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A three-dimensional computed tomographic volume rendering methodology to measure the tibial torsion angle in dogs

Longo, Federico ; Nicetto, Tommaso ; Pozzi, Antonio ; Contiero, Barbara ; Isola, Maurizio

Abstract: **OBJECTIVE:** To describe a three-dimensional (3D) computed tomographic (CT) methodology to measure the tibial torsion angle (TTa) and to evaluate intrarater and interrater agreements and accuracy through comparison with anatomic measurements. **STUDY DESIGN:** Ex vivo cadaveric study. **SAMPLE POPULATION:** Thirty-six tibiae from 18 dogs. **METHODS:** Tibial torsion angle of each tibia was measured by using two CT techniques (axial and 3D volume rendering) by three raters who blindly measured TTa in duplicate. A semitransparent bone filter was used to enhance the visibility of the target anatomical landmarks for the 3D volume rendering CT technique. Tibial torsion angle was also quantitated in tibial specimens. Intrarater and interrater agreements were analyzed by using intraclass coefficients (ICC). Accuracy was evaluated by using adjusted R^2 coefficients ($R^2 > 80\%$ was considered acceptable). **RESULTS:** The 3D volume rendering CT technique had excellent intrarater and interrater agreements ($ICC > 0.94$) and an R^2 value of 97%. The axial CT technique had good to excellent intrarater and interrater agreements ($0.8 < ICC < 0.95$) and an R^2 of 86%. No difference was found between axial and 3D CT techniques. A mean internal TT angle of approximately -6° was found with CT and anatomic measurements. **CONCLUSION:** The 3D volume rendering and axial CT techniques were precise and accurate for measuring TTa in dogs unaffected by patellar luxation. **CLINICAL RELEVANCE:** Combining 3D bone manipulation with application of a semitransparent filter allows simultaneous visualization of anatomic landmarks, which may facilitate the evaluation of complex bone deformations. Internal tibial torsion may be present in nonchondrodystrophic dogs without patella luxation.

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1 **A three-dimensional computed tomographic**
2 **volume rendering methodology to measure the**
3 **tibial torsion angle in dogs**

4

5 **Internal tibial torsion was found in healthy dogs**

6

7 Federico Longo¹ DVM, Ph.D, Tommaso Nicetto² DVM, Ph.D, Antonio Pozzi¹ DVM,
8 ACVS, ECVS, ACVSMR, Barbara Contiero³ MsS, Maurizio Isola³ DVM, Ph.D

9

10 1: Department of Small Animal Surgery, Vetsuisse Faculty University of Zurich,
11 Winterthurerstrasse 260, 8057 Zurich, Switzerland

12 2: Diagnostica piccoli animali – Clinica veterinaria Pedrani, Vicenza, Italy

13 3: Department of Animal Medicine, Productions and Health, University of Padova,
14 Legnaro, Italy

15

16 Corresponding author: Federico Longo (federico.longo2@uzh.ch)

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Objectives: To describe a three-dimensional (3D) computed tomography (CT) methodology to measure the tibial torsion angle (TTa) and to evaluate intra- and inter-rater agreements and accuracy through comparison with anatomic measurements.

Study design: Ex-vivo cadaveric study.

Sample population: Thirty-six tibiae of 18 dogs.

Materials: TTa of each tibia was measured using two CT techniques (axial and 3D volume rendering) by 3 raters, who blindly measured TTa in duplicate. For the 3D volume rendering CT technique, a semitransparent bone filter was used to enhance the visibility of the target anatomical landmarks. TTa was also quantified in tibial specimens. Intra- and inter-rater agreements were analyzed using intraclass coefficients (ICCs). Accuracy was evaluated using adjusted R^2 coefficients ($R^2 > 80\%$ was considered acceptable).

Results: The 3D volume rendering CT technique had excellent intra-rater and inter-rater agreements ($ICC > 0.94$) and an R^2 value of 97%. The axial CT technique had good to excellent intra-rater and inter-rater agreements ($0.8 < ICC < 0.95$) and an R^2 of 86%. No difference was found between axial and 3D CT techniques. A mean internal TT angle of $\cong -6^\circ$ was found with CT and anatomic measurements.

Conclusions: The 3D volume rendering and axial CT techniques were precise and accurate for measuring TTa in dogs unaffected by patellar luxation.

