The Effect of Examiner Variability on Multiple Canine Stifle Kinematic Gait Collections in a 3-Dimensional Model

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Objective: To evaluate examiner variability in a superficial skin marker model of canine stifle kinematics.

Study Design: Experimental.

Animals: Six clinically normal dogs.

Methods: Dogs had 11 retroreflective markers fixed to the skin on the right hindlimb. Dogs were trotted 5 times through the calibrated testing space and this was repeated on 4 different testing days. Examiner A applied all markers to a dog and collected 6 good trials for analysis. The markers were then removed and Examiner B immediately repeated the process on the same dog. This was repeated for each dog on the 4 testing days. The dogs were trotted at a velocity of 1.70–2.10 m/s through the testing space to obtain the dynamic data sets. Comparisons were performed with Fourier analysis and Generalized Indicator Function Analysis (GIFA). Significance was set at $P < .05$ for all comparisons.

Results: Fourier analysis and GIFA found differences within and between examiners. Fourier analysis found no differences in sagittal and transverse planes for the experienced (A) and novice examiner (B), respectively. Fourier analysis detected fewer differences for the experienced examiner (A).

Conclusion: Variability occurs within and between examiners using the same kinematic model. Transverse and frontal plane kinematics produce variable results between examiners. Prior experience with the model reduces the amount of variability and results in consistent and repeatable sagittal plane kinematic data collection.

Three-dimensional kinematic analysis is used for the study of normal and pathologic locomotion.1,2 For this analytical tool to become widely accepted as useful and clinically relevant in veterinary medicine, its repeatability and sources of variability must be established. Previous research has identified sources of variability for kinetic data.3 However, there are currently no reports establishing the repeatability and sources of variability during 3-dimensional kinematic testing.

The objectives of this study were to (1) assess the intra-examiner variability on 4 separate testing sessions, and (2) assess the inter-examiner variability on 4 separate testing sessions between an experienced examiner (A) and a novice examiner (B) using a 3-dimensional, superficial skin marking system.4–7 The hypotheses tested was that intra- and inter-examiner differences would exist within and between testing days and that the level of examiner experience would not influence variability.

MATERIALS AND METHODS

Animals
Six adult dogs (body weight 20–30 kg) from a research colony were evaluated in this study. Use of these animals was approved by the University of Georgia Institutional Animal Care and Use Committee (AUP # - A2006-10042-c1). All dogs had normal bilateral hip and stifle radiographs, force plate analysis, complete blood counts, serum biochemistry analysis, and physical examinations before the study. The dogs were housed indoors in a climate-controlled environment and fed commercial dog food ad libitum.

Motion Data Collection
A 3-dimensional model of the canine stifle was utilized in this study as previously described.4–7 In this method, the segment
Table 1. Anatomic Landmarks for Skin Marker Locations for Kinematic Modeling of a Canine Hindlimb

<table>
<thead>
<tr>
<th>Segment</th>
<th>Landmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femur</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td></td>
<td>Cranio lateral aspect of the quadriceps m.</td>
</tr>
<tr>
<td></td>
<td>Lateral femoral condylea</td>
</tr>
<tr>
<td>Tibia</td>
<td>Fibular head</td>
</tr>
<tr>
<td></td>
<td>Proximal aspect of tibial crestb</td>
</tr>
<tr>
<td></td>
<td>Distal aspect of tibial crestb</td>
</tr>
<tr>
<td></td>
<td>Junction of gastrocnemius m. and tendon</td>
</tr>
<tr>
<td></td>
<td>Medial malleolusaa</td>
</tr>
<tr>
<td></td>
<td>Lateral malleolus</td>
</tr>
<tr>
<td>Phalange</td>
<td>Lateral metatarsophalangeal joint</td>
</tr>
</tbody>
</table>

*Markers removed during the acquisition of dynamic trials.

of femur and tibia were assumed as a rigid body, and the local coordinate system for each segment was defined by markers attached on the segments during static calibration. Three nonorthogonal unit vectors of these axes described joint motion. A toe marker was utilized to define the gait cycle as previously described. Velocity and acceleration were recorded with a series of 5 photocells placed 0.5 m apart and 0.5 m above the walkway.

