The Effect of Marker Location Variability on Noninvasive Canine Stifle Kinematics

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The use of superficial skin markers is currently the most widely reported method of in vivo kinematic data acquisition in veterinary medicine.¹⁴ Previous reports have elucidated the effect of asymmetric marker placement in a bilateral model⁹ as well as on kinematic waveform data in unilateral models.¹³⁻⁶ These reports have demonstrated that inconsistent marker placement can produce disparities in flexion and extension joint angles. However, the effect of marker placement errors in specific directions has not been reported.

Our purpose was to evaluate the effect of marker placement on 3-dimensional kinematics of the canine stifle with the use of 3 distinct marking systems.¹⁰ Our hypotheses were that marker placement error of a single marker during dynamic gait testing will result in detectable differences in gait data. Also, those errors in the horizontal plane (cranial and caudal marker location) will result in a greater degree of difference than errors in the vertical plane (dorsal and ventral marker location).

MATERIALS AND METHODS

Animals
Five adult mixed-breed dogs weighing 20–30 kg from an established research colony were studied. All dogs were ~5 years of age. All dogs had normal bilateral hip and stifle radiographs with no detectable pathologic changes. Force plate analysis (peak vertical force and vertical impulse), CBC, serum chemistry, and complete physical exams were performed before initiation of the study and were all normal. Dogs were housed indoors in a climate controlled environment and feed commercially available dog food ad libitum.

Motion Collection
Fifteen spherical retroreflective markers (8 mm in diameter) were used to produce all the models evaluated (Table 1).
Ten markers were affixed with double-sided tape and cyanoacrylate to the right rear leg. Four additional markers, attached similarly, were placed at a distance of 2 cm around the greater trochanter (GT) marker at a cranial, caudal, dorsal, and ventral position. These markers were used to mimic marker placement error. One lateral toe (metatarsophalangeal joint) was utilized to establish gait cycle. All markers were applied by only 1 person throughout the study. All markers were secured and no detachment occurred. Any loss of markers requiring reattachment would have resulted in recollection of all trials for that dog on that day.

A 3-dimensional testing space was established on a 13 m 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. Before each day’s 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. Marker locations were captured by a kinematic system of 8 infrared cameras (Vicon MX03, Vicon Motion Systems, Los Angeles, CA) arranged around the gait platform. Data was captured at 200 Hz and then recorded and analyzed by a motion-analysis program (Peak Motus 9.2, Vicon Motion Systems).

Initially, a static or anatomic trial of each dog was collected, as described previously. Four markers (noted by an asterisk in Table 1) were removed during subsequent dynamic trials. These markers were reconstructed from the static or anatomic trial and were used as virtual markers during the dynamic trials, as described previously.11,12 Dogs were then recorded moving through the calibrated space at a walk and trot. The order each gait was performed was identical for all dogs. Dogs were walked across the testing space at a velocity between 0.9 and 1.2 m/s and trotted at a velocity between 1.7 and 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. All dogs were gaited by the same handler.

Kinematic Models

Three distinct models were used to define the canine hind limb, stifle joint rotation center, and kinematics including (1) Sagittal Linear Model (LIN), (2) Sagittal Segmental Model (SEG), and (3) Joint Coordinate System (JCS) Model as illustrated in Fig 1. These models were used as described previously.10 Sagittal flexion and extension angles were obtained simultaneously for all 3 methods (LIN, SEG, JCS). For each method, the GT marker was reassigned in each individual trial to a cranial, caudal, ventral, and dorsal position within the motion analysis program to establish the new

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**Table 1** Marker Locations for 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</td>
<td>Fibular head</td>
</tr>
<tr>
<td>2 cm caudal to the greater trochanter</td>
<td>Proximal aspect of tibial crest*</td>
</tr>
<tr>
<td>2 cm cranial to the greater trochanter</td>
<td>Distal aspect of tibial crest*</td>
</tr>
<tr>
<td>2 cm dorsal to the greater trochanter</td>
<td>Junction of gastrocnemius m. and tendon</td>
</tr>
<tr>
<td>2 cm ventral to the greater trochanter</td>
<td>Medial malleolus*</td>
</tr>
<tr>
<td>Craniolateral aspect of the quadriceps m.</td>
<td>Lateral malleolus</td>
</tr>
<tr>
<td>Lateral femoral condyle*</td>
<td>Gait determinant marker</td>
</tr>
<tr>
<td>Medial femoral condyle</td>
<td>Metatarsophalangeal joint #5</td>
</tr>
</tbody>
</table>

*Markers that are removed during the acquisition of dynamic trials.

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**Figure 1** Illustrative representation of the body segments and kinematic marker placement on the skin of the canine hind limb. (A) Sagittal Linear Model (LIN), (B) Sagittal Segmental Model (SEG), (C) Joint Coordinate System Model (JCS).
femoral segment in those respective positions. This reassignment of the GT marker within the motion analysis software allowed for the production of 5 different, yet simultaneously collected data sets for each individual trial as illustrated in Fig 2. Therefore, each normal individual trial and the corresponding variants (cranial, caudal, dorsal, ventral) differed by only the location of the GT. The JCS method additionally provided internal/external rotation and abduction/adduction angles for all 5 GT locations. The sagittal flexion and extension waveforms for each of the 3 models (LIN, SEG, JCS) were then analyzed.

**Analysis Methods**

Waveforms were generated for all 3 models and GT locations simultaneously during each gait cycle, and were compiled graphically (Fig 2). These simultaneously collected sagittal waveforms were compared by Generalized Indicator Function Analysis (GIFA), as described previously.\(^{10,13}\) Significance was set at \(P < .05\).

