

An in silico comparison of a novel CORA-based cranial closing wedge ostectomy methodology with three other techniques

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Abstract

Objective: To describe a CORA-based cranial closing wedge ostectomy methodology (CCWO_{CORA}) and to determine whether the CCWO_{CORA} achieves a more accurate and precise postoperative tibial plateau angle (TPA_{POST}) than three previously described methods.

Study design: In silico study.

Sample population: Thirteen client-owned dogs.

Methods: Computed tomography (CT) scans of six Labrador retriever, six German shepherd, six Rottweiler, and six small-breed dog (<10 kg) tibiae, originally acquired for unrelated purposes, were used for in silico planning and execution of the CCWO_{CORA} and previously described procedures. The TPA_{POST}, tibial long axis shift, change in tibial length and wedge angle were recorded and a linear mixed-effects model was used to compare differences amongst techniques.

Results: The median TPA_{POST} for the CCWO_{CORA} method was 5.00° (range: 5.00–5.00°) across a variety of tibial morphologies, whereas all other methods showed greater variability. Differences in TPA_{POST} were evident amongst methods ($p < .001$) and breeds ($p < .001$).

Abbreviations: 3D, three dimensional; ACA-CORA, angulation correction axis center of rotation of angulation; CBLO, CORA based leveling osteotomy; CCWO, cranial closing wedge ostectomy; CCWO_{CORA}, CORA-based cranial closing wedge ostectomy; CORA, center of rotation of angulation; COV, coefficient of variation; CrCl, cranial cruciate ligament; CT, computed tomography; DICOM, digital imaging and communications in medicine; DMA, distal mechanical axis; FDR, false discovery rate; GSDs, German Shepherd Dogs; HSD, Tukey's Honestly Significant Difference; LBR, labrador retriever; LSM, least squares means; MAA, mechanical axis advancement; PJOL, proximal joint orientation line; PMA, proximal mechanical axis; Rot, Rottweiler; SMB, small breed dogs; tBL, transverse bisecting line; TPA, tibial plateau angle; TPA_{POST}, post operative tibial plateau angle; TPA_{PRE}, preoperative tibial plateau angle; TPLO, tibial plateau leveling osteotomy; Δ TL, change in tibial length.

The preliminary findings of this study were presented at the European College of Veterinary Surgeons (ECVS) 33rd Annual Scientific meeting on 5 July, 2024 in Valencia, Spain.

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Conclusions: In silico, CCWO_{CORA} methodology always achieved the target TPA_{POST} due to its intrinsic geometric principles. As such, CCWO_{CORA} surgeries achieved a more accurate TPA_{POST} than previously described CCWO techniques.

Clinical significance: The CCWO_{CORA} provides clinicians with a cranial closing-wedge osteotomy methodology with entirely predictable TPA_{POST}.

1 | INTRODUCTION

Cranial closing wedge osteotomy (CCWO) was first described in 1984 as a method for eliminating cranial tibial translation in the cranial cruciate ligament (CrCL) deficient stifle.¹ Numerous clinical, cadaveric, and in silico reports since this initial report have described adaptations and modifications of this technique.^{2–7}

The postoperative tibial plateau angles (TPA_{POST}) of tibial plateau leveling osteotomy (TPLO) can be selected accurately as the tibial plateau is rotated until the desired TPA_{POST} is achieved.⁸ As they are not geometrically founded, existing CCWO planning methodologies do not enable calculation of a precise TPA_{POST} following acute surgical correction. Inaccurate correction of TPA can lead to unsatisfactory outcomes with CCWO.⁹ Ex vivo, a CCWO that achieves a TPA_{POST} between 4° and 6° satisfactorily eliminates cranial tibial thrust, whereas a TPA_{POST} < 4° results in caudal tibial subluxation.¹⁰ Furthermore, TPA_{POST} > 6° may not adequately eliminate cranial tibial thrust.¹⁰ An explanation for the inherent inaccuracies observed with existing CCWO methodologies is that tibial mechanical axis shift is neither quantifiable nor predictable. Tibial mechanical axis shift and TPA_{POST} are linked intrinsically, therefore, failure to control or account for tibial mechanical axis shift leads to unreliable TPA_{POST}.¹¹

Center of rotation of angulation (CORA) principles were described in 1994 as a method of correcting angular limb deformities in human patients,¹² these principles have been utilized by veterinary surgeons to correct angular limb deformity.^{13–15} The principles are integral to the CORA based leveling osteotomy (CBLO) technique described for the stabilization of the CrCL-deficient canine stifle.¹⁶ The authors believed that, if CORA principles were applied to CCWO methodology, precise quantification of mechanical axis shift would occur and produce a more accurate and predictable correction, overcoming the limitations of previous CCWO methodologies. The aims of this study were therefore: (1) to describe a CORA-based CCWO methodology (CCWO_{CORA}) and (2) to conduct an in silico study to determine whether the CCWO_{CORA} achieves more accurate and repeatable TPA_{POST} compared with three previously described techniques.^{4–6} It was hypothesized that: (1) the CCWO_{CORA} technique would always achieve the desired TPA_{POST}, and (2) that the CCWO_{CORA} technique

would achieve more accurate and predictable TPA_{POST} across a range of tibial morphologies.

2 | MATERIALS AND METHODS

2.1 | Study population, ethics and eligibility criteria

Prior to study commencement, approval was granted by the University of Liverpool institutional ethics committee (approval number: VREC1379). Archived computed tomography (CT) scans obtained between March 2008 and April 2022 of the pelvic limbs of Labrador retriever (LBR), German shepherd dogs (GSDs), Rottweilers, and small-breed dogs (<10 kg) were reviewed retrospectively. To be eligible, scans of the complete tibia and tarsus had to be available. Dogs were not eligible if there was any evidence of tibial pathology. Images were obtained using an 80-slice multidetector unit (Canon Medical Systems. Aquilion Lightning CT Scanner. Otawara, Japan: Canon Medical Systems Corporation) with a slice thickness of 0.5 mm. Digital Imaging and Communications in Medicine (DICOM) files were imported into medical image processing software (Materialise. Mimics Innovation Suite, version 25.0. Leuven, Belgium: Materialise; 2022) to create three-dimensional (3D) tibial bone models; these models were exported to computer-aided design software (Materialise. 3-matic, version 17.0. Leuven, Belgium: Materialise; 2023) for in silico surgical planning and execution.

