Comparison of Simultaneously Collected Kinetic Data with Force Plates and a Pressure Walkway

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Abstract

Objective This article compares simultaneously collected kinetic data (percent limb distribution and limb symmetry) with force plates (FP) and a pressure walkway.
Animals This study included 18 healthy client-owned adult dogs.
Methods Vertical ground reaction force and pressure data were collected during two sessions 1 week apart (days 1 and 7) using both FP and pressure mat systems. Vertical ground reaction forces and vertical pressure data were each collected alone as well as simultaneously. A mixed effects model was used to test for differences in force, force percent data and symmetry indices (SI) that were calculated for the thoracic and pelvic limb pairs, between collection systems. A Pearson's correlation was used to test for correlations between force, force percentage and SI.
Results There was no difference in peak vertical force (PVF) or total pressure index (TPI) data collected alone or when collected with pressure mat overlay the FP. Small but significant differences were found in percent limb distribution between PVF% and TPI%. Significant differences were found in the calculated SI for forelimbs and hindlimbs. Correlations between the PVF% and TPI% distribution were significant in both the fore- and hindlimbs. While there was a significant correlation between the forelimb SI, there was no significant correlation between the SI in the hindlimbs.
Clinical Significance The method of calculating PVF and TPI percentages allowed for comparison between the collection methods. Significant differences were noted in the calculated SI between the collection methods and direct comparisons is not advisable.

Keywords
- ► canine gait analysis
- ► ground reaction force in dogs
- ► instrumentation testing
- ► kinetics

Introduction

Canine gait analysis is an important tool for objectively evaluating normal and abnormal gaits. While there are many methods for collecting the temporal and spatial parameters of gait analysis, currently force plates (FP) are considered the gold standard for measuring ground reaction forces (GRF) and related indices generated from those forces.[1–4] The data collected from FP have proven to be an effective method for assessing lameness, as well as the success of medical or surgical interventions, or a combination, in dogs with musculoskeletal pathology.[5–13] However, there are limitations to the use of FP.[14] A major drawback in the use of FP is that they cannot distinguish between several feet simultaneously in contact with the plate. Data collection can be time-consuming, or multiple consecutive FP are needed to gather data of all limbs. Additional kinetic data collection techniques have been reported, including pressure mats (PM).[15–19] Pressure mats may provide a solution to distinguishing between several feet on the ground as they contain a dense array of pressure sensors with a high measuring frequency, enabling them to distinguish simultaneous impacts of different limbs. This equipment

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allows measuring kinetic as well as spatiotemporal data. Some PM systems can provide GRF similar to FP, while other PM systems only measure pressure changes.[17]

Currently, there is very little data comparing FP and the PM systems.[17] Considering that PM systems may provide important data in the evaluation of lameness in dogs, it is imperative that the relationships between the FP and PM be identified. The objective of this study was to compare the distribution of force or pressure between limbs during a given gait cycle of healthy dogs at a trot, as well as symmetry of measured forces or pressures between the limb pairs. The first hypothesis being tested was that there would be no difference between GRF measured by FP (peak vertical force represented as a percentage of total limb distribution [PVF%]) as compared with vertical pressure data collected from the PM (total pressure index represented as a percentage of total limb distribution [TPI%]) for the fore- and hindlimbs in healthy dogs at a trot. The second hypothesis being tested was that there would be no difference in symmetry indices (SI) between the two methods for the fore- and hindlimbs in healthy dogs at a trot.

Materials and Methods

Animals

Eighteen healthy, adult, non-chondrodystrophic dogs (hound and mixes 25 to 35 kg) were used. Each dog underwent complete physical examination as well as radiographic evaluation of the stifle and hip joints, bilaterally. Sample size calculations were based upon preliminary gait data from six dogs. Data from a pilot study in dogs revealed a 4 to 5% difference between kinetic data collected by the two systems evaluated in this study. Given a standard deviation of GRF/pressure collection of 1% with either method alone, power analysis suggested that 14 dogs would be sufficient. The study was approved by the College of Veterinary Medicine, Clinical Research Committee. Owners of each dog were provided a written consent form prior to inclusion of their dog and each owner signed it prior to entrance into the study.

