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CLINICAL RESEARCH

WILEY

A mismatch of planning and achieved tibial plateau angle in cranial closing wedge surgery: An in silico and clinical evaluation of 100 cases

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Abstract

Objective: (1) To determine whether Oxley's modified cranial closing wedge osteotomy (CCWO) results in a tibial plateau angle (TPA) of 5° in silico, (2) compare in silico to clinical postoperative TPA and (3) determine the impact of ostectomy distalization in silico.

Study design: Cross-sectional retrospective radiographic in silico study.

Sample population: A total of 100 stifle radiographs; 90 dogs (small ≤25 kg = 84; large >25 kg = 16).

Methods: Tibial plateau angles were measured preoperatively (TPA_{Pre}), after in silico planning (TPA_{Plan}), and postoperatively (TPA_{Post}). Virtual ostectomies were evaluated for plate fit. Postoperative ostectomy position was measured. Virtual ostectomies were performed 5/7.5/10/15 mm from the patellar tendon insertion in 10 dogs from each preoperative TPA category (≤20°/21–25°/ 26–30°/31–35°/>35°). Comparisons for TPA_{Pre}, TPA_{Post}, and TPA_{Plan} were made between small and large dogs, and the outcome to the target 5° between TPA categories and ostectomy positions.

Results: Mean ± SD TPA_{Pre} was 28.6 ± 6.2° and higher in small than large dogs. Mean TPA_{Plan} was 7.6 ± 2.7°. Plate fit was appropriate in all. In silico, TPAs were greater than 5° except for cases with TPA_{Pre} > 35°. Median TPA_{Post} was 5.5° (−4–21) and was higher in small (7°) than large (4.5°) dogs. Postoperative ostectomy position was more distal than Oxley's guidelines. When distalized >7.5 mm in silico, the magnitude of under-correction increased.

Conclusions: Oxley's modified CCWO did not result in TPA of 5° in most cases. Ostectomy distalization exacerbated under-correction.

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Clinical impact: Current guidelines should be modified to achieve 5° TPA postoperatively.

1 | INTRODUCTION

Cranial cruciate ligament disease (CCLD) is the most common cause of hindlimb lameness in dogs.[1] Surgical treatment is recommended for management, and a range of techniques have been described. Proximal tibial osteotomy techniques including cranial closing wedge ostectomy (CCWO) and tibial plateau leveling osteotomy (TPLO) aim to reduce the tibial plateau angle (TPA) to 5°, which has been shown to dynamically stabilize the cranial cruciate ligament deficient stifle joint.[2] Biomechanical studies corroborate that a reduction in TPA to 4–6° will sufficiently eliminate cranial tibial thrust, and clinical investigations consistently demonstrate good to excellent clinical outcomes for these procedures.[3–5]

CCWO was first described by Slocum and Devine and assumed that to achieve a postoperative TPA (TPA_{Post}) of 5°, the apex angle of the triangular wedge ostectomy would be equivalent to TPA minus 5°.[6] TPA is calculated using the tibial long-axis, and the proximal landmark for establishing the mechanical axis of the tibia is the center of the tibial eminences. However, as the osteotomized wedge is reduced, the tibial eminences are displaced cranially resulting in a tibial long axis shift (TLAS), which ultimately leads to an under-correction of TPA_{Post}. The degree of TLAS is increased when the ostectomy is performed more distally, and as the wedge angle is increased.[6]

In an attempt to account for the aforementioned challenges, modified ostectomy planning methods with adjusted wedge angle calculations have been described to attempt to achieve the desired TPA_{Post}.[3,7–12] One of the most popular and widely adopted variations was described by Oxley et al. They reported a modified CCWO (mCCWO) which used an isosceles wedge positioned more proximally along the tibial tuberosity. A further characteristic was the maintenance of a caudal "hinge" of cortical bone to provide intraoperative alignment and stability.[3] The ostectomy wedge size required varied by the preoperative TPA (TPA_{Pre}) based on grouped ranges of increasing TPA with wedge angles between TPA_{Pre} minus 5° and TPA_{Pre} minus 2°. The proximodistal ostectomy position was determined by bodyweight, with a more distal ostectomy performed in larger dogs (>25 kg) to allow for sufficient proximal bone stock that is appropriately sized for adequate implants. In a clinical case series using this method mCCWO resulted in a median TPA_{Post} of 6.5°. In that study, all dogs were > 20 kg; however, mCCWO is also applied to small dogs.[3]

The aims of this study were: (1) to determine whether the Oxley mCCWO gives the desired TPA_{Post} of 5° in dogs of all sizes with varying TPA_{Pre} in silico (TPA_{Plan}) using orthopedic planning software, (2) to compare the postoperative TPA in clinical cases executed according to the Oxley mCCWO guidelines to the in silico planned outcome, and (3) to determine the effect of distalizing the ostectomy in silico on TPA_{Plan}.

