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Effect of tibial plateau angle < 5° on ground reaction forces in dogs treated with tibial plateau leveling osteotomy for cranial cruciate ligament rupture up to 6 months postoperatively

F. Volz [a,*], D. Eberle [b], J. Klever [c], Y. Zablotski [a], M. Kornmayer [a]

[a] Small Animal Clinic, Ludwig-Maximilians University, Veterinaerstraße 13, Munich 80539, Germany
[b] Small Animal Clinic Stuttgart Plieningen, Hermann-Fein-Straße 15, Stuttgart 70599, Germany
[c] Royal Veterinary College, University of London, Hawkshead Ln, Brookmans Park, Hatfield AL97TA, UK

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ABSTRACT

Tibial plateau leveling osteotomy (TPLO) has been commonly performed in dogs with cranial cruciate ligament disease (CCLD) since the introduction by Slocum and Slocum (1993). To reduce cranial tibial thrust the TPLO technique aims for a postoperative tibial plateau angle (TPA) of 5–6.5°. In recent years studies have shown that a postoperative TPA below 5° could be beneficial regarding stifle stability or meniscal load. Dogs with CCLD that were treated with TPLO, were examined preoperatively, six weeks, three and six months postoperatively with gait analysis and grouped according to their postoperative TPA. The aims of study was (1) to evaluate if dogs with a postoperative TPA below 5° would have a faster limb function recovery up to six months postoperatively as measured objectively with ground reaction forces (GRFs) and (2) to determine whether the postoperative TPA correlates with the outcome measurements. Dogs with TPA <5° showed no faster limb function recovery postoperatively up to six months as measured with peak vertical force (PVF) or vertical impulse (VI) ($p > 0.05$). No correlation for the postoperative TPA <5° on GRFs was demonstrated. But the postoperative TPA showed a significant correlation with the symmetry indices of PVF (SIPVF) and VI (SIVI) for all dogs (>5° and <5° TPA together), indicating that with lower postoperative TPA dogs had a more symmetrical gait in hindlimbs SIPVF ($r = 0.144$, $p < 0.05$) and SIVI ($r = 0.189$, $p < 0.01$). The study indicates that a lower postoperative TPA could be beneficial regarding hindlimb symmetry indices of GRFs.

Introduction

For the treatment of cranial cruciate ligament disease (CCLD), Tibial Plateau Levelling Osteotomy (TPLO) was introduced by Slocum and Slocum (1993) in 1993. The outcomes of different surgical techniques for CCLD have been investigated, and TPLO has been reported to be superior to other surgical techniques (Beer et al., 2018; Bergh et al., 2014; Gordon-Evans et al., 2013; Knebel et al., 2020; Krotscheck et al., 2016). For neutralization of cranial tibiofemoral shear forces the tibial plateau angle (TPA) after TPLO should be ideal between 5 and 6,5° (Slocum and Devine, 1998; Slocum and Slocum, 1993; Warzee et al., 2001).

On the contrary, more recent studies were demonstrating that a TPA of less than 5° may be beneficial regarding meniscus load (Schmutterer et al., 2022) or cranio-caudal stifle stability (Rebentrost, 2019). Rebentrost (2019) evaluated dogs with a TPA of 0° and a TPA of 5° preoperatively and 6 – 8 weeks postoperatively with uniplanar fluoroscopic cinematography. They demonstrated that 93% of dogs with a TPA of 0° showed no cranio-caudal instability postoperatively compared to only 62% of dogs with a TPA of 5°. The regression analysis showed that there was a significantly greater probability of stifle joint stability with lower postoperative TPAs. Other studies have also demonstrated that TPLO is not restoring normal/physiological stifle kinematics, and many dogs may have persistent cranio-caudal instability (Kim et al., 2009; Rebentrost, 2019; Tinga et al., 2020). With regard to the meniscal load after TPLO Schmutterer et al. (2022) biomechanically demonstrated that the contact forces on both menisci were significantly lower after TPLO with a 1° TPA compared to the intact stifle but not with a TPA of 6°. Other studies have reported that postoperative TPAs below 5–6,5° increase caudal instability and are thought to be a risk factor for caudal

* Corresponding author.
E-mail address: Frederik.volz@chir.vetmed.uni-muenchen.de (F. Volz).