**RESULTS**

Sagittal flexion and extension angles were obtained simultaneously for all 3 methods (LIN, SEG, JCS). No marker detachment occurred.

Each GT marker location (normal, cranial, caudal, dorsal, ventral) produced visually similar waveform shapes. However the cranial, caudal, dorsal, and ventral GT locations resulted in a “shifting” of the waveform away from normal, up or down along the y-axis. The greatest shift from normal was seen in the cranial and caudal GT marker locations (Fig 2).

Significant differences (\(P < .05\)) were found between methods (LIN, SEG, JCS) for all dogs in each of the 5 GT locations.
locations (normal, cranial, caudal, dorsal, ventral), at a walk and trot. The degree of difference between models was greatest between the JCS and each of the 2 remaining models (SEG, LIN).

Significant differences ($P < .05$) were found between all locations (normal, cranial, caudal, dorsal, ventral) for all dogs within each of the 3 models (LIN, SEG, JCS), at both a walk and trot. In all 3 models, the degree of difference compared with normal was greatest for the cranial and caudal markers and less for the dorsal and ventral markers at both the walk and trot (Fig 3).

**DISCUSSION**

Marker placement has been shown to influence kinematic analysis by altering the gait cycle waveform. We elected to evaluate a more heterogeneous population to more closely resemble what would be encountered in a clinical setting.

The GT was chosen to evaluate the effect of marker placement on kinematics in this study. This marker is a shared marker location for all models (LIN, SEG, JCS) in the study and provides for an accurate assessment between and within them. Additionally, the GT is a universally used marker location in veterinary hindlimb kinematics and has generous soft tissue coverage; therefore, allowing for the greatest chance of erroneous placement in the commonly used models of canine sagittal plane kinematics.

Analysis of the sagittal flexion and extension angles revealed differences between each marker location (normal, cranial, caudal, dorsal, and ventral). The different locations affected each model (LIN, SEG, JCS) similarly. Interestingly, the most significant degree of difference occurred in the cranial and caudal positions, while dorsal and ventral marker locations revealed a lesser degree of difference from the anatomically normal position (Figs 2 and 3). This indicates that whereas marker placement errors produce statistically significant differences, errors in the cranial and caudal directions produce a greater degree of difference than errors in the dorsal and ventral direction.

Waveform shapes were similar for all GT locations in all models (LIN, SEG, JCS). However, while the normal, dorsal, and ventral marker locations for all models (LIN, SEG, JCS) are tightly clustered along the y-axis, the cranial and caudal locations produced waveforms that were translated a greater distance away from normal (Fig 3). This is secondary to greater angular changes produced in the sagittal plane at the cranial and caudal locations. The cranial location produces a more obtuse stifle angle while the caudal location produces a more acute angle.

These data support previous reports of kinematic gait waveform translocation along the vertical axes secondary to marker placement. A normalization procedure has been shown to be effective at minimizing this shifting along the vertical axis. These reports implemented Fourier Analysis (FA) for comparative assessment. Analysis methodologies such as FA are affected by differences in waveform position and therefore may benefit from normalization. However, GIFA analysis is a methodology that compares differences between waveform shapes and the position on the y-axis is
unimportant. Interestingly, because GIFA is unaffected by waveform position these data also indicate that marker location affects the overall waveform shape. The clinical relevance of this has yet to be discerned.

These data elucidate the concern with reapplication of markers for intraday testing. Whereas visually similar waveform shapes were attained, variability was detected by GIFA. Furthermore, overall angular measurement can vary as is evident by the shifting along the vertical axis. This may prove most important when singular point data is utilized for analysis purposes. Therefore, great care should be taken to provide for secure attachment of all markers to prevent the need for reapplication during testing. Unfortunately, from this data we can only assert this concern regarding reapplication of the GT marker. The effect of multiple marker reapplication or variation was not evaluated in this study.

All efforts were made to limit experimental error. It is possible that some variations in marker placement may have occurred between dogs. In an attempt to decrease this, markers were applied by only 1 person throughout the study. While all markers were secured and no detachment occurred, any loss of markers requiring reattachment would have resulted in recollection of all trials for that dog on that day. Also, all dogs were gaited by the same handler. Additionally, the use of superficial skin markers for the evaluation of joint motion has been a source of controversy. The major concern with skin marker systems is primarily marker motion secondary to soft tissue movement artifact. However, in this study, with the exception of GT marker reassignment, all marker data was simultaneously collected and identical. Therefore, for comparison and analysis purposes any variability attributable to marker motion was uniform for all trials.

A limitation to this study was the evaluation of only 1 marker. The use of a solitary marker allowed for the evaluation of isolated directional motion of markers. However, no information regarding other markers can be gleaned from this data. It is expected that similar results would have been obtained from identical testing of the lateral malleolar marker, because of the mirror-image location. However the limited soft tissue coverage in that area makes errors of similar magnitude, especially in the cranial and caudal direction unattainable and unexpected in a clinical setting.

The hypotheses in this study were accepted. Simulated marker placement error resulted in detectable differences in gait data. Errors in the horizontal plane (cranial and caudal marker location) resulted in a greater degree of difference than errors in the vertical plane (dorsal and ventral marker location) in this stifle kinematic collection protocol. Additionally, errors in the horizontal plane produced the greatest shift along the y-axis as compared with the anatomically normal position.

REFERENCES