Accuracy of noninvasive, single-plane fluoroscopic analysis for measurement of three-dimensional femorotibial joint poses in dogs treated by tibial plateau leveling osteotomy

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Objective—To compare accuracy of a noninvasive single-plane fluoroscopic analysis technique with radiostereometric analysis (RSA) for determining 3-D femorotibial poses in a canine cadaver stifle joint treated by tibial-plateau-leveling osteotomy (TPLO).

Sample—Left pelvic limb from a 25-kg adult mixed-breed dog.

Procedures—A CT scan of the left pelvic limb was performed. The left cranial cruciate ligament was transected, and a TPLO was performed. Radiopaque beads were implanted into the left femur and tibia, and the CT scan was repeated. Orthogonal fluoroscopic images of the left stifle joint were acquired at 5 stifle joint flexion angles ranging from 110° to 150° to simulate a gait cycle; 5 gait cycles were completed. Joint poses were calculated from the biplanar images by use of a digitally modified RSA and were compared with measurements obtained by use of hybrid implant-bone models matched to lateral-view fluoroscopic images. Single-plane measurements were performed by 2 observers and repeated 3 times by the primary observer.

Results—Mean absolute differences between results of the single-plane fluoroscopic analysis and modified RSA were 0.34, 1.05, and 0.48 mm for craniocaudal, proximodistal, and mediolateral translations, respectively, and 0.56°, 0.85°, and 1.08° for flexion-extension, abduction-adduction, and internal-external rotations, respectively. Intraobserver and interobserver mean SDs did not exceed 0.59 mm for all translations and 0.93° for all rotations.

Conclusions and Clinical Relevance—Results suggested that single-plane fluoroscopic analysis by use of hybrid implant-bone models may be a valid, noninvasive technique for accurately measuring 3-D femorotibial poses in dogs treated with TPLO. (Am J Vet Res 2014;75:486–493)
other stifle joint rotations and translations. Abnormal joint kinematics may be responsible for the progression of osteoarthritis seen in stifle joints treated by TPLO.\textsuperscript{7,8} A better understanding of the in vivo effects of TPLO on joint stability may enable refinement of the clinical techniques and recommendations for dogs with cranial cruciate ligament insufficiency.

The ability to detect subtle kinematic abnormalities requires precise methods for tracking joint motion. Hybrid implant-bone modeling involves the creation of a 3-D model incorporating both bone and implant geometry.\textsuperscript{9} Single-plane fluoroscopy performed by use of CT-derived bone models has been used to accurately quantify joint kinematics during dynamic activities in various joints of humans.\textsuperscript{9–11} The principal advantage of this technique over other kinematic analysis methods includes the use of readily accessible equipment and the lack of requirement to surgically place bone markers. However, the accuracy of this kinematic analysis technique in TPLO-treated dogs cannot be extrapolated from human studies because of differences in osseous morphology and implant geometry; validation of single-plane fluoroscopy for TPLO-treated dogs is therefore required to conduct in vivo dynamic studies that use this methodology.

Radiostereometric analysis is accepted as the gold-standard method for tracking bone motion,\textsuperscript{12} with an error accuracy of 0.06 mm for translations and 0.31\textdegree\textsuperscript{13} for rotations described in dogs.\textsuperscript{13} The purpose of the study reported here was to determine the accuracy of a digital hybrid implant-bone model–based single-plane fluoroscopic technique for measuring 3-D femorotibial poses in a TPLO-treated canine stifle joint. We hypothesized that single-plane fluoroscopic analysis would offer a high degree of accuracy for rotations and translations in the sagittal plane (flexion-extension, cranio-caudal, and proximodistal), with reduced accuracy for rotations and translations out of the sagittal plane (mediolateral, abduction-adduction, and internal-external), and that this technique would have a high level of inter- and intra-operator repeatability.

