Comparison of Canine Stifle Kinematic Data Collected with Three Different Targeting Models

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Objective: To model the kinematics of the canine stifle in 3 dimensions using the Joint Coordinate System (JCS) and compare the JCS method with linear and segmental models.

Study Design: In vivo biomechanical study.

Animals: Normal adult mixed breed dogs (n = 6).

Methods: Dogs had 10 retroreflective markers affixed to the skin on the right pelvic limb. Dogs were walked and trotted 5 times through the calibrated space and the procedure was repeated 5 days later. Sagittal flexion and extension angle waveforms acquired during each trial with all 3 models (JCS, Linear, and Segmental) were produced simultaneously during each gait. The JCS method provided additional internal/external and abduction/adduction angles. Comparison of sagittal flexion and extension angle waveforms was performed with generalized indicator function analysis (GIFA) and Fourier analysis. A normalization procedure was performed.

Results: Each model provided consistent equivalent sagittal flexion-extension data. The JCS provided consistent additional internal/external and abduction/adduction. Sagittal waveform differences were found between methods and testing days for each dog at a walk and a trot with both GIFA and Fourier analysis. After normalization, differences were less with Fourier analysis and were unaltered with GIFA.

Conclusions: Whereas all methods produced similar flexion-extension waveforms, JCS provided additional valuable data.

Clinical Relevance: The JCS model provided sagittal plane flexion/extension data as well as internal/external rotation and abduction/adduction data.

Clinical kinematic studies have been under used in veterinary medicine.¹ Previously, studies have focused on joint motion with respect to flexion and extension; however, joint movement is complex and incompletely represented in a 2-dimensional (2-D) model.² Interestingly, recent evidence has indicated that kinematic evaluation may be more sensitive than force platform, or kinetic, evaluation for detection of subclinical orthopedic disease.³

Historically, linear-link models of the canine hindlimb have been used to define sagittal plane motion.⁴–⁷ Whereas these models provide accurate and repeatable information about uniplanar motion they are limited in their ability to assess true 3-D joint motion. The Joint Coordinate System (JCS) was developed to describe 3-D joint motion by 6 independent coordinates or 6 degrees of freedom. Additionally, it facilitates the description and understanding of joint motion between biomechanical and clinical fields.² The benefit of a segmental rigid-body model, such as the JCS, is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with 6 degrees of freedom.

Whereas analysis of kinematic gait data in veterinary medicine has often focused on associated gait waveforms, analysis methodology has varied. Gait waveforms have been analyzed with polynomial equations⁶,⁸; Fourier analysis⁴,⁵,⁷,⁹; and principal component analysis.¹⁰ Another methodology that may prove useful in the evaluation of canine gait waveforms is generalized indicator function analysis (GIFA).¹¹ This is a multivariate vector waveform analysis method that maximizes signal power while maintaining a large signal-to-noise ratio, and provides the ability to assess differences at specific points along the waveforms.

Our purpose was to model 3-D kinematics of the canine stifle with the JCS,¹² and compare the JCS method with more traditional sagittal plane models of the canine stifle. Our hypothesis was that the JCS model would provide sagittal plane flexion/extension femorotibial angles...
comparable with those of more traditional sagittal plane models while also supplying internal/external rotation and abduction/adduction data. We also hypothesized that use of GIFA for waveform analysis will prove comparable to Fourier analysis, a more familiar frequency spectrum reconstruction analysis methodology.4,5,7

MATERIALS AND METHODS

Dogs

Adult dogs (n = 6; weighing, 20–30 kg) with normal bilateral hip and stifle radiographs and no detectable pathologic changes, from an established research colony were studied. Force plate gait analysis, hematologic and serum biochemical profiles, and complete physical examinations were performed before study start and no abnormalities were detected. Dogs were housed indoors in a climate-controlled environment and fed commercially available dog food ad libitum.

Motion Collection

Ten spherical retroreflective markers (8 mm diameter) were fixed with double-sided tape and cyanoacrylate to the right pelvic limb (Table 1). A 3-D testing space was established on a 13 m walkway. Right-handed orthogonal coordinate axes were used to describe the testing space in 3-D with 0, 0, 0 (X, Y, Z) located in the center of the testing space. Cameras captured sample data at 200 Hz. Before each day’s collection, the system was calibrated with a calibration frame (Vicon Peak Motus L-Frame, Vicon-Peak, Vicon Motion Systems Inc., Centennial, CO) of known dimensions and by dynamic linearization with a custom made 0.700 m wand. Marker locations were captured by a kinematic system of 6 infrared cameras (Vicon MX03, Vicon Motion Systems Inc.) arranged around the gait platform. Data were recorded and analyzed by a motion-analysis program (Peak Motus 8.5, Vicon Motion Systems Inc.).