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cruciate ligament damage (Reif et al., 2002; Warzee et al., 2001). Further, it was demonstrated that dogs with CCLD have a high probality of a concurrent caudal cruciate ligament damage with rates up to 94% (Agnello et al., 2022; Sumner et al., 2010). Brown et al. (2014) have shown in a biomechanical computer model, that with a TPA lower 5° the cranial drawer was converted to a caudal drawer, which could supposedly damage the caudal cruciate ligament. However, it remains unclear that in clinical cases the theoretical findings of the abovementioned studies hold true, as a study of a second-look asrthroscopy post TPLO showed in 32 stifles fraying and 3 had a complete rupture of the caudal cruciate ligament (Hulse et al., 2010). The TPAs for the dogs with complete rupture were respectively 0°, 7° and 10° postoperatively (Hulse et al., 2010).

Regarding the effect of the TPA on the clinical outcome, one study showed no differences in ground reaction forces (GRFs) and no correlation between the postoperative TPA and GRFs (Robinson et al., 2006). In this retrospective study, only 5 dogs had a TPA <4° and the postoperative gait analysis was performed at a mean of 7.4 months after TPLO with a range of 4–17months (Robinson et al., 2006). Slocum and Slocum (1993) stated that after TPLO, dogs should return to normal limb function approximately three months postoperatively. In other studies, dogs returned to normal function between three to six months post TPLO (Knebel et al., 2020; Krotscheck et al., 2016; Volz et al., 2024). To improve and recover more rapidly after TPLO, many studies have investigated various treatment modalities, such as physiotherapy, cold compression therapy, low level laser or extracorporeal shockwave therapy, with different results (Barnes et al., 2019; Monk et al., 2006; Rogatko et al., 2017; Romano and Cook, 2015; von Freeden et al., 2017).

The purpose of this study was to confirm the results from Robinson et al. (2006) in a more homogenous and standardized population, with a larger population of dogs having a TPA <5°. Our hypotheses were (1) TPA correlates with postoperative GRFs and (2) dogs with a TPA<5° would have faster limb recovery up to 6 months after TPLO, as measured by objective gait analysis.

Materials and methods

Study design

This was a retrospective study with data from one veterinary teaching hospital. The cases included in this study were used in two previous studies, Knebel et al. (2020), and Volz et al. (2024). Written informed consent for the aforementioned studies was obtained from the owners of all included patients. We included only patients in whom a TPLO due to CCLD and no other treatment was performed and no other concurrent orthopedic or neurologic disease was recorded. For inclusion in this study data for GRFs from preoperative, six weeks, three and six months postoperatively had to be available, as well as preoperative and postoperative radiographs with the tarsus and stifle 90° flexed for TPA measurement. The other inclusion criterion was a bodyweight between 20 and 40 kg. All dogs underwent TPLO performed by one of three experienced surgeons (two Dipl. ECVS, one Full Professor for small animal surgery). In each patient, preopartive magnetic resonance imaging (MRI) was performed to confirm the diagnosis of CCLD and to exclude meniscal injury. If meniscal injury was suspected based the on preoperative MRI findings, caudal mini arthrotomy was performed, and the torn portion of the medial meniscus was excised as described by Böddeker et al. (2012). Patients with a bilateral CCLD were included, but only the second surgery was evaluated. Other collected data included age, sex, bodyweight, breed, degree of rotation, and whether a meniscectomy was performed.

Radiographs and TPA measurement

Mediolateral radiographs of the affected stifle with 90° flexion of stifle and tarsus were acquired preoperatively and immediately postoperatively according to the TPLO procedure (Slocum and Devine, 1998; Slocum and Slocum, 1993). TPA was determined using the built-in TPA/TPLO measurement tool in the commercial DICOM viewing software dicomPACS® (version 9.1.26, Oehm und Rehbein GmbH, Rostock, Germany). The TPA was measured as previously described (Slocum and Devine, 1983; Slocum and Devine, 1998; Slocum and Slocum, 1993). First, the long axis of the tibia was determined with a line from the middle of the apices of the intercondylar notch to the center of the talocrural joint. Then, the most cranial and caudal points of the tibial plateau was connected with a line. Finally, a line perpendicular to the long axis of the tibia is drawn at the point where the other lines intersect. The angle between this perpendicular line and the line that connects the cranial and caudal point of the tibial plateau reflects the TPA. Three observers with different levels of experience (Resident ECVS, Diplomate ECVS, Diplomate ECVDI) independently measured the TPA. If there was ≥2° difference in TPA measurements between the observers, the case was discussed among the observers until consent was achieved. Otherwise, the mean value of the three measurements was used for data analysis.