Clinical relevance: Combining 3D bone manipulation with application of a semitransparent filter allows simultaneous visualization of anatomic landmarks, which may facilitate the evaluation of complex bone deformations. Internal tibial torsion may be present in non-chondrodystrophic dogs without patella luxation.

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51 **Introduction**

52 Angular limb deformities may result from abnormal physal growth,^{1,2} congenital
53 malformations,¹⁻⁴ dietary or hormonal causes,³⁻⁵ or bone malalignment secondary to
54 fracture malunion.⁶ Long bone deformities are broadly classified in frontal, sagittal,
55 and axial plane deformities.⁷⁻¹¹ The terms torsional and rotational deformities are often
56 erroneously used as synonyms. Torsion is an axial plane deformity defined as the
57 twisting of a single bone unit in the transverse plane around its longitudinal axis.^{2,12-14}
58 Rotation is a multiplanar deformity that involves at least two bone units, has a pivot
59 point in the joint, and is defined as an angulation around an axial or longitudinal axis.²
60 By an anatomical perspective, tibial torsion (TT) is expressed as an external or internal
61 torsion of the distal tibial epiphysis relative to the proximal tibial epiphysis.^{13,15,16}
62 Abnormal TT has been proposed as an etiopathogenic factor that may predispose to
63 patella instability and osteoarthritis of the stifle in dogs.¹⁷⁻¹⁹ Tibial torsion was detected
64 in grade IV patella luxation cases along with concurrent complex skeletal
65 malformations such as femoral frontal and axial malalignment,^{8,17} metatarsal rotation
66 and pes deviation.²⁰ An accurate method to evaluate and quantify TT would be
67 beneficial when evaluating complex hind limb deformities, especially for planning
68 surgical corrections.

69 In human medicine, different diagnostic approaches such as clinical examination,^{16,21}
70 radiography,^{13,22} computed tomography (CT),^{12,23-25} ultrasound,²⁶ and fluoroscopy,^{15,27}
71 have been described for assessing TT. The first reports in veterinary medicine,
72 focusing on TT, have investigated the accuracy of radiography¹⁸ and CT.²⁸ The main
73 findings highlighted that radiography failed to discriminate between internal torsion
74 and rotation,¹⁸ whereas CT exhibited a satisfactory measurement accuracy.²⁸ Aper et
75 al.²⁸ described an axial CT assessment of TT in a group of medium to large mixed-

breed dogs using two different pairs of reference axes adapted from human literature.¹⁶
Other studies investigated the TT using only one of the two pairs of axes proposed by
Aper et al.²⁸ in individual breeds.^{19,29-31} As a result, different values, depending on the
pair of axes used, were found, suggesting the presence of either external or internal TT
in dogs.^{19,28-30,32}

By reviewing the veterinary literature on TT, the authors found two main areas of
interest for further investigation. First, the identification of the distal cranial tibial
(CnT) axis was somewhat unclear, as it was not defined in which CT slice of the distal
tibial epiphysis the CnT axis should be drawn. Second, the direction of physiological
TT (external or internal) in dogs unaffected by patella luxation was conflicting.^{19,28,30,32}
Furthermore, to the authors' knowledge no previous reports on tibial torsion
investigated the intra- and inter-rater agreements for the measurement of TT angle
(TTa).

Therefore, the objective of this study was three-fold: 1) describe a 3D volume
rendering CT methodology for measuring TTa; 2) investigate its precision (intra- and
inter-rater agreement)^{33,34} and accuracy (comparison with anatomic measurements),
and 3) compare the 3D volume rendering and axial CT TTa measurements. The TTa
was quantified by using the proximal caudal tibial condylar (CdC) and the distal
cranial CnT pair of axes.

Our hypotheses were that 1) a 3D volume rendering CT technique would be precise
and accurate, and 2) there would be a physiological internal TT in dogs not affected by
patella luxation.

Methods:

Canine tibiae were collected from client-owned dogs that were euthanized for reasons unrelated to the present study. The tibia specimens were enrolled under the condition of informed consent signed by the owners. Sex, age, weight, and breed were recorded. Medical record reviews, orthogonal radiographic surveys of the stifle and the tibia, and gross physical examinations of the fresh cadavers were performed to exclude the presence of patellar luxation and frontal plane deformities.