Materials and Methods

Specimen preparation—The pelvis and intact normal pelvic limbs were collected by disarticulation at the lumbosacral joint from a 25-kg skeletally mature dog that was euthanized for reasons unrelated to the study. A CT scan\textsuperscript{a} of both pelvic limbs, from the hips to the tarsocrural joint, was obtained. The right pelvic limb was used in a separate study\textsuperscript{15} for analyzing bone model–based shape-matching techniques for the normal stifle joint. Radiopaque marker beads 2 mm in diameter were implanted into the cortices of the left femur and tibia for determining the precise position and orientation of the femur and tibia relative to each other, by use of a digital modification to the originally described RSA.\textsuperscript{12} The left cranial cruciate ligament was transected via a medial stifle joint arthrotomy, and a TPLO was performed by a board-certified surgeon (SEK), as described.\textsuperscript{2} The osteotomy was stabilized with a precontoured, locking 3.5-mm TPLO plate\textsuperscript{b} by use of 3.5-mm locking screws in the plateau segment and 3.5-mm cortical screws in the distal tibial segment. By use of a 3-D laser scanner,\textsuperscript{c} a digital 3-D model of the plate and locking screws was created by scanning an identical plate–locking screw construct as used in the specimen. Exact anatomic positioning of the marker beads was not required; beads were positioned such that most markers would not overlap or be obscured by metallic TPLO implants on orthogonal fluoroscopic images. Following marker bead implantation and TPLO, a second CT scan was obtained in similar fashion.

Fluoroscopic image acquisition—The specimen was mounted to a custom-designed jig that allowed unconstrained passive movement of the hip, stifle, and hock joints; the specimen was positioned with the left stifle joint centered within the field of view of the fluoroscope with a source-to-detector distance of 1,100 mm. Optical geometry of a ceiling-mounted fluoroscopic system\textsuperscript{d} was determined by use of a calibration object with known spatial positions of metal beads.\textsuperscript{15} This object measured 160 × 160 × 160 mm and contained 35 radiopaque metal beads; a CT scan of the calibration object allowed accurate determination of these metal bead locations. The x-ray source was configured to supply a 76-kV beam with a 20-mA beam current by use of a 1-shot fluoroscopy acquisition program. The flat panel detector had a field of view of 40 × 30 cm; image resolution was 1,024 × 1,024 pixels. By use of a goniometer, the left stifle joint was sequentially positioned at 5 flexion angles, ranging from 150° to 110° of extension, to simulate a normal gait cycle range of motion. With the right limb manually moved out of the field of view, mediolateral and cranio-caudal projection fluoroscopic images of the left stifle joint were obtained for each pose, while ensuring the specimen did not move between orthogonal image acquisitions. Images were acquired through 5 individual gait cycles.

3-D model creation and coordinate assignment—Three-dimensional bone models were created from CT-scan Digital Imaging and Communication in Medi-

![Figure 1—Digital 3-D femoral model (A) created from initial CT scan data of a cadaveric hindquarter specimen from a dog and digital 3-D hybrid implant-tibial model (B) constructed from pre- and post-TPLO CT scans and laser-scanned TPLO implants.](image-url)
cine (DICOM) images by use of an open-source 3-D segmentation software program. This semiautomatic application uses bone contour edges to create surface models of the bones. For single-plane fluoroscopic analysis of the stifle joint, the femoral bone model was created from the first CT scan, which was free from any metal artifact (Figure 1). A reverse engineering software program was used to construct a hybrid tibial bone model by amalgamating scan data from the first and second CT scans as well as the laser-scanned TPLO plate-screw construct. The initial CT scan was used to create a tibial model free from artifact associated with the metallic implants. Data from the second CT scan were used to ascertain the precise position of the implanted plate-screw construct on the tibia. The reverse engineered TPLO plate-screw construct was then superimposed over this tibial model. For RSA, marker-based models were created from the second CT scan. Femoral and tibial 3-D models used for RSA did not include the bone, bone plate, or screws around the implanted metallic beads and contained only the implanted beads in these regions (Figure 2).