Data Collection

Vertical GRF data were collected for all four limbs by means of two in-line FPs (Model OR-6–6, Advanced Mechanical Technology Inc., Newton, Massachusetts, United States) and at a frequency of 1000 Hz.[20] Vertical pressure data, or TPI, were collected with a 6.10 $\times$ 0.61-m portable PM system with 23,040 encapsulated sensors and at a frequency of 180 Hz.[18] For all data collection (FP and PM), velocity and acceleration were maintained between 1.7 and 2.1 m/s, and an acceleration of -0.5 to 0.5 m/s^2. This was measured using a dedicated computer and software program (Acquire, Version 7.3, Sharon Software Inc., East Lansing, Michigan, United States) and a series of five photocells placed 0.5 m apart and 0.5 m above the gait platform. Data were collected with the following methods: (a) (FP alone): Vertical GRF data were collected with the FP alone; (b) (PM alone): Vertical pressure (TPI) was collected with PM alone; (c) (Simultaneous FP + PM): A PM-onlay method was utilized to simultaneously collect both FP and PM data. This was achieved by placement of the PM directly over the FPs—with the FPs centred under the PM. These methods provided four unique sets of data: (1) Vertical GRF data collected with FP-alone, (2) vertical GRF data collected with PM-onlay method, (3) vertical pressure (TPI) data collected with PM alone, and (4) vertical pressure (TPI) collected with PM-onlay method. Data collected with [FP alone] (a) and (PM alone) (b) were used to validate the use of the (Simultaneous FP + PM) (c) for the collection of simultaneous FP and PM data (►**Tables 1** and **2**). Only data collected with the [Simultaneous FP + PM] method (c) were utilized for FP and PM comparisons in this study (►**Tables 3** and **4**). The use of simultaneously collected FP and PM data can aid in the reduction of common sources of variability encountered during kinetic data collection, such as trial velocity and acceleration. Thus, with simultaneous collection, identically matched data (velocity, acceleration etc.) from each system were collected.

Table 1 Peak vertical force measurements (% body weight) collected with the force plates from the fore- and hindlimb with or without the pressure mat overlaying the force plates

Limb	Method	PVF (% body weight)
Fore	FP alone	111.35 ± 10.70
	FP + PM	110.42 ± 10.55
Hind	FP alone	73.25 ± 8.03
	FP + PM	72.86 ± 7.53

Abbreviations: FP, force plates; PM, pressure mat; PVF; peak vertical force.

Table 2 Total pressure index measurements collected with the pressure mat on the ground and then collected when the mat was overlying the force plates

Limb	Method	TPI
Fore	PM alone	49.64 ± 11.01
	FP + PM	50.02 ± 11.14
Hind	PM alone	34.18 ± 8.49
	FP + PM	34.38 ± 8.15

Abbreviations: FP, force plates; PM, pressure mat; TPI; total pressure index.

Table 3 Calculated percent limb distribution PVF % and TPI% for each simultaneously collected gait cycle

Limb	Method	Mean	*p*-Value
Front	PVF %	0.300 ± 0.016[a]	0.007
	TPI%	0.295 ± 0.016	
Hind	PVF%	0.198 ± 0.012	0.002
	TPI%	0.203 ± 0.12[a]	

Abbreviations: PVF, peak vertical force; TPI, total pressure index.
[a]Indicates the measurement that is significantly increased for the fore- and hindlimb.