Gait analysis

All dogs walked on the same force plate treadmill system with four Kistler force plates (Spezialelemente Deutsche Sporthochschule Köln, Cologne, Germany). The treadmill was combined with an optical system system (Vicon Nexus Vicon Motion Systems Ltd., Oxford, United Kingdom, Quadruped Locomotion Software). The treadmill speed was patient individually adjusted in 0.02 m/s increments until the dogs showed a comfortable walk on the treadmill. Final speed was kept constant for all the rechecks. Valid trials were evaluated while the dog was walking constant and comfortably on the treadmill. The following GRFs were obtained and evaluated: peak vertical force (PVF), vertical impulse (VI) and the symmetry indices of PVF (SIPVF) and VI (SIVI) of the hindlimbs. The PVF and VI were normalized to the bodyweight of the dog in percent. The symmetry indices were calculated with the formula: SIPVF = |(200 x (PVF right – PVF left / PVF right + PVF left) | and SIVI = |(200 x (VI right – VI left / VI right + VI left) |as previously described (Voss et al., 2007). To determine if the dogs were objectively lameness free, the cut-off value for the SIPVF < 9% at walk as described by Voss et al. (2007), was applied.

Statistical methods

Statistical software was used for statistical analysis (IBM SPSS 28.0.1.1, IBM Corp., Armonk, New York, United States, R version 4.2.1 (2022–06–23)). Descriptive statistics, normality checks (Shapiro-Wilk normality test) and group comparisons for demographic data were calculated with SPSS using t-test for parametric, normal distributed data and Mann-Whitney-U test for not normal distributed and/or non-parametric data. Outcome variables (PVF, VI, SIPVF, SIVI) were studied via linear mixed effect models with interaction between predictors group and time. All models were checked for (1) normality of residuals (Shapiro-Wilk normality test and visualization), (2) heteroscedasticity (Breusch-Pagan test), (4) presence of outliers and influential points. In case the assumptions were not satisfied, robust model was created, compared (via AIC, BIC and R2) to the non-robust model and the qualitatively best model was selected. All models included patient number as random effect on the intercept. All estimates reported in the results are mean estimates with 95% confidence intervals. A p-value ≤0,05 was considered statistically significant.

Results

In the analysis 51 dogs were included and grouped by their postoperative TPA. In 29 dogs the postoperative TPA was >5° (Overgroup, OG) and 22 dogs had a postoperative TPA <5° (Undergroup, UG).

The OG consisted of mixed breed dogs (n=9), Dobermann Pinscher (n=3), German Shepherd (n=3), Labrador Retriever (n=3), Boxer (n=2), Entlebucher Mountain Dog (n=2) and one of each dog breed, Alaskan Malamute, Beagle, German Wirehair, Golden Retriever, Magyar Vizsla, Breton, Sleddog. Meniscal damage on preoperative MRI was present in 12/26 patients. In the OG 44% (13/29 dogs) had bilateral CCLD, in which only the second surgery was evaluated.

The UG consisted of Labrador Retrievers (n=9), mixed breed dogs (n=3), Golden Retrievers (n=3), German Shepherds (n=2), Olde English Bulldogs (n=2) and one of each dog breed, Beagle, Bearded Collie, and German Wachtel. A total of 11/22 dogs had a meniscal damage diagnosed on the preoperative MRI. In the UG, 36% (8/22 dogs) were bilaterally affected, and only the second surgery was evaluated.