The cadavers were positioned on a foam cradle in dorsal recumbency with the hind limbs extended and the tibiae placed as parallel as possible to the CT table. CT examination of the whole hind limbs (from the ilial wing body to the metatarsus) was performed using a 4-multi-detector-row CT scanner (Asteion S4, Toshiba Medical Systems Europe; Zoetermeer, Netherlands) in helical acquisition mode using a slice thickness of 1 mm (reconstruction interval: 0.8 mm) with a distal-to-proximal scanning direction. Scans were reconstructed with commercially available DICOM (digital imaging and communications in medicine) software (Osirix, version 5.8, Pixmeo Sàrl; Bernex, Switzerland), which was also used for TTa measurements.

Three raters blindly measured TTa in duplicate with two different CT methodologies (axial and 3D volume rendering CT). The raters had different levels of experience in using the software. They were: one professor of small animal orthopedics, one experienced orthopedic surgeon, and one low-experienced orthopedic surgeon.

To prevent any measurement conditioning, each CT scan was anonymized, labeled as “LT” (left tibia) or “RT” (right tibia), and randomized with an open source program (Research Randomizer, version 4.0). An additional fourth examiner (no experience in orthopedic surgery) performed the TTa calculation, in duplicate, on digital images obtained from tibia specimens.

CT axial measurement of TTa

A methodology similar to that described by Aper et al.²⁸ was used as follows:

- 1- The proximal axial CT slice, where the most caudal points of the tibial condyles were simultaneously identifiable, was selected (Fig 1A, D).
- 2- The most caudal points of the tibial condyles were aligned according to the horizontal toolbar provided by the DICOM software. The CdC axis was drawn as a line parallel to the caudal condylar tibial cortex (Fig 1A, D). The “propagate ROI function” was selected, so that the CdC remained visible while scrolling through CT slices.
- 3- The slice tracing the CnT axis was defined as the CT transverse section nearly proximal to the talocrural joint. Therefore, the distal tibial epiphyses, calcaneus, and lateral malleolus were all detectable (Fig 1B, E).
- 4- The CnT axis was drawn as the line passing through the most prominent points of the cranial tibial cortex (Fig 1B, E).
- 5- The TT angle (TTa) was directly measured using the “Cobb angle function” (Fig 1 C, F). When the vertex angle was directed medially, a negative value was assigned to the CdC/CnT angle (internal TT, Fig 1 C), while a positive value (external TT) was assigned when the vertex of the TTa was lateral (Fig 1 F).

3D volume rendering CT measurement of TTa

- 1- The multiplanar reconstruction (MPR) function was selected. Proximal and distal fiducial markers (green points in Fig 2) were positioned on the target tibia using the reference proximal and distal landmarks of the mechanical tibial axis.³⁵
- Therefore, the proximal point was centered between the intercondylar tubercles,

whereas the distal point was positioned on the craniodistal intermediate ridge of the tibia (Fig 2 A).³⁵

- 2- The 3D volume rendering function was selected. The tibia was isolated from the femur and metatarsus. A medial sagittal view was used to detect the most caudal point of the medial tibial condyle (Fig 2B). The proximal tibial epiphysis was then slightly externally rotated to visualize the most caudal point of the lateral tibial condyle.
- 3- A distal-to-proximal axial tibial view was used to identify the most prominent points of the distal cranial tibial cortex. The tibia was thereafter positioned in the opposite direction (proximal-to-distal) (Fig 2 B).
- 4- A semitransparent bone filter (dark bone filter, 4) was applied. The histogram that routinely appears in the chromatic toolbar was adjusted by shadowing the surrounding soft tissues and increasing the bone transparency. As a result, the proximal and distal cortical profiles of the tibial epiphyses were visible as well as the intra-medullary tibial canal (Fig 2 C).
- 5- The proximal and distal fiducial markers, simulating the mechanical axis of the tibia, were superimposed (Fig 2 C).
- 6- The 3D reconstructed image was saved as a DICOM file. The CdC and CnT axes were drawn on the axial 2D image and the TTa measured using the “Cobb function” (Fig 2C). The same criterion previously described for axial CT was used to attribute negative and positive values to the TTa.