The hypotheses were that: (1) the TPA_{Plan} would achieve the desired 5° TPA, (2) there would be no difference between the TPA_{Plan} and TPA_{Post}, and (3) a more distal ostectomy would be subject to greater TLAS and the resulting TPA would be under-corrected.

2 | MATERIALS AND METHODS

Electronic medical records were retrospectively reviewed to identify dogs that underwent mCCWO for the management of CCLD at a single institution between March 2016 and March 2021. Radiographic inclusion criteria required DICOMs of diagnostic quality of pre- and postoperative straight mediolateral radiographs of the stifle including the distal femur and tarsus. Cases that presented for the management of postoperative complications or had undergone previous CCWO at other institutions were excluded. Case details including signalment, bodyweight, and operated limb were collected. Dogs were categorized into two groups: small dogs weighing ≤25 kg and large dogs weighing >25 kg based on previous criteria for wedge ostectomy positioning.[3]

Radiographs were imported to orthopedic planning software (vPopPro, VetSOS Education Ltd). The TPA_{Pre} was measured using the previously established methodology.[13] A proximal isosceles mCCWO was performed in silico according to Oxley et al. (Figure 1); briefly, the ostectomy was positioned at 5 and 10 mm distal to the patellar tendon insertion on the tibial tuberosity for small (≤25 kg) and large dogs (>25 kg), respectively, and the wedge angle was calculated according to Oxley's guidelines based on TPA_{Pre} (Table 1).[3] The apex angle of the isosceles wedge was calculated from TPA_{Pre} minus a set value dependent upon the TPA_{Pre}. An additional group was made for dogs with a TPA_{Pre} > 35° (eTPA), extrapolating the calculation from cases with a TPA_{Pre} of 31–35°, as eTPAs were not included in the Oxley paper. After performing the mCCWO in silico, the TPA_{Plan} was measured. Each image was subjectively evaluated for plate fit by superimposing a scaled TPLO implant based on patient weight and manufacturer guidelines (DePuy Synthes Vet, West Chester, Pennsylvania).

The TPA_{Post} was measured on immediate postoperative radiographs. The distance from the patellar tendon

