteotomy at a wedge angle equal to the pre-operative tibial plateau angle. The distal osteotomy line was transposed until it intersected the proximal osteotomy at about 66% of its length from the cranial cortex of the tibia. Image created using vPOP-pro.

at a point 66% of its length from the cranial cortex of the tibia. The wedge was excised, and the ostectomy reduced by the software. The proximal tibial segment was then translated caudally to align the cranial cortices. The described post-correction target TPA of the technique was 0°.[8]

2.1.4 | PTNWO[9]

The proximal tibial JOL was determined (Group D, Figure 4). Next, a proximal mechanical axis was drawn to pass through the intercondylar eminences and intersect with the JOL to reflect a mechanical caudal proximal tibial angle (mCaPTA) of 83.5° (Figure 4A). This corresponded with a target TPA of 6.5°.[19] A distal tibial mechanical axis was drawn from the center of the tibiotalar joint to maximally overlie the caudal cortex of the proximal tibial metaphysis, overlying the caudal cortex at this level. This axis was so determined by mimicking the post-correction position of the tibial mechanical axis following a standard TPLO. The CORA location and magnitude were then determined from the intersection of the proximal and distal mechanical axes (Figure 4B). This intersection point between the two axes also represented the location of the angulation correction axis (ACA). The ACA is the hinge axis that the angular correction is centered around. When the ACA passes through the CORA, this point can be termed the ACA-CORA.[20] Next, a proximal osteotomy was drawn parallel to the proximal JOL and positioned 3 mm distal to the patellar ligament insertion on the cranial cortex. The distal osteotomy was drawn such that it intersected the proximal osteotomy at an angle equal to the magnitude of the CORA (Figure 4C). The distal osteotomy line was then transposed proximally until the diameter of the tibia at that level was equal to the length of the proximal osteotomy from the cranial cortex to the point of intersection. The ostectomy was performed and the proximal segment rotationally realigned pivoting around the ACA-CORA by the software (Figure 4D).

2.2 | Statistical analysis

For comparison between groups, a percent change from baseline (%CFB) was used to assess tibial length and mechanical cranial distal tibial angle (mCrDTA) which served as an indicator of mechanical axis shift. The TPA correction accuracy for each procedure was calculated by dividing the actual TPA change (preoperative TPA minus postoperative TPA) by the intended change in TPA (preoperative TPA minus the target TPA). After assessing for normality, techniques were compared with a one-way ANOVA with Tukey's multiple comparisons test. Data analysis was performed with statistical software