Table 4 Calculated symmetry indices (PVF SI and TPI SI) for each simultaneously collected gait cycle

Limb	Method	Mean	*p*-Value
Front	PVF SI	5.08 ± 2.38	< 0.0001
	TPI SI	7.09 ± 3.28[a]	
Hind	PVF SI	5.96 ± 2.25	0.01
	TPI SI	8.17 ± 2.88[a]	

Abbreviations: PVF, peak vertical force; SI, symmetry indices; TPI, total pressure index.
[a]Indicates the measurement that is significantly increased for the fore- and hindlimb.

In this study, a valid FP trial was defined as a forefoot strike on the first FP with an ipsilateral hind foot striking the same plate afterward and the contralateral feet striking the second FP in the same manner. The GRF data (PVF) were collected in newtons and normalized to the individual body weight. For purposes of comparing to the data collected by the PM, the PVF was then expressed as its percentage, where % = (single limb)/(sum of all combined limbs for a single trial). The vertical GRF data were collected for all four limbs with the aid of a dedicated computer and software program (Acquire, Version 7.3, Sharon Software Inc, East Lansing, Michigan, United States).[20] This was consistent for both the FP alone and the FP with PM onlay. A valid PM trial occurred when the designated software (Gait4Dog, Version 4.9Wq, CIR Systems Inc., Havertown, Pennsylvania, United States) was able to process the output data from the current trial and when a valid trial from the FP was collected at the same time.[18] Vertical pressure data were expressed as its percentage in the same way as PVF to allow comparison between the two values. Ten trials were used for analysis of all datasets.

Data Analysis

Peak vertical force obtained from the FP system with and without PM onlay was used to calculate the percentage of total PVF placed on the ground during each gait cycle.[21] Total pressure index[18] obtained from the PM system was used to calculate the percentage of overall TPI (TPI%; the sum of peak pressure values recorded from each activated sensor by a paw during mat contact/total sum of peak pressure values for all feet $\times$ 100) placed on the ground during each gait cycle.[22] Symmetry indices were calculated for the thoracic and pelvic limb pairs with the PVF[23,24] and TPI[18,22] data from each limb of each gait cycle, using the following: $SI = [(Xs - Xi)] / [1/2(Xs + Xi)] \times 100$, where Xs = limb measuring the superior or higher value of PVF or TPI between the two limbs of an ipsilateral limb pair and Xi = limb measuring the inferior or lower value of PVF or TPI between the two limbs of an ipsilateral limb pair.

Statistical Analysis

All analyses were performed for forelimbs and hindlimbs separately. A mixed effects model was used to compare force, force percentage data and SI between methods to include both correlation between measurements on the same limb within the same dog and between limbs within the same dog. The full mixed effects model included fixed factors for method, side (left or right) and a method by side interaction term and a random intercept for each dog. Both method and side were repeated within dog. Multiple comparisons were adjusted for using Tukey's test. A mixed effects model (or repeated measures analysis) was also used to compare SI data. The full mixed effects model included a fixed factor for method and a random intercept for each dog. A Lin's concordance correlation coefficient (CCC) was calculated to test data collected (PVF and TPI) during a given trial. Pearson correlation was used to test for correlations between TPI and PVF in terms of percent per distribution of force and SI. All hypothesis tests were two-sided and the significance level was set at $p \leq 0.05$. All analyses (except the Lin's CCC) were performed using SAS Version 9.3 (Cary, North Carolina, United States). The Lin's CCC was performed using the epiR (Version 0.9.69, 2015).

Results

There were no differences found in PVF data for either the fore- or hindlimb when collected with or without the PM overlaying the FP (►**Table 1**). Additionally, there were no differences in TPI data collected overlaying the FP or on solid flooring (►**Table 2**). Thus, using the overlay technique to compare simultaneous data collections was justified. Comparing the calculated TPI and PVF in terms of percent per distribution of force in all four limbs during a single gait cycle did produce small significant differences (►**Table 3**). There were significant differences in the calculated SI for forelimbs and hindlimbs (►**Table 4**). The CCC was found to be 0.88 (95% confidence interval: 0.87–0.89). Additionally, correlations between the PVF and TPI as percent distribution in all four limbs were moderate with $r = 0.73$ ($p < 0.001$) for the forelimb data and $r = 0.78$ ($p < 0.001$) for the hindlimb data. While the calculated SI correlations showed a moderate association between the forelimb SI with $r = 0.68$ ($p = 0.0018$) but no significant correlation between the SI in the hindlimb.