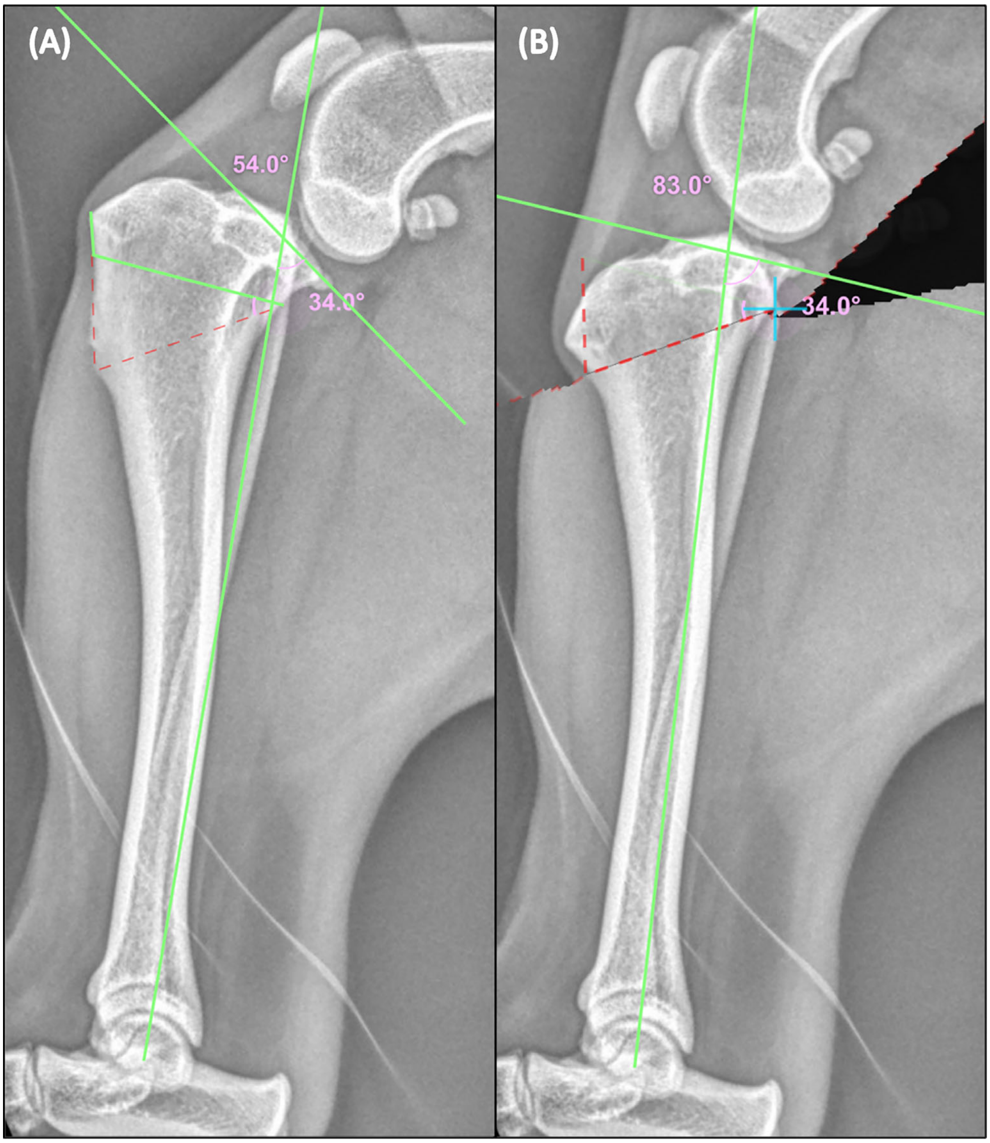

FIGURE 1 An example of in silico modified cranial closing wedge osteotomy (mCCWO) planning in a small dog (≤25 kg) using vPOPPro. (A) Preoperative mediolateral stifle radiograph, with a measured tibial plateau angle of 36°. An isosceles wedge with an apex angle of 34° (TPA-2) was plotted 5 mm from the tibial tuberosity with the base parallel to the cranial cortex of the tibia. (B) Planned virtual ostectomy reduced giving a postoperative tibial plateau angle of 7°.

TABLE 1 Oxley et al. preoperative tibial plateau angle (TPA) category. The apex angle of the isosceles wedge was calculated from preoperative TPA minus a set value dependent upon the preoperative TPA. TPA5* group was created to include dogs with excessive tibial plateau angle, not previously accounted for in the Oxley publication.

Preoperative TPA category	Preoperative TPA (°)	Wedge angle calculation
TPA1	≤20	TPA − 5°
TPA2	21–25	TPA − 4°
TPA3	26–30	TPA − 3°
TPA4	31–35	TPA − 2°
TPA5*	>35	TPA − 2°

insertion on the tibial tuberosity to the proximal aspect of the ostectomy line at the cranial cortex of the tibia was measured to assess the position of the clinically executed ostectomy (OP).

To determine the effect of distalizing the ostectomy on post-planning TPA, 10 dogs per TPA category (Table 1), were randomly selected. In silico ostectomies were planned and executed at an increasing distal distance from the patellar tendon insertion as follows: 5 mm (D_5)—small dog recommended position, 7.5 mm ($D_{7.5}$), 10 mm (D_{10})—large dog recommended position, and 15 mm (D_{15}) (Figure 2). The post-planning TPA with increasing distal distance (TPA_{PlanD}) was remeasured for each ostectomy position.

2.1 | Statistical analysis

Statistical analyses were performed using SPSS (IBM SPSS Statistics, version 28.0. Armonk, New York: IBM Corp). Data were assessed for normality and outliers using Shapiro–Wilk and the outlier labeling rule

