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CUT-OFF VALUES FOR GAIT VARIABLES TO DETECT FORELIMB LAMENESS IN INDIVIDUAL DOGS

For the degree of Master of Science

Is approved by the final examining committee:

Gert J. Breur

Nicolaas E. Lambrechts

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Approved by Major Professor(s): Gert J. Breur

Approved by: Stephen B. Adams 6/30/2014

Head of the Department Graduate Program Date

CUT-OFF VALUES FOR GAIT VARIABLES TO DETECT FORELIMB LAMENESS IN INDIVIDUAL DOGS

A Thesis
Submitted to the Faculty
of
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by
Jennifer G. Carr

In Partial Fulfillment of the
Requirements for the Degree
of
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This thesis is dedicated to all of my mentors in the Small Animal Surgery and Neurology Department with special thanks to Dr. Gert Breur.

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LIST OF ABBREVIATIONS

OGA = Observational Gait Analysis

IGA = Instrumented Gait Analysis

PVF = Peak Vertical Force

VI = Vertical Impulse

SI = Symmetry Index

CV = Coefficient of Variation

ROM = Range of Motion

ABSTRACT

Carr, Jennifer G. M.S., Purdue University, August 2014. Cut-off Values for Gait Variables to Detect Forelimb Lameness in Individual dogs. Major Professor: Gert Breur.

The objective of this study was to characterize kinetic and kinematic variables in dogs with forelimb lameness and determine lameness cut-off values of gait variables using ROC analysis with observational gait analysis (OGA) as reference. Twenty client-owned dogs with unilateral lameness were included. Dogs underwent orthopedic exam, including OGA, and instrumented gait analysis (IGA; kinetic and kinematic analysis). Kinetic variables with the highest accuracy were PVF and %WD with an area under the curve (AUC) of 0.73 and 0.92, respectively. Optimal cut-off value for PVF and %WD were ≤ 10.6 kgf (sensitivity 70% and specificity 75%) and ≤ 29.7% (sensitivity 90% and specificity 85%), respectively. Results of the ROC analysis indicate that KVs were most useful in determining lameness.

CHAPTER 1: INTRODUCTION

Lameness probably is the most common clinical manifestation of canine musculoskeletal conditions and therefore recognition of lameness is an essential part of the diagnostic process for canine orthopedic diseases.[1,2] Lameness may be defined as an abnormality of gait caused by nociceptive stimuli originating from the affected limb or restricted movement within the affected limb and is almost always caused by musculoskeletal pathology.[1,3] Lameness must be differentiated from abnormal gait caused by pathology of the neurological system.

Two major techniques have been employed to detect lameness in dogs: observational gait analysis (OGA) and instrumented gait analysis (IGA). Gait is most commonly evaluated by an observer (OGA). With OGA, lameness is described in terms of visual changes including: decreased loading of the affected limb and shifting of the load to the unaffected limbs, decreased length of the swing phase, decreased duration of the stance phase, and alterations in joint angle.[1,2] However, subtle visual changes are difficult to discern and it is not known how much deviation from normal is needed to denote lameness. In addition, OGA is susceptible to observer prejudice, for instance following surgery or treatment where an improved outcome is expected.[2] Unfortunately, it is almost impossible to completely eliminate this form of bias.[4] Several techniques have been employed to make observational gait analysis more objective, such as lameness scoring rubrics, the use of more than one observer, making videos for more than one observer to evaluate, and visual analog scales.[4-7] Regardless, observational gait analysis remains a subjective technique of evaluating gait.

Instrumented gait analysis (IGA) may be used as a way to quantify and objectively define lameness in dogs.[8,9] Because gait analysis equipment has become more easily available, the use of IGA as a way to systematically measure normal and abnormal gait patterns in dogs has gained popularity in the last decades.[3] With IGA, lameness mostly has been defined as a decrease of the peak vertical force (PVF) of the affected limb.[4,10] Derivatives of PVF also have been suggested as indicators of lameness: vertical impulse (VI), PVF normalized for body weight (%PVF), dynamic weight distribution (%WD), L-R symmetry indices (SI), rate of loading and unloading, and Fourier analysis.[10-12] However, just as with OGA, criteria that denote lameness have not been well defined. In most canine IGA studies, gait variables of a group of experimental dogs is compared with gait variables of a control group, carefully matched for body weight and breed.[11,13] A statistically significant difference between the two groups may then signify improvement or deterioration of gait, but not necessarily lameness. However, in a clinical setting, it is unpractical to determine lameness with group comparisons and the interest is in determining lameness in *individual* dogs. Several approaches to discriminate lame from non-lame *individual* dogs of different body weight, body size and body shape have been proposed, including normalization of gait variables (dynamic similarity), establishing cut-of values using receiver operating characteristics (ROC) analysis, and defining lameness using normal values of gait variables. However, as of yet, none of these approaches has resulted in robust criteria to detect lameness in dogs.

The purpose of the research in this thesis is to characterize kinetic and kinematic variables in dogs with forelimb lameness, and to compare the obtained variables to a set of established normal ranges.

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CHAPTER 2: REVIEW

Gait has been defined as a sequence of movements which propel an animal forward.[1] A full repetitive movement or gait cycle includes both a swing and stance phase of a particular body segment or body segments. In dogs, normal gait can be divided into symmetric and asymmetric gaits.[2,3] Normal symmetric gaits include the walk, trot, amble and pace. These are called symmetric because the movements of the left and right side of the animal are a temporo-spatial mirror of each other in terms of movement of joints and placement of limbs. However, even in normal dogs with a symmetric gait, there is usually mild asymmetry of forces, timing, and joint angles. [4-6] If, during a gait the movement of the right and left side of the body do not mirror each other, the gait is asymmetrical. An example of such is the gallop; limb movements of one side do not mirror the ones from the other side and the interval between foot falls is uneven.[1] A normal walk is a slow, symmetrical gait where at any time two, three (usually) or four (rarely) legs are on the ground.[3] In contrast, in a normal trot no more than two limbs are ever touching the ground at the same time.[3] Symmetrical gaits are ideal for detecting lameness because visible asymmetry of a symmetrical gait is seen as an indicator of lameness.[2,3,7,8,9] The walk and trot are the two most commonly used gaits when evaluating lameness, because in contrast to amble and pace, they are easy to elicit.[2]

Lameness has been defined as an interference of normal gait of an animal, usually involving the propulsion mechanism of one or more limbs.[3] Two methods for the evaluation of lameness have been described. The oldest and most commonly used method is observational gait analysis (OGA). More recently, instrumented gait analysis (IGA) has gained popularity as a method of trying to more objectively evaluate lameness. The purpose of this review is to outline these two types of gait analysis and identify their limitations.

Observational Gait Analysis is often considered the gold standard of gait analysis. In its basic form, it is easy to use and inexpensive. It does not take too much time to complete and does not require a large amount of space or equipment. However, the use of multiple observers and/or the use of recorded evaluations make OGA much more complex. Unfortunately OGA is subjective and inherently susceptible to observer bias.[10]

With OGA, gait is most commonly observed and assessed by a single observer with an assistant walking and trotting the dog.[3] This is done by observing the animal move both towards and away from the observer and from both sides of the animal.[3] The animal may also be walked in circles to stress different limbs or to rule out ataxia.[3] When the animal is moving away from the observer, it is evaluated for pelvic limb asymmetry, while when the dog is moving towards the observer, the focus is on thoracic limb asymmetry. Limb and joint motion is best evaluated from the side.[3] This is ideally done in an examination area long enough for the animal to maintain a steady velocity during walking or trotting, and wide enough for the observer to watch from different viewpoints. In some cases, the dog may be asked to walk up or down stairs, on inclines or on a treadmill to induce or accentuate lameness.[3] Lameness may be more exaggerated at a trot than at a walk, which has been confirmed with IGA.[3,8]

Lameness is often described in terms of visual changes of asymmetry related to forces, joint angles, and temporo-spatial gait characteristics. Even though many criteria for lameness have been reported, there is scant information on descriptions of deviations that denote normal from abnormal gait. For example, decreased loading of a limb is seen as a sign of lameness, but the extent of the decrease needed for it to be called lameness has not been defined. The exact extent to which visual changes must occur in order to call a gait “lame” is a significant source of variability in the evaluation and description of lameness.

Forelimb lameness can be characterized by an abbreviated length of time the affected leg is on the ground. To further decrease the loading of the affected limb, the dog with forelimb lameness typically also has a head “bob”, where the head is lifted when the affected leg contacts the ground. The hindlimbs may also be carried further under the body to receive weight that is shifted away from the front limbs[1]. Hindlimb lameness is also defined by a shortened stance phase duration. Dogs with unilateral hindlimb lameness may have a pelvic tilt away from the affected limb and pelvic oscillations during their gait. To transfer weight to the forelimbs and unload the affected hindlimb(s), a dog with hindlimb lameness also may extend and lower its head[1]. When the affected limb is placed on the ground, the dog may exaggerate the downward motion of the head and neck to lessen weight on the hindlimbs. Tail movement also has been used as an indicator of hindlimb lameness: rather than swinging the tail from side to side as in the normal dog, the lame dog may move its tail up and down with the up motion occurring when the injured extremity contacts the ground.[2] Joint angles can also be used to detect lameness, although much variability exists among and between breeds.[3] In the hindlimb, the most movement is generated at the hip joint. Very little movement takes place in the stifle joint until the end of the stance phase.[3] In the forelimb, most of the movement is between the shoulder blades until the end of the swing phase where the rest of the limb is extended.[3,11] Motion of the thoracic and pelvic joints can be accentuated while moving up stairs and ramps.[12-14] Again, even though many criteria for lameness have been reported and are being used, descriptions of deviations that denote normal from abnormal gait have not been reported.

Findings of OGA can be described qualitatively or semi-quantitatively. Traditionally, lameness has been described qualitatively using criteria described above. To make the evaluation less subjective, semi-quantitative methods like scoring rubrics that treat lameness as categorical data, and visual analog scales that consider them as continuous data have been proposed. Many scoring rubrics have been reported but all are subjective due to the poor definitions of the categories.[10,15,16] For instance, there is no true definition of a so-called moderate lameness. Visual analogue scales (VAS), where the observers grades the lameness with a score between 0 and 10 have been used as another way to improve the objectivity of observational lameness exams. In a study comparing numerical scoring and VAS for lameness in sheep, VAS scoring by veterinarians and veterinary students was found to correlate well with numerical scoring when the lameness was mild or severe, but not for moderate lameness.[15] In another study, a VAS questionnaire given to dog owners was found to be a repeatable and valid test when evaluating mild or moderate lameness.[17] Other reported approaches to make OGA less subjective include the use of multiple observers or by recording trials and subsequent evaluation of the video recordings obtained at one or more time points.[16,18] The purpose of both these methods is to increase the precision and accuracy of the observations by taking into account more than one observer's opinion. With multiple observers, the lameness scores are typically combined and an average score is given to each animal. Several studies have demonstrated that multiple observers, often after a training period, can obtain a high degree of inter-observer agreement as demonstrated by correlation or the so-called kappa statistic.[15,17] However, we could not find studies that demonstrated that multiple observers really improved the accuracy of the findings over those of a single observer.

Another major limitation of the use of OGA is observer bias in the form of inter or intra-observer variability. Inter-observer variability, the variability due to systematic differences between observers may, at least partly, be caused by different levels of experience of the observers.[17,19] It has been suggested that over time the effect of the level of experience may become less profound, meaning that over time an observer is expected to become more experienced.[16] Inter-observer variability may occur in practices with multiple veterinarians, where different clinicians may be evaluating a patient at different recheck visits. Intra-observer variability may become a factor if an observer interprets or grades signs of lameness differently over time.[19,20] Both inter- and intra-observer variability may be reduced with video recorded exams.[19,21,22] When an observer can perform all lameness evaluations at the same time, it becomes more likely that identical lameness criterion definitions are being used for the evaluations thus reducing intra-observer variability. In studies where multiple observers review recorded exams, all observers can evaluate the same lameness exam which may result in reduced inter-observer variability.[16,19] Observer bias affecting qualitative and semi-quantitative techniques also may occur if the observer has information pertaining to the medical history or observations at home, prior to examination. This form of bias may be avoided by blinding the observers to this information.[19] Nevertheless, even if efforts are made to avoid observer bias, OGA remains a subjective technique and it is almost impossible to completely eliminate observer bias.[10]

In veterinary medicine, motion analyses (kinematic analysis), force analyses (kinetic analysis) and Paw Pressure Analyses (PPA: pedobarography) are the most commonly used IGA modalities to detect lameness.[2,19] Less commonly used are electromyography (EMG), accelerometry and inverse dynamics.[2,23,24] For a more thorough description of EMG, accelerometry and inverse dynamics the reader is encouraged to review a textbook and recently published work.[24-26]

Kinematic analysis is the study of absolute or relative motion between rigid bodies.[2] Kinematic analysis determines the displacement, velocity, and acceleration of various body segments and can be divided into measurements of joint angle variables (goniometry) and of temporo-spatial variables (TSVs).[2,27]

Temporo-spatial variables of gait are used to describe velocity during locomotion and durations of both the stance and swing phases of gait.[2] The TSVs provide information about the gait cycle and include: duration of gait cycle, stance and swing phase duration and length of stride and step. TSVs can be acquired with kinematic or kinetic systems.[28] Kinematics can also be used to record angular motion of joints and body segments including joint flexion and extension, joint range of motion, and velocity and acceleration of joints.[29] For each kinematic variable the associated Symmetry Index (SI), a measure comparing a variable value of a limb with that of the contralateral limb and the inter-trial coefficient of variation (CV), a measure of inter-step variability, also can be calculated.[4,5,30,28]

Many kinetic variables, variables used to describe the force of limbs in relation to the ground, have been used to describe gait. The principle force measured with kinetic gait analysis is the ground reaction force (GRF), the force exerted by the ground on a body in contact with it according to Newton’s Third Law.[2,26] The most commonly used variable to describe GRF is the peak vertical force (PVF), the maximum force perpendicular to the ground during stance. Commonly used variables derived from PVF include PVF as a percentage of body weight (%PVF), dynamic weight distribution (%WD; the PVF of a limb as a percentage of the total PVF of all four limbs), vertical impulse (VI; the total vertical force generated during the stance phase), and paw contact area (PCA); the latter a measure of surface area covered by each paw. Just as for kinematic variables, for each kinetic variable a symmetry index and inter-trial coefficient of variation can be calculated.[4,5,28,30]

To describe lameness with IGA, PVF or PVF derivatives like PVF normalized for bodyweight (%PVF), vertical impulse (VI), %WD, L-R symmetry indices (SI), and rate of loading and unloading are used. In addition, Fourier analysis is a method that has also been used to detect subtle changes in IGA data of dogs with hindlimb lameness.[31,32] A decreased PVF or PVF derivative of the affected limb usually is seen as a sign of lameness, but there only is scant literature on how much of a decrease signifies true lameness.[33,34] Two main approaches have been used to define lameness: by evaluating groups of dogs and by evaluating individual dogs. When evaluating lameness in a group of dogs, the means of the gait variable of the experimental limbs can be compared with the mean values of the contralateral, unaffected limbs.[31,35] Alternatively, a group of presumed lame dogs may be compared to themselves longitudinally or to a control group in a cross-sectional manner. A study with IGA of an experimental and control group is an example of the latter, whereas a study using IGA to compare outcome over time after a treatment is an example of the former.[20,36] There are several limitations to this type of approach. Only statistically significant differences between group means are detected, but the comparisons do not indicate whether a mean variable value signifies lameness or not. Also, mean variable values do not provide information about individual dogs within the group, and particularly if dogs within a group are not of the same breed, body weight or body size, it may be difficult to assess variability within a group. Another reported approach is using a 10% or more deviation of gait variables from the control group as evidence of lameness.[9] However, there is no scientific evidence in support of this 10% criterion.[37] Finally, these approaches are of limited clinical use as they cannot be applied to determine lameness or soundness of *individual* dogs.

Several approaches have been proposed to discriminate between lame and non-lame *individual* dogs, independent of body weight, body size or body shape. One reported approach is to normalize gait data using the principal of dynamic similarity.[38] Dynamic similarity is the process of normalizing gait variables to body size as well as body weight. It is based on the assumption that animals of different sizes move in a 'dynamically similar' way at 'body size-normalized' velocities. Previous studies have shown that in trotting dogs normalizing PVF to body weight alone is insufficient to account for differences in body size and velocity.[38,39] Others attempted to describe force platform-obtained gait variables of trotting dogs as a function of body weight, body size (represented by height of withers) and body shape (breed).[8,38] In these dogs, velocity was kept within a standard range. With the exception of forelimb VI and pelvic limb PVF, correlations between gait variables, body weight or body size alone were found to be only moderately strong (mean r^2=0.72, range 0.01 – 0.97), suggesting that most kinetic variables cannot be normalized and used to predict lameness based on body weight. Even after full normalization to body weight and wither height, gait parameters still varied by approximately 10%, and were different for different breeds. In a similar study of walking dogs it was found that PVF was best described as a function of body weight and that velocity or limb length did not strengthen the model.[29] The authors also reported that %PVF was inversely related to body weight, which would make this variable unsuitable for comparison of the PVF of dogs of different body weight, body size, or body shape. Collectively these data suggest that present normalization techniques do not allow comparison of gait variables from dogs with different body weight, body size, body shape, gait or velocity. Nevertheless, without suitable normalization techniques it will be difficult to compare gait variables and develop universal definitions of criteria to discriminate between lame and non-lame *individual* dogs.

Another approach to discriminate lame from sound individuals is by evaluation of IGA gait variables of known lame dogs using a receiver operating characteristics (ROC) analysis. Evans et al used ROC curves and area under the curve (AUC) to determine the sensitivity and specificity of force plate variables for detection of gait abnormalities in Labrador retrievers after surgery for ruptured CCL.[40] PVF alone as a variable yielded 89% accuracy. The combined PVF–FS (falling slope) was the most sensitive predictor and had a sensitivity of 93% and a specificity of 94%. Falling slope is the slope of the line between maximum force and end of stance phase and is the rate at which the limb is unloaded.[40] They concluded that in trotting dogs a combination of PVF and falling slope could best distinguish lame from non-lame dogs