2.2 | Preoperative planning

The tibial mechanical axis and proximal joint orientation lines (PJOL) were plotted on each tibia.¹⁷ A point 5 mm distal to the insertion of the patellar tendon was marked. The center of the talus, the base of the medial malleolus, and the base of the intercondylar eminences were marked to allow consistent calculation of postoperative mechanical axis advancement (MAA) and change in tibial length (Δ TL) (Figure 1). These marks remained unchanged for each surgery to ensure consistency in planning, preoperative and postoperative measurements across techniques. Preoperative tibial plateau angle

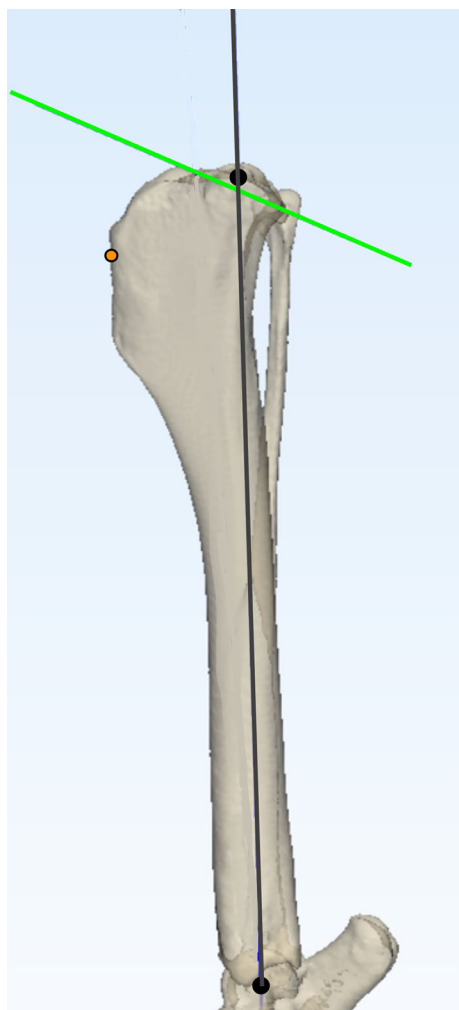


FIGURE 1 Landmark and axis planning on a three-dimensional tibial bone model. Three anatomical landmarks were agreed by consensus: (1) a point 5 mm distal to the insertion of the patellar tendon on the cranial aspect of the tibial crest (orange circle); (2) the center of the talus (distal black circle); and (3) the base of the intercondylar eminences (proximal black circle). The mechanical axis (gray line) was plotted between the center of the talus and the base of the intercondylar eminences. Points at the cranial and caudal aspect of the tibial plateau were identified by consensus. These points were joined to determine the proximal joint orientation line (green line).

(TPA_{PRE}) was determined as described previously.¹⁸ The distance between the base of the intercondylar eminences and base of the medial malleolus was calculated and recorded as the tibial length.

2.3 | Terreros and Daye ($CCWO_{TPA-5}$) & Frederick and Cross ($CCWO_{TPA}$) methodologies

$CCWO_{TPA-5}$ ⁶ (Figure 2) and $CCWO_{TPA}$ ⁵ (Figure 3) surgeries were planned as described previously,

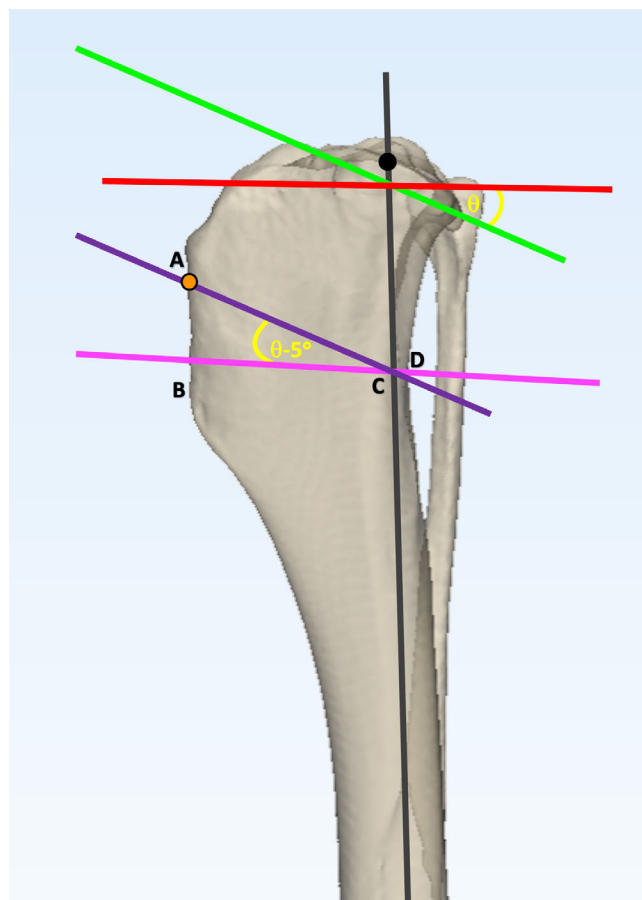


FIGURE 2 Planning of the $CCWO_{TPA-5}$ methodology on a three-dimensional tibial bone model. The mechanical axis (gray line) was plotted between the center of the talus and the base of the intercondylar eminences. Points at the cranial and caudal aspect of the tibial plateau were agreed by consensus. These points were joined to determine the proximal joint orientation line (PJOL) (green line). A line was plotted at 90° to the mechanical axis at the level of its intersection of the tibial PJOL (red line) and the tibial plateau angle (TPA) (θ) was measured. The proximal osteotomy line (AC) (purple line) was plotted parallel to the PJOL starting at a point 5 mm distal to the point of insertion of the patellar tendon (orange circle). The second osteotomy line (BD) (pink line) was planned at 85° to the mechanical axis, thus creating a wedge angle equal to $TPA - 5^\circ$. The distal osteotomy line was moved either proximally or distally, to ensure the line AC was the same length as BD.

ensuring that the proximal osteotomy exited the cranial tibial cortex 5 mm below the insertion of the patellar tendon.

2.4 | Oxley methodology ($CCWO_{ISO}$)

The $CCWO_{ISO}$ ⁴ surgeries were planned as previously described with minor modifications to maintain repeatability across tibial morphologies (Figure 4). A