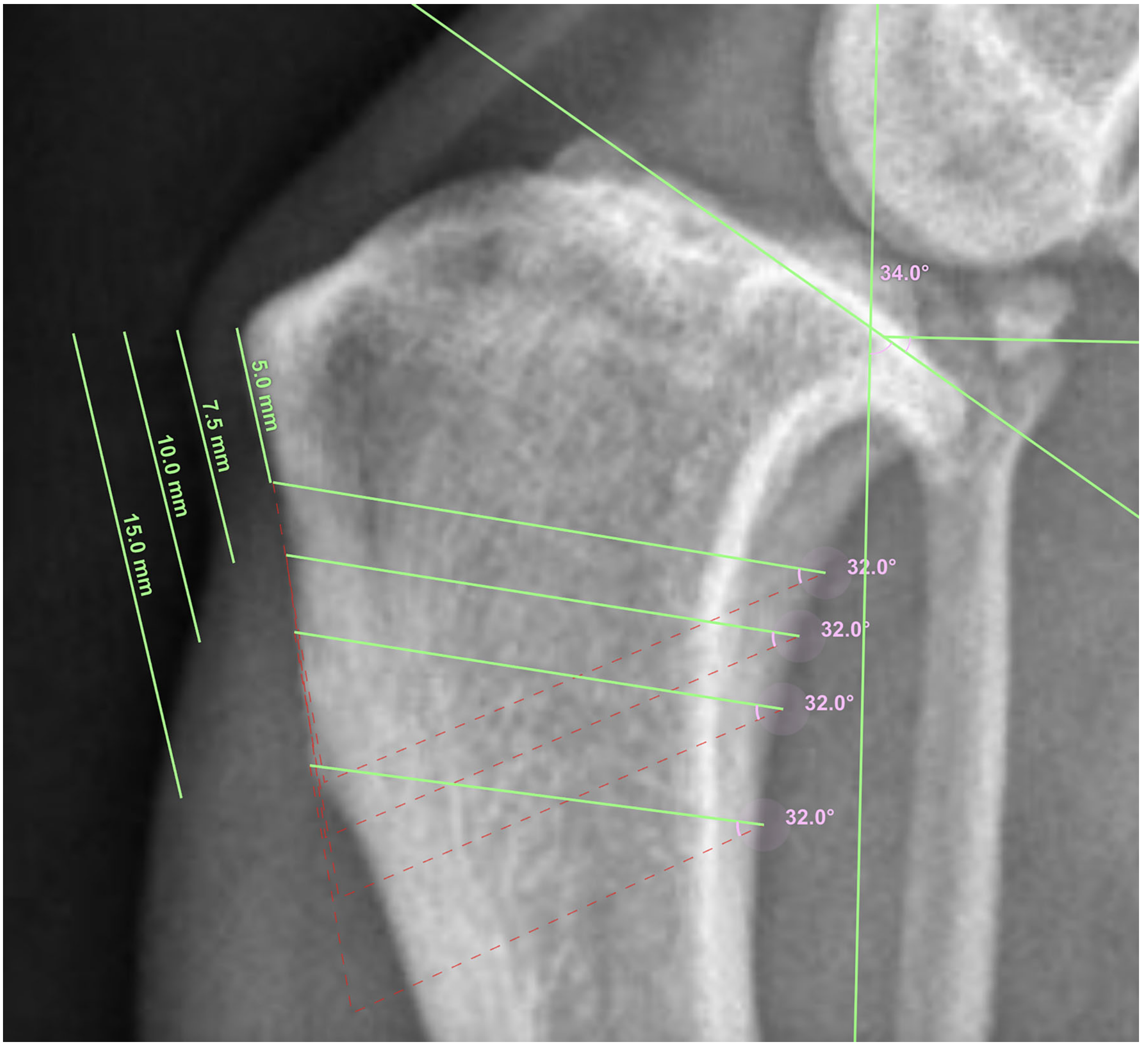

FIGURE 2 An example of in silico modified cranial closing wedge osteotomy (mCCWO) planning with progressive ostectomy distalization using vPOPPro. (A) The preoperative tibial plateau angle was 34°. An isosceles wedge with an apex angle of 32° (TPA-2) was plotted 5, 7.5, 10, and 15 mm distal to the tibial tuberosity. The virtual ostectomy was executed at each level and the TPA_{PlanD} was measured.

($K = 2.2$). Descriptive statistics were generated accordingly. Mean or median TPA_{Pre}, TPA_{Plan}, TPA_{Post}, and OP were assessed overall and compared between small and large dogs using independent *t*-tests and Mann–Whitney U for normally and non-normally distributed data respectively. One sample *t*-tests and Wilcoxon signed-rank were used to compare the mean or median TPA_{Plan} and TPA_{Post} to the target of 5° and to compare OP to 5 and 10 mm

TABLE 2 Average preoperative, post planning, and postoperative tibial plateau angle (TPA) and postoperative ostectomy position in overall cases, small (≥ 25 kg) and large (>25 kg) dogs. *p*-value represents the difference between small and large dogs.

