Many biomechanical studies on the canine hind limb have been reported in recent decades. These studies assist veterinarians in understanding biomechanical maneuvers and facilitate evaluation of treatment effects. Gait analysis is a modern, in vivo noninvasive approach to biomechanical analysis that has been applied to canine hind limb studies. However, compared with the extensive 3-D kinematic measurements in human subjects, most studies on canine hind limbs have focused on 2 dimensions. True 3-D gait analysis in veterinary medicine is limited and has been performed with the aid of invasive external fixators, stereoradiographic methods, or cadaveric models. Furthermore, most studies focus primarily on the stifle joint. To the authors’ knowledge, there are no reports of 3-D kinematic analysis of the entire hind limb.

The purpose of the study recorded here was to evaluate a 3-D kinematic model of the hind limb developed by use of a joint coordinate system in dogs. Furthermore, techniques and algorithms commonly used for biomechanical studies, such as marker drop-out and skin movement errors during motion, were integrated into the model for advanced biomechanical analysis.

Objective—To evaluate a 3-D kinematic model of the hind limb developed by use of a joint coordinate system in dogs.

Animals—6 clinically normal adult mixed-breed dogs.

Procedures—17 retroreflective markers were affixed to the skin on the right hind limb of each dog. Eight infrared cameras were arranged around a gait platform to record marker locations as dogs were recorded moving through the calibrated space 5 times during a walk and trot at velocities of 0.9 to 1.2 m/s and 1.7 to 2.1 m/s, respectively. Local and global coordinate systems were established, and a segmental rigid-body model of the canine hind limb was produced. Dynamic 3-D joint kinematic measurements were collected for the hip, stifle, and tarsal joints.

Results—Sagittal (flexion-extension), transverse (internal-external rotation), and frontal (abduction-adduction) plane kinematic measurements were acquired during each trial for the hip, stifle, and tarsal joints.

Conclusions and Clinical Relevance—The joint coordinate system allowed acquisition of 3-D kinematic measurements of the hip, stifle, and tarsal joints of the canine hind limb. Methods were described to model 3-D joint motion of the canine hind limb. (Am J Vet Res 2010;71:1118–1122)

Materials and Methods

Six adult mixed-breed dogs weighing 20 to 30 kg from an established research colony were evaluated in this study. All dogs had normal findings of bilateral hip and stifle joint radiography, force plate evaluation, CBC, serum biochemical analysis, and complete physical examinations prior to initiation of the study. The dogs were housed indoors in a climate-controlled environment and fed commercially available dog food ad libitum. Use of the dogs was approved by the University of Georgia Institutional Animal Care and Use Committee.

A 3-D testing space was established on a 13-m walkway. Right-handed orthogonal coordinate axes located in the center of the testing space were used to describe the testing space in 3 dimensions. Marker locations were captured at 200 Hz by 8 infrared cameras arranged around the gait platform. Digital videography of all trials was performed at 60 Hz. Marker trajectories were recorded by use of a motion analysis program, and data were smoothed by use of a generalized, cross-validated spline function. Data filtering was not performed, to minimize potential data loss. The canine hind limb model was developed on a computer software program.

Seventeen retroreflective markers (8 mm in diameter) were affixed with double-sided tape and cyano-
acrylate to the right hind limb (Figure 1; Appendix). Initially, a static or anatomic trial of each dog with all markers visible was performed. Four markers were then removed during subsequent dynamic trials. These detached markers were mathematically reconstructed from the static trial.39,40 Dogs were then recorded moving through the calibrated space 5 times each at a walk and trot. Dogs were walked across the testing space at a velocity of 0.9 to 1.2 m/s and trotted at a velocity of 1.7 to 2.1 m/s. Passes in which the dog visibly changed velocity, turned its head, broke stride, or made any aberrant motions were discarded.

A static trial of each dog was performed and recorded, and the marker relationships were analyzed to minimize the effect of skin movement and marker drop-out during dynamic motion.39,40 Detailed calculations have been described.39 An ith marker $\mathbf{m}_i$ on a rigid body segment translating from time 0 (static) to time t (dynamic) can be represented as follows:

$$\mathbf{m}_i = \mathbf{p}_0 + \mathbf{V} + R(\mathbf{p}_i - \mathbf{p}_0)$$

where $\mathbf{p}_0$ and $\mathbf{p}_i$ are position vectors of $\mathbf{m}_i$; $\mathbf{V}$ is the exact translation, and $R$ is the exact rotation matrix. Because it is impossible to determine an exact $\mathbf{V}$ and $R$ from skin markers, it is necessary to determine the approximated values $\hat{\mathbf{V}}$ and $\hat{R}$ from the minimum of the least squares function as follows:

$$f(\hat{\mathbf{V}}, \hat{R}) = \frac{1}{m} \sum_{i=1}^{m} [\mathbf{m}_i - \mathbf{p}_0 - \hat{\mathbf{V}}(\mathbf{p}_i - \mathbf{p}_0)]^T [\mathbf{m}_i - \mathbf{p}_0 - \hat{\mathbf{V}}(\mathbf{p}_i - \mathbf{p}_0)]$$

with the following constraint conditions: $\hat{R}^T \hat{R} = I$ and $\det(\hat{R}) = 1$. Thus, with the known $\mathbf{p}_0$ from static trials and the remaining from the dynamic trials, the $\hat{\mathbf{V}}$ and $\hat{R}$ can be determined.