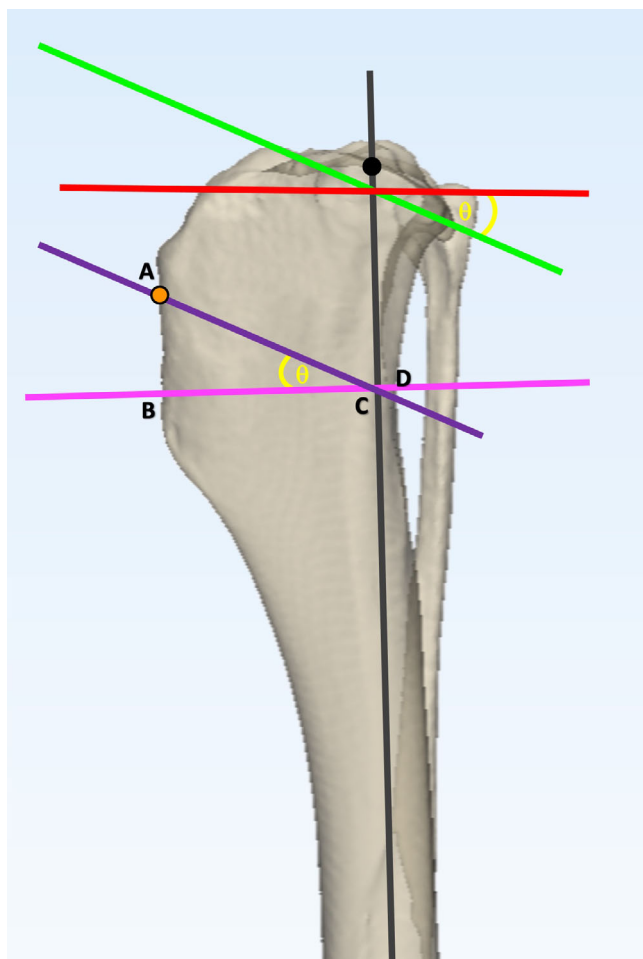


FIGURE 3 Planning of the CCWO_{TPA} methodology on a three-dimensional tibial bone model. The mechanical axis (gray line) was plotted between the center of the talus and the base of the intercondylar eminences. Points at the cranial and caudal aspect of the tibial plateau were agreed by consensus. These points were joined to determine the proximal joint orientation line (PJOL) (green line). A line was plotted at 90° to the mechanical axis at the level of its intersection with the PJOL (red line) and the tibial plateau angle (TPA) (θ) was measured. The proximal osteotomy line (AC) (purple line) was plotted parallel to the PJOL starting at the point 5 mm distal to the point of insertion of the patellar tendon (orange circle). The second osteotomy line (BD) (pink line) was planned at 90° to the mechanical axis thus creating a wedge angle equal to the TPA (θ). Line BD was moved either proximally or distally to ensure the line AC was the same length as BD.

line was plotted from the most cranial aspect of the tibial tuberosity to the most cranial aspect of the tibial crest. This line became the base of an isosceles triangle. The isosceles triangle was plotted with the proximal osteotomy exiting 5 mm distal to the insertion of the patellar tendon. The apex of the isosceles triangle was positioned 75% along the length of the proximal osteotomy.

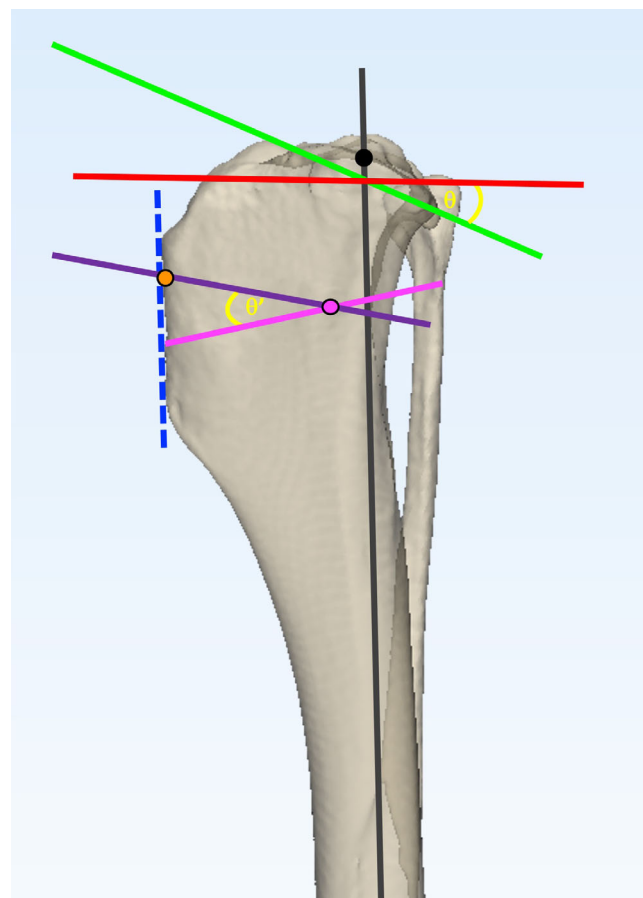


FIGURE 4 Planning of the CCWO_{ISO} methodology on a three-dimensional tibial bone model. The mechanical axis (gray line) was plotted between the center of the talus and the base of the intercondylar eminences. Points at the cranial and caudal aspect of the tibial plateau were agreed by consensus. These points were joined to determine the proximal joint orientation line (PJOL) (green line). A line was plotted at 90° to the mechanical axis at the level of its intersection with the PJOL (red line) and the tibial plateau angle (θ) was measured. The cranial cortex of the tibial tuberosity was plotted (blue dashed line). An isosceles triangle was plotted perpendicular to the cranial cortex of the tibial tuberosity with the wedge angle (θ') determined as follows: TPA under 20°: $\theta' = \text{TPA} - 5^\circ$, TPA between 21 and 25°: $\theta' = \text{TPA} - 4^\circ$, TPA between 26 and 30°: $\theta' = \text{TPA} - 3^\circ$ and TPA between 31 and 35°: $\theta' = \text{TPA} - 2^\circ$. The apex of the wedge (pink circle) was located at 75% of the width of the tibia along the proximal osteotomy line (purple line). The proximal osteotomy was plotted so it exited the cranial cortex of the tibia 5 mm distal to the point of insertion of the patellar tendon (orange circle). The distal osteotomy (pink line) was planned so that it passed through the intended apex of the wedge at the desired wedge angle relative to the proximal osteotomy.

2.5 | CCWO_{CORA} methodology

The tibial mechanical axis was advanced by rotating the mechanical axis cranially by 3° from the center of the talus generating a distal mechanical axis (DMA) (Figure 5A). Next, the proximal mechanical axis (PMA)

