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Original Article

Automated computation of femoral angles in dogs from three-dimensional computed tomography reconstructions: Comparison with manual techniques

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ABSTRACT

The aim of this ex vivo study was to test a novel three-dimensional (3D) automated computer-aided design (CAD) method (aCAD) for the computation of femoral angles in dogs from 3D reconstructions of computed tomography (CT) images. The repeatability and reproducibility of three manual radiography, manual CT reconstructions and the aCAD method for the measurement of three femoral angles were evaluated: (1) anatomical lateral distal femoral angle (aLDFA); (2) femoral neck angle (FNA); and (3) femoral torsion angle (FTA). Femoral angles of 22 femurs obtained from 16 cadavers were measured by three blinded observers. Measurements were repeated three times by each observer for each diagnostic technique. Femoral angle measurements were analysed using a mixed effects linear model for repeated measures to determine the levels of intra-observer agreement (repeatability) and inter-observer agreement (reproducibility). Repeatability and reproducibility of measurements using the aCAD method were excellent (intra-class coefficients, ICCs $\geq$ 0.98) for all three angles assessed. Manual radiography and CT exhibited excellent agreement for the aLDFA measurement (ICCs $\geq$ 0.90). However, FNA repeatability and reproducibility were poor (ICCs $<$ 0.8), whereas FTA measurement showed slightly higher ICCs values, except for the radiographic reproducibility, which was poor (ICCs $<$ 0.8). The computation of the 3D aCAD method provided the highest repeatability and reproducibility among the tested methodologies.

Femoral bone deformities might predispose dogs to patellar luxation (Gibbons et al., 2006; Johnson et al., 2006; Kowaleski et al., 2011; Piermattei and Flo, 2015). Traditionally, clinicians have assessed these deformities using plain radiographs (Mostafa et al., 2008; Bound et al., 2009; Miles, 2016). Several studies have shown that femoral angle measurements can be performed reliably using computed tomography (CT) (D'Amico et al., 2011; Barnes et al., 2015) and magnetic resonance imaging (Kaiser et al., 2001a; Ginja et al., 2009). CT allows three-dimensional (3D) evaluation of bone morphology and manipulation of the images to make measurements in the correct imaging plane. This eliminates positioning errors that result during the acquisition of radiographic images (D'Amico et al., 2011; Barnes et al., 2015).

The accuracy of radiography (Swiderski et al., 2008) and the precision of CT (Oxley et al., 2013; Barnes et al., 2015) for measurement of femoral angles have been reported. We developed a novel 3D Python-based algorithm using computer-aided design (CAD) software for computation of femoral angles and applied this algorithm to dogs with femoral deformities (Savio et al., 2016). The femoral angles were computed on polygonal mesh models generated by 3D scanning of isolated anatomic specimens. The method offered reliable information about the 3D morphology of the anatomical specimens, with the possibility of performing an automated computation of morphometric parameters.

The aim of this study was to assess the repeatability and reproducibility (Lee et al., 1989; Smith et al., 1997) of computing three femoral angles in dogs using a novel automated CAD-based

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(aCAD) technique, applied to 3D reconstructions of CT images: (1) anatomical lateral distal femoral angle (aLDFA); (2) femoral neck angle (FNA); and (3) femoral torsion angle (FTA). We compared the repeatability and reproducibility of the aCAD technique with manual measurements of aLDFA, FNA and FTA made from radiographs or CT reconstructions of the same femurs. We hypothesised that aCAD would have better repeatability and similar reproducibility when compared to manually determined angles from radiographs or CT reconstructions.

Materials and methods

We used cadavers of sixteen adult medium to large breed dogs euthanased for reasons unrelated to this study, with full consent from the owners. The mean age was 7.8 years (range 2.0–13.7) and the mean bodyweight was 29.3 kg (range 15.5–43.2 kg); there were four German shepherds, three Labrador retrievers, two each of Irish Setter, Doberman Pinscher and cross-breed, and one each of Dalmatian, Rottweiler and Breton. The study was performed in a double-blind fashion by three investigators from November 2015 to March 2017. All images were acquired by the same operator, who provided the anonymised studies to two experienced small animal orthopaedic surgeons and one experienced radiologist. Each investigator calculated three femoral angles (aLDFA, FNA and FTA) in triplicate using three different diagnostic techniques (radiography, CT and aCAD).

Radiographic examination

Cadavers were radiographed with digital radiographic equipment (Kodak Point of Care CR-360 System, Carestream Health). Dogs with radiographic evidence of diseases of the stifle and hip joints were excluded, since these could have altered the analysis during the measurement and computational process. Cranio-caudal and distal-proximal axial femoral radiographic projections were performed for each femur and the proper radiographic positioning was assessed. Positioning was considered to be acceptable following literature guidelines for both the cranio-caudal (Tomlison et al., 2007; Palmer et al., 2011; Miles et al., 2015) and distal-proximal axial femoral projection (Dudley et al., 2006).

Computed tomography

The cadavers were positioned on a foam cradle in a supine position with the legs extended and adducted. Correct positioning was obtained by tying the pelvic limbs above the stifles. CT scans were performed in a caudo-cranial direction using a four multi-detector row CT scanner (Toshiba Asteion S4, Toshiba Medical Systems Europe) in the helical acquisition mode. An exposure time of 0.725 s, voltage of 120 kV, amperage of 150 mA, and slice thickness of 1 mm (reconstruction interval 0.8 mm) were used. CT images were reconstructed with a high-resolution filter for bones and displayed in a bone window (window length 1000 Hounsfield units, HU; window width 4000 HU).