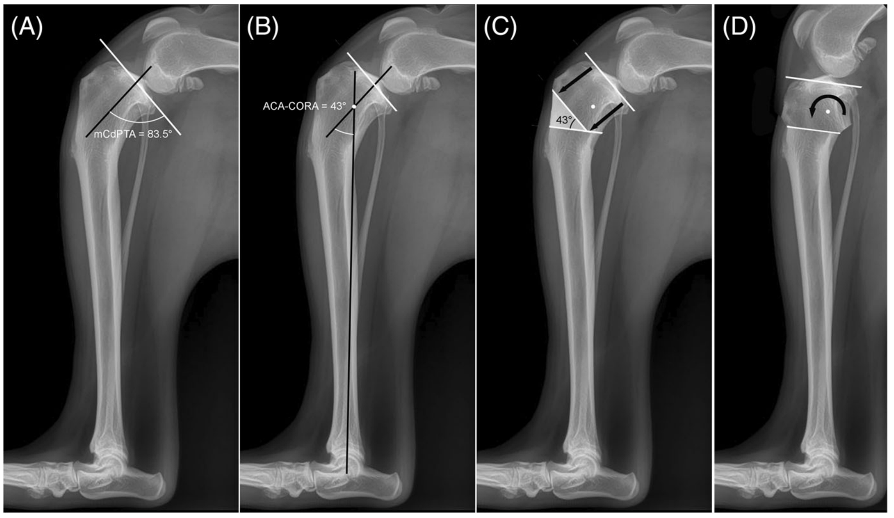

FIGURE 4 Group D-proximal tibial neutral wedge osteotomy. (A) The proximal tibial joint orientation line (JOL) (white) and a proximal mechanical axis (black) were drawn to reflect a mechanical caudal proximal tibial angle (mCaPTA) of 83.5°. (B) A distal tibial mechanical axis (black) was drawn from the center of the tibiotalar joint distally as usual, but overlying the caudal cortex of the proximal tibial metaphysis proximally. The angulation correction axis (ACA)-center of rotation of angulation (CORA) (white dot) location and magnitude were then determined from the intersection of the proximal and distal mechanical axes. (C) A proximal osteotomy was drawn parallel to the proximal JOL and positioned 3 mm distal to the patellar ligament insertion. The distal osteotomy was drawn such that it intersected the proximal osteotomy at an angle equal to the magnitude of the CORA. (D) The ostectomy was performed and reduced around the ACA-CORA, resulting in translation of the segments, but maintaining collinearity.

(GraphPad Prism, GraphPad Software, San Diego, California) with significance set to $p < .05$.

3 | RESULTS

Sixteen dogs (27 tibias) met the inclusion criteria for the study. Mean age at presentation was 3.1 years (range, 1.5–6.1 years) and mean bodyweight was 35.3 kg (range, 15.3–69 kg). There were nine castrated males and seven spayed females. Breeds represented were mixed breed ($n = 5$), Golden retriever ($n = 2$), Great Pyrenees ($n = 2$), Rottweiler ($n = 2$), and one each of Greater Swiss mountain dog, English bulldog, Siberian husky, Australian cattle dog, and beagle. Eleven dogs were bilaterally affected with five cases unilaterally affected based on available imaging.

The mean precorrection TPA was 42.67 ± 6.1° for all tibias. Mean post-correction TPA was 10.47 ± 2.1° for Group A, 6.77 ± 1.6° for Group B, 4.76 ± 1.5° for Group C, and 7.09 ± 1.3° for Group D (Figure 5). There was no difference in post-correction TPA between Groups B and D ($p = .895$), but differences did exist between all other groups.

When assessing for TPA correction accuracy, numbers >1.00 represented over-correction while numbers <1.00 represented under-correction of TPA. Mean TPA accuracy was 1.02 ± 0.07 for Group A, 0.95 ± 0.04 for Group B, 0.89 ± 0.03 for Group C, and 0.98 ± 0.04 for Group D. Groups A and D had the least variation from their respective target TPA's and differed from each other ($p = .02$) (Figure 6). Groups B, C and D resulted in under-correction of TPA to varying degrees while Group A slightly over-corrected.

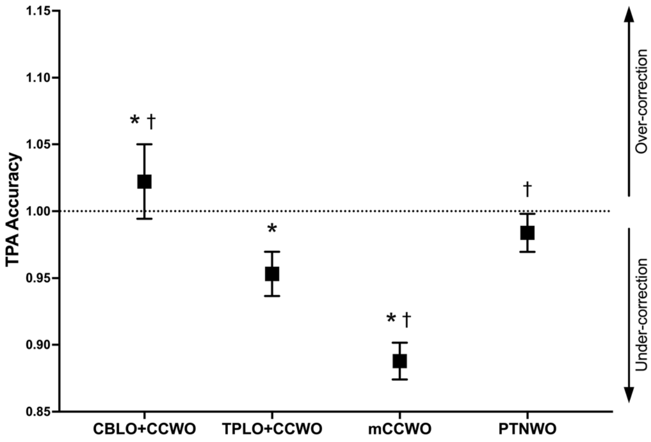

FIGURE 6 Tibial plateau angle (TPA) correction accuracy following four tibial osteotomy procedures. Values are depicted in degrees, as mean (95% confidence interval). Procedures with similar symbols (*, †) are different from each other ($p < .05$). Combination center of rotation of angulation-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO); combination TPLO and CCWO; modified CCWO (mCCWO); proximal tibial neutral wedge osteotomy (PTNWO).