Anatomic measurements

Every tibia was disarticulated and placed onto a plexiglass support. The tibial diaphysis was slightly elevated by using a sponge material to ensure that the caudal

aspects of the tibial condyles were touching the plexiglass plane and the cranial cortex of distal tibia was partially visible. Proximal and distal Kirschner wires were used to mimic the orientation of the CnT and CdC axes (Fig 3 A, B). They were fixed onto the bone with glue. Digital images were obtained in a proximal-to-distal direction (axial view) with a predetermined digital camera lens-to-bone distance. An additional examiner measured the anatomic TTa in duplicate with the same DICOM software and Cobb angle function used by the three raters for CT measurements (Fig 3 C).

Statistical analysis

Three software packages (MedCalc version 17.3, MedCalc Software; Ostend, Belgium; and SAS version 9.4, SAS Institute; Cary, NC; R package version 4.0.1; <https://www.r-project.org>) were used. Data normality of all datasets was tested using the Shapiro-Wilk test. The circular moments of the TTa calculated with CT and anatomic methodologies (axial CT TT, 3D CT TT, and A-TT) were extrapolated using a macro for circular data analysis (SAS code for circular statistics: www.researchgate.net/publication/269762898).

The precision (intra- and inter-rater agreement) of the measurements was assessed using intra-class coefficients (ICCs) with 95% confidence intervals (95% CI). ICC was considered fair when <0.8 , good if >0.8 and excellent when >0.9 .^{33,34}

The adjusted R^2 was adopted to investigate the strength of agreement between the CT measurements (axial CT TTa and 3D volume rendering CT TTa) and anatomic measurement on tibial specimens (A-TT). Accuracy was considered acceptable when $R^2 > 80\%$.^{28,36} An ANOVA model for circular data (R package “circular”) was adopted to test the effect of the 3 methods (axial CT vs A-TT and 3D volume rendering CT vs A-TT). Using the same approach, the effect of the 3 raters for the two

CT measurements (axial and 3D volume rendering CT) was assessed. Statistical significance of P-value was set at < 0.05 . A Bland-Altman plot was used to compare axial CT and 3D volume rendering CT measurements with the anatomic measurements. A calculation of the statistical power of the test was conducted, referring to the literature that used the same pair of axes,^{28,32} and based on the available sample size. *A posteriori* calculation of the sample dimension was performed using paired t-test.

Results:

Thirty-six tibiae obtained from 18 non-chondrodystrophic cadaver dogs were used, of which 9 were female and 9 male. The mean age was 5.2 years (range: 2.3 years to 13 years; median: 6.7 years). The mean body mass was 24.8 kg (range: 19.3 kg to 39 kg; median: 29.2 kg). The breeds used were German shepherd (5), mixed-breed dogs (4), Labrador retriever (4), Draahtaar (2), Dobermann (2), and Irish setter (1).

All the data met the normality assumption. Overall, there was good intra-rater agreement for the axial CT technique (ICC = 0.87; Table 1) and an excellent intra-rater agreement for the 3D volume rendering CT technique (ICC = 0.95; Table 1). The intra-rater ICCs for each rater are displayed in Table 1. The anatomical measurements were the most reproducible (ICC = 0.98). There was an overall excellent inter-rater agreement for both techniques (axial CT ICC: 0.91; 3D volume rendering CT ICC: 0.95; Table 2). All 3 raters exhibited good to excellent ICCs in terms of either intra- (Table 1) or inter-rater agreements (Table 2). Rater 1 was the worst compared to raters 2 and 3. However, through ANOVA, we did not find a rater effect within each CT technique (axial CT: $P = 0.940$; 3D CT: $P = 0.942$).

With regard to accuracy assessment, the adjusted R^2 values of both axial and 3D CT measurements were greater than the 80% threshold (Fig 4 A). In detail, the axial CT R^2 was 86%, while the 3D volume rendering CT R^2 was 97%. The measurements were well-aligned along the regression lines, most strongly for 3D volume rendering CT TT measurements (Fig 4 A). The Bland-Altman plot (Fig 4 B) showed that less homogenous measurements were performed when $-5^\circ < \text{TT angle} < 0^\circ$ and $5^\circ < \text{TT angle} < 10^\circ$.