No differences regarding age, weight or preoperative TPA were found ($p \geq 0,05$). The postoperative TPA differed significantly between groups ($p < 0.001$). Group demographics are summarized in Table 1. Postoperative TPA measurements for statistical evaluation are displayed in Table 2. Final speed of the treadmill was for all dogs while walking between 0.8 – 1.2 m/s and was held constant at all follow-up examinations. Mean values of the GRFs at all rechecks of the operated and non-opertaed limb are summarized in Tables 3, 4 and 5. Statistical evaluation was performed for the GRFs of the operated limbs and the SIPVF and SIVI. All dogs in both groups showed significant improvement in limb function, as measured by GRFs; for OG ($p < 0.001$) estimated PVF change 14.12 (95% confidence interval [95%CI]: 11.25 – 16.98), for UG ($p < 0.001$) estimated PVF change 7.55 (95%CI: 4.26 – 10.84). Preoperatively, there was a significant difference for PVF between OG and UG ($p < 0.001$), with an estimated mean 5.19 (95%CI: 2.12 – 8.26). No other time revealed a difference of PVF between groups ($p \geq 0.05$). The VI singnificantly improved over time in both groups; OG ($p < 0.001$) estimated change 4.13 (95%CI: 2.89 – 5.37) and UG ($p < 0.001$) estimated change 2.72 (95%CI: 1.3 – 4.15). A significant difference was found preoperatively between groups ($p = 0.028$) of 1.41 (95%CI: 0.15 – 2.67). No difference ($p \geq 0.05$) was found at all other time points up to six months postoperative for VI. For the SIPVF, all dogs showed improvement regardless of group ($p < 0.001$). OG dogs showed an estimate improvement of SIPVF by 45.79 (95%CI: 37.88 – 53.70) and UG dogs showed an estimate improvement by 18.73 (95%CI: 9.65 – 27.8). The SIPVF differed significantly ($p < 0.0001$) with a mean estimate of 27.48 (95%CI: 20.28 – 34.67) preoperatively between OG and UG. Six weeks postoperativly, there was also a significant difference ($p = 0.005$) between OG und UG with a mean estimate of 10.24 (95%CI: 3.05 – 17.43). At three and six months postoperatively, no differences between groups were observed ($p > 0.05$) The SIVI showed significant improvement from preoperative to six months postoperative in both groups ($p < 0.001$). For OG the dogs SIVI improved by estimate of 62.21 (95%CI: 50.86 – 73.5) and the UG dogs showed an improvement of SIVI by an estimate of 24.15 (95%CI: 11.13 – 37.2). Preoperatively, there was a significant difference for SIVI between groups ($p < 0.001$) by 39.44 (95%CI: 29.0 – 49.9). Six weeks postoperative SIVI differed significantly between groups ($p = 0.002$), with a mean estimate of 16.5 (95%CI: 6.06 – 26.9). No differences ($p > 0.05$) were observed three and six months postoperative regarding SIVI. The improvements of the GRFs for both groups over time are displayed in Fig. 1. To determine if the dogs were free of lameness according to the SIPVF, 75% (20/29 dogs) in the OG and 81% (18/22 dogs) in the had a SIPVF < 9% and stated therefore objectively as lameness free.

For all dogs, from both groups, the postoperative TPA showed a positive correlation with the SIPVF ($r = 0.144$, $p < 0.05$) and SIVI ($r = 0.189$, $p < 0.01$), which indicates a more symmetrical gait in the hindlimbs with lower postoperative TPAs. When performing the correlations for OG and UG separately, only for OG a positive correlation for SIVI ($r = 0.268$, $p < 0.001$) was found, which indicates with lower TPA a more symmetrical SIVI. For the OG the PVF revealed a significant negative correlation ($r = -0.195$, $p < 0.05$) indicating better PVF values with lower TPAs. No significant correlations were found for UG dogs.

Table 1
Group demographics and comparisons between groups regarding age, weight and tibial plateau angle; Over 5° postoperative TPA (OG) and under 5° postoperative TPA (UG). Values are displayed as mean values ± standard deviation.

	OG	UG	p - value
Age in years	6.59 ± 2.76	5.82 ± 2.65	0.32
Weight in kg	28.99 ± 5.96	30.97 ± 5.28	0.22
Preoperative TPA in °	24.63 ± 2.89	23.67 ± 3.21	0.27
Postoperative TPA in °	7.76 ± 1.89	3.11 ± 1.31	< 0.001

TPA, tibial plateau angle; OG, over 5° postoperative TPA; UG, under 5° postoperative TPA.

Table 2
Measurements of postoperative TPAs for each dog in OG and UG displayed in °.