Eleven spherical retroreflective markers (8 mm diameter) were fixed with double-sided tape and cyanoacrylate to the right hindlimb (Table 1). All dogs were short-haired and hair was not clipped before application. A 3-dimensional testing space was established on a 13-meter walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3 dimensions with 0,0,0 (X, Y, Z) located in the center of the testing space. Eight infrared cameras (Vicon MX03, Vicon Motion Systems, Inc., Centennial, CO) arranged around the gait platform captured marker location data at 200 Hz. Each day, before data collection, the system was calibrated with a calibration frame (Vicon Peak Motus L-Frame, Vicon-Peak, Centennial, CO) of known dimensions and by dynamic linearization with a custom made 0.700 m wand. Data were recorded and analyzed by a motion-analysis program (Peak Motus 9, Vicon Motion Systems, Inc.). The kinematic model was established as previously described on a computer software program (MATLAB, version 7.0 R14, The Math-Works Inc, Natick, MA).

Two different examiners were evaluated. Both examiners had knowledge of canine anatomy. Examiner A had prior experience with kinematic data collection using the current model. Examiner B had no prior experience. Examiner B was provided with a brief study description, a list of marker locations (Table 1), as well as a written description of the markers and method of placement before the study began.

Data Collection. Examiner A applied all markers. Initially, a static trial of the dog being tested was collected. Then, 4 markers (noted * on Table 1) were removed during subsequent dynamic trials. These markers were reconstructed from the static trial and were employed as virtual markers during the dynamic trials. The test dog was then recorded moving through the calibrated testing space in a trot at an average velocity of 1.70–2.10 m/s and an average acceleration of −0.50–0.50 m/s². Six good trials were collected for analysis. Examiner A then removed the markers with acetone, leaving no visual trace. Examiner B then immediately applied the same markers, repeating the process. This was repeated for each dog on 4 separate testing days (Days 0, 3, 5, and 9). The order of marker application between examiner A and examiner B as well as the order of dog was randomized. The same handler gaited all dogs. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately. In the case of any loss of markers requiring reattachment, data collection of all trials on that day was to be repeated.

Data Analysis

Waveforms were generated during each gait cycle and were compiled graphically, represented with 95% confidence intervals (Fig 1). These waveforms were compared by Fourier analysis and Generalized Indicator Function Analysis (GIFA). Eight Fourier coefficients were used to characterize stifle joint motion. All analyses were performed using SAS V 9.2 (SAS Institute, Cary, NC). A paired t-test was used to assess differences in Fourier coefficients (A1–A8 and B1–B8) between examiners for each day and plane of motion. The t-tests were performed on the difference of the mean coefficient for each dog (averaged over 6 replications) for Examiner A and the mean coefficient for each dog for Examiner B (averaged over 6 replications) for each day, plane, and coefficient separately. All hypothesis tests were 2-sided and significance was set at P < .05 for each test. A repeated measures analysis was used to test for difference in Fourier coefficients (A1–A8 and B1–B8) between days for each examiner and plane. The repeated measures analysis was performed on the data averaged over 6 replications and a Tukey-adjusted P-value was used for multiple comparisons. The hypothesis test was 2-sided and significance was set at P < .05. The GIFA was used to compare waveforms as previously described, with significance set at P < .05.

RESULTS

Sagittal (flexion and extension), transverse (internal and external rotation), and frontal (abduction and adduction) plane kinematics during movement of the distal segment relative to the proximal segment for the stifle joint were generated and collected from each dog during each dynamic gait cycle at a trot. Each plane of motion was evaluated separately for comparative analysis.

Fourier Analysis

Intra-Examiner Results. Examiner A had intra-examiner differences in the frontal plane and in the transverse plane...
but no intra-examiner differences in the sagittal plane. Examiner B had intra-examiner differences in the frontal plane and in the sagittal plane (Table 3) but no intra-examiner differences in the transverse plane.

**Inter-Examiner Results.** There were significant differences between the Fourier coefficients produced by Examiners A and B in all planes of motion (Table 4).

**GIFA**

Sagittal waveform analysis with GIFA found significant intra- and inter-examiner differences within and between all testing days. These differences were similar for both the experienced (A) and novice (B) examiner.

