Comparison of two methods for analyzing kinetic gait data in dogs

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Objective—To compare results of single-point kinetic gait analysis (peak and impulse) with those of complete gait waveform analysis.

Animals—15 healthy adult mixed-breed dogs.

Procedures—Dogs were trotted across 2 force platforms (velocity, 1.7 to 2.1 m/s; acceleration and deceleration, 0.5 m/s²). Five valid trials were recorded on each testing day. Testing days 1 and 2 were separated by 1 week, as were days 3 and 4. Testing days 1 and 2 were separated from days 3 and 4 by 1 year. A paired t test was performed to evaluate interday and interyear differences for vertical and craniocaudal propulsion peak forces and impulses. Vertical and craniocaudal propulsion force-time waveforms were similarly compared by use of generalized indicator function analysis (GIFA).

Results—Vertical and craniocaudal propulsion peak forces and impulses did not differ significantly between days 1 and 2 or days 3 and 4. When data were compared between years, no significant differences were found for vertical impulse and craniocaudal propulsion peak force and impulse, but differences were detected for vertical peak force. The GIFA of the vertical and craniocaudal force-time waveforms identified significant interday and interyear differences. These results were identical for both hind limbs.

Conclusions and Clinical Relevance—Findings indicated that when comparing kinetic data over time, additional insight may be gleaned from GIFA of the complete waveform, particularly when subtle waveform differences are present. (Am J Vet Res 2012;73:189–193)
surement, with $\alpha$ (type I error) set at 0.05 and $\beta$ (type II error) set at 0.20. Craniocaudal propulsion force was identified as the variable for which comparisons would require the largest sample size ($n = 14$).

Each dog underwent complete physical and orthopedic examinations, hematologic and serum biochemical analyses, and bilateral hip and stifle joint radiographic evaluation. These evaluations were performed again the following year when measurements were repeated. All dogs were housed in a climate-controlled indoor animal facility and were fed a measured quantity of a commercially available diet. The study protocol was approved by the University of Georgia Institutional Animal Care and Use Committee.

Study design—Data were collected by use of 2 inline force plates mounted in succession at the center of a 12-m platform. Each dog was trotted across the platform by a handler at a maintained velocity between 1.7 and 2.1 m/s with an acceleration and deceleration of 0.5 m/s². Ground reaction force data were collected with the aid of a dedicated computer and software program, as described elsewhere. A valid trial was defined as a forefoot strike on the first force plate, with the ipsilateral hind foot striking the same force plate a short period afterward and the contralateral feet striking the second force plate in the same manner with no extraneous movements. Five valid trials were recorded for each dog on each testing day.

Data collection—Testing occurred on 4 days. Testing days 1 and 2 were spaced 1 week apart, as were testing days 3 and 4. Days 3 and 4 were separated from days 1 and 2 by 1 year. Body weights were recorded prior to each testing session. The hind limb GRF data collected on each testing day were normalized to each dog's body weight and were expressed as the percentage of body weight. The peak vertical force, vertical impulse, peak craniocaudal propulsion force, and craniocaudal propulsion impulse as well as the vertical and craniocaudal force-time waveforms were obtained for the left and right hind limbs.

Statistical analysis—For all testing days, the means of the point data and waveforms for each hind limb from the 5 valid trials were calculated. Means of the hind limb GRF data were compared between days (day 1 vs day 2 and day 3 vs day 4; interday) and the 2 years (interyear) by use of 2 analysis methods. The collected vertical and craniocaudal propulsion force data for both hind limbs were separately analyzed for each method. First, a traditional inferential statistical method was used. A paired $t$ test was performed to evaluate interday and interyear differences in vertical and craniocaudal propulsion peak forces and impulses. All hypothesis tests were 2-sided, and significance was set at a value of $P < 0.05$.

The vertical and craniocaudal force-time waveforms were similarly compared with GIFA, as described elsewhere. The GIFA method produces a multidimensional vector representing the most significant difference between the groups being compared. For illustrative purposes, this vector is depicted on a graph as a waveform corresponding to the temporal differences between force-time waveforms. Changes in amplitude from the baseline value (0) represent the degree of difference detected between groups. The establishing vector is unitless; therefore, the direction of waveform movement along the vertical axis, away from baseline, is arbitrary.