Dog Number	OG TPA measurement consent (°)	UG TPA measurement consent (°)
1	8,4	1,8
2	9,1	4,3
3	6,6	3,9
4	8,9	4,3
5	7,3	4,3
6	6,0	3,9
7	6,1	3,6
8	8,5	4,0
9	9,0	0,7
10	7,8	3,1
11	8,5	3,9
12	10,8	1,5
13	11,0	1,0
14	11,4	3,0
15	7,6	3,6
16	5,8	4,7
17	9,3	3,60
18	5,6	4,43
19	11,8	2,87
20	7,0	0,10
21	8,9	2,47
22	5,9	3,37
23	6,5	
24	5,6	
25	5,4	
26	5,4	
27	6,1	
28	6,7	
29	8,3	

TPA, tibial plateau angle; OG, over 5° postoperative TPA.

Table 3
Ground reaction forces (GRFs) of the operated limb; peak vertical force in % bodyweight (PVF), vertical impulse in % bodyweight (VI), displayed as mean and 95% confidence interval.

	PVF (95%CI)		VI (95%CI)	
	OG	UG	OG	UG
preoperative	26.86* (22.5–31.3)	32.28* (29.0–35.5)	7.08* (5.8–8.4)	8.88* (7.6–10.1)
6 weeks post-op	34.09 (31.9–36.3)	36.77 (34.6–38.9)	9.02 (8.2–9.8)	10.47 (9.4–11.6)
3 months post-op	38.31 (36.4–40.3)	36.47 (34.4–38.5)	10.53 (9.9–11.2)	10.13 (9.9–11.1)
6 months post-op	41.01 (39.0–43.0)	39.98 (38.1–41.9)	11.14 (10.5–11.8)	11.5 (10.8–12.2)
p-value	<0.001	<0.001	<0.001	<0.001

PVF, peak vertical force in % bodyweight; 95%CI, 95% confidence interval; VI, vertical impulse in % bodyweight; OG, over 5° postoperative TPA; UG, under 5° postoperative TPA; post-op, postoperative; *, statistical difference between OG and UG p≤0.005.

Table 4
Ground reaction forces (GRFs) of the non-operated limb; peak vertical force in % bodyweight (PVF), vertical impulse in % bodyweight (VI), displayed as mean and 95% confidence interval.

	PVF (95%CI)		VI (95%CI)	
	OG	UG	OG	UG
preoperative	45.35 (42.2–48.5)	42.89 (40.3–45.5)	14.4 (12.9–15.9)	12.8 (11.6–14.0)
6 weeks post-op	44.15 (41.7–46.6)	42.37 (40.0–44.8)	12.84 (11.9–13.8)	12.37 (11.2–13.6)
3 months post-op	42.74 (40.5–45.0)	40.63 (38.2–43.1)	12.12 (11.4–12.8)	11.48 (10.5–12.5)
6 months post-op	42.31 (40.3–44.3)	41.64 (39.3–44.0)	11.79 (11.2–12.4)	11.9 (11.1–12.8)

PVF, peak vertical force in % bodyweight; 95%CI, 95% confidence interval; VI, vertical impulse in % bodyweight; OG, over 5° postoperative TPA; UG, under 5° postoperative TPA; post-op, postoperative.

Table 5
Ground reaction forces (GRFs); symmetry index of PVF (SIPVF) and symmetry index of VI (SIVI) displayed as mean and 95% confidence interval.

	SIPVF (95%CI)		SIVI (95%CI)	
	OG	UG	OG	UG
preoperative	57.47* (38.1–76.8)	30.23* (18.7–41.8)	73.61* (52.5–94.7)	38.84* (24.5–53.2)
6 weeks post-op	26.8* (19.9–33.7)	14.9* (10.2–19.6)	37.49* (27.6–47.4)	18.44* (12.5–24.4)
3 months post-op	12.33 (7.7–16.9)	12.65 (7.5–17.8)	17.02 (10.9–23.2)	14.83 (9.6–20.1)
6 months post-op	7.25 (5.3–9.2)	6.13 (3.5–8.8)	10.59 (7.5–13.6)	7.8 (5.1–10.6)
p-value	<0.001	<0.001	<0.001	<0.001

SIPVF, symmetry index of peak vertical force; 95%CI, 95% confidence interval; SIVI, symmetry index of vertical impulse; OG, over 5° postoperative TPA; UG, under 5° postoperative TPA; post-op, postoperative; *, statistical difference between OG and UG p≤0.005.