Initially, a static trial of each dog was collected. Four markers (see *, Table 1) were removed during subsequent dynamic trials. These markers were mathematically reconstructed from the initial static trial and were used as virtual markers during the dynamic trials.13–16 This was necessitated by limitations in marker visibility while gaiting because of the partial or complete truncal concealment of certain markers. Dogs were then recorded moving through the calibrated space at a walk and trot. Gait order was identical for all dogs and each test day. Dogs were walked across the testing space at a velocity of 0.9–1.2 m/s and trotted at a velocity of 1.7–2.1 m/s. Each gait was recorded 5 times for analysis. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded immediately. The procedure was repeated 5 days after the first in similar fashion, providing a total of 10 trials for analysis.

Kinematic Models

Three distinct models were used to define the canine hind limb, stifle joint rotation center, and kinematics including (1) Sagittal Linear Model, (2) Sagittal Segmental Model, and (3) JCS Model.

Sagittal Linear Model (Fig 1A). In this model, the femur was represented by a line connecting the greater trochanter (GT) to the lateral femoral condyle (LFC). The tibia was represented by a line connecting the LFC to the lateral malleolus (LMA). The stifle joint center was defined as the point of articulation between the femoral and tibial segments. The stifle joint center of rotation was defined as the axis passing through the LFC and perpendicular to the intersecting lines that define the femoral and tibial segments.

Sagittal Segmental Model (Fig 1B). Similar to the linear model, the femur was represented by a line connecting GT to LFC; however, the tibia was represented by a line connecting the fibular head (FH) to LMA. The stifle joint center of rotation was defined as the intersection of the 2 segments at the distal aspect of the femoral component and the proximal tibia component. The axis of rotation of the stifle joint was defined as an axis perpendicular to the two segment lines, and passing through the joint center.

Stifle joint angles were calculated by the following equations:

\[
\theta_k = \cos^{-1} \frac{\vec{V}_{\text{femur}} \cdot \vec{V}_{\text{tibia}}}{|\vec{V}_{\text{femur}}||\vec{V}_{\text{tibia}}|}
\]

where the vectors of femur and tibia were defined by position vectors of GT, LFC, and LMA measured from the motion capture system:

\[
\vec{V}_{\text{femur}} = \vec{V}_{\text{GT}} - \vec{V}_{\text{LFC}}
\]

\[
\vec{V}_{\text{tibia}} = \frac{\vec{V}_{\text{LMA}} - \vec{V}_{\text{LFC}}}{2}
\]

In the segmental model, the \(\vec{V}_{\text{tibia}}\) was defined by substituting \(\vec{V}_{\text{LFC}}\) by \(\vec{V}_{\text{FH}}\) in Equation 3.

JCS Method (Fig 1C). In this model, the segment of femur and tibia were assumed as a rigid body, and first the local coordinate system (LCS) for each segment was defined by markers attached on the segments during static calibration.

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**Table 1** Marker locations for Joint Coordinate System Kinematic Modeling of a Canine Stifle Unilaterally

<table>
<thead>
<tr>
<th>Femoral Markers</th>
<th>Tibial Markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater trochanter (GT)</td>
<td>Fibular head (FH)</td>
</tr>
<tr>
<td>Cranialateral aspect of the</td>
<td>Proximal aspect of tibial crest (PTC)*</td>
</tr>
<tr>
<td>quadriceps muscle</td>
<td></td>
</tr>
<tr>
<td>Lateral femoral condyle (LFC)*</td>
<td>Distal aspect of tibial crest (DTC)*</td>
</tr>
<tr>
<td>Medial femoral condyle (MFC)*</td>
<td>Junction of gastrocnemius muscle and tendon</td>
</tr>
<tr>
<td></td>
<td>Medial malleolus (MMA)*</td>
</tr>
<tr>
<td></td>
<td>Lateral malleolus (LMA)</td>
</tr>
</tbody>
</table>