**DISCUSSION**

Both research hypotheses in this study were accepted, that is, intra- and inter-examiner differences existed within and between testing days, and the level of examiner experience did not influence variability. While both examiners produced similar sagittal waveforms (Fig 1), GIFA was able to detect significant differences within and between all testing days for all planes of motion, indicating that while temporal and examiner variability exists, experience level does not affect variability. Fourier analysis also found significant differences within 2 planes of motion and between all planes of motion although the extent of differences was less than with GIFA.

Sagittal plane kinematics provided consistent results for the experienced examiner (A) with no differences detected by Fourier analysis. Historically, hindlimb motion in the sagittal plane has been the focus of motion analysis in veterinary medicine.1,11–13 This is likely because of the available camera equipment (2-dimensional systems) and a quantitatively large degree of motion in the sagittal plane compared to the transverse and frontal planes. However, failure to address simultaneous motion occurring in the transverse and frontal planes limits the understanding of true 3-dimensional joint motion and hinders our ability to advance in the field of veterinary kinematics. Hence, the intent was to examine all planes of motion in the current study.

In this study, both transverse and frontal plane kinematics produced variable data for the experienced examiner (A). Interestingly, the transverse plane produced consistent data for the novice examiner (B). The reason for the difference between examiners is unknown. The evaluation of the additional planes of motion (transverse and frontal) can prove challenging. Marker visualization by the cameras (most notably medially placed markers) can be problematic in both people and animals. Marker visualization can be difficult during data collection of dogs because of truncal and/or
Table 3 Results (Tukey-Adjusted P-Value) of Intra-Examiner Fourier Analysis for Examiner A (Experienced)

<table>
<thead>
<tr>
<th>Day</th>
<th>Joint Motion</th>
<th>Comparison</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>A6</th>
<th>A7</th>
<th>A8</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>B7</th>
<th>B8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse</td>
<td>(Internal-External rotation)</td>
<td>1 vs 2</td>
<td>0.566</td>
<td>0.433</td>
<td>0.250</td>
<td>0.032</td>
<td>0.874</td>
<td>0.644</td>
<td>0.373</td>
<td>0.996</td>
<td>0.359</td>
<td>0.996</td>
<td>0.880</td>
<td>0.475</td>
<td>0.793</td>
<td>0.918</td>
<td>0.997</td>
<td>0.997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 vs 3</td>
<td>0.875</td>
<td>0.980</td>
<td>0.027</td>
<td>0.853</td>
<td>1.000</td>
<td>0.646</td>
<td>0.977</td>
<td>0.784</td>
<td>0.556</td>
<td>0.988</td>
<td>0.827</td>
<td>0.328</td>
<td>0.910</td>
<td>0.764</td>
<td>0.967</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 vs 4</td>
<td>0.823</td>
<td>0.504</td>
<td>0.526</td>
<td>0.990</td>
<td>0.998</td>
<td>0.961</td>
<td>0.907</td>
<td>0.961</td>
<td>0.928</td>
<td>0.992</td>
<td>0.939</td>
<td>0.994</td>
<td>0.902</td>
<td>0.976</td>
<td>0.996</td>
<td>0.997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 vs 3</td>
<td>0.940</td>
<td>0.256</td>
<td>0.604</td>
<td>0.153</td>
<td>0.917</td>
<td>0.126</td>
<td>0.611</td>
<td>0.082</td>
<td>0.984</td>
<td>0.976</td>
<td>0.463</td>
<td>0.025</td>
<td>0.900</td>
<td>0.999</td>
<td>0.999</td>
<td>0.859</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 vs 4</td>
<td>0.969</td>
<td>0.999</td>
<td>0.941</td>
<td>0.556</td>
<td>0.787</td>
<td>0.850</td>
<td>0.752</td>
<td>0.993</td>
<td>0.734</td>
<td>1.000</td>
<td>0.578</td>
<td>0.372</td>
<td>0.949</td>
<td>0.944</td>
<td>0.972</td>
<td>0.930</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 vs 4</td>
<td>1.000</td>
<td>0.308</td>
<td>0.303</td>
<td>0.694</td>
<td>0.991</td>
<td>0.428</td>
<td>0.710</td>
<td>0.968</td>
<td>0.907</td>
<td>0.965</td>
<td>0.997</td>
<td>0.426</td>
<td>0.854</td>
<td>0.951</td>
<td>0.811</td>
<td>1.000</td>
</tr>
<tr>
<td>Frontal</td>
<td>(Abduction-Adduction)</td>
<td>1 vs 2</td>
<td>0.800</td>
<td>0.535</td>
<td>0.290</td>
<td>0.366</td>
<td>0.811</td>
<td>0.969</td>
<td>0.989</td>
<td>0.998</td>
<td>0.434</td>
<td>0.903</td>
<td>0.301</td>
<td>0.063</td>
<td>0.857</td>
<td>0.923</td>
<td>0.992</td>
<td>0.181</td>
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<tr>
<td></td>
<td></td>
<td>1 vs 3</td>
<td>1.000</td>
<td>0.818</td>
<td>0.580</td>
<td>0.395</td>
<td>0.300</td>
<td>0.988</td>
<td>0.104</td>
<td>0.871</td>
<td>0.181</td>
<td>0.981</td>
<td>0.988</td>
<td>0.045</td>
<td>0.772</td>
<td>0.997</td>
<td>0.583</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 vs 4</td>
<td>0.859</td>
<td>0.206</td>
<td>0.522</td>
<td>0.171</td>
<td>0.233</td>
<td>0.825</td>
<td>0.858</td>
<td>0.977</td>
<td>0.124</td>
<td>0.966</td>
<td>0.506</td>
<td>0.043</td>
<td>0.354</td>
<td>0.682</td>
<td>0.366</td>
<td>0.986</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 vs 3</td>
<td>0.851</td>
<td>0.959</td>
<td>0.944</td>
<td>1.000</td>
<td>0.786</td>
<td>0.999</td>
<td>0.176</td>
<td>0.937</td>
<td>0.930</td>
<td>0.990</td>
<td>0.461</td>
<td>0.998</td>
<td>0.998</td>
<td>0.844</td>
<td>0.421</td>
<td>0.674</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 vs 4</td>
<td>0.999</td>
<td>0.894</td>
<td>0.967</td>
<td>0.956</td>
<td>0.691</td>
<td>0.978</td>
<td>0.963</td>
<td>0.934</td>
<td>0.840</td>
<td>0.670</td>
<td>0.977</td>
<td>0.997</td>
<td>0.797</td>
<td>0.958</td>
<td>0.243</td>
<td>0.305</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 vs 4</td>
<td>0.903</td>
<td>0.638</td>
<td>1.000</td>
<td>0.941</td>
<td>0.998</td>
<td>0.948</td>
<td>0.361</td>
<td>0.656</td>
<td>0.998</td>
<td>0.863</td>
<td>0.696</td>
<td>1.000</td>
<td>0.878</td>
<td>0.565</td>
<td>0.978</td>
<td>0.044</td>
</tr>
</tbody>
</table>