The 3D volume rendering CT technique exhibited a superior precision and was 10% more accurate compared to the axial CT technique. However, when comparing the

variances between the measurement averages of both CT techniques, ANOVA showed that there was no significant difference between them ($P = 0.877$). The means, standard deviations, and medians of TT angles are shown in Table 3. A mean internal TT was found in all the specimens examined. Specifically, the anatomic TTa was -6° ($\pm 5.9^\circ$), the axial CT TTa -6.5° ($\pm 5.9^\circ$), and the 3D volume rendering CT TTa was -5.8° ($\pm 5.7^\circ$).

Based on the preliminary power analysis and considering three potential scenarios, the statistical power of the test was calculated using a difference between CT and anatomic measurements equal to 3° , 3.5° and 4° , a standard deviation equal to 5.1° and a Type I error equal to 5%. The power of statistical test resulted equal to 69%, 82% and 91%, respectively.

Based on the results obtained, a *posteriori* power analysis was performed. The paired difference between the two methods (anatomic and CT) was 0.25 ± 1.01 . Considering a mean significant difference between anatomic and CT measurements equal to 0.5, and the standard deviation of the difference between the two methods equal to 1.01, assuming a type 1 error equal to 0.05 and a power of 80%, the sample size requested for the paired samples t-test was equal to 34.

Discussion

This *ex vivo* study describes the use of a 3D volume rendering CT function to quantify TTa in medium to large non-chondrodystrophic dogs, unaffected by patellar luxation. Intra- and Inter-rater agreement was good, prompting us to accept our first hypothesis. Furthermore, our findings imply that the measurements performed on reconstructed CT images were similar to those derived from digital images obtained from tibia specimens (accuracy).

In this study we used the same pair of axes (CdC/CnT) adopted by Aper et al.²⁸ and Newmann et al.³² We have, also, assessed the precision for using this pair of axes because it was not previously investigated.

Although the 3D volume rendering CT technique showed a superior accuracy with more homogeneous measurements, the results support that the axial CT is, also, a reliable technique for measuring TTa. CT axial technique exhibited good to excellent precision and a good accuracy, and it was not significantly different when compared with 3D volume rendering CT technique. Therefore, we would support the use of both techniques for TT evaluation, considering, also, that the variable experience of the readers did not affect the results.

The accuracy is a statistical parameter defined by how close a calculated value is to an assumed true value, which implies that a ‘true’ value must be both detectable and measurable.³⁴ In this study, the authors have assumed the anatomical measurements as the gold standard method, as was previously described.^{28,35} To support the assumption, we assessed the intra-rater agreement of anatomical measurements and we found that they were the most repeatable measurements. This result was not unexpected, as the reported benefits of an *ex vivo* measurement include the easy accessibility of bony landmarks to direct observation.²⁸ As a result, anatomical measurements historically

provided the reference database for assessing angles, and thus, are referred to as the gold standard in measurement methodology.

The 3D volume rendering CT technique allowed the raters to easily draw the proximal and distal tibial axes, due to a well-defined identification of the anatomical landmark of interest on the tibial cortex. This observation may be relevant especially in the most complex cases of multiplanar deformities. We agree with Barnes et al.,³⁷ that some of the anatomical landmarks proposed by the current literature on TT^{16,28} are challenging to be detected with the axial CT technique. First, the profile of the most prominent points of the tibial distocranial cortex may change across a range of breeds.³⁷ Second, it was not previously defined which was the most appropriate slice of the transverse view of distal tibial epiphysis as to where the CnT axis should be drawn.²⁸ When scrolling through CT slices in a proximal-to-distal direction, the profile of the tibial distocranial prominences changes, thus influencing the CnT inclination. Barnes et al.³⁷ used a distal “malleolar reference line” to bypass the problem related to the detection of distal tibial prominences.³⁷ However, the definition of TT implies the detection of intrinsic tibial landmarks. Therefore, we decided to use some of the previously reported tibial landmarks²⁸ but using an alternative CT methodology. The 3D volume rendering methodology allowed the raters to directly visualize the most prominent points of the distal cranial tibial cortex, without needing to choose which was the most appropriate CT slice to draw the CnT axis.