*Markers that are removed during the acquisition of dynamic trials.
In the femur, the unit vector of z-axis of the LCS was defined by LFC and the medial femoral condyle marker (MFC)

\[
\hat{z} = \frac{\vec{V}_{LFC} - \vec{V}_{MFC}}{\sqrt{\vec{V}_{LFC} - \vec{V}_{MFC}}} \tag{4}
\]

The unit vector of x-axis was defined by a cross product of the vector from LFC to GT and the unit vector of the z-axis

\[
\hat{x} = \frac{(\vec{V}_{GT} - \vec{V}_{LFC}) \times \hat{z}}{|(\vec{V}_{GT} - \vec{V}_{LFC}) \times \hat{z}|} \tag{5}
\]

Consequently, the last unit vector of the y-axis was defined by a cross product of two unit vectors of the x- and z-axes

\[
\hat{y} = \hat{z} \times \hat{x} \tag{6}
\]

The origin of the femoral LCS was set at the GT. In the tibia, the origin for the tibia LCS was at the proximal tibial crest (PTC), and the axes of the LCS were defined in a similar manner to the femoral LCS, in that the z-axis unit vector was defined by the lateral and medial malleolus (LMA and MMA):

\[
\hat{z} = \frac{\vec{V}_{LMA} - \vec{V}_{MMA}}{\sqrt{\vec{V}_{LMA} - \vec{V}_{MMA}}} \tag{7}
\]

And the x-axis unit vector was defined as

\[
\hat{x} = \frac{(\vec{V}_{PTC} - \vec{V}_{DTC}) \times \hat{z}}{|(\vec{V}_{PTC} - \vec{V}_{DTC}) \times \hat{z}|} \tag{8}
\]

Where PTC and DTC were the proximal and distal tibial crest markers, and the y-axis unit vector was the same as Equation 6. Three non-orthogonal unit vectors of these axes described joint motion. The JCS flexion/extension angle was converted to a complimentary angle as previously described.5,13

Analysis Methods

Waveforms were generated for all 3 models simultaneously during each gait cycle and were compiled graphically, represented with 95% confidence intervals (95% CI). A normalization procedure was then performed on all flexion/extension waveforms as previously described (Fig 2).6,7,17 These simultaneously collected sagittal waveforms, both pre- and postnormalization, were then compared by GIFA11 and a Fourier Transformation.7,17

GIFA sought to find a set of 1 or more Eigen vectors (in our case, the Eigen vectors contain information concerning differences between gaits), which best distinguished between the means of the measurements, while accounting for variance in the data (i.e., dimensions in which variance is large, are suppressed). The covariance of each statistically significant Eigen vector indicates distinctive differences between the sets of measurements. If no statistically significant Eigen vectors are found, this indicates that no differences were found between the measurements when
Figure 2  Graphs of mean stifle flexion and extension angles for all dogs at a walk and a trot with all 3 methods illustrated. Original and Normalized waveforms are depicted. After normalization the variance was diminished as is evident by the change in the 95% confidence interval (95% CI) between pre- and postnormalization flexion and extension waveforms. Quantitative angular change is indicated by the appropriate waveform with 95% CI. Internal/external and abduction/adduction angles were acquired only by the Joint Coordinate System (JCS).
the overall variance of the measurements was taken into account. Significance was set at $P < .05$.

Fourier analysis was performed as described. Data for inter-day comparisons was normalized separately for each testing day. Ten Fourier coefficients were used to characterize sagittal stifle joint motion (Table 2). Comparison of the Fourier coefficients was accomplished using a repeated measures ANOVA performed by statistical analysis software (SAS v 9.2, Cary, NC). Multiple comparisons were adjusted using Tukey’s test. All hypothesis tests were 2-sided and significance was set at $P < .05$.

RESULTS

Sagittal flexion and extension waveforms were obtained for each method (Linear, Segmental, and JCS) simultaneously during each gait cycle. In addition, JCS provided data on internal/external and abduction/adduction movement around the stifle joint (Fig 2).

GIFA

Significant intra-dog differences ($P < .05$) were found between methods for all dogs (Fig 3A and B) at the walk and trot. Significant inter-dog differences ($P < .05$) were found between dogs within all methods (Fig 4A and B) at both walk and trot. However, when the data were pooled, no significant differences were found between methods in the sagittal waveforms from all dogs at a walk and trot. No inter-day differences existed for all dogs at both a walk and trot. When the data was pooled no inter-day differences were present. Normalization of the data yielded identical results.