	TPA_{Pre} (°) mean ± SD	TPA_{Plan} (°) mean ± SD	TPA_{Post} (°) median (range)	Ostectomy position
All dogs	28.6 ± 6.2	7.6 ± 2.7	5.5 (−4–2)	8.6 mm (3.2–20.6 mm)
Small dogs	29.3 ± 6.3	7.5 ± 2.8	7.0 (−4–21)	8.3 mm (3.6–20.6)
Large dogs	25.3 ± 4.0	7.7 ± 2.3	4.5 (−3–10)	12.6 (3.2–19.0 mm)
p-value	.02	.84	.06	.00

for small and large dogs, respectively. A one-way ANOVA or Kruskal–Wallis H test was performed to assess for variance in TPA_{Plan} and TPA_{Post} between wedge angle categories. A repeated measures ANOVA was performed to assess for variance in TPA_{PlanD} between ostectomy positions.

3 | RESULTS

A total of 84 small dogs and 16 large dogs were included, giving 100 stifle radiographs including 10 bilateral cases. The median (range) weight was 13.1 kg (4.1–44.7 kg). The mean ± SD age was 7 years 1 month ± 2 years 9 months. A total of 51 CCWOs were performed on right hindlimbs and 49 on left hindlimbs.

The mean overall TPA_{Pre} was 28.6 ± 6.2° (Table 2). The mean TPA_{Pre} was greater in small than large dogs; 29.3 ± 6.3° and 25.3 ± 4.0°, respectively ($p = .02$). When the mCCWO was performed in silico the mean overall TPA_{Plan} was 7.6 ± 2.7°. There was no difference between small and large dogs ($p = .84$), and hence higher than 5° in both small and large dogs. Scaled TPLO plate fit was considered appropriate in all cases. For clinical cases, the median overall TPA_{Post} was 5.5° (−4–21). The median TPA_{Post} for small dogs was 7° (−4–21) and 4.5^0 (−3–10) for large dogs. The median TPA_{Post} was higher than the 5° target in small dogs only ($p = .001$). The ostectomy was performed a median of 8.6 mm (3.2–20.6 mm) from

TABLE 4 Mean tibial plateau angle following in silico virtual ostectomy performed 5, 7.5, 10, and 15 mm from the patellar tendon insertion.

Ostectomy position	TPA_{PlanD} (°) mean ± SD	Number in group
5 mm	7.5 ± 2.9	10
7.5 mm	8.0 ± 2.5	10
10 mm	8.7 ± 2.5	10
15 mm	10.1 ± 2.8	10

Abbreviations: TPA, tibial plateau angle.

TABLE 3 Mean post-planning and postoperative tibial plateau angle (TPA) for each preoperative TPA category ($_p$TPA). Asterisk (*) demonstrates a difference between categories based on one-way ANOVA and Games-Howel post hoc test. One-sample *t*-test results demonstrating the difference between TPA outcome and 5° target.

TPA category (°)	TPA_{Plan} (°) Mean ± SD	5° target *p*-value	TPA_{Post} (°) Mean ± SD	5° target *p*-value
<20	8.4 ± 2.5	.00	4.7 ± 5.2	.86
21–25	8.2 ± 2.2	.00	4.5 ± 3.3*	.51
26–30	7.6 ± 2.6	.00	6.2 ± 3.3	.03
31–35	7.1 ± 2.7	.01	7.5 ± 5.9	.07
>35	6.4 ± 3.2	.10	10.7 ± 6.1*	.00
p-value	.20		.01	