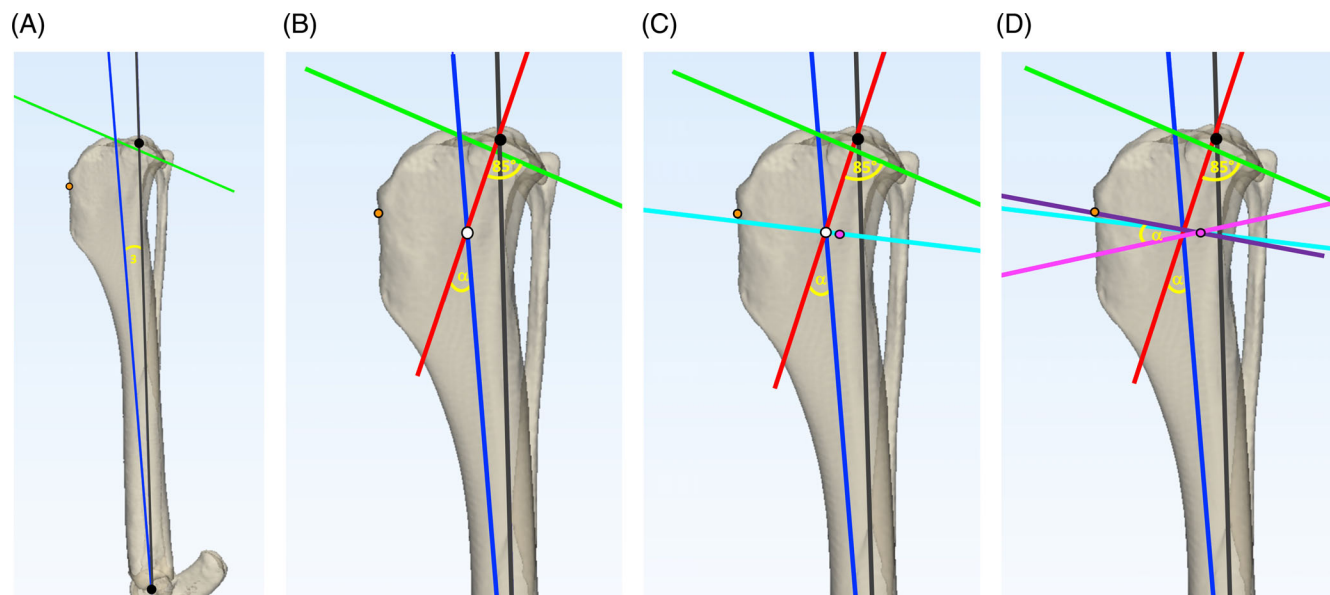


FIGURE 5 Planning of the CCWO_{CORA} methodology on a three-dimensional tibial bone model. The mechanical axis (gray line) was plotted between the center of the talus and the base of the intercondylar eminences (black circles). Points at the cranial and caudal aspect of the tibial plateau were agreed by consensus and joined to determine the proximal joint orientation line (PJOL) (green line). The mechanical axis was advanced cranially by 3° (blue line) to create a distal mechanical axis (DMA) (A). The proximal mechanical axis (PMA) was plotted 5° caudal to a line perpendicular to the PJOL (red line). The intersection of the DMA and PMA determined the location (white circle) and magnitude (α) of the CORA (B). The transverse bisecting line (light blue line) and an angulation correction axis-CORA (ACA-CORA) 75% along this line was plotted (pink circle) (C). The cranial closing osteotomies were then planned. The proximal osteotomy (purple line) originated at the ACA-CORA (pink circle) and exited at the mark 5 mm distal to the insertion of the patellar tendon (orange circle). The distal osteotomy (pink line) originated at the ACA-CORA and was plotted at an angle equal to α (D).

was plotted 5° caudal to a line perpendicular to the PJOL. The intersection of the DMA and PMA determined the location and magnitude (α) of the CORA (Figure 5B). The transverse bisecting line (tBL) was plotted and an angulation correction axis-CORA (ACA-CORA) 75% along this line was marked (Figure 5C). A cranial closing wedge was plotted with the proximal osteotomy originating at the ACA-CORA and exiting 5 mm distal to the insertion of the patellar tendon. The distal osteotomy originated at the ACA-CORA and was plotted at an angle equal to α (Figure 5D). The wedge osteotomy was executed in silico and the proximal fragment rotated about the ACA-CORA until the bone fragments contacted; the cranial cortices were not aligned (Figure 6).

2.6 | CCWO_{CORA} methodology small-breed group

In the small-breed group, a CCWO_{CORA} surgery was completed as outlined above with a MAA of 3° (CCWO_{CORA3}). A second CCWO_{CORA} surgery was completed on each tibia. The only difference for the second surgery was that step 1 was modified so that a MAA of 5° was plotted (CCWO_{CORA5}) (Figure 7).

2.7 | Postoperative measurements

Postoperative TPA_{POST}, MAA, Δ TL and wedge osteotomy angle were recorded for each dog. TPA_{POST} was measured as per the TPA_{PRE} using the same landmarks. The MAA was measured as the angle between the preoperative tibial mechanical axis and the postoperative tibial mechanical axis. Postoperative tibial length was calculated by measuring the length between the mark at the base of the intercondylar eminence and the mark at the center of the medial malleolus on the postoperative tibiae (Figures 6 and 7). The Δ TL was calculated by dividing preoperative tibial length by postoperative tibial length and multiplying by 100. Wedge osteotomy angles were equal to α .

2.8 | Data handling and statistical analysis

The primary outcome was TPA_{POST}, with all other postoperative measurements being secondary outcomes. Based on a two-tailed, a priori power analysis, at least 17 CCWO_{CORA}, and 68 in silico surgeries were necessary to ensure a power of at least 95% ($\alpha = 0.05$, effect size = 0.8, paired

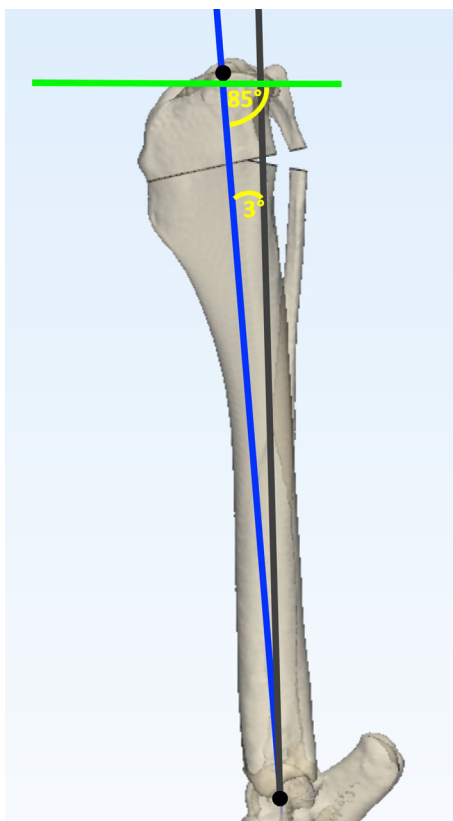


FIGURE 6 Execution of planned CCWO_{CORA} surgery on a three-dimensional tibial bone model. The gray line represents the original mechanical axis of the tibia. The distal mechanical axis (blue line), which was advanced by 3°, now represents the postoperative mechanical axis. The preoperatively determined points at the cranial and caudal aspects of the tibial plateau were connected to determine the new proximal joint orientation line (green line). The mechanical caudal proximal tibial angle is exactly 85°.

t-test). Data are reported as median (range), unless indicated, and the threshold for statistical significance was $p < .05$, with all analyses being two sided.

Statistical analysis was performed using an online, open-access statistical language and environment (R version 4.3.1),¹⁹ along with several additional packages.^{20–31} The Kruskal–Wallis test, with Dunn's post hoc test, was used to compare differences in TPA_{PRE} amongst breeds. Linear mixed-effects models were used to compare differences in postoperative measurements (TPA_{POST}, MAA, Δ TL and wedge angle) among methods. Dog and leg (left or right) were included as random effects, with leg nested within dog. Method, breed, and the interaction between method and breed were included as fixed effects. The distribution of the residuals from all models were tested for skewness and normality by visual inspection and with the Shapiro–Wilk test, and the possibility of heteroscedasticity was assessed by

visually inspecting a plot of residuals against predictions and with Levene's test. The nlme package version 3.1–66²¹ was used for these analyses, because unequal variance amongst groups could be accounted for (e.g., in models where there was evidence of heteroscedasticity). Pairwise contrasts were calculated both between methods, and amongst breeds within each method. Tukey's honestly significant difference (HSD) test was used for these comparisons, enabling *p* values to be corrected for false discovery rate (FDR). The results of these analyses are reported as least squares means (LSM) and their 95% confidence interval (95% CI). Cohen's *d* was calculated to determine the effect size using the “eff_size” function of the “emmeans” package,²² interpreted according to Lakens:²³ $d < 0.1$ is classified as very small, $0.1 \leq d < 0.3$ is small, $0.3 \leq d < 0.5$ is medium, and $d \geq 0.5$ is large.