Fourier Analysis

Significant intra-dog differences ($P < .05$) were found between methods for 2 dogs at a trot and 4 dogs at a walk. Significant inter-dog differences ($P < .05$) were found between dogs within all methods at both the walk and trot. When the data were pooled, significant differences ($P < .05$) were found between methods at a walk and trot (Table 2). Significant inter-day differences ($P < .05$) were found for all dogs at a walk and trot. Inter-day differences ($P < .05$) were also found when the data was pooled (Table 2).

After normalization, there were no significant intraindog differences between methods for all dogs at a trot; however, significant intrain-dog differences between methods were found for 2 dogs at a walk. Differences between methods in pooled data were unchanged (Table 2). No significant inter-dog differences existed between dogs within all methods at both the walk and trot. Significant inter-day differences were found in 1 dog at a trot and 4 dogs at a walk. Inter-day differences in the pooled data were still present (Table 2).

DISCUSSION

We confirmed the use of a skin marker system based on the JCS for collection of canine stifle kinematics. JCS allows

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Mean Fourier Coefficients from All Methods for the Sagittal Femorotibial Joint Angle in all Dogs at a Walk and a Trot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
</tr>
<tr>
<td></td>
<td>JCS</td>
</tr>
<tr>
<td>A1</td>
<td>5.45</td>
</tr>
<tr>
<td>A2</td>
<td>2.74</td>
</tr>
<tr>
<td>A3</td>
<td>0.06</td>
</tr>
<tr>
<td>A4</td>
<td>−0.12</td>
</tr>
<tr>
<td>A5</td>
<td>−0.04</td>
</tr>
<tr>
<td>A6</td>
<td>−0.02</td>
</tr>
<tr>
<td>A7</td>
<td>0.01</td>
</tr>
<tr>
<td>A8</td>
<td>0.01</td>
</tr>
<tr>
<td>A9</td>
<td>0.01</td>
</tr>
<tr>
<td>A10</td>
<td>0.01</td>
</tr>
<tr>
<td>B1</td>
<td>5.81</td>
</tr>
<tr>
<td>B2</td>
<td>−1.42</td>
</tr>
<tr>
<td>B3</td>
<td>−0.44</td>
</tr>
<tr>
<td>B4</td>
<td>−0.06</td>
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<tr>
<td>B5</td>
<td>0.00</td>
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<tr>
<td>B6</td>
<td>0.01</td>
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<td>B7</td>
<td>0.01</td>
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<tr>
<td>B8</td>
<td>0.01</td>
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<tr>
<td>B9</td>
<td>0.01</td>
</tr>
<tr>
<td>B10</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Coefficients from the original and normalized waveforms are depicted. A1−A10, cosine coefficients; B1−B10, sine coefficients.

*Significant differences between methods for trot.

†Significant differences between methods for walk.

‡Significant inter-day differences between methods for the walk or trot.
acquisition of stifle flexion and extension angles in the sagittal plane, similar to the more traditional sagittal segmental and linear models evaluated, while also providing acquisition of internal/external and abduction/adduction motion around the stifle joint.

Traditionally in veterinary medicine, sagittal flexion/extension angles have been the primary data collected and reported for in vivo dynamic kinematic analysis of canine gait. In this report, a 3-D system was used to obtain sagittal flexion and extension angles from all models (Linear, Segmental, and JCS). The use of a 3-D system for collection of 2-D motion capture has recently been evaluated. In that study, canine flexion and extension angles were collected with a 2-D and 3-D camera system and compared, with the use of a traditional linear marking system. Both systems provided reliable and comparable angular data measurement in the sagittal plane.