Discussion

Similar to the previous findingy by the study of Robinson et al. (2006), the postoperative TPA had no effect on the GRFs three to six months after TPLO in this study. The hypothesis that a TPA <5° leads to a faster recovery of limb function in our study demonstrated no postoperative differences regarding PVF or VI at any time point up to six months postoperatively and confirms the findings of Robinson et al. (2006). Preoperatively, there were significant differences between OG and UG regarding all GRFs, indicating less severe lameness in the UG dogs. Unfortunately, in the OG, two dogs had a non-weight bearing lameness, the preopartive PVF and VI were 0 and the SIPVF and SIVI were 200. The demonstrated postoperative differences between OG and UG regarding the SIPVF and SIVI are probably because we already had preoperative differences. It is unlikely that the postoperative differences in SIPVF and SIVI are due to the TPA itself, it is more likely that these differences are due to preoperative differences between groups. It remains unclear whether TPAs <5° leads to a faster return to a symmetrical gait at six weeks postopertive, but regarding PVF and VI no faster recovery of the operated limb itself could be detected. The recommendation for postoperative TPA after TPLO is 5–6,5° according to the original technique description (Slocum and Devine, 1998; Slocum and Slocum, 1993). Several previous studies have reported a potential negative effect on the caudal cruciate ligament with a TPA <5° (Brown et al., 2014; Reif et al., 2002; Warzee et al., 2001). This negative effect was not assessed in our study by means of postoperative MRI or second look arthroscopy. However, based on the findings in the studies by Hulse et al. (2010), Agnello et al. (2022) and Sumner et al. (2010) a large proportion of dogs presented with CCLD have already a degree of damage to the caudal cruciate ligament. It seems, therefore unrelated to the postoperative TPA itself, as the caudal cruciate ligament could already be injured preoperatively. A clinical study by Hulse et al. (2010) involving second-look arthroscopy showed that dogs with a complete caudal cruciate ligament tear had more frequently a postoperative TPA >5°. Hence the potential caudal cruciate ligament tears secondary to lower TPAs was considered unlikely, as the objective outcome after TPLO measured with objective gait analysis showed significant improvement. In addition, approximately 75% of dogs in our study were objectively free of lameness, as well as in the studies where the dogs were included, more than 80% of the dogs were free of lameness at the 6 months recheck (Knebel et al., 2020; Volz et al., 2024).

We were able to demonstrate that lower postoperative TPAs correlates with a more symmetrical gait in the hindlimbs measured with SIPVF and SIVI. This was demonstrated for all dogs togethter but not for OG and UG separately. When analyzing groups the groups individually, significant correlations were found only in the OG dogs for SIVI and PVF. This indicates that a postoperative TPA approaching towards 5°, leads to a more symmetrical/lower SIVI and increased PVF of the operated limb. Such a trend was not observed in UG dogs with postoperative TPAs below 5°, suggesting that the optimal postoperative TPA regarding SIVI and PVF is close to 5°. This finding supports the results of Wilson et al. (2018), as they demonstrated that a lower TPA at the recheck 6–12 weeks postoperatively correlated with greater improvements in weight bearing on the stance analyzer. The immediately postoperatively measured TPA showed no correlation with improvement or postoperative weight bearing on the stance analyzer (Wilson et al., 2018). In contrast to our study Wilson et al. (2018) showed no correlation with the SIPVF, as we were able to demonstrate a significant negative correlation. However, a direct comparison between studies is difficult, as Wilson et al. (2018) used a stance analyzer and evaluated the bodyweight distribution and the improvement of the operated limb, while in this study, a treadmill-based gait analysis with GRFs was used. Other studies have shown that a TPA of 0° leads to more stable stifles in the fluoroscopic gait analysis (Rebentrost, 2019), and a TPA of 1° reduces the load on both menisci (Schmutterer et al., 2022), suggesting that a TPA of 5–6.5° may not be the optimal postoperative TPA after TPLO regarding stifle biomechanics and gait. However, based on our study findings, a postoperative TPA below 5° does not improve the recovery of limb function as measured with GRFs up to six months postoperative, as there were no differences between OG and UG. This study demonstrated when considering all dogs together, a lower postoperative TPA correlates with a more symmetrical gait in hindlimbs as measured with SIPVF and SIVI. Furthermore, only in OG dogs (>5° postoperative TPA) a lower postoperative TPA correlates with improved values for SIVI and PVF. Taken together, these findings suggests that a postoperative TPA close to or trending towards 5° is beneficial for SIVI, SIPVF and PVF. Further prospective, controlled clinical and biomechanical studies are needed to determine the most appropriate TPA post TPLO.