Finally, the Wilcoxon signed-ranks test was used to compare the results in the small-breed group for CCWO_{CORA} methodology utilizing different angles of advancement (3° MAA and 5° MAA). Effect size was determined using the rank-biserial correlation and interpreted as described by Funder and Ozer:²⁴ < 0.05 , tiny; 0.05–0.10, very small; 0.10–0.20, small; 0.20–0.30, medium; 0.30–0.40, large; > 0.40 very large.

3 | RESULTS

3.1 | Study dogs

The scans of three LBRs ($n = 6$ tibia), three Rottweilers (6), three GSDs (6), two Yorkshire terriers (3) and two West Highland white terriers (3) met the inclusion criteria, totaling 24 tibiae. The mean age at CT acquisition was 28 months for LBRs, 29 months for Rottweilers, 42 months for GSDs, and 65 months for small-breed dogs. Mean $\pm$ standard deviation (SD) TPA_{PRE} was $24.15 \pm 2.30^\circ$, $24.10 \pm 1.75^\circ$, $25.00 \pm 0.34^\circ$ and $33.28 \pm 2.17^\circ$ for LBR, Rottweilers, GSDs and small-breed dogs, respectively.

3.2 | Postoperative TPA

Differences in TPA_{POST} amongst methods are shown in Figure 8A. The median (range) TPA_{POST} for all CCWO_{CORA} surgeries was 5.00° (range: 5.00° to 5.00°); it was 3.35° (range: 2.53° to 5.24°) for all CCWO_{TPA} surgeries; 6.33° (range: 5.37° to 7.04°) for all CCWO_{ISO} surgeries, and 7.52° (range 6.85° to 9.42°) for all CCWO_{TPA-5} surgeries. Variability was less for the CCWO_{CORA} method than for all other methods (Levene's test, $p < .001$; Table 1). In the linear mixed-effects model, TPA_{POST} varied by planning method ($p < .001$, Cohen's *d* 1.00, a large effect), with

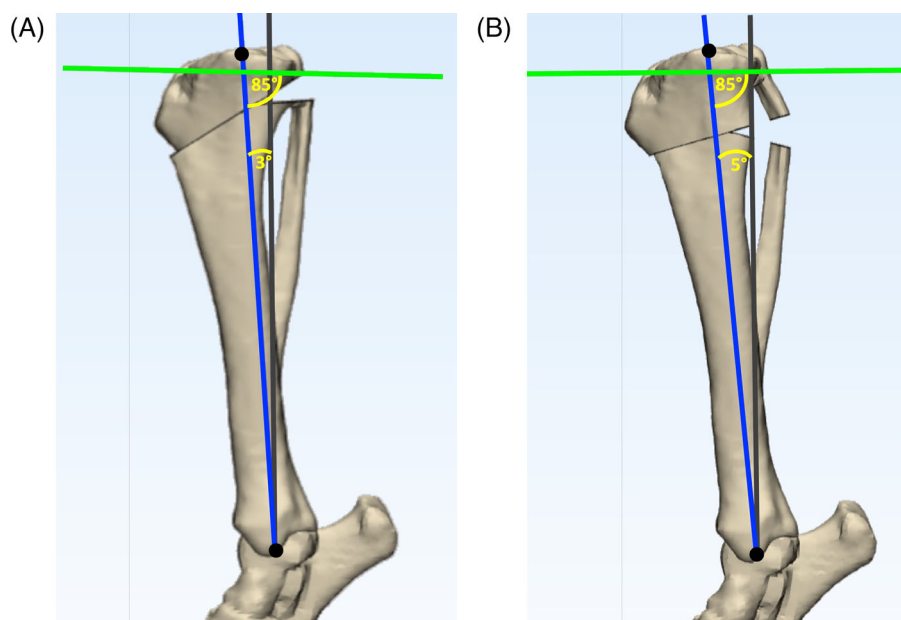


FIGURE 7 The effects of different mechanical axis advancement on small-breed dogs undergoing CCWO_{CORA} on a three-dimensional tibial bone model. The gray line represents the original mechanical axis of the tibia. The preoperatively determined points at the cranial and caudal aspects of the tibial plateau were connected to determine the proximal joint orientation line (PJOL) (green line). The distal mechanical axis was advanced by 3° in (A) and by 5° in (B), both of which resulted in a postoperative tibial plateau angle of exactly 5°. In small-breed dogs with steeper tibial plateau angles, a greater distal mechanical axis advancement results in a larger proximal bone fragment.

post hoc comparisons demonstrating that all methods differed from one another ($p < .001$; Table 2). The TPA_{POST} also varied amongst methods within each breed ($p < .05$) (Table 3), except for the comparison of CCWO_{CORA} with CCWO_{TPA} in small-breed dogs ($p = .331$).

3.3 | Mechanical axis advancement

Differences in MAA amongst methods are shown in Figure 8B. Median (range) mechanical axis advancement for CCWO_{CORA} surgeries was 3.00° (range: 3.00° to 3.00°); it was 3.35° (range: 2.53° to 5.24°) for CCWO_{TPA} surgeries, 2.61° (range: 1.84° to 5.12°) for CCWO_{ISO} surgeries, and 2.52° (range: 1.85° to 4.42°) for CCWO_{TPA-5} surgeries. Variability was less for the CCWO_{CORA} method than for all other methods (Levene's test, $p < .001$; Table 1). In the linear mixed-effects model, MAA varied by planning method ($p < .001$, Cohen's d 1.00, a large effect), with *post hoc* comparisons demonstrating that MAA for all methods differed from one another (CCWO_{CORA} and CCWO_{TPA-5} $p = .004$; all other contrasts $p < .001$; Table 1), except between CCWO_{CORA} and CCWO_{ISO} ($p = .884$). For most comparisons, MAA also varied amongst methods within each breed ($p < .05$) (Table 3), except between CCWO_{CORA} and CCWO_{TPA} in LBR ($p = .992$), rottweilers