One of the advantages of the 3D volume rendering function is that it allows the bone morphology to be freely manipulated in 3D space.^{31,33,34} Several DICOM software provide a semitransparent bone filter as an additional tool to analyze 3D bone

models.^{32,38} This function offers a significant advantage compared to both axial CT and 3D volume rendering CT without a semitransparent filter, because some anatomical landmarks may be undetectable when superimposing the proximal and distal epiphyses. The bone transparency allows for the assessment of the regions of interest with the desired plane of view, as it has been already described for the evaluation of radial,³⁸ femoral,^{8,37} and tibial axial and frontal alignment.³² The use of 3D volume rendering function implemented with a semitransparent bone filter may be particularly helpful when evaluating complex tibial multiplanar deformities. In cases with severe patella luxation, tibial torsion may often be detected along with other deformities such as tibial varus/valgus, pes deviation or metatarsal rotation.^{8,17,20} The simultaneous presence of these deformities may complicate the detection of anatomical landmarks, the axis drawing, and angle measurements with both axial and 3D volume rendering CT techniques. A further study, comparing both CT techniques, is recommended to evaluate whether the 3D volume rendering evaluation of tibiae affected by multiplanar deformities is superior to standard axial CT technique.

All three raters found that the 3D manipulation of the bone model was a great advantage of the 3D volume rendering CT technique, as they performed the measurements, regardless of the initial bone positioning. Furthermore, the superimposition of the two reference points, used to find the frontal tibial mechanical axis, allowed the raters to use a consistent proximal-to-distal positioning during their measurements. This may partially explain the high accuracy and excellent precision found with 3D volume rendering CT technique. The axial CT technique may be affected by a potential positioning artifact.²⁸ When the bone is not positioned orthogonal to the CT gantry, the angular relationship between the CdC and CnT

changes, owing to the angular change between the tibia and the CT gantry.

Furthermore, the plane of the CT slice would not be representative of the same tibial landmarks that have been used for the anatomic measurements.²⁸

We accept our second hypothesis, as an overall mean of approximately -6° of internal TT was found in dogs unaffected by patella luxation. This finding implies that, in this group of dogs, the distal tibial epiphysis was slightly internally oriented compared to the proximal tibial epiphysis. Our results are also consistent with the outcomes of the two studies that used the same pair of axes.^{26,27} The comparison between studies that have used CT for evaluating TT could be misleading, with some of them reporting a physiological internal torsion^{28,32} and others external torsion.^{19,28-31} Explanations for this measurement discrepancy are primarily ascribable to the use of two different pairs of axes to calculate the same object (TTa) (Fig 5 and Table 4).^{19,28-32,37} As a result, depending on which pair of axes was adopted, the angular value for TT changes.

Second, we found an inconsistency concerning the criteria for assigning a negative or positive value to the angle measured. Aper et al.²⁸ attributed negative and positive values depending on whether a clockwise or counter-clockwise offset was respectively found. Additionally, the authors considered which tibia (left/right) was examined. This implies that, in the case of an internal TT, a negative value was assigned to the left tibia and a positive value to the right tibia. Other studies, by convention, assigned a negative value when an internal TT was found and positive value to the external TT, regardless of the limb side.^{19,29,30} To avoid any further ambiguity, in a proximal-to-distal axial view we attributed a negative value when the vertex of the CdC/CnT angle was found medially (internal TT) and a positive value (external TT) when it was found in the lateral direction.

The findings of this study should be considered in light of some study limitations. We used a heterogeneous group of medium- to-large-sized dogs. Thus, unlike several other studies, we did not investigate TT in a single breed.^{19,29-32} As a result, we could not provide a breed reference range. Furthermore, we did not include toy breeds. It is possible that those breeds could be characterized by a physiological external TT, as was highlighted by the outcomes of some studies.^{19,30,31} The mean value of internal TT found may have been mitigated by the heterogeneity of tibiae evaluated. Second, it is possible that this study was not adequately powered to show a difference that actually exists among the considered variables. Thus, the presence of a type II statistical error could not be completely excluded. Considering a 3.5° difference between CT and anatomic measurements, 36 samples were enough to assure statistical power of 82%. The axial CT technique the tibia was oriented only according to the frontal plane and thus, we may not have been as consistent with positioning, as we were with the 3D volume rendering technique. The use of the 3D MPR function would have been a reliable option for better orienting the tibia. Finally, only one additional examiner performed the measurements on the digital images of the anatomic specimens. This may have eventually led to a more uniform dataset for the anatomical model measurements.