A1–A8, cosine coefficients; B1–B8, sine coefficients.

*Significant difference noted between days—the bold P-values indicate which Fourier coefficient was significantly different within examiner for the days being compared.

Both 2-dimensional and 3-dimensional systems have been used for veterinary kinematic gait analysis. Lower cost, 2-dimensional systems can obtain accurate and repeatable sagittal plane data. However, 2-dimensional systems suffer from parallax and perspective error, and simultaneous collection of transverse and frontal planes of motion is not possible. Parallax error occurs as the subject moves away from the optical axis of the camera and can be minimized but not eliminated. Perspective error occurs when the subject moves out of the calibrated plane of motion (sagittal, transverse, or coronal).
frontal plane). Methods of estimating and correcting for parallax and perspective error have been evaluated, but clinical application is often difficult. It is possible that use of a treadmill may minimize these sources of error by providing a stationary platform for ambulation. However, while sagittal plane kinematic of the canine hindlimb during overground and treadmill-based walking and trotting are comparable, small differences in the transverse and frontal planes have been described. Three-dimensional systems do not suffer from parallax or perspective error and allow simultaneous collection of all planes of joint motion. The model used in the current study is a unique superficial skin marker system of the canine hindlimb that establishes a rigid body model of the canine stifle that can be used to report true 3-dimensional joint motion.