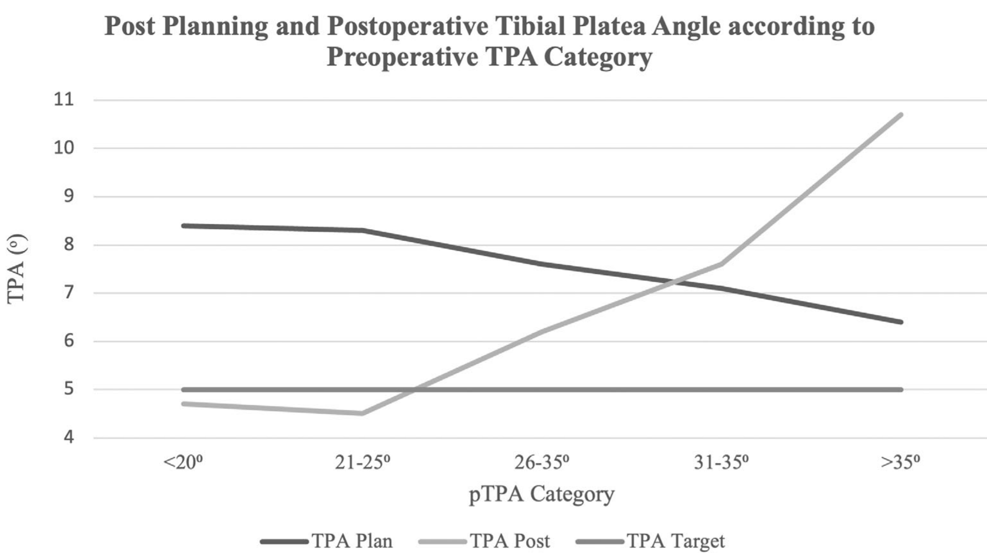

FIGURE 3 Line graph showing post planning (in silico) and postoperative (clinical) tibial plateau angle (TPA) between preoperative TPA categories.

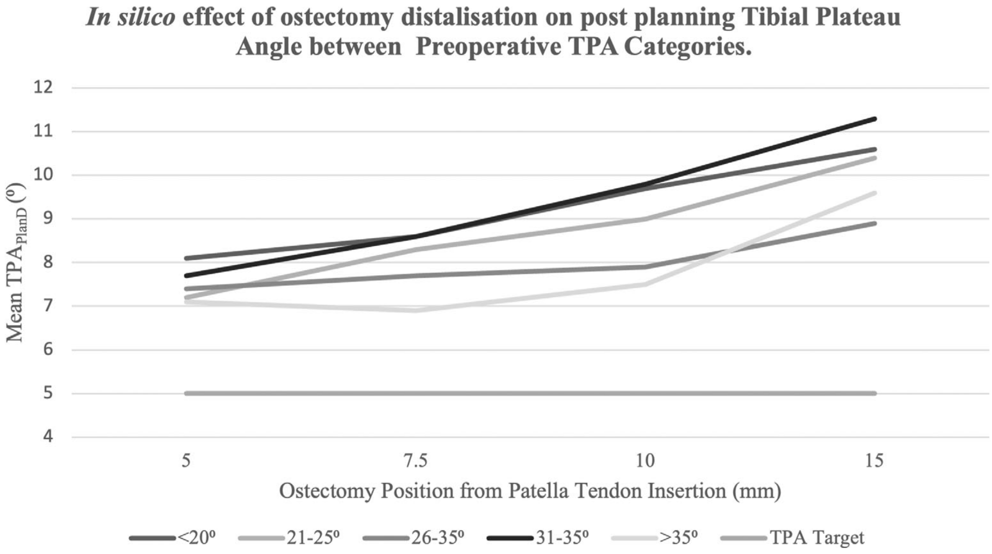

FIGURE 4 Line graph showing the effect of performing the ostectomy more distally in silico.

the patellar tendon insertion. The position was more distal in large than small dogs; 12.6 mm (3.2–19 mm) and 8.3 mm (3.6–20.6 mm), respectively. The median ostectomy position was more distal than recommended 5 mm in small dogs and more distal than 10 mm in large dogs ($p = .001$ and .01, respectively). There was no difference between TPA_{Plan} and TPA_{Post} ($p = .05$).

For in silico cases, when wedge angle categories were considered, there was no difference in mean TPA_{Plan} between categories (Table 3, Figure 3). There was a trend for progressive under-correction as the preoperative TPA decreased. Category 5 (eTPA) was the only group that did not differ from the target of 5° ($p = .10$) with a TPA_{Plan} of $6.4 \pm 3.2°$.

For clinically executed cases, there was an inverse trend, with a progressive under-correction as preoperative TPA increased (Table 3). There was a difference between TPA_{Post} when preoperative TPA category was accounted for ($p = .01$). Post hoc testing demonstrated a difference between categories 2 and 5 alone. Cases with a preoperative TPA of 26–30 and eTPA were different from the target of 5° ($p = .03$ and $p = .01$, respectively).