Whereas sagittal plane evaluation provides an easy assessment of flexion and extension, it greatly limits the evaluation of true joint motion and under utilizes the 3-D camera systems, if only used for evaluation of flexion and extension. Because joint motion occurs in 3-D, an inability to assess movement in these additional dimensions hinders our understanding of both normal and pathologic joint motion. Previous in vivo studies have evaluated canine kinematics in pathologic joints; however, these studies have reported changes in the flexion/extension angle. The use of the JCS marking system allowed evaluation of sagittal plane stifle motion, similar to traditional linear and segmental models, while providing information on internal/external and abduction/adduction angular motion. Three-dimensional kinematic evaluations of normal and cranial cruciate deficient canine stifles confirm that joint motion is augmented in > 1 plane after cranial cruciate ligament rupture (CCLR). It has been proposed that restoration of normal 3-D stifle motion as determined by stifle kinematics may need to be considered in evaluating surgical treatment modalities for CCLR. To date, much of the information regarding 3-D changes after CCLR has been provided by cadaveric or

Figure 3  Mean stifle flexion and extension angle at a walk (A) and trot (B) with 95% confidence intervals for an individual dog measured with differing methods. Significant differences, as illustrated by this comparison between methods for an individual dog, were found for all individual dogs between methods at both a walk and trot. The temporal differences between methods are indicated by the generalized indicator function analysis (GIFA) Difference Vector plot. GIFA produces a multidimensional vector representing the most significant difference between the groups being compared. For illustrative purposes this vector is depicted on the graph as a waveform corresponding to the temporal differences between gaits. Changes in amplitude away from baseline [0] correspond to the degree of difference detected between groups. However, the establishing vector is unitless and therefore the direction of waveform movement along the vertical axis, away from baseline [0], is arbitrary. The GIFA Difference Vector Covariance plot depicts a statistically significant change between methods. Each (•) represents an individual trial. Small movements along the vertical axes within a method indicate slight variation between individual trials within that method. Differences in vertical axes position between the groups (LIN, JCS, and SEG) indicate significant differences between groups. The distance between the groups along the vertical axes denotes the degree of difference between them. The actual position of the groups along the vertical axis represents a relative quantity. LIN, Sagittal Linear Model; SEG, Sagittal Segmental Model; JCS, Joint Coordinate System Model.
invasive in vivo methods of data collection—which are not applicable in the clinical setting. The JCS method evaluated in this study provides a means to evaluate 3-D stifle motion in a non-invasive and clinically feasible manner.

Fourier analysis has been used in earlier studies of canine gait. Previoursly, these reports limited the analysis to the essential coefficients, defined as the coefficients needed to reconstruct ≥95% of the waveform. The number of essential coefficients needed to characterize the stifle joint angle varied in these studies. The first 5 coefficients were used at a walk, and 3 coefficients at a trot. In our study, determination of essential coefficients was not performed and all 10 coefficients produced were used to characterize the stifle flexion and extension angle at the walk and the trot. Notably, significant differences were found within the first 6 coefficients of the original data for both the walk and trot. Within the normalized data, significant differences extended to 5 coefficients for the walk and 7 for the trot. These results identify detectable differences beyond the previously established essential coefficients. This additional data may provide valuable comparative information; however, further study is warranted before any conclusions can be gleaned regarding the inclusion or exclusion of non-“essential” coefficients and the resulting affect on overall analysis.

Normalization of the sagittal waveform data were performed in this report. Previous reports have documented a shift in gait waveforms along the vertical axis secondary to differences in marker placement. In an attempt to decrease the affect of this shift on analysis, normalization procedures were implemented in these reports. Normalization of the data seeks to decrease this shift and reduce a substantial source of variability that may not represent true temporal changes in the waveform, and thus true differences in movement.

Comparison between analysis methodologies proved valuable. Both GIFA and Fourier analysis were able to detect differences between methods; however, unlike GIFA, analysis of the Fourier coefficients was altered by the normalization process. Fourier analysis is affected by the position of the waveform along the vertical axis. Therefore, after normalization, less variability existed among the studied waveforms. Alternatively, GIFA compares the waveform shape and is unaffected by the position along the vertical axis. Interestingly, while individual comparisons were altered by normalization, comparison of the pooled data was unaffected.