The measurement of TPA on radiographs is influenced by several factors such as: limb positioning (Reif et al., 2004), observer variability up to 4.8° (Caylor et al., 2001; Fettig et al., 2003), the degree of osteoarthritis (Fettig et al., 2003), or the differences between experienced and unexperienced observers (Caylor et al., 2001), which are limitations when measuring TPA on radiographs. To avoid data bias, and the effects of experience and interobserver variability, cases with ≥ 2° difference in postoperative TPA between observers were discussed by the three observers with different experience fields and levels until a consent was achieved. We measured the TPAs on radiographs, which are influenced by several factors, as mentioned before, and should be seen as a limitation when interpreting the results. Using 3D imaging modalities are more precise compared to radiographs when evaluating TPAs (Todorovic et al., 2022), so the results could differ when using 3D imaging modalities. The preoperative TPA of the dogs in this study is similar to the reported ones (Todorovic et al., 2022). The values of the postoperative TPAs of the dogs in this study are similar to those of other

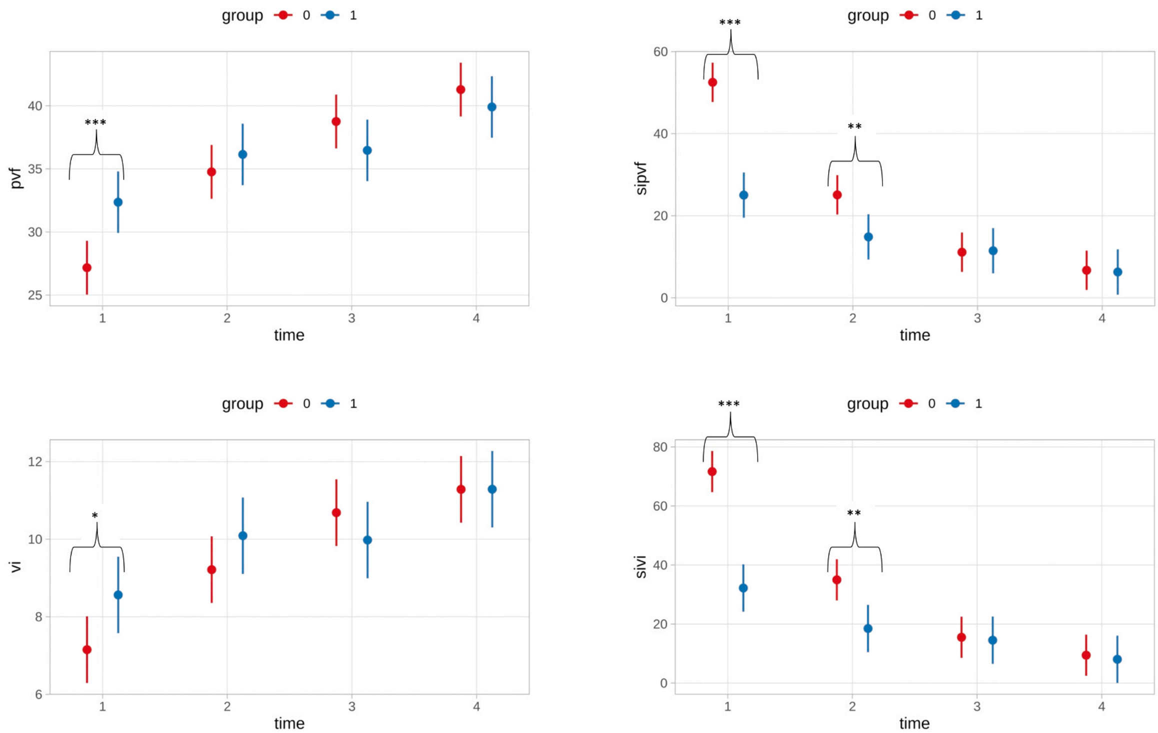

Fig. 1. Improvement of ground reaction forces (GRFs), peak vertical force in % bodyweight (PVF), vertical impulse in % bodyweight (VI), symmetry index of peak vertical force (SIPVF) and symmetry index of vertical index (SIVI) over time from preoperative (1) to six months postoperative (4). Red Boxplots/group "0" = Over 5° TPA (OG), Blue Boxplots/group "1"= Under 5° TPA (UG); statistic significant differences between groups, OG and UG, ***=p≤0.001, **=p≤0.01, *=p≤0.05.