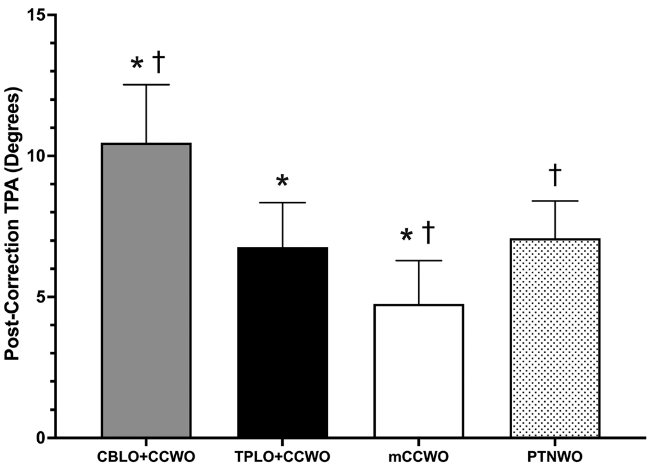

FIGURE 5 Post-correction tibial plateau angle (TPA) following four tibial osteotomy procedures. Values are depicted in degrees, as mean (95% confidence interval). Procedures with similar symbols (*, †) are different from each other ($p < .05$). Combination center of rotation of angulation-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO); combination TPLO and CCWO; modified CCWO (mCCWO); proximal tibial neutral wedge osteotomy (PTNWO).

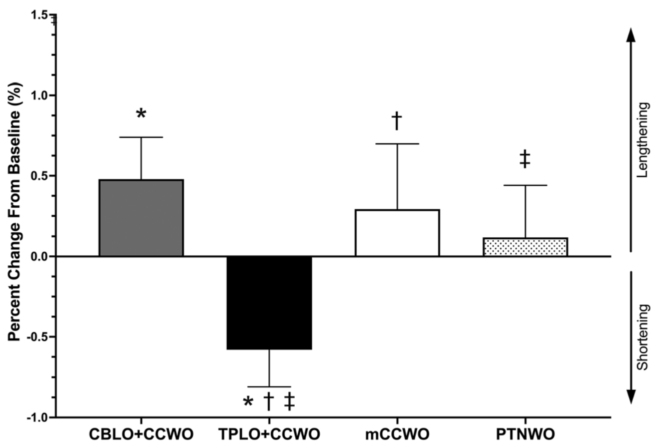

FIGURE 7 Change in tibial length following four tibial osteotomy procedures. Values are depicted in percentages, as mean (95% confidence interval). Procedures with similar symbols (*, †, ‡) are different from each other ($p < .05$). Combination center of rotation of angulation-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO); combination TPLO and CCWO; modified CCWO (mCCWO); proximal tibial neutral wedge osteotomy (PTNWO).

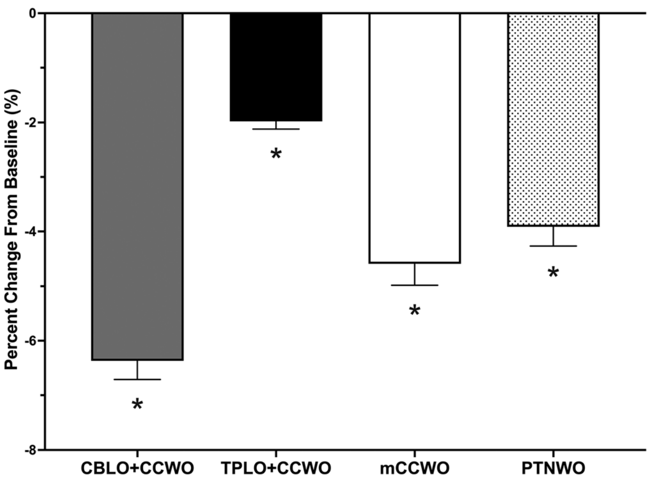

FIGURE 8 Change in mechanical cranial distal tibial angle. Values are depicted in percentages, as mean (95% confidence interval). Procedures with similar symbols (*) are different from each other ($p < .05$). Combination center of rotation of angulation-based leveling osteotomy (CBLO) and coplanar cranial closing wedge ostectomy (CCWO); combination TPLO and CCWO; modified CCWO (mCCWO); proximal tibial neutral wedge osteotomy (PTNWO).