Figure 4 Mean stifle flexion and extension angle at a walk and trot with 95% confidence intervals of two different dogs. Significant differences, as illustrated by this typical comparison of two different dogs, were found between all individual dogs at a walk and trot. (A) For the walk, the generalized indicator function analysis (GIFA) Difference Vector plot illustrates temporal differences of a relatively low frequency, as indicated by a smooth waveform. This is due to fine differences in the timing of maximal extension. (B) For the trot, the GIFA Difference Vector plot illustrates temporal changes of a comparatively higher frequency as indicated by a less smooth waveform. The majority of these high-frequency differences occur at the time of maximal extension. The GIFA Difference Vector Covariance plots for both the walk and trot depict significant differences between Dog A and Dog B.
Limiting the influence of waveform position on analysis methodology may prove valuable when data collection will occur at multiple time points. In this study, GIFA analysis found no significant differences between the waveform shapes of dogs between testing days. Examination of this same data with Fourier analysis yielded differing results. It found significant differences between testing days in all dogs; however, after normalization those differences were diminished for both the individual and pooled data. This suggests that when comparing normal dog gaits from multiple testing sessions, while inter-day variation may occur, waveform shape remains consistent between testing days.

The differences between methods detected with GIFA were attributed to the variations in marker locations used to establish the models and joint center definitions associated with the corresponding models. Historically, the canine stifle joint center has commonly been established as the midpoint between the LFC and the FH, in linear models. That demarcation was not used in our study as that marker location was not uniformly represented in all 3 models tested, and therefore would not allow simultaneous data collection. As a result, the LFC was used to represent the stifle joint center in the linear model (Fig 1A), similar to previous studies. The joint center in the segmental model used the point of bisection between the femoral and tibial segment, at approximately the area between the LFC and the FH (Fig 1B); however, the JCS model (Fig 1C) does not use a traditional joint center, like the linear and segmental models. Instead all rotations are described by the relative relationship between the defined femoral and tibial axes. Therefore, because rotation occurs around a fixed axis, the center of rotation could be most aptly described as a point located in the center of the MFC and LFC. Even with these inter-model differences, the general waveforms generated from each model were equivocal. Thus, while model methodology provided for some waveform variability, all 3 methods produced similar flexion/extension waveforms. These results are consistent with previous kinematic studies of the canine stifle. Interestingly, while GIFA identified individual differences, when all dog gaits were combined no significant difference existed between measurement methods. The implication of these results is that, although on a one-by-one comparison level the methods may differ in a consistent way, the overall variance in large sets of dog gaits masks any consistent differences in measurement methods, at the population level. The same cannot be stated for Fourier analysis, which found differences on the individual and population levels.

Efforts were made to alleviate sources of experimental error. All dogs were gaited by 1 handler (A.S.). Additionally, in an attempt to limit variations in marker placement between dogs on the 2 testing days, markers were placed on the dogs by only 1 person (J.P.). This was kept consistent throughout the study. Despite this, some variation in marker placement did occur between dogs on the 2 collection days as is evident by the Fourier analysis. While all markers were secured and no detachment occurred, any loss of markers requiring reattachment would have resulted in recollection of all trials on that day. The use of skin markers and the accuracy of a skin marker system for non-invasive kinematic evaluation of joint motion has been a source of controversy in gait analysis. Ideally, for accurate evaluation of joint motion the markers delineating the targeted bones should be rigidly affixed to the skeletal system so as to provide precise representations of bone motion. However, rigid fixation techniques currently require invasive measures and long surgical recovery times before data collection that are not conducive to applications in the clinical setting. Unfortunately, to date no direct comparison between rigidly affixed and skin markers for kinematic evaluation of dogs has been evaluated. The major concern with skin marker systems is primarily marker motion secondary to soft tissue movement artifact. A previously published investigation into marker motion with a similar marking and collection system used in this study detected marker movement of 2 mm and revealed < 2% marker movement during a complete dynamic gait cycle for both the femoral and tibial markers. While these data do not account for movement of a particular marker relative to its assigned anatomic site, it does document minimal movement between markers.

Our study hypotheses were accepted. Each model provided useful and repeatable flexion-extension data; however, only the JCS provided data from the additional axes. It was not surprising that these 3 measurement methodologies provided similar results as they were collected simultaneously in the dogs. It was also not unexpected to see subtle but significant differences in these sagittal flexion-extension waveforms because of the different markers used to create the models. Additionally, in regard to waveform analysis, both GIFA and Fourier analysis provided the ability to assess differences in waveforms. Unlike the Fourier analysis in this study, which only assesses if the waveforms are similar or dissimilar, GIFA gives rise to Eigen vectors that are functions of time and therefore may prove beneficial in temporally isolating gait differences. This may also allow for a sensitive measure of variability between gait waveforms in which only fine timing differences occur.

REFERENCES