studies that evaluated the effect of TPA on the outcome (Krotscheck et al., 2012; Robinson et al., 2006; Wilson et al., 2018). Furthermore, the results of this study could also be influenced by the postoperative change in TPA over time, the so called "rock-back" or subsidence phenomen, which is reported in several previous studies with changes in TPA between 2.05 ± 3.05° (Souza et al., 2021), 1.5 ± 2.2° (Moeller et al., 2006), 1.9 ± 0.19 (Conkling et al., 2010), 2.2 ± 2.7 (Krotscheck et al., 2012), 1.11 ± 3.5° (Wilson et al., 2018). Therefore a change in TPA due to subsidence could have pushed dogs previously in the UG group into the OG group. This is clearly a limitation of the study, as this study was retrospectively performed, and radiographs for TPA measurement at reevaluation for up to six months postoperatively were unavailable. Moreover, the surgeons performing the surgery utilized the standard TPLO technique with the aim of achieving a postoperative TPA within the range of 5–6.5°. Consequently, the UG represented the smaller subset, exhibiting a mean postoperative TPA of 3.11 ± 1.31°, which subjectively aligns closer to the target of 5° compared to the mean TPA of the OG, which was 7.76 ± 1.89° (Tables 1 and 2). Due to the noted limitations in measurement variability, some dogs could fall into either the OG or UG groups since the mean ± standard deviation closely approximates the 5° cut-off value. This potential variability might explain the lack of significant differences between the groups, as both the OG and UG means hover around the 5° threshold. Notably, the correlation of postoperative TPA with symmetry indices was only evident when considering all dogs collectively and in OG not in the UG.

As CCLD often occurs bilaterally (Buote et al., 2009; Grierson et al., 2011), we included unilateral and bilateral affected dogs in this study. Therefore, the hindlimb SI of PVF and VI was calculated and compared between groups. However, a load shift on the frontlimbs may have affected our results. Both groups had a comparable amount of bilateral patients included, so both groups were equally exposed to this limitation. To prevent further data bias, we evaluated only the second surgery, assuming that the first stifle had adequate stability. As bilateral cases reflects the clinical presentation of CCLD, bilateral cases are often included in clinical studies (Knebel et al., 2020; Trillig et al., 2022; Volz et al., 2024). Most of the published studies with only unilateral affected dogs have lower case numbers or a shorter evaluation time (Amimoto et al., 2019; Ferreira et al., 2016).

As this was a retrospective study, the nature of this design has its limitations. There were significant differences preoperatively between OG and UG, revealing more severe lame dogs in the OG, as measured with PVF, VI and the symmetry indices. Therefore, it is difficult to clearly evaluate whether one group had a faster limb function recovery than the other, which is clearly a limitation of this study. Most dogs returned to normal limb function at the last follow-up, confirming that TPLO restored normal limb function in most cases, as measured with GRFs.

Conclusions

In conclusion, a TPA under 5° seems not to be beneficial for a faster return to normal limb function measured with GRFs and partially confirms the findings of Robinson et al. (2006), as there were no differences in PVF and VI postoperatively up to six months. Our results suggests that a postoperative TPA <5° or close to 5° may have a positive effect on an earlier return to normal values of symmetry indices of PVF and VI. Considering the limitations of our study, a TPA of less than 5° does not appear to have negative effects on the return to normal limb function. Further prospective biomechanical and clinical studies are needed to investigate the effect of a postoperative TPA <5°.

CRediT authorship contribution statement

Julius Frederick Klever: Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Yury Zablotski**: Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Matthias Kornmayer**: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Frederik Volz**: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniela Eberle**: Writing – review & editing, Data curation, Conceptualization.

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Declaration of Competing Interest

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

Data availability

The data that support the findings of this study are available on reasonable request from the corresponding author, F.V.

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