The RSA marker-models were aligned with the corresponding hybrid bone models, and coordinate systems were applied simultaneously to both models. This eliminated variability in the comparative measurements that may have occurred from use of different coordinate systems for each 3-D model. Femoral coordinates were applied so that the mediolateral axis passed through the center of the lateral and medial femoral condyles with the femoral origin located at the midpoint between the centers of the condyles, on this axis. The proximodistal axis passed proximally, perpendicular to the mediolateral axis at the origin, in a plane common to the center of both femoral condyles and the femoral head. Tibial coordinates were applied so that the mediolateral axis passed from the outermost edge of the lateral and medi-tibial condyles; the tibial point of origin was set midway between these 2 points on the mediolateral axis. The proximodistal axis passed from distal to proximal, perpendicular to the tibial origin in a plane common to the mediolateral axis and the midpoint of the distal portion of the tibia. The cranio-caudal axes for the femur and tibia were created from the cross-product of the mediolateral and proximodistal axes, creating a Cartesian coordinate system.

3-D to 2-D shape matching—Two-dimensional fluoroscopic images and 3-D bone and hybrid models were imported into a custom-written open-source shape-matching software program. For the biplanar RSA, 3-D models of implanted beads were superimposed over the mediolateral and cranio-caudal projection fluoroscopic images simultaneously and manually manipulated to overlay the beads in the orthogonal fluoroscopic images (Figure 2). This process was repeated 3 times for all images to assess for repeatability of the modified RSA technique. For the single-plane fluoroscopic analysis, the femoral and hybrid tibial 3-D models were superimposed over the mediolateral fluoroscopic images and manually manipulated to match the silhouette of the respective bones and metallic implants (Figure 3). Each individual fluoroscopic frame was analyzed in a random fashion so that the shape-matching from one frame could not bias the

Figure 2—Representative digital images of a canine femur and tibia obtained by use of shape-matching software used for a modified RSA performed with CT-derived femoral and tibial beaded models after TPLO. The CT models are matched by use of implanted metal beads that appear blue and orange in cranio-caudal (A) and mediolateral (B) fluoroscopic images.

Figure 3—Representative digital images of a canine femur and tibia obtained by use of shape-matching software and single-plane fluoroscopy. The femoral model was derived from the first CT scan; the tibial model was derived from a combination of the first and second CT scans as well as a laser scan of an identical TPLO plate-screw construct. The femoral and tibial models are matched to the silhouette of the bones and TPLO implants on the lateral-view fluoroscopic image by use of edge-detection (A) and 3-D (B) modes. In panel A, the implanted metal beads appear as black dots.
next corresponding frame in that gait cycle. All frames were analyzed 3 times by the primary observer (SCJ) to assess intraobserver repeatability. A second observer (GT) completed the process once for all 5 gait cycles, to assess interobserver variability. Interobserver variability was assessed by comparison of the 5 cycles completed the first time by the primary observer with the 5 cycles completed by the second observer. Both observers underwent training in the shape-matching procedure before study commencement; this involved tutoring from an engineer experienced with the fluoroscopic analysis technique (SAB). Three-dimensional position and orientation of each bone model were determined from the shape-matching software; these data were then imported into a custom-written transformation matrix decomposition program, which transformed the data into clinically relevant femorotibial poses in 6 DOF.

Statistical analysis—A statistical software package was used for all analyses. Rotations (flexion-extension, abduction-adduction, and internal-external) and translations (craniocaudal, mediolateral, and proximodistal) calculated by use of RSA and single-plane fluoroscopic analysis were compared. The accuracy for each DOF was defined by the mean absolute difference and RMS errors between RSA and single-plane fluoroscopic analysis. Intraobserver repeatability was assessed by comparison of the 3 trials completed by the primary observer. Standard deviations were determined for each DOF, from each fluoroscopic frame over the 3 times they were analyzed. A single repeatability measure was determined by calculation of the mean SD for each DOF (75 frames).