The mean TPA_{PlanD} differed between ostectomy positions (Table 4, Figure 4). Post hoc analysis demonstrated that the TPA_{PlanD} did not differ when performed at 5 mm or 7.5 mm from the patellar tendon insertion ($p = .45$) but was higher at increased distances (10 and 15 mm). There was a progressive under-correction of the TPA_{PlanD} as the ostectomy was distalized ($p = .01$). The TPA_{PlanD} was closest to the target of 5° when the ostectomy was performed 5 and 7.5 mm from the patellar tendon insertion; however, the mean TPA_{PlanD} for all groups was greater than 5° ($p = .00$). These findings were consistent when TPA categories were accounted for.

4 | DISCUSSION

We evaluated the planning methodology and resultant TPA following a modified CCWO as described by Oxley et al.; comparing the in silico result to clinically executed cases. When executed in silico, the wedge angle calculations proposed by Oxley et al. accounted for increasing preoperative TPA; however, the intended 5° was not achieved in any group but was closest in the eTPA group. We therefore reject our first hypothesis. Assuming that it is important to achieve 5° which has been shown to eliminate cranial tibial thrust during weight bearing, the current guidelines should be modified.[5]

Although surgical planning gave a consistent reduction in TPA to 6.4–8.4° irrespective of TPA_{Pre}, TPA_{Post} from clinically executed cases differed, and we reject our second hypothesis. This suggests that surgical planning or intraoperative execution differed from Oxley's recommendations in the cases included in our study. Surgical correction to the target TPA was better in dogs with a lower TPA_{Pre} and the least effective correction was achieved in cases with eTPA. Furthermore, the position of the ostectomy in clinical cases was more distal than the recommended 5 and 10 mm from the patellar tendon insertion in small and large dogs, respectively. Distalizing the ostectomy in silico demonstrated a progressive under-correction of TPA irrespective of TPA_{Pre}. This supports previous evidence that the impact of tibial long-axis shift is greater when the ostectomy is performed more distally.[14]

There are several possible explanations for the poor correlation between postoperative and in silico outcomes. First, decision-making intraoperatively may have resulted in performing a more distal ostectomy to allow perceived sufficient room for implant placement. Subjective assessment of plate fit in this study demonstrated that the appropriately sized plate according to weight and manufacturer guidelines could be placed sufficiently distal to the stifle joint, and proximal to the virtual ostectomy performed at 5 mm from the patellar tendon insertion in all cases. In addition, performing the ostectomy at 5 and 7.5 mm distal to the patellar tendon insertion achieved the TPA closest to the 5° target. The lack of statistically significant difference between the post-planning TPA at these positions suggests some flexibility for plate positioning intraoperatively. Although hypodermic needles are used intraoperatively to identify the tibial plateau in surgery, the soft tissues, and medial buttress will reduce the confidence of the surgeon compared with an in silico radiographic plate application. Inevitably this will lead to a more distal osteotomy, although exceeding 7.5 mm may reduce the degree of TPA correction achieved. Further, clinical cases were planned preoperatively with alternative software in which a virtual ostectomy and preoperative assessment of the resulting TPA could not be made, and this may have influenced how close the executed surgery was to the plan. Finally, in planning the wedge size, the apex angle of the isosceles triangle was plotted and then the actual distance (mm) of the base of the isosceles triangle along the cranial border of the tibial crest was determined in planning and executed at surgery. It is impossible to know how accurately the measured distance was achieved retrospectively, nor be able to account for the sagittal saw blade thickness, which may have contributed to the discrepancy in clinical outcome versus TPA_{Plan}. Further research is warranted to directly compare the clinical outcome of cases undergoing mCCWO planned with Oxley and alternative methods.

Although the Oxley mCCWO is widely applied to small dogs, Oxley et al. did not include dogs weighing <20 kg, or dogs with eTPA. An additional category of eTPA was established for dogs with TPA >35. As this TPA angle was not described in Oxley et al., and clinical cases had been managed as per group 31–35, with a reduction of 2°, the in silico cases were also calculated as TPA − 2. The current study demonstrated no difference in planned or postoperative TPA in small and large dogs and therefore the methodology for all dogs and those with eTPA is supported. CCWO may be considered preferable to TPLO in dogs with a preoperative TPA greater than 35°, or excessive tibial plateau angle (eTPA), due to rotation of osteotomy past the “safe point” in TPLO could result in tibial tuberosity fracture.[8,15] However, studies investigating complications following TPLO, including dogs with eTPA have not repeatedly demonstrated an increase in this complication.[16,17] A combination of CCWO and TPLO has been described to mitigate these effects, although the major postoperative complication rate was high.[11]