The segmental embedded coordinate system (or LCS) for each canine hind limb segment was defined according to the International Society of Biomechanics recommendations23 and published reports.24 Marker locations on the body segments were chosen on the basis of 5 major considerations: visibility, repeatability, nonlinearity, skin movement, and reconstruction of clinical planes.24 In addition, each segment required a minimum of 3 markers for subsequent analysis.

For example, in calculating the right stifle joint angles, LCSs for the adjacent segments (femur and tibia) were defined by the affixed markers. In the right femur, the origin of the femoral LCS was set at the right greater trochanter (RGT; Appendix), and the unit vector of the z-axis of the LCS was defined by right lateral epicondyle (RLEP) and right medial epicondyle (RMEP) as follows:

$$\hat{z} = \frac{\mathbf{V}_{RLEP} - \mathbf{V}_{RMEP}}{||\mathbf{V}_{RLEP} - \mathbf{V}_{RMEP}||}$$

The unit vector of the x-axis was defined by the cross product of the vector from RLEP to RGT and the unit vector of z-axis as follows:

$$\hat{x} = \frac{(\mathbf{V}_{RGT} - \mathbf{V}_{RLEP}) \times \hat{z}}{||\mathbf{V}_{RGT} - \mathbf{V}_{RLEP}|| \times \hat{z}}$$

Consequently, the last unit vector of the y-axis was defined by the cross product of the 2-unit vector of x- and z-axes as follows:

$$\hat{y} = \hat{z} \times \hat{x}$$

In the tibia, the origin for the LCS was at the right proximal tibia crest (RPTC) and the axes of the LCS were defined similarly as the femoral LCS in that the unit vector of z-axis was defined by right lateral malleolus (RLMA) and right medial malleolus (RMMA) as follows:

$$\hat{z} = \frac{\mathbf{V}_{RLMA} - \mathbf{V}_{RMMA}}{||\mathbf{V}_{RLMA} - \mathbf{V}_{RMMA}||}$$

The unit vector of the x-axis was defined as follows:

$$\hat{x} = \frac{(\mathbf{V}_{RPTC} - \mathbf{V}_{RDTC}) \times \hat{z}}{||\mathbf{V}_{RPTC} - \mathbf{V}_{RDTC}|| \times \hat{z}}$$

where RDTC is the right distal tibial crest. The unit vector of the y-axis was defined by the cross product of

Figure 1—Illustration of the LCS (embedded on the segments) and global coordinate system (x, y, and z) of a canine kinematic hind limb model.
Figure 2—Mean (solid lines) and 95% confidence intervals (dashed lines) for joint angles in dogs in a study of sagittal (flexion-extension), transverse (internal-external rotation), and frontal (abduction-adduction) plane kinematics during movement of the distal segment relative to the proximal segment while walking or trotting. A—Values obtained during walking. B—Values obtained during trotting.
the 2-unit vector of x- and z-axes the same as for the femur.

The LCSs for the present canine hind limb model were determined (Figure 1). For the pelvis, the LCS was defined by right ilial wing, left ilial wing, right ischial tuberosity, and left ischial tuberosity markers and the origin was at the right ilial wing for the right limb and at the left ilial wing for the left limb, if applying the model to the left hind limb. For the foot, the LCS was defined by right caudalateral calcaneus, right fifth metatarsophalangeal joint, and right second metatarsophalangeal joint markers and the origin was at the right caudalateral calcaneus.

The 3-D hip, stifle, and tarsal joint angles for the canine hind limb were calculated as documented and described joint motion as movement of the distal segment relative to the proximal segment. Three non-orthogonal unit vectors of these axes described joint motion. The first vector defined flexion and extension around a fixed axis (z-axis) on the proximal segment (ie, femur at the stifle joint). The second vector defined internal and external rotation around a fixed axis (y-axis) on the distal segment (ie, tibia at the stifle joint). The third vector defined abduction and adduction as a floating axis, perpendicular to the described fixed bone axes. The gait cycle for both a walk and trot was determined to be initiated on the first foot strike and terminated on the second foot strike of the right hind limb. This was established by identifying the lowest vertical point of the right fifth metatarsophalangeal joint marker trajectory and establishing that as the initiation and subsequent termination of the gait cycle. Additionally, the stance phase was defined temporally as the first foot strike to toe-off and the swing phase as toe-off to the second foot strike. The demarcation between stance and swing phases was determined individually for each trial from the synchronized digital video recording. The sagittal plane joint angles were converted to a more traditional expression (over 100°) for comparison.