Figure 4—Bland-Altman plots of the agreement between measurements made in 3 trials by use of a modified RSA and the mean of these 3 measurements for determining craniocaudal (A), proximodistal (B), and mediolateral (C) translations of a canine femorotibial joint treated by TPLO. The solid line represents the mean difference between the measurements; the dashed lines represent limits of agreement, between which 95% of differences between the measurements are expected.

Figure 5—Bland-Altman plots of the agreement between measurements made in 3 trials by use of modified RSA and the mean of these 3 measurements for determining flexion-extension (A), abduction-adduction (B), and internal-external (C) rotations of a canine femorotibial joint treated by TPLO. The solid line represents the mean difference between the measurements; the dashed lines represent limits of agreement, between which 95% of differences between the measurements are expected.
for all 5 cycles that were completed 3 times. Interobserver agreement was assessed by use of a paired t test performed on the absolute difference between the single-plane fluoroscopic analysis and RSA for each DOF. Similarly, repeatability was assessed by determination of the SD for each DOF in each fluoroscopic frame measured by both observers, with overall repeatability described with the mean SD for each DOF. The agreement between the fluoroscopic analysis and RSA for both intra- and interobserver analysis was further described by the limits-of-agreement approach, as described by Bland and Altman. Agreement between the measurements, repeated 3 times on all biplanar images, was evaluated by use of Bland-Altman plots. For all statistical analyses, values of $P < 0.05$ were considered significant.

**Results**

Agreement between the repeated biplanar images by use of the modified RSA was high, as indicated by narrow 95% limits of agreement in all 6 DOF on Bland-Altman plots (Figures 4 and 5). The absolute values of the differences of the means for single-plane fluoroscopic analysis and RSA were determined (Table 1). Mean absolute differences between the 2 techniques were $\leq 1.05$ mm for all translations and $\leq 1.08^\circ$ for all rotations. The RMS errors between the single-plane fluoroscopic analysis and RSA were $\leq 1.23$ mm all translations and $\leq 1.44^\circ$ for all rotations. For intraobserver repeatability, no significant differences were found between RSA and fluoroscopic analysis in the absolute mean differences in any of the 6 DOF measured by use of the modified RSA.

**Discussion**

Consistent with the primary hypothesis, results indicated that single-plane fluoroscopic analysis with hybrid implant-bone models was a highly accurate method for measuring 3-D femorotibial joint kinematics in a canine stifle joint treated by TPLO. The largest mean difference between RSA and single-plane fluoroscopy was $\leq 1.05$ mm for translations and $1.08^\circ$ for rotations. The results were in accordance with similar human kinematic studies that used a single-plane fluoroscopic technique, in which normal knees and knees modified with metallic implants had reported mean errors of $\leq 1.20$ mm for sagittal plane translation and $\leq 1.30^\circ$ for all rotations.

Results of a companion study indicated that single-plane fluoroscopic analysis of a normal canine pelvic limb by use of CT-derived bone models is highly accurate. Results of the study reported here suggested that accuracy is higher with hybrid implant-bone models, compared with bone-only models. Greater accuracy was found for all 6 DOF in the TPLO-treated limb, compared with accuracy attained by use of this single-plane fluoroscopic technique in a normal canine pelvic limb. The TPLO-treated tibia had more marker beads and wider bead dispersion, compared with the normal tibia. This was conducted to avoid metal overlap between the TPLO plate and the beads on the fluoroscopic images. Both of these factors may have nominally increased the accuracy of the modified RSA. The mean absolute difference between results of RSA and single-plane fluoroscopic analysis for TPLO-treated stifle joints was smaller than the values obtained from normal stifle joints by 0.26, 0.23, and 0.16 mm for craniocaudal, proximodistal, and mediolateral translations, respectively.

**Table 1**—Comparison of the mean ± SD absolute differences, 95% CIs, and RMS errors obtained by use of single-plane fluoroscopic analysis versus a modified RSA technique evaluating 6 DOF for all fluoroscopic images, each assessed 3 times in a canine femorotibial joint treated by TPLO.