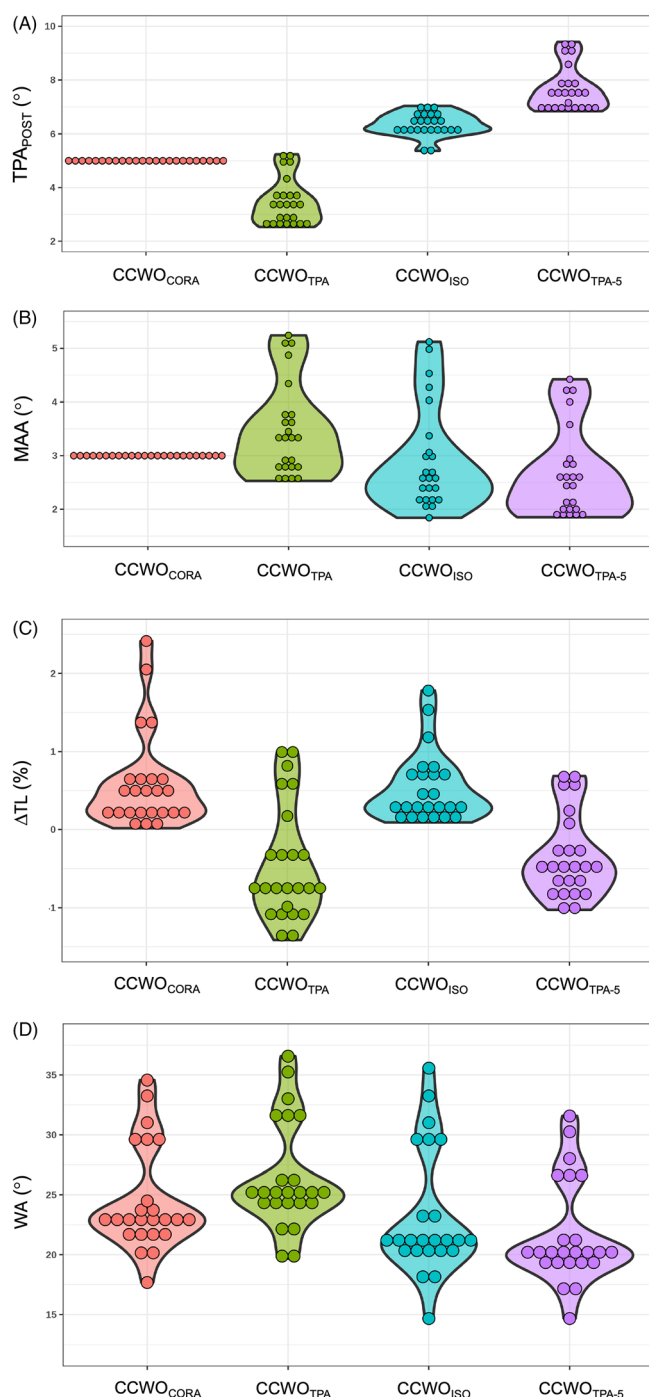
($p = .999$) and GSDs ($p = .839$), and between CCWO_{CORA} and CCWO_{ISO} in GSDs ($p = .053$).

3.4 | Percentage change in tibial length (Δ TL)

Figure 8C shows differences in Δ TL amongst methods. Median (range) Δ TL for CCWO_{CORA} surgeries was +0.44% (range: +0.02% to +2.42%), -0.71% (range: -1.41% to +1.00%) for CCWO_{TPA} surgeries, +0.33% (range: +0.09% to +1.78%) for CCWO_{ISO} surgeries and -0.48% (range: -1.03% to +0.67%) for CCWO_{TPA-5} surgeries. There was no difference in variability amongst methods (Levene's test, $p = .331$; Table 1). In the linear mixed-effects model, Δ TL varied by planning method ($p < .001$, Cohen's d 1.00, a large effect), with *post hoc* comparisons demonstrating that Δ TL for all methods differed at $p < .001$ (Table 1), except between CCWO_{CORA} and CCWO_{ISO} ($p = .796$), and between CCWO_{TPA} and CCWO_{TPA-5} ($p = .498$). For most comparisons, Δ TL also varied amongst methods within each breed ($p < .05$) (Table 3), except between CCWO_{TPA} and CCWO_{TPA-5} in all breeds (GSDs $p = .421$; LBR $p = .482$, Rottweilers $p = .487$, small-breed dogs $p = .396$), and for CCWO_{CORA} and CCWO_{ISO} in GSDs ($p = .962$), LBR ($p = .986$), and Rottweilers ($p = .786$).

3.5 | Wedge angle

Differences in wedge angle amongst methods are shown in Figure 8D. Median (range) wedge angles for CCWO_{CORA} surgeries were 23.1° (range: 17.7° to 34.6°), 25.1° (range: 19.7° to 36.6°) for CCWO_{TPA} surgeries, 21.1° (range: 14.7° to 35.6°) for CCWO_{ISO} surgeries, and 20.1° (range: 14.7° to 31.6°) for CCWO_{TPA-5} surgeries. There was no difference in variability amongst methods (Levene's test, $p = .928$; Table 1). In the linear mixed-effects model, wedge angle varied by planning method ($p < .001$, Cohen's d 1.00, a large



effect), with *post hoc* comparisons demonstrating that wedge angle for all methods differed from one another ($p < .001$; Table 2). Wedge angle also varied amongst method within all breeds ($p < .002$ for all; Table 3).

3.6 | Comparison of CCWO_{CORA3} and CCWO_{CORA5} in small-breed dogs

Median (range) TPA_{POST} did not differ between CCWO_{CORA3} (5.00°; range: 5.00° to 5.00°) and CCWO_{CORA5} (5.00°; range: 5.00° to 5.00°) surgeries ($p = 1.000$; rank biserial 0.05, a small effect), but median MAA was less in CCWO_{CORA3} (3.00°; 3.00° to 3.00°) than in CCWO_{CORA5} (5.00°; range: 5.00° to 5.00°). There was no difference in median ΔTL between CCWO_{CORA3} planned surgeries (+1.37%; +0.75% to +1.90%) and for CCWO_{CORA5} planned surgeries (+1.29%; +1.01% to +1.67%; $p = 1.00$; rank biserial 0.05, a small effect). However, median wedge angle differed between CCWO_{CORA3} (30.5°; range: 29.7° to 32.7°) and CCWO_{CORA5} (32.5°; range: 31.7° to 34.7°) surgeries ($p = .031$; rank biserial 1.00, a large effect).

4 | DISCUSSION

This study demonstrated that, compared with other methods, the CCWO_{CORA} methodology achieved an exact target TPA_{POST}, with much less variability, across all tibial morphologies. This suggests that this new approach is more predictable than existing methods.

FIGURE 8 Violin plot demonstrating the absolute postoperative tibial plateau angles (TPA_{POST}), mechanical axis advancement (MAA), percentage change between preoperative and postoperative tibial length (Δ TL), and wedge angle for CCWO_{CORA}, CCWO_{ISO}, CCWO_{TPA-5}, and CCWO_{TPA} planned surgeries. The circles represent the absolute postoperative TPA_{POST} (A), MAA (B), Δ TL (C) and wedge angle (D). In (A), the shaded area around the individual circles represents the kernel density estimation to show the distribution shape of the data whereas the shaded area in Figure 8B–D is a compact display of the continuous distribution, where the width is proportionate to the data density in each region. Mean TPA_{POST} varied amongst planning methods ($p < .001$), and variability was least for the CCWO_{CORA} method (Levene's test, $p < .001$). Mean MAA varied amongst planning methods ($p < .001$), and variability was least for the CCWO_{CORA} method (Levene's test, $p < .001$). Mean ΔTL varied amongst planning methods ($p < .001$), but there was no difference in variability amongst methods (Levene's test, $p = .331$). Mean wedge angle varied amongst planning methods ($p < .001$) but there was no difference in variability amongst methods (Levene's test, $p = .928$).

TABLE 1 Coefficients of variations of measurements made in cranial closing wedge osteotomy planning.

CCWO Method	TPA _{POST} (%)	MAA (%)	Δ TL (%)	Wedge angle (%)
CCWO _{CORA}	0.0	0.0	103.0	17.7
CCWO _{ISO}	6.8	32.7	81.7	22.7
CCWO _{TPA}	24.9	24.9	171.1	17.0
CCWO _{TPA-5}	10.7	30.9	156.8	19.8

Note: The coefficients of variation for TPA_{POST}, MAA, ΔTL, and wedge angle for all surgeries performed using the four CCWO techniques studied.