**Results**

Sagittal (flexion-extension), transverse (internal-external rotation), and frontal (abduction-adduction) plane kinematic measurements during movement of the distal segment relative to the proximal segment for all 3 joints (hip, stifle, and tarsal) were made during each dynamic gait cycle for the walk and trot. These waveforms were compiled and graphically represented as mean angles with 95% confidence intervals (Figure 2).

**Discussion**

A 3-D kinematic hind limb model was established in the present study. Techniques and algorithms developed in human motion analysis were successfully integrated and applied to canine kinematic analysis. The calculated joint angles were consistent with published studies. With the use of this integrated model, a 3-D canine hind limb biomechanical study can be conducted and may provide clinically relevant data and a greater understanding of specific biomechanical maneuvers, the characteristics of neuromusculoskeletal deficits, and the effect of surgical implants on musculoskeletal biomechanics. Additionally, these data may aid in the design and management of rehabilitation programs and provide objective outcome measurements for various therapeutic modalities.

Previous studies have used linear-link models of the canine hind limb to define joint motion in the sagittal plane. These models provide accurate and repeatable information regarding uniplanar motion; however, they are limited in their ability to assess true 3-D joint motion. The method described here records 3-D joint motion by use of 6 independent coordinates, or 6 degrees of freedom. Thus, the benefit of this segmental rigid-body model is that it provides an anatomically accurate and clinically relevant 3-D description of joint motion with 6 degrees of freedom.

The current canine hind limb model uses a minimum of 3 affixed reflective markers on each body segment during dynamic gait acquisition. An important aspect of a passive-marker–based kinematic study of the musculoskeletal system is the determination of motion for each body segment from the measured marker data. It is usually assumed that each segment is a rigid body and there is no relative movement between the affixed markers and the body segment. However, in vivo measurements may differ because of skin movement artifacts and soft tissue deformities.

One unique complication with 3-D passive-marker–based motion measurements in veterinary medicine is the visibility of medial markers during quadrupedal motion. During locomotion, the trunk may partially or completely conceal the medial markers. This was addressed with mathematical reconstruction from an initial static trial. Additionally, an overabundance of hair on animals may cause more relative movement between markers and the underlying bone; therefore, an increase in skin movement artifact may be present, compared with human subjects. Clipping the hair prior to marker placement may minimize the effect on marker motion. However, further research is warranted to assess the extent to which clipping influences skin movement artifact. In the present study, marker visibility and skin movement were addressed by use of an unweighted least squares method. In future studies, an advanced algorithm, such as an optimization method to minimize skin movement errors, may be considered to improve the accuracy of the model.

**References**


**Appendix**

Marker locations for kinematic modeling of the right hind limb of the dog.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Marker label</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>RIMG*</td>
<td>Right ilial wing</td>
</tr>
<tr>
<td></td>
<td>RITB</td>
<td>Right ischial tuberosity</td>
</tr>
<tr>
<td></td>
<td>LWBD</td>
<td>Left ilial wing</td>
</tr>
<tr>
<td></td>
<td>LITB</td>
<td>Left ischial tuberosity</td>
</tr>
<tr>
<td>Femur</td>
<td>RGTR*</td>
<td>Right greater trochanter</td>
</tr>
<tr>
<td></td>
<td>RLEP</td>
<td>Right lateral epicondyle</td>
</tr>
<tr>
<td></td>
<td>RMEPT</td>
<td>Right medial epicondyle</td>
</tr>
<tr>
<td></td>
<td>RDQA</td>
<td>Right quadriceps</td>
</tr>
<tr>
<td>Tibia</td>
<td>RFH</td>
<td>Right fibular head</td>
</tr>
<tr>
<td></td>
<td>RLMA</td>
<td>Right lateral malleolus</td>
</tr>
<tr>
<td></td>
<td>RGAS</td>
<td>Right gastrocnemius</td>
</tr>
<tr>
<td></td>
<td>RPTC†</td>
<td>Right proximal tibial crest</td>
</tr>
<tr>
<td></td>
<td>RDTC†</td>
<td>Right distal tibial crest</td>
</tr>
<tr>
<td></td>
<td>RMMA†</td>
<td>Right malleolus</td>
</tr>
<tr>
<td>Foot</td>
<td>RHEE*</td>
<td>Right caudolateral calcaneus joint</td>
</tr>
<tr>
<td></td>
<td>RPM5</td>
<td>Right fifth metatarsophalangeal joint</td>
</tr>
<tr>
<td></td>
<td>RMP2</td>
<td>Right second metatarsophalangeal joint</td>
</tr>
</tbody>
</table>

*Origin of the LCS for specific segment. †Markers removed during acquisition of dynamic trials.