Plots of GIFA differences in vector covariance were constructed to display the change between force-time waveforms being compared. In such plots, each circle represents the results of an individual force-platform trial. Small movements along the vertical axes within a group indicate slight variation between individual trials within a group. Differences in vertical axis position between groups indicate significant differences between groups compared. The distance between the groups along the vertical axis
denotes the degree of difference between them. The actual position of the groups along the vertical axis represents a relative quantity.

Results

Dogs—No evidence of orthopedic abnormalities or other health concerns were detected prior to the study for both years in which it was conducted. All 15 dogs completed the study. The overall waveforms for the vertical and craniocaudal forces were similar (Figure 1).

Traditional inferential statistical analysis—No significant interday differences were detected for vertical and craniocaudal propulsion peak forces and impulses. Interyear differences were lacking for vertical impulse and craniocaudal propulsion peak force and impulse; however, significant \((P < 0.05)\) interyear differences were evident for vertical peak force. These results were identical for the left and right hind limbs (Table 1), and no difference between limbs was detected.

Waveform analysis—Generalized indicator function analysis of the vertical and craniocaudal time-force waveforms revealed significant interday and interyear differences. These results were identical for the left and right hind limbs (Figure 2), and again no difference between limbs was detected.

Table 1—Mean ± SD vertical and craniocaudal propulsion force point data for both the right and left hind limbs of 15 orthopedically normal dogs at a trot.

<table>
<thead>
<tr>
<th>Time</th>
<th>Vertical force</th>
<th>Craniocaudal propulsion force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right peak (%BW)</td>
<td>Right impulse (%BW) X s</td>
</tr>
<tr>
<td>Day 1</td>
<td>74.2 ± 4.4</td>
<td>9.4 ± 0.7</td>
</tr>
<tr>
<td>Day 2</td>
<td>73.8 ± 4.9</td>
<td>9.4 ± 0.6</td>
</tr>
<tr>
<td>Day 3</td>
<td>76.4 ± 5.4</td>
<td>9.4 ± 0.6</td>
</tr>
<tr>
<td>Day 4</td>
<td>77.4 ± 4.8</td>
<td>9.3 ± 0.6</td>
</tr>
<tr>
<td>Year 1</td>
<td>74.0 ± 4.4</td>
<td>9.4 ± 0.7</td>
</tr>
<tr>
<td>Year 2</td>
<td>76.9 ± 5.0*</td>
<td>9.3 ± 0.6</td>
</tr>
</tbody>
</table>

*Value differs significantly \((P < 0.05)\) from that for year 1.

%BW = Percentage of body weight.

Figure 2—Mean (solid line) and 95% confidence interval (dashed lines) kinetic force-time waveforms of the dogs in Figure 1 at a trot on evaluation days 1 and 2 (A, D, and G) and years 1 and 2 (remaining panels). Significant \((P < 0.05)\) differences were evident in each interday and interyear comparison of vertical (A and B) and craniocaudal (C) force-time waveforms. The GIFA produces 2 graphic plots to represent significant differences in waveform data between compared groups. The temporal differences between waveforms are indicated by the GIFA difference vector plots (D, E, and F). The GIFA difference vector covariance plot (G, H, and I) depicts a significant change between compared force-time waveforms. Each circle represents an individual force-platform trial. Differences in vertical axes position between groups indicate significant differences between compared groups. The distance between the groups along the vertical axes denotes the degree of difference between them.
Discussion

Kinetic analysis is an established method in veterinary medicine for assessing lameness. Historically, GRF evaluation has been performed by comparing peak force and impulse values. However, these are static points within a dynamic cycle and thus may provide an incomplete description of the entire stance phase. The uncommon nature of analyzing data in an entire force-time waveform is due in part to the data's challenging high dimensionality, temporal dependence, high variability, and correlated disposition. Resolving these challenging characteristics of kinetic data through complete waveform analysis can complement evaluations of singular GRF point data.