Potential limitations of CCWO include limb shortening and distalization of the patellar tendon, resulting in patellar baja, patellar tendonitis, or stifle joint hyperextension.[4] Using the Oxley mCCWO, removing a proportionately large wedge for cases with eTPA may result in a more pronounced effect. Other mCCWO techniques have been described to account for this. However, all reports are isolated case series and do not make direct comparisons between the different CCWO iterations. Wallace et al described a 25° neutral wedge ostectomy resulting in TPA correction whilst removing a smaller wedge and reducing limb shortening.[8] Frederick et al. demonstrated lower short-term complications using this technique.[7] Christ et al described a juxta-articular mCCWO to maximize bone contact across the osteotomy while reducing the effect of tibial long-axis shift.[9] Consistent reduction of TPA within 1° of the target TPA and no major complications were reported.[9,10] Guenego et al. described an anatomical-mechanical-axis (AMA-based) mCCWO in order to correct the caudal bowing of the proximal tibia which is frequently demonstrated in dogs with CCLD.[12] Patellar baja and patellar tendonitis following mCCWO is likely theoretical and has not been demonstrated in recent studies.[7,9,12]

The clinical outcome of the cases included here was not explored as an aim of this study. Although tibial plateau leveling procedures aim to reduce the TPA to 4–6°, previous studies have demonstrated good to excellent clinical outcomes with higher postoperative TPAs, including up to 14°.[18] Further research is needed to assess the clinical outcome measures in relation to final TPA following the Oxley mCCWO in dogs, particularly in cases with eTPA in which higher complications have been reported.[11,18] A small number of cases in the current study had a negative TPA_{Post}. This outcome was not observed in in silico cases and suggests that intraoperative execution differed from the in silico planning, and hence more care should be taken to accurately reproduce the plan to achieve a result closer to the planned outcome. As tibial plateau leveling converts cranial tibial thrust into caudal tibial thrust, a negative TPA would transfer the strain to the caudal cruciate ligament which acts as the primary stabilizer of the stifle during axial loading.[2] Caudal cruciate ligament tearing has been reported in up to 94% of cranial cruciate ligament deficient stifles prior to tibial plateau leveling surgeries.[19] Therefore, excessive tibial plateau leveling can result in caudal cruciate ligament injury.[13] We expect the negative TPAs to be the result of inaccuracies during surgery which did not correlate well with the surgical planning. The clinical implication of a negative TPA is unclear but is considered unlikely to be of benefit to the stabilization of the stifle joint.

For all radiographic studies, positioning and the presence of osteophytosis may have impacted the accuracy of

TPA measurements. Radiographs were included only if appropriately positioned to reduce the impact of positioning on measurement accuracy. Osteoarthritis and osteophytosis are common with CCLD but have been documented to have minimal impact on measurement repeatability.[20] Finally, radiographs were measured by a single observer (an ECVS resident experienced in measuring joint angles). Previous studies have documented interobserver variability in TPA measurements of 0.8–4.8°.[20,21] Wide variability between measurements may have impacted the overall TPA outcome and therefore comparison to the 5° target TPA; however, having a single observer should minimize variation.

In conclusion, the modified CCWO described by Oxley et al. requires modification to achieve the planned 5° TPA target. The current study demonstrates that this methodology achieves a consistent reduction in TPA for cases with excessive preoperative TPA. Clinical cases appeared to differ from surgical plans, although in some situations achieved a TPA closer to the target. Ostectomy distalization is not necessary according to planning to allow for appropriate implant fit and should be avoided where possible due to its effect on tibial long axis and potential under-correction of the final TPA achieved. Further work is required to determine whether there is a clinical impact of under-correction and whether the Oxley planning method should be modified to achieve a 5° TPA target.

AUTHOR CONTRIBUTIONS

Banks C: Contributed to the study design, data acquisition, statistical analysis, and interpretation and wrote the manuscript. Jones, GMC: Contributed to the statistical analysis and interpretation of the results and approved the manuscript. Meeson RL: Contributed to the conceptualization and design of the study, supervised the acquisition and interpretation and contributed to the manuscript. All authors approved the submitted manuscript and are publicly accountable for relevant content.

CONFLICT OF INTEREST

There are no conflicts of interest to disclose.

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