Abbreviations: CCWO, Cranial closing wedge osteotomy; MAA, mechanical axis advancement; ΔTL, change in tibial length; TPA_{POST}, precise postoperative tibial plateau angle.

TABLE 2 Least squares means by method from linear mixed-effects models.

CCWO method	TPA _{POST} (°)	MAA (°)	Δ TL (%)	Wedge angle (°)
CCWO _{CORA}	4.96 ^a (4.59, 5.33)	2.96 ^a (2.58, 3.34)	+0.58 ^a (+0.33, +0.83)	24.5 ^a (23.4, 25.6)
CCWO _{ISO}	6.31 ^b (5.96, 6.65)	2.89 ^a (2.56, 3.22)	+0.52 ^a (+0.27, +0.77)	23.1 ^b (22.1, 24.2)
CCWO _{TPA}	3.44 ^c (3.13, 3.75)	3.44 ^b (3.11, 3.76)	−0.45 ^b (−0.70, −0.20)	26.4 ^c (25.3, 27.4)
CCWO _{TPA-5}	7.63 ^d (7.33, 7.94)	2.63 ^c (2.31, 2.95)	−0.36 ^c (−0.61, −0.11)	21.6 ^d (20.5, 22.7)

Note: Results reported are least squares means and 95% confidence intervals derived from the linear mixed-effects models. For each variable, methods that differed at $p < .05$ are shown by different superscript letters.

Abbreviations: CCWO, Cranial closing wedge osteotomy; MAA, mechanical axis advancement; ΔTL, change in tibial length; TPA_{POST}, precise postoperative tibial plateau angle.

The MAA must occur during CCWO irrespective of the planning methodology.²⁵ Most CCWO surgeries follow Paley's third rule of osteotomy correction, namely that angular correction is achieved through translation and failure to align the proximal and distal mechanical/anatomical axes.²⁶ This translation will have an unpredictable and varying magnitude of effect on the MAA, as evidenced by the wider coefficient of variation (COV) seen in this study. Increasing MAA diminishes the effect of a defined wedge angle on TPA_{POST} and, therefore, any technique that induces more MAA requires a larger wedge angle to achieve target TPA_{POST}. In a recent meta-analysis, the reported prediction interval for MAA ranged from 2.5° to 5.4° (mean of 3.9°).²⁷ Based upon these findings, the MAA was set at 3° for all surgeries in the current study.

A TPA_{POST} ranging from 3.8° to 5.9° eliminates cranial tibial subluxation *ex vivo*.¹⁰ Given that an angle of 5° is generally accepted as the target TPA_{POST} for tibial plateau-leveling procedures, this was selected as the target TPA_{POST} in the current study.²⁸ The predictability of the CCWO_{CORA} technique is a direct consequence of defining the desired MAA and TPA_{POST} allowing application of CORA methodology. Plotting a PMA (based on target TPA_{POST}) and DMA (based on desired MAA) defines the precise location and magnitude of the CORA. In doing so, the location of the wedge apex and the exact wedge angle

required to achieve the target TPA_{POST} could be accurately calculated.

A 3° MAA and a 5° target TPA_{POST} were maintained to allow comparison across techniques and tibial morphologies. The main advantage of the described CCWO_{CORA} technique is that these parameters are selectable depending on surgeon preference and tibial morphology. Some authors have argued that a TPA_{POST} of 10° is more suitable for a tibial plateau-leveling procedure,¹⁶ achieved by defining PMA at 80° rather than the 85° used in this study. Similarly, if a 3° TPA_{POST} were desired, then the PMA could be defined at 87°.

Certain tibial morphologies may require a greater MAA to execute the surgery successfully. In the current study, although a 3° MAA was technically possible in small-breed tibial morphologies, the resultant osteotomy was deemed too proximal and the resultant bone stock too limited to allow safe bone-plate application. This finding is unsurprising given the link between MAA and TPA; indeed, the mean MAA for large-breed dogs was 2.6°, compared with 4.31° for small-breed dogs with the other CCWO methodologies. By increasing the MAA from 3° to 5° in the small-breed group, a more feasible CCWO_{CORA} was possible without affecting surgical accuracy.

The effects of mechanical axis advancement on stifle mechanics following tibial plateau altering osteotomy procedures have not been investigated but the effects of

TABLE 3 Least squares means by method within breed from linear mixed-effects models.

CCWO Method	TPA _{POST} (°)				Mechanical axis advancement (°)				Δ Tibial length (%)				Wedge angle (°)			
	LBR	GSD	ROT	SMB	LBR	GSD	ROT	SMB	LBR	GSD	ROT	SMB	LBR	GSD	ROT	SMB
CCWO _{CORA}	5.08 ^a (4.31, 5.85)	5.05 ^a (4.30, 5.81)	5.08 ^a (4.31, 5.86)	4.64 ^a (3.84, 5.43)	3.00 ^a (2.21, 3.79)	3.00 ^{ab} (2.24, 3.76)	3.00 ^a (2.21, 3.79)	2.84 ^a (2.12, 3.56)	+0.41 ^a (+0.10, +0.93)	+0.32 ^a (-0.18, +0.82)	+0.29 ^a (-0.23, +0.80)	+1.29 ^a (+0.83, +1.75)	21.8 ^a (19.6, 24.1)	23.0 ^a (20.8, 25.1)	22.1 ^a (19.9, 24.3)	31.3 ^a (29.0, 33.1)
CCWO _{ISO}	6.49 ^b (5.77, 7.22)	6.54 ^b (5.84, 7.25)	6.35 ^b (5.62, 7.07)	5.85 ^a (5.10, 6.60)	2.41 ^a (1.73, 3.09)	2.49 ^a (1.84, 3.15)	2.43 ^a (1.75, 3.11)	4.22 ^b (3.62, 4.82)	+0.37 ^a (-0.15, +0.89)	+0.38 ^a (-0.12, +0.88)	+0.41 ^a (-0.11, +0.92)	+0.93 ^b (+0.08, +1.00)	20.1 ^b (17.9, 22.4)	21.0 ^b (18.8, 23.1)	20.3 ^b (18.0, 22.5)	31.4 ^a (29.1, 33.3)
CCWO _{TPA}	3.14 ^c (2.48, 3.79)	3.21 ^c (2.58, 3.85)	3.10 ^c (2.44, 3.76)	4.31 ^b (3.63, 5.00)	3.05 ^b (2.38, 3.73)	3.16 ^b (2.51, 3.81)	3.02 ^b (2.34, 3.69)	4.52 ^c (3.93, 5.11)	-0.58 ^b (-1.10, -0.07)	-0.92 ^b (-1.41, -0.42)	-0.83 ^b (-1.35, -0.32)	0.54 ^c (+0.08, +1.00)	23.3 ^c (21.1, 25.5)	25.0 ^c (22.8, 27.1)	24.1 ^c (21.9, 26.3)	33.3 ^b (31.0, 35.1)
CCWO _{TPA-5}	7.30 ^d (6.66, 7.95)	7.38 ^d (6.76, 8.01)	7.34 ^d (6.69, 7.99)	8.50 ^c (7.82, 9.18)	2.22 ^c (1.56, 2.89)	2.33 ^c (1.69, 2.97)	2.25 ^c (1.59, 2.92)	3.71 ^d (3.13, 4.29)	-0.40 ^b (-0.92, +0.11)	-0.72 ^b (-1.22, -0.22)	-0.65 ^b (-1.17, -0.14)	0.34 ^c (-0.12, +0.80)	19.1 ^d (16.9, 21.4)	20.0 ^d (17.8, 22.1)	19.1 ^d (16.9, 21.3)	28.3 ^c (26.0, 30.1)

Note: Results reported are least squares means, and 95% confidence intervals derived from the linear mixed-effects models. For each variable, methods that differed within breeds at $p < .05$ are shown by different superscript letters.