Discussion

Calculating TPI and PVF in terms of percent per distribution of force, as well as SI, allowed for direct comparisons between the two collection methods of kinetic data in the dog. Furthermore, the data collected by the systems separately and with the PM on top of the FP were not significantly different. Thus, we were able to use data collected simultaneously to compare with each other. The first hypothesis that there would be no difference in total limb distribution collected by the FP (PVF%) and by the PM (TPI%) was rejected. There was a small but significant difference between the two measurement systems. While statistically different, the amount of difference was extremely small. A small difference (variation) in trotting velocity between collection methods may have contributed to differences in this study. The ability to detect a significant difference at such small levels of difference shows the repeatability that objective kinetic gait data collection techniques can produce in healthy dogs at a trot. These small differences are likely not clinically significant in healthy animals, but lame dogs have not been evaluated and therefore the same assumptions may not be true.

The second hypothesis that there were no differences in SI between the two methods in healthy dogs at a trot was also rejected. Differences were found and the differences in SI in both the fore- and hindlimbs were more pronounced than the percent total limb distribution data. Given the common use of SI data collected from both types of system, it is clear from the current data that those results cannot be directly compared.[13,23,25–30] The present data show much smaller SI and standard deviations when collecting with two FP versus the PM. These FP data are similar to a previous study.[31] Current data found larger SI and associated standard deviations than previously reported with the same PM system. However, in that earlier study the population was limited to only one breed (Labrador Retrievers).[18] The current population was heterogeneous and thus may explain the differences. Furthermore, it has been noted in the earlier study that the standard deviation for the SI calculated from TPI was greater than many of the other temporal–spatial gait variables.[18] It speculated that this may be due to weight and conformation differences in the tested dogs, as bigger dogs with bigger paws may activate more sensors in the PM. All of these variables (larger SI and associated standard deviations) must be considered when using SI measurements from PM in future study design and data analysis. The amount of 'normal' variation must be accounted for in the powering of future studies that may look to compare pre- and post-treatment SI data as an outcome measurement. As an example, a recent study used cut-off values (average PVF SI + two times the standard deviation) to distinguish between normal hindlimbs and abnormal hindlimbs with a PM system.[32] It is also interesting to note that different PM systems produce different SI data for healthy dogs. The PM system used in the current study of a heterogeneous population had larger SI and wider standard deviations than a different PM system also examining a heterogeneous population.[26] A final consideration is that the methods for GRF data collection using modern FP systems have been studied and refined extensively for almost 50 years, yet the same rigor has not been applied to collection methods with PM systems. Thus, the lack of consistency in PM collection methods may play a role in the differing SI data reported throughout the literature. The major limitation to this study is the small population of dogs used for comparison. Additionally, this was a heterogeneous population; certainly not all conformations, body weights or breeds were represented.

Given the data from the current study and earlier works, it is paramount that investigators understand that SI values are likely to be different between FP and PM systems. Additionally, results obtained from different PM systems may vary. Therefore, investigators need to account for these differences when planning studies. Although in the current study only small differences were detectable in total limb distribution collected by FP and PM, the clinical significance of these differences is unknown.[17]

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Conflict of Interest
None.

Author Contributions
Gabriella Sandberg and Steven Budsberg contributed to conception of study, study design, acquisition of data and data analysis and interpretation. Bryan Torres contributed to conception of study, study design and data analysis and interpretation. Amanda Berjeski contributed to study design, acquisition of data and data analysis and interpretation. All authors drafted, revised and approved the submitted manuscript.

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