In conclusion, evaluating TT using 3D reconstructed CT images is a reliable alternative to the previously described axial CT technique. The 3D volume rendering CT methodology exhibited excellent precision and accuracy. The evaluation of torsional deformity using a 3D bone model, assessed through a semitransparent filter, allows the rater to position the bone in a true axial plane, with the main advantage of being able to detect all the required anatomical landmarks simultaneously.

A physiological internal TT of -6° was found in dogs unaffected by patella luxation. Although this outcome was consistent with the results of some publications, the present study could not confirm whether these findings could be suggested as reference values for a large canine population. Further TT assessments using the same methodology need to be performed in target canine breeds that are commonly affected by patella luxation.

Disclosure

The authors declare no conflict of interest related to the study

Disclosure

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Author contribution statement

FL designed the study, performed the measurements, analyzed and interpreted the data, and drafted the manuscript. **TN** participated in the design of the study, performed the measurements, and interpreted the data. **AP** participated in the design of the study, interpreted the data, and revised the manuscript. **BC** performed statistical analysis and analyzed the data, and **MI** performed the measurements, interpreted the data and revised the manuscript. All authors read and approved the final manuscript.

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Figure legends

Fig 1: Evaluation of tibial torsion angle (TTa) using an axial computed tomography (CT) technique in a right tibia of a German shepherd (A–C) and a left tibia of a mixed breed dog (D–F). The CT slice where the most caudal points of the proximal tibial epiphysis appeared was identified (A, D). The caudal condylar axis (CdC) was drawn as a line passing through the most caudal tibial points (pink line, A, D). A CT slice proximal to the talocrural joint was selected: the distal tibia, calcaneus, and lateral malleolus were all visible (B, E). The cranial tibial axis (CnT) was defined as a line passing through the most prominent points of the distal cranial cortex (purple line, B, E). The axial CT TTa was measured (C, F). An internal TT of -7° (C) and an external TT of 14° (F) were measured.

Fig 2: Evaluation of tibial torsion angle (TTa) using a three-dimensional volume-rendering computed tomography (3D CT) technique in a right tibia of a German shepherd. The multiplanar reconstruction (MPR) function was selected. The proximal and distal tibial landmarks necessary to draw the mechanical tibial axis were found: MPR frontal and medial views (A). The target tibia was cropped from the femur and metatarsus. A sagittal medial view of the tibia was used to identify the most caudal point of the medial tibial condyle (B, left image). The tibia was slightly externally rotated to visualize the most caudal point of the lateral tibial condyle (B, central image). The most prominent points of the distal cranial tibial cortex were marked. The tibia was positioned in the axial plane but in proximo-to-distal direction (B, right image). A semitransparent bone filter was used to achieve sufficient transparency to simultaneously evaluate the proximal and distal tibial epiphyses (C, left image). The proximal and distal points for the mechanical axis projection were superimposed (C,

central image). The caudal condylar (CdC, pink line) and cranial tibial (CnT, purple line) axes were drawn, and the TT angle was calculated (C, right image).

Fig 3: Anatomic measurement of tibial torsion angle (TTa). Each tibia specimen was positioned in a plexiglass support. Two Kirschner wires of an appropriate diameter were used to simulate the cranial tibial (CnT) (A) and caudal condylar (CdC) axes (B). A digital image with a predetermined lens-to-bone distance was obtained in the proximal-to-distal direction (B). The CnT (C, purple line) and CdC (C, pink line) axes were superimposed onto the Kirschner wires. The TTa was quantified (C).

Fig 4: Graphical representation of regression line analysis (A) and Bland-Altman plot (B) for the comparison between the tested methods (axial and 3D computed tomography (CT)) and the reference method (anatomic). Figure A shows that the R^2 coefficient for both CT techniques is above 80%, with the 3D CT having a superior accuracy ($R^2 = 97\%$) to axial CT ($R^2 = 86\%$). Figure B shows that the axial CT technique (left plot) has wider lower and upper limits of agreement (dashed brown lines), a larger gap between the parallel line of the X axis (dashed yellow line) and mean line (continuous blue axis), and wider confidence interval limits (continuous yellow lines) compared to the 3D CT technique. The dashed purple line represents the regression line.