Abbreviations: CCWO, Cranial closing wedge osteotomy; GSD, German shepherd dogs; LBR, Labrador retriever; MAA, mechanical axis advancement; ΔTL, change in tibial length; ROT, Rottweiler; SMB, Small Breed Dogs; TPA_{POST}, precise postoperative tibial plateau angle.

tibial anatomical-mechanical axis angles (AMA-angles) have.^{29,30} Postoperatively, differences between the anatomical axis and mechanical axis resulting in an AMA-angle of greater than 3° results in increased caudal displacement of the weightbearing axis, which causes a focal increase in joint forces at the caudal aspect of the tibial plateau.³⁰ The CCWO_{CORA} methodology allows the surgeon to align the anatomical axis and mechanical axis, which allays concerns regarding a caudally orientated force, although the effects of transferring joint forces cranially have not been investigated.

Similarly, wedge orientation can be modified to facilitate technical execution and proximal fragment bone stock. In the current study, the proximal osteotomy of the wedge exited 5 mm distal to the patellar tendon insertion to maintain consistency across techniques. This resulted in osteotomies of unequal lengths for the CCWO_{CORA} surgeries. The cranial cortices were, therefore, not aligned as doing so would have caused Paley's third rule of osteotomy correction to apply, preventing achievement of the target TPA_{POST}. Alignment of the cranial cortices in the sagittal plane in vivo may be technically easier to assess in the operating theater. During preoperative planning, provided that the apex of the defined wedge remains at the calculated ACA-CORA, the wedge can be rotated until osteotomies of equal length are achieved, which will allow the cranial cortices to be aligned, while still obeying Paley's first rule of osteotomy correction; angular correction and alignment of the proximal and distal axes is achieved. If this adjustment is not made, surgeons should ensure that sagittal alignment is determined at the level of the apex of the wedge.

Previous reports have raised concerns over tibial shortening following CCWO.^{32–34} In the current study, change in tibial length was $\pm 1\%$, depending on technique used, with CCWO_{CORA} and CCWO_{ISO} increasing tibial length and CORA_{TPA} and CORA_{TPA-5} decreasing tibial length. A theoretical advantage of CCWO_{CORA} and CCWO_{ISO} is that tibial length is maintained but, clinically, the tibial shortening reported is likely to be clinically insignificant, being less than the 6% to 20% decrease in limb length that is tolerated following acute limb shortening.^{35–37}

In silico surgical planning is commonly used across human surgical disciplines and, more recently, has also been used as the basis for CCWO planning in dogs.⁷ This approach offers multiple advantages over cadaveric studies. More surgeries can be performed and multiple surgeries can be performed on the same bone, which is advantageous when making case-control comparisons. It also avoids both the expense and ethical concerns resulting from the use of cadaveric specimens, while enabling exact surgical planning and execution that would not be replicable even in the hands of an experienced surgeon. This is particularly useful in

proof-of-concept studies where a geometric principle is being investigated.

As with the TPLO procedure, CCWO_{CORA} methodology can determine the exact correction required to achieve the target TPA_{POST}. Cranial closing wedge osteotomy does offer some advantages over the TPLO procedure. First, there is no reliance on specialized equipment,⁹ making the surgery potentially more accessible. The TPLO procedure has been demonstrated as a safe technique to stabilize cranial cruciate ligament-deficient stifles with excessive TPA,³⁸ CCWO may be more suited to dogs with this conformation, avoiding the need for substantial rotation of the proximal bone fragment. The CCWO_{CORA} methodology described is well suited for the treatment of concurrent torsional, varus, or valgus tibial deformities.¹¹ This could be facilitated by in silico planning and the use of 3D-printed surgical guides to improve accuracy.³⁹

The main limitation of this study is the ex vivo, in silico design. Although this approach ensures that conditions are well controlled, enabling perfect surgical planning and execution, the same degree of accuracy is unlikely to be achieved clinically. Following on from this proof-of-concept study, a prospective, randomized cohort study measuring the accuracy of TPA_{POST} of CCWO_{CORA}, against another of the described CCWO methodologies, is now indicated. Whilst MAA is an inevitability of any CCWO procedure, its consequence on stifle biomechanics is not fully understood. Further research may focus on the impact of MAA on stifle stability and changes in stifle joint contact mechanics.

4.1 | Conclusion

This novel CCWO_{CORA} is the first method to be described that can accurately and predictably achieve target TPA_{POST}. Further studies are required to establish whether these results can be transferred to the clinical setting.

AUTHOR CONTRIBUTIONS

Petchell WHR, BVMedSci, BVM, BVS, AFHEA, MRCVS: Contributed to the design of the study, identified suitable medical records, planned the in silico surgeries, interpreted data, and drafted and revised the manuscript. Bostock AR, BEng, MSc: Planned and performed all in silico surgeries to acquire data; provided scientific in-line editing of the manuscript. German AJ, BVSc, PhD, CertSAM, DipECVIM-CA, SFHEA, FRCVS: Performed statistical analysis of the data and provided scientific in-line editing of the manuscript. Tomlinson AW, BVSc, CertAVP(GSAS), DipECVS, FHEA, MRCVS: Conceptualized the methodology, contributed the design of the study, identified suitable medical records, planned the in silico

surgeries, and provided scientific in-line editing of the manuscript. All authors provided a critical review of the manuscript and endorsed the final version. All authors are aware of their respective contributions and have confidence in the integrity of all contributions.

ACKNOWLEDGMENTS

The authors wish to thank Dan Jones of Fusion Implants for his generous support in the preparation of this manuscript.

FUNDING INFORMATION

The authors received no grants or financial support related to this report.

CONFLICT OF INTEREST

Alexander J. German is an employee of the University of Liverpool, but his position is financially supported by Royal Canin. Alexander J. German has also received financial remuneration and gifts for providing educational material, speaking at conferences, and consultancy work, all unrelated to the current study. Anna R. Bostock is an employee of Fusion Implants who design and manufacture veterinary orthopedic implants. The authors declare no other potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors declare no other commercial or financial relationships that could be construed as a potential conflict of interest with respect to the research, authorship and publication of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Petchell WHR, Bostock AR, German AJ, Tomlinson AW. An in silico comparison of a novel CORA-based cranial closing wedge osteotomy methodology with three other techniques. *Veterinary Surgery.* 2025;1-13. doi:[10.1111/vsu.14277](https://doi.org/10.1111/vsu.14277)