Proper choice of analysis method is paramount for accurate interpretation of gait data. Application of the more traditional inferential statistical method along with GIFA may allow for a complete description of the overall gait GRF in numeric terms. One study in which Fourier analysis was used revealed subtle differences between visibly normal and abnormal vertical waveforms that were not recognized through conventional evaluation, suggesting vertical force point data alone are not capable of recognizing all subtle gait pattern changes. Although Fourier analysis can be used to evaluate whether there are differences between waveforms, it cannot be used to determine at which point along the waveforms these differences occur. The same conclusions can be drawn for principal component analysis. However, GIFA can be used to identify waveform differences at a specific time point.

In the present study, GIFA was able to detect differences between complete gait waveforms when no differentiation was detected by standard evaluation of single peak and impulse data. The interday standard analysis for both years found no differences in peak or impulse point data. However, GIFA was able to detect differences between similar vertical and craniocaudal force waveforms. These temporal differences are graphically represented by the difference vector plot. The differences between visually similar vertical and craniocaudal force-time waveforms did not appear to have affected the singular peak and impulse data between testing days, indicating that multiple day evaluations in which similar variables are used may yield consistent singular peak forces and impulse data, with subtle differences detectable with complete waveform analysis.

Initiation of stance resulted in the greatest difference between complete waveforms in our study. This period corresponds to the loading and braking events of the vertical and craniocaudal GRFs (Figure 2). When ground contact occurs, variations in the response to the external environment by the coordinated musculoskeletal and nervous systems may contribute to these differences between the similar waveforms, suggesting the impossibility of perfect repetitions. With environmental differences known to cause variability within the same subject at a given time, an adequate number of repetitive trials are obtained to represent the general GRF's accurately.

Trial repetition is an inherent source of variation during collection of GRF data. The variation found in repetitive trials can be influenced by subject habituation, such as a dog's familiarity with the gait laboratory environment and the procedure used to collect GRF data. Measurable effects of habituation on vertical GRF may correspond to an increase in peak vertical force. The dogs in the present study underwent additional kinetic gait testing during the interyear period. Interestingly, the conventional interyear comparison identified differences in the peak vertical force data for both hind limbs, with larger values collected during the second year in relation to the first year. Similarly, complete waveform analysis with GIFA identified interyear differences for the vertical force waveforms. These findings may suggest some habituation of dogs to the testing conditions between testing times.

Historically, vertical peak force and impulse point data have been reliable objective measures. When significant differences have been detected, measurable changes within these data have been correlated with the differences in stance time. Perhaps because of the close succession of the interday comparisons in our study, similar stance times existed, contributing to the lack of differences found between vertical peak forces and impulses. The prolonged nature of the interyear comparison may have led to the interyear differences observed. The decrease in stance time corresponded to peak forces being increased, which may have been observed when year 2 data were compared with year 1 data. The decrease in stance time is an effect of habituation, which may further support the effect of habituation between testing years.

Efforts were made to alleviate sources of experimental error in the study reported here. The variation introduced by multiple dog handlers was limited given that only 2 handlers led dogs while gait data were obtained. It can be argued that variance of GRF singular point data attributed to handlers was trivial, compared with the effect of trial repetitions in dogs. Minor differences in trot velocity existed for individual dogs. Use of a narrow control range for velocity allowed for dogs to achieve a comfortable, self-selected trot and consequently ensured that individually representative trot GRF data were collected. When a dog trots at a self-selected velocity, it reduces its energy cost, whereas when forced to trot at a fixed velocity, a dog increases its energy cost and reduces efficiency. It is possible that within the year-long study period, a change in gait mechanics could produce an adaptive response, changing the results. Nevertheless, such a transformation could happen within a shorter duration as well.

When kinetic data are compared, additional insight may be gleaned from the analysis of the complete waveform, particularly when subtle differences are present. In the present study, no intrayear differences were evident when GRF singular point data were compared. However, interyear comparisons yielded significant differences. The ability to incorporate simultaneous kinematic and kinetic waveform analysis could prove beneficial in clarifying the reason for these differences. Differences in joint angles of the hip, stifle, and tarsus throughout the swing phase into stance phase may contribute to the observed differences in gait waveform. The clinical importance of these differences has yet to be elucidated. Analysis of both standard GRF singular
point data and complete waveforms may be a useful combination for comparing the gaits of healthy dogs and lame dogs or for establishing treatment effects in therapeutic trials.

References