A 3D volume reconstruction of the CT scans was performed using commercially available DICOM-processing software (Osirix version 2.7, pixmeo SARL). Using a bone filter and the magnification function, the pelvis, tibia, tail and contralateral hind limb were cropped to isolate the femur. During the cropping procedure, care was taken to avoid unintentional alteration of the profile of the femoral condyles. The orientation of the 3D CT reconstructions was manipulated to create a true craniocaudal view of the femur following the procedure described by Oxley et al. (2013). The orientation of the 3D CT reconstructions was manipulated to create a true proximal to distal axial view of the femur with the caudal most points of the femoral condyles aligned with a horizontal reference line. Positioning was considered satisfactory when the cranial and caudal edges of femoral neck were detectable and the femoral diaphysis was partially visible above the proximal edge of trochanteric fossa. Once the femur was correctly positioned in both projections, the images were anonymised, saved, as a JPEG file, and labelled.

Three-dimensional reconstruction

The 3D reconstructed femurs were analysed with the algorithm presented in Savio et al. (2016) using commercial CAD software (Rhinoceros version 5, Robert McNeell & Associates) as a platform. The algorithm is designed to calculate the femoral angles on isolated reconstructions of an individual bone. Right and left femurs were present in all the CT scans.

The 3D reconstructions were exported as stereolithographic files (STL) (Botsch et al., 2010; Melchels et al., 2010; Skoog et al., 2014), a file format that is required to perform 3D computations with the CAD software. To create STL files within Osirix, the examiner segmented every femur in the axial, frontal and sagittal planes, then the region of interest (ROI) menu function was selected and the grow region (2D/3D segmentation) option was chosen. Once the mean value of the density of the femur was established, segmentation parameters were set up, resulting in generation of a new imaging series (bitmapped) of the femur. The segmented femur was exported to the 3D surface rendering tool embedded in Osirix, allowing the 3D reconstruction to be exported as a STL file.

Image collection and measurement technique

Radiographic and CT images used for manual measurements were prepared using Osirix. An open source programme (Research Randomizer, Version 4.0[1]) was used to randomise the order of presentation of the femoral samples for each series, changing the order for each investigator. A randomised set of three series of 30 samples each was created for every diagnostic technique, with the only restriction being avoidance of presenting femurs from the same dog sequentially to the same observer. All images were anonymised using a legend to prevent any conditioning for the observers. An interpretation key was used at the end of the measurement session to assemble all the collected data.

The investigators measured aLDFA and FNA on the radiographs (Fig. 1a) and CT images (Fig. 1b) from the cranio-caudal views, following published guidelines (Petazzoni, 2008; Yasukawa et al., 2016) and the FTA from the axial images, as previously described for radiographs (Dudley et al., 2006; Fig. 2a). For FTA measurements from CT images (Fig. 2b), investigators used the same anatomical landmarks as for the axial radiographic images (femoral head, neck and condyles), but a different orientation of the femur was adopted.

The investigators imported the STL files in the CAD software (Fig. 3), where the STL files were reconstructed to perform further image processing (Savio et al., 2016). The internal mesh, which appeared as a coloured area in the inner part of the bone was deleted (Fig. 4). Only the surface of the femur (external mesh) was used for the computation of femoral angles. The procedure was initiated by clicking a point on the femoral head. The algorithm computed the femoral angles (aLDFA and FNA: Fig. 1c; FTA: Fig. 2c), displaying these on screen, which the investigator then recorded. We modified the methodology previously published (Savio et al., 2016) to improve the identification of the centre of the femoral head.

Statistical analysis

The intra-observer and inter-observer intra-class coefficients (ICCs) with 95% confidence intervals (95% CI) were calculated (MedCalc Statistical Software version 17.3) for each angle measured, to assess the repeatability and reproducibility of the three imaging techniques. The ICC scores ranged from 0 (no agreement) to 1 (perfect agreement): poor: $ICC < 0.8$; good: $ICC \geq 0.8$; excellent: $ICC > 0.9$ (McGraw and Wong, 1996; Lopez et al., 2008). Descriptive statistics (means and standard deviations, median and interquartile range and coefficient of variance) were calculated for each angle (aLDFA, FNA and FTA) measurements for each observer and imaging technique (SPSS Statistics for Macintosh, version 24.0, IBM).

The measurements for each angle were analysed with three mixed-effect linear models for repeated measurements (by the same observer), with femur as the crossed random effect, and diagnostic technique, observer and measurement repetition as fixed factors. Since the repetition was not a significant source of variation, it was not included in any of the three final models. Least square means were used to compare the mean angle measurements and Bonferroni's adjustment for multiple comparisons was applied to evaluate differences among the different levels of the analysed factors. $P < 0.05$ was considered to be statistically significant.

Results

Twenty-two femurs (10 right and 12 left) from 16 dogs (10 males and 6 females) were included in this study. Ten femurs were excluded from the evaluation because they did not satisfy the inclusion criteria. The reasons for exclusion were severe degenerative joint disease (DJD) of the proximal femoral epiphysis with femoral head deformation and neck thickening (6 cases), DJD of the distal femoral epiphysis with modification of the profile of femoral condyles (2 cases), and neoplastic-like alteration of the bone structure in the femoral head and in the distal epiphysis of the femur (2 cases).

The intra-observer and inter-observer ICCs for the aCAD technique were excellent (12/12; $ICCs \geq 0.98$), while those of manually calculated femoral angles from radiographs or CT images exhibited an excellent agreement only for aLDFA (Table 1). The aLDFA was the most repeatable and reproducible angle for all three techniques (12/12; $ICCs > 0.90$), whereas FNA was the least repeatable (5/9, 55.6%; $ICCs < 0.8$) and reproducible (2/3, 66.7%; $ICC < 0.8$) (Table 1). The mean value, standard deviation from the mean, interquartile range and coefficient of variance of the

[1] See: http://www.randomizer.org/ (accessed 20 January 2017).