The choice of analysis methodology in veterinary gait studies is an important consideration. Fourier analysis is common in veterinary kinematic studies. Some reports have limited the analysis of joint motion to essential coefficients, defined as the coefficients needed to reconstruct ≥95% of the waveform. These investigations found the first 3 coefficients were essential and used them to evaluate stifle joint motion in dogs at a trot. Interestingly, our previous study detected significant differences in an extended range of coefficients (≥8 Fourier coefficients) from dogs at a trot. The current study yielded similar findings. Recently, GIFA was introduced as a method of comparing gait waveforms in dogs. Previous studies have shown GIFA detected differences between visually similar gait waveforms when Fourier analysis did not. Multiple studies, including this one, use GIFA and Fourier analysis concurrently to assess dog gaits. In the current study, approximately 35% of the intra-examiner differences and 50% of the inter-examiner differences were detected in coefficients beyond the previously established essential coefficients for the stifle joint, which raises the question of how many coefficients should be evaluated. The additional, non-essential coefficient data may provide valuable comparative and clinically important information but current work is not conclusive.

Experience level did not affect the ability of the examiner to detect differences although Fourier analysis found fewer differences in the experienced examiner. Minor inconsistencies in marker location can cause variations resulting in a shift in the vertical position of the gait waveform. Recognition of this variation has led to the recommendation for data normalization. Others have found that differences are more likely due to changes in the gait patterns of subjects and less likely related to inconsistencies in marker location. A recent study demonstrated that normalization reduces but does not eliminate differences between individual dogs and the evaluation of pooled data is unaffected. Interestingly, GIFA is unaffected by the position of waveforms along the vertical axis and thus the differences detected by this analysis are likely because of true differences in the waveform shapes and not just inconsistencies in marker placement. However, it is possible that the differences for both analysis methods are because of the cumulative effect of small differences created on each testing day.

The goal of objective kinematic modeling is to provide researchers and clinicians with a biologically accurate and clinically relevant means of evaluating musculoskeletal motion during ambulation. How the data obtained from these models is analyzed is also critical. Evaluation methods must assess the entire gait cycle or gait waveform rather than a single point, data analysis. Inherent differences in analysis methods may enhance or diminish the ability to detect differences. Currently, there is not a single ideal method of kinematic data analysis. Instead, the synergistic use of multiple analyses may provide a composite assessment of gait kinematics. For example, while Fourier analysis can be used to determine if 2 gait cycles are similar, it is unable to determine where along the gait cycle they differ. The addition of GIFA allows determination of where along the gait cycle these differences occur. This added ability to assess where in the stance or swing phases difference occur may be beneficial.

Skin movement artifact with the use of skin marker systems has been a longstanding concern for gait analysis in people and animals. A common strategy is to place markers
over bony landmarks. This has the advantage of providing an easily identified and repeatable location for marker placement. In addition, these marker locations have minimal underlying soft tissue that may reduce skin and soft tissue movement artifact. Kim et al. recently evaluated skin movement artifact in a superficial skin marker model of the canine hindlimb. They found that skin movement affected gait data and that these changes occurred in a cyclic pattern throughout the gait cycle. Recommendations were made to characterize skin movement in canine kinematics to improve skin marker systems and more accurately represent underlying bone movement. However, skin movement must be evaluated at all sites of marker attachment in the model being used. Until additional data are available regarding skin marker movement at all marker sites, it must be accepted that kinematic data includes some skin movement artifact that is unrelated to movement of the underlying bones. In the present study, skin movement was addressed by use of an unweighted least squares method. It has been suggested that advanced algorithms, such as an optimization method, may also help minimize skin movement artifact.

Efforts were made to reduce sources of experimental error. The order of marker application between examiners as well as the order of dog was randomized. The same handler gaited all dogs. The first examiner was not allowed to observe the application or removal of markers by the second examiner. Efforts were made to remove all signs of previous marker attachment on the dogs before application of markers by the second examiner. No markers became detached during data collection.

Intra- and inter-examiner differences were found for both the experienced and novice examiner. While each examiner produced similar waveforms, the extent of differences detected varied according to the analysis method. The GIFA was unaltered by experience level while Fourier analysis found that experience reduced variability, reflecting differences inherent to the analysis methods. These findings indicate that consistent and repeatable kinematic data from the sagittal plane can be obtained from the kinematic model tested but experience, and intra- and inter-examiner variability can occur. Despite the use of a 3-dimensional system, data acquisition in the frontal and transverse planes remains inconsistent and refinement of the technique is necessary to improve reliability and accuracy in these planes.

DISCLOSURE

The authors declare no conflicts of interest related to this report.

REFERENCES