Fig 5: Evaluation of tibial torsion angle (TTa) using anatomical, axial and 3D computed tomography (CT), techniques in a right tibia of a Labrador retriever, using different reported methods.^{19,28,31,32} The TTa was assessed using either caudal condylar/cranial tibial (CdC/CnT) or transcondylar/cranial tibial (TC/CnT) pair of

axes. Figures A and B depict the anatomical measurement of TTa using CdC/CnT axes (A; TTa: $-12,4^{\circ}$), and TC/CnT axes (B; TTa: -7°). Figures C and D show the measurement of the TTa using the axial CT with CdC/CnT axes (C; TTa: $-11,6^{\circ}$) and the TC/CnT axes (D; TTa: -3.7°).²⁸ Figure E shows the measurement of TTa (-12°) with CdC/CnT axes, adopting the methodology presented by Newman et al.³² Figure F depicts the TTa measurement (-0.6°) using TC/CnT axes, following the methodology described by Fitzpatrick et al.¹⁹ In figure G, the TTa (-12°) is measured using the 3D CT technique reported in this study. Figure H depicts the TTa measurement (-9.8°) with TC/CnT axes, as was reported by Yasukawa et al.³¹

Table 1: Intra-rater intra-class correlation coefficients (ICC) calculated for each rater with axial CT and 3D volume rendering CT techniques.

Technique	Intra-rat. ₁ ICC*	Intra-rat. ₂ ICC*	Intra-rat. ₃ ICC*	Intra-rat. _{1,2,3} ICC*	Intra-rat. Examiner ICC
Axial CT	0.80 (0.65-0.89)	0.92 (0.83-0.96)	0.90 (0.82-0.95)	0.87 (0.65-0.96)	
3D CT	0.94 (0.88-0.96)	0.96 (0.93-0.98)	0.95 (0.91-0.97)	0.95 (0.88-0.98)	
Anatomic					0.98 (0.97-0.99)

* : 95% confidence interval.

Table 2: Inter-rater intra-class correlation coefficients (ICC) calculated for each rater for axial CT and 3D volume rendering CT techniques.

Technique	Inter-rat. _{1, 2} ICC*	Inter-rat. _{1, 3} ICC*	Inter-rat. _{2, 3} ICC*	Inter-rat. _{1,2,3} ICC*
Axial CT	0.89 (0.80-0.94)	0.90 (0.81-0.94)	0.95 (0.91-0.97)	0.91 (0.80-0.97)
3D CT	0.96 (0.92-0.98)	0.95 (0.91-0.97)	0.96 (0.94-0.98)	0.95 (0.91-0.98)

* : 95% confidence interval.

Table 3: Mean angle, circular standard deviation of tibial torsion (TT) angle measured by the three raters with axial and 3D volume rendering CT techniques and by the additional examiner for the anatomic specimens. Negative values mean internal TT and positive values external TT.

TT angle (°)	Rat ₁	Rat ₂	Rat ₃	Rat _{1,2,3}	Examiner
Axial CT (deg)	-6.79 ± 5.95	-6.33 ± 6.10	-6.39 ± 5.84	-6.51 ± 5.97	
3D CT (deg)	-5.96 ± 5.70	-5.92 ± 5.99	-5.53 ± 5.39	-5.80 ± 5.70	
Anatomic (deg)					-6.05 ± 5.97

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Table 4: Reported means and standard deviations of tibial torsion angle (TTa) measured with CT in canine breeds not affected by patella luxation. Two pairs of axes were used: the proximal caudal condylar axis (CdC)/ distal cranial tibial axis (CnT) or the proximal transcondylar axis (TC)/ CnT. Negative values mean internal TT and positive values external TT.

TT angle (°) (breed)	Aper ²⁸	Newman ³²	Author	Fitzp. ¹⁹	Lusetti ²⁹	Yasuk. ³¹	Phet. ³⁰
CdC/CnT	-4.85° ± 5.19° (Multiple breeds)	-4.51° ± 3.95° (Bull terrier)	-5.80° ± 5.70° (Multiple breeds)				
TC/CnT	4.15° ± 6.05° (Multiple breeds)			9.1° ± 4.1° (Yorkshire)	4.0° ± 8.82° (En. Bulldog)	11.3° ± 4.3° (Toy Poodle)	6.7° ± 3.2° (Chihuahua)