<table>
<thead>
<tr>
<th>DOF</th>
<th>Difference (mean ± SD)</th>
<th>95% CI</th>
<th>RMS error</th>
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<tbody>
<tr>
<td>Craniocaudal (mm)</td>
<td>0.34 ± 0.32</td>
<td>0.30–0.38</td>
<td>0.39</td>
</tr>
<tr>
<td>Proximodistal (mm)</td>
<td>0.65 ± 0.64</td>
<td>0.59–0.70</td>
<td>1.23</td>
</tr>
<tr>
<td>Mediolateral (mm)</td>
<td>0.48 ± 0.39</td>
<td>0.39–0.57</td>
<td>0.62</td>
</tr>
<tr>
<td>Flexion-extension (°)</td>
<td>0.56 ± 0.37</td>
<td>0.48–0.64</td>
<td>0.67</td>
</tr>
<tr>
<td>Abduction-adduction (°)</td>
<td>0.85 ± 0.86</td>
<td>0.86–1.04</td>
<td>1.20</td>
</tr>
<tr>
<td>Internal-external (°)</td>
<td>1.08 ± 0.97</td>
<td>0.86–1.30</td>
<td>1.44</td>
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</table>

**Table 2**—Mean absolute differences between results of single-plane fluoroscopic analysis and a modified RSA of DOF measurements repeated over 3 trials in a canine femorotibial joint treated by TPLO.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Craniocaudal (mm)</th>
<th>Proximodistal (mm)</th>
<th>Mediolateral (mm)</th>
<th>Flexion-extension (°)</th>
<th>Abduction-adduction (°)</th>
<th>Internal-external (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31</td>
<td>1.30</td>
<td>0.41</td>
<td>0.56</td>
<td>0.95</td>
<td>1.39</td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
<td>0.85</td>
<td>0.49</td>
<td>0.86</td>
<td>0.66</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.29</td>
<td>0.85</td>
<td>0.53</td>
<td>0.96</td>
<td>0.93</td>
<td>0.84</td>
</tr>
</tbody>
</table>

**Table 3**—Intraobserver and interobserver variation (mean SDs) of DOF measurements obtained by use of single-plane fluoroscopic analysis of a canine femorotibial joint treated by TPLO by 2 observers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Craniocaudal (mm)</th>
<th>Proximodistal (mm)</th>
<th>Mediolateral (mm)</th>
<th>Flexion-extension (°)</th>
<th>Abduction-adduction (°)</th>
<th>Internal-external (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraobserver</td>
<td>0.33</td>
<td>0.59</td>
<td>0.41</td>
<td>0.31</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>Interobserver</td>
<td>0.38</td>
<td>0.46</td>
<td>0.56</td>
<td>0.37</td>
<td>0.61</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Intraobserver data represent analysis completed 3 times on all fluoroscopic images by each observer. Interobserver data represent analysis completed on all fluoroscopic images by both observers.
mediolateral translations, respectively, and 0.07°, 0.64°, and 0.50° for flexion-extension, abduction-adduction, and internal-external rotations, respectively. Of particular note was the increased accuracy attained with abduction-adduction and internal-external rotations. These rotations are out of the sagittal plane. Lateral-projection single-plane fluoroscopy has excellent accuracy for motions in the sagittal plane with reduced accuracy for out-of-plane rotations and translations.11 We suspect that the well-defined geometry of the metallic implants in the TPLO-treated stifle joint made the shape-matching process more accurate. The laser-scanned plate and locking screws in the hybrid model were of particular benefit in orienting the model for abduction-adduction and internal-external rotations, which were more subtle and difficult to detect on the lateral-view fluoroscopic images of normal bones.

In contrast to the normal limb, in which significant differences in the mean absolute error between RSA and single-plane fluoroscopic analysis were found in 4 of the DOF measurements, these differences were not observed in the TPLO-treated limb. The increased accuracy for abduction-adduction and internal-external rotations in the stifle joint may be attributed to the well-defined geometry of the metallic implants and the presence of the DP-L and TPLO plates. The increased accuracy for these rotations in the stifle joint may be due to the well-defined geometry of the metallic implants and the presence of the DP-L and TPLO plates. The increased accuracy for these rotations in the stifle joint may be due to the well-defined geometry of the metallic implants and the presence of the DP-L and TPLO plates.
the 6 DOF, no significant differences were found for any of the 6 DOF in the TPLO-treated stifle joint over the 3 times they were measured. The improved repeatability of this technique was again attributed to the improved accuracy attained when the TPLO plate and locking screw construct was used in the hybrid model for the shape-matching process. Interobserver repeatability for single-plane fluoroscopic analysis was also high, with no significant differences observed in the magnitude of error between 2 observers for 5 of the 6 DOF. A significant difference in errors between observers was found for mediolateral translations. Motion in this plane is perpendicular to the radiographic beam, making assessment of this variable difficult by use of the single-plane fluoroscopy method. The mediolateral alignment of the stifle joint is highly constrained in dogs and could be estimated during the shape-matching process by use of the free-view feature in the shape-matching software. The free-view function allows the operator to view and manipulate the femoral and tibial bone models from any perspective; major discrepancies in the mediolateral alignment between femur and tibia could be visualized and corrected for as previously described. The accuracy in the mediolateral translations was thus a reflection of the observer's best guess in this DOF; therefore, we do not recommend the use of this technique for assessing mediolateral stifle joint translations.

During 3-D model creation, it was possible to preserve the tibial plateau in the hybrid tibial model. This aided shape matching, particularly in relation to proximodistal translations and abduction-adduction rotations. Because of CT metal artifact, the position of the TPLO plate and screws dictates the regions of bone that can be reconstructed into the 3-D model. It must be noted that the application of a more proximal TPLO plate may preclude the ability to reconstruct the tibial plateau, which could potentially affect the ability to define the exact relationship of the femoral and tibial articulating surfaces. A TPLO plate and locking screws,
identical to the implanted construct, were laser scanned and incorporated into the hybrid tibial 3-D model. Cortical screws were not included in this scanned model because of the directional variability encountered during screw placement. A TPLO performed by use of only cortical screws would therefore preclude the ability to incorporate screws in the laser-scanned model, likely with an associated reduction in accuracy. Improperly placed locking screws would not identically match a corresponding laser-scanned locking screw construct and are a limitation to this technique.

The limitations of this fluoroscopic analysis technique have been thoroughly explored. In brief, images were obtained under static conditions, which may not reliably replicate dynamic in vivo image quality. Furthermore, limb overlap, which is inevitable in dynamic trails and could affect the accuracy of this technique, was avoided in the present study. Fluoroscopic images were analyzed in random fashion; however, a previous dynamic trial revealed that similar or improved accuracy may be attainable when performed in vivo owing to the operator's knowledge of bone position and orientation in the previous frame. The shape-matching technique involves a distinct learning curve; the accuracy of future studies will be dependent on the training of the individual and the attention to detail with the shape-matching process. Contrary to our hypothesis of greatest accuracy in the sagittal plane, inaccuracy of proximodistal translations was more than twice that of the other translations. We ascribe this apparent reduced accuracy for the proximodistal translations to the graphic method used to superimpose the bones on the fluoroscopic image. Finally, potential variations in the accuracy of this technique may be associated with dogs of different sizes, anatomic anomalies, or radiographically evident disease such as osteoarthritis.

Single-plane fluoroscopic analysis by use of bone and hybrid implant-bone models had excellent accuracy for measuring 3-D femorotibial poses in dogs following TPLO. This technique may allow for noninvasive, accurate quantification of femorotibial kinematics in clinical subjects that have undergone TPLO to treat cranial cruciate ligament insufficiency.

References