When assessing changes in tibial length, a positive change from baseline corresponded with tibial lengthening while a negative change corresponded to tibial shortening. Mean percent change in tibial length from baseline was 0.48% ± 0.66% for Group A, −0.58% ± 0.58% for Group B, 0.29% ± 1.03% for Group C, and 0.12% ± 0.81% for Group D. Change in tibial length was different between Group B and each of the other groups. Group B resulted in shortening of the tibia compared to each of the other groups (Figure 7).

Mean percent change in mCrDTA from baseline was −6.37% ± 0.86% for Group A, −1.98% ± 0.36% for Group B, −4.59% ± 1.0% for Group C, and − 3.91% ± 0.88% for Group D, with negative numbers corresponding to a cranial mechanical axis shift. All techniques caused a cranial mechanical axis shift following virtual correction. Change in mCrDTA was different between all groups. Group A demonstrated the greatest deviation and thus the greatest mechanical axis shift, while Group B demonstrated the least deviation (Figure 8).

4 | DISCUSSION

Based on these results, we rejected our hypothesis as the described surgical techniques resulted in different effects on post-correction TPA and tibial morphology. While predictability of post-correction TPA appears to be best in Groups A (CBLO + CCWO) and D (PTNWO), all groups achieved clinically acceptable TPAs.[21] Although an optimal postoperative TPA has yet to be determined, Robinson and colleagues did not find a difference in ground reaction forces among Labrador retrievers following TPLO with a postoperative TPA between 0 and 14°.[21] Furthermore, a TPA threshold of ≤14° has been associated with superior owner-perceived outcome following TPLO for dogs with eTPA compared to a postoperative TPA > 14°.[6] Based on the discrepancies in the literature regarding the determination of an ideal target TPA, additional research that corroborates the proposed clinically acceptable TPA range is needed.

As each procedure varied in the method of TPA reduction, we utilized the target TPAs (CBLO + CCWO = 11°; TPLO + CCWO = 5°; mCCWO = 0°; PTNWO = 6.5°) described by the respective authors,[5,7–9] rather than applying a single target TPA to all corrections. The calculation of TPA correction accuracy allowed us to compare variation across techniques by incorporating each procedure's specific target TPA.

The mean postoperative TPA ranged from 4.76 to 10.47° in the present study. Clinical outcome studies are available for those techniques represented by Groups A, B and C. Specifically, these studies report that the TPLO + CCWO's desired post-correction TPA is 5° with the mean clinical postoperative TPA of 8°, the CBLO + CCWO desired TPA is 9–13° with the mean clinical postoperative TPA of 10° and the mCCWO technique targets a TPA of 0° with a clinically obtained mean postoperative TPA of 8.3 ± 4.8°.[5,7,8]

Mean post-correction TPA in the current study was 10.47 ± 2.1° for Group A, 6.77 ± 1.6° for Group B, 4.76 ± 1.5° for Group C, and 7.09 ± 1.3° for Group D. Results between the previously reported studies and Groups A and B were similar (mean post-correction TPAs within 2°), whereas there was a slightly greater deviation between the reported clinical postoperative TPA using mCCWO and Group C (~3.5°).

Multiple studies have demonstrated that CCWO tends to under-correct TPA, and in general, it is more challenging to achieve intended reduction of the tibial plateau in cases with eTPA.[11,13,22,23] More specifically, Bailey et al. demonstrated that a distal osteotomy position and alignment of the caudal cortices increased tibial long axis (what we interpret to represent the mechanical axis) shift and resulted in under-correction of TPA.[22]

Modifications of the CCWO in the form of a neutral wedge ostectomy have been described and are associated with less tibial shortening, reduced tibial mechanical axis shift and improved accuracy in achieving target TPA compared to a standard CCWO.[8,9,12,20,24] Alterations in tibial length are important to consider given the desire to preserve the fibula for stability. Further, shortening the tibia without fibular ostectomy could impart stress on the fibula and potentially result in its postoperative fracture. Of the available studies evaluating change in tibial length following CCWO, <3 mm of tibial shortening has been proposed to be clinically insignificant.[11–13] However, it is important to note that each study in that body of work used different methods of standardization making direct comparison challenging.[11–13]

The current study utilized the tibial mechanical axis in the sagittal plane, which is defined as the straight line connecting the center of the tibiotalar joint to the center of the stifle. We believe this to be roughly analogous to what is referred to in much of the literature as the tibial long axis and draw comparisons between the two with caution. Historically, tibial long axis shift >3° has been more frequently associated with CCWO compared with other surgical procedures analyzed addressing eTPA.[6] As the tibial long axis or mechanical axis represents the weight bearing axis of the tibia, a shift in its position could potentially alter load bearing across associated joints and may be undesirable, although it is unclear what impact this has on functional outcome in dogs with eTPA. Group A (CBLO + CCWO) demonstrated the greatest degree of tibial mechanical axis shift in the current study as indicated by the largest change in mCrDTA.

The PTNWO is similar in execution to the mCCWO in that it uses a neutral wedge ostectomy. A neutral wedge osteotomy is based on a neutral CORA and is performed by doing both a closing wedge ostectomy and opening wedge osteotomy simultaneously, thereby minimizing length changes in the bone. When performed at a level different than the CORA and angulation correction axis, co-linearity of the resulting segments of bone can be achieved but requires intentional translation. The difference with the PTNWO technique, is that the angular correction is based on the magnitude of a proximal tibial CORA rather than the pre-operative TPA used with the mCCWO. This requires the calculation of a proximal tibial mechanical axis and its intersection with a distal tibial axis which the Frederick et al. technique does not include. A potential advantage, therefore, of the PTNWO, is when proximal tibial morphology is noted as documented by Osmond et al. in which an excessive slope is not the only deformity present.[25] The determined CORA can help to define any additional deformity of the proximal tibia.

The most common complications reported with surgical correction of dogs with eTPA include secondary loss of tibial plateau leveling, tibial tuberosity fracture, or implant-associated complications.[6–8,12] Duerr et al. found that the use of additional implants was associated with a reduced risk of tibial plateau leveling loss postoperatively.[6] All procedures analyzed in the current study describe the use of supplemental fixation in addition to a medially applied bone plate: cranial compression screw +/− k-wire or standard cortical screw in very active dogs,[7] figure-of-8 pin and tension band apparatus +/− second bone plate in larger dogs,[5] figure-of-8 pin and tension band apparatus,[8] and hemicerclage.[9] Surgeons generally avoid rotation of the tibial plateau segment distal to the point of patellar ligament insertion when performing a proximal radial osteotomy due to concern for tibial tuberosity fracture secondary to decreased buttress support.[5] Although this has been demonstrated in an ex vivo study,[26] it has yet to be documented as a risk factor for tibial tuberosity fracture clinically.[5,6,17,27] However, all techniques investigated here make specific attempts to avoid this occurrence.

This study possesses some important limitations. First, this work represents a non-clinical, radiographic investigation, and may not accurately reflect what is achieved clinically with each technique. Additionally, all techniques were performed following the methods as previously described and did not take into account individual modifications that surgeons may use clinically. The variability in clinical cases that results from saw kerf could also not be accounted for in this study. Lastly, the small sample size may have contributed to a type I error in the results.

In conclusion, each of the procedures in the current study had different effects on mechanical axis shift, tibial length, and accuracy in achieving the desired post-correction TPA. It is important for the surgeon to consider the potential tibial morphologic changes and effects on TPA that can result from various available procedures used to address dogs with eTPA. However, it is remains unknown what, if any, these differences have on clinical performance postoperatively. Further clinical investigation using objective outcome assessment such as gait analysis may be helpful to elucidate if one procedure has significant benefit over others in management of cases of eTPA.

AUTHOR CONTRIBUTIONS

Story AL, cDVM, DACVS: Substantial contribution to study design, data acquisition, data analysis, data interpretation, drafting and revision of the article. Torres BT, DVM, PhD, DACVS, DACVSMR: Substantial contribution to data analysis, data interpretation, drafting and revision of the article. Fox DB, DVM, PhD, DACVS: Substantial contribution to the conception and design of this study, data acquisition, data analysis, data interpretation, drafting and revision of the article.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest related to this report.

ORCID

Ashton L. Story https://orcid.org/0000-0001-7746-8304

REFERENCES

1. Duerr FM, Martin KW, Rishniw M, Palmer RH, Selmic LE. Treatment of canine cranial cruciate ligament disease. *Vet Comp Orthopaed*. 2014;27(6):478-483. doi:10.3415/vcot-14-03-0047
2. Bergh MS, Sullivan C, Ferrell CL, Troy J, Budsberg SC. Systematic review of surgical treatments for cranial cruciate ligament disease in dogs. *J Am Anim Hosp Assoc*. 2014;50(5):315-321. doi:10.5326/jaaha-ms-6356
3. Kowaleski MP, McCarthy RJ. Geometric analysis evaluating the effect of tibial plateau leveling osteotomy position on postoperative tibial plateau slope. *Vet Comp Orthopaed*. 2004;17(1):30-34. doi:10.1055/s-0038-1632797
4. Kowaleski MP, Apelt D, Mattoon JS, Litsky AS. The effect of tibial plateau leveling osteotomy position on cranial tibial subluxation: an in vitro study. *Vet Surg*. 2005;34(4):332-336. doi:10.1111/j.1532-950x.2005.00051.x
5. Talaat MB, Kowaleski MP, Boudrieau RJ. Combination tibial plateau leveling osteotomy and cranial closing wedge osteotomy of the tibia for the treatment of cranial cruciate ligament-deficient stifles with excessive tibial plateau angle. *Vet Surg*. 2006;35(8):729-739. doi:10.1111/j.1532-950x.2006.00217.x
6. Duerr FM, Duncan CG, Savicky RS, Park RD, Egger EL, Palmer RH. Comparison of surgical treatment options for cranial cruciate ligament disease in large-breed dogs with excessive tibial plateau angle. *Vet Surg*. 2008;37(1):49-62. doi:10.1111/j.1532-950x.2007.00348.x
7. Schlag AN, Peycke LE, Hulse DA. Center of rotation of angulation-based leveling osteotomy combined with a coplanar cranial closing wedge ostectomy to manage cranial cruciate ligament insufficiency in dogs with excessive tibial plateau angle. *Vet Surg*. 2020;49(6):1125-1131. doi:10.1111/vsu.13480
8. Frederick SW, Cross AR. Modified cranial closing wedge osteotomy for treatment of cranial cruciate ligament insufficiency in dogs with excessive tibial plateau angles: technique and complications in 19 cases. *Vet Surg*. 2017;46(3):403-411. doi:10.1111/vsu.12614
9. Fox DB. Excessive tibial slope correction discussion: the neutral wedge technique. Presented at: the American College of Veterinary Surgeons Symposium; October 19. 2019 Las Vegas, NV.
10. Dismukes DI, Tomlinson JL, Fox DB, Cook JL, Witsberger TH. Radiographic measurement of canine tibial angles in the sagittal plane. *Vet Surg*. 2008;37(3):300-305. doi:10.1111/j.1532-950x.2008.00381.x
11. Wallace AM, Addison ES, Smith BA, Radke H, Hobbs SJ. Modification of the cranial closing wedge ostectomy technique for the treatment of canine cruciate disease. *Vet Comp Orthopaed*. 2011;24(6):457-462. doi:10.3415/vcot-10-11-0159
12. Christ JP, Anderson JR, Youk AO. Modified cranial closing wedge ostectomy in 25 dogs. *Vet Surg*. 2018;47(5):683-691. doi:10.1111/vsu.12912
13. Campbell KA, Payne JT, Doornink MT, Haggerty J. Outcome of tibial closing wedge osteotomy in 55 cranial cruciate ligament-deficient stifles of small dogs (<15 kg). *Vet Surg*. 2016;45(8):1056-1062. doi:10.1111/vsu.12558
14. Reif U, Probst CW. Comparison of tibial plateau angles in normal and cranial cruciate deficient stifles of labrador retrievers. *Vet Surg*. 2003;32(4):385-389. doi:10.1053/jvet.2003.50047
15. Raske M, Hulse D, Beale B, Saunders WB, Kishi E, Kunze C. Stabilization of the CORA based leveling osteotomy for treatment of cranial cruciate ligament injury using a bone plate augmented with a headless compression screw. *Vet Surg*. 2013;42(6):759-764. doi:10.1111/j.1532-950x.2013.12035.x
16. Kishi EN, Hulse D. Owner evaluation of a CORA-based leveling osteotomy for treatment of cranial cruciate ligament injury in dogs. *Vet Surg*. 2016;45(4):507-514. doi:10.1111/vsu.12472
17. Bergh MS, Rajala-Schultz P, Johnson KA. Risk factors for tibial tuberosity fracture after tibial plateau leveling osteotomy in dogs. *Vet Surg*. 2008;37(4):374-382. doi:10.1111/j.1532-950x.2008.00391.x
18. Kowaleski MP, Boudrieau RJ, Pozzi A. Stifle Joint. In: Johnston SA, Tobias KM, eds. *Veterinary Surgery: Small Animal*. Vol 1. 2nd ed. Elselvier; 2018:1071-1168.
19. Warzee CC, Dejardin LM, Arnoczky SP, Perry RL. Effect of tibial plateau leveling on cranial and caudal tibial thrusts in canine cranial cruciate-deficient stifles: an in vitro experimental study. *Vet Surg*. 2001;30(3):278-286.
20. Paley D. Osteotomy concepts and frontal plane realignment. In: Paley D, Herzenberg JE, eds. *Principals of Deformity Correction*. 1st ed. SpringerVerlag; 2002:99-154.
21. Robinson DA, Mason DR, Evans R, Conzemius MG. The effect of tibial plateau angle on ground reaction forces 4–17 months after tibial plateau leveling osteotomy in labrador retrievers. *Vet Surg*. 2006;35(3):294-299. doi:10.1111/j.1532-950x.2006.00147.x
22. Bailey CJ, Smith BA, Black AP. Geometric implications of the tibial wedge osteotomy for the treatment of cranial cruciate ligament disease in dogs. *Vet Comp Orthopaed*. 2007;20(3):169-174. doi:10.1160/vcot-06-02-0012
23. Apelt D, Pozzi A, Marcellin-Little DJ, Kowaleski MP. Effect of cranial tibial closing wedge angle on tibial subluxation: an ex vivo study. *Vet Surg*. 2010;39(4):454-459. doi:10.1111/j.1532-950x.2010.00670.x
24. Terreros A, Daye RM. Modified cranial closing wedge osteotomy to treat cranial cruciate ligament deficient stifles with excessive tibial plateau angles: complications, owner satisfaction, and midterm to long-term outcomes. *Vet Surg*. 2020;49(6):1109-1117. doi:10.1111/vsu.13431
25. Osmond CS, Marcellin-Little DJ, Harrysson OL, Kidd LB. Morphometric assessment of the proximal portion of the tibia in dogs with and without cranial cruciate ligament rupture. *Vet Radiol Ultrasound*. 2006;47(2):136-141.
26. Hamilton K, Tarlton J, Parsons K, Toscano M, Burton N. Effect of osteotomy position and tibial plateau rotation on the tensile force required for failure of the canine quadriceps mechanism. *Vet Surg*. 2015;44(6):763-771. doi:10.1111/vsu.12339
27. Mehrkens LR, Hudson CC, Cole GL. Factors associated with early tibial tuberosity fracture after tibial plateau leveling osteotomy. *Vet Surg*. 2018;47(5):634-639. doi:10.1111/vsu.12915

How to cite this article: Story AL, Torres BT, Fox DB. Morphologic impact of four surgical techniques to correct excessive tibial plateau angle in dogs: A theoretical radiographic analysis. *Veterinary Surgery*. 2024;53(1):96-103. doi:10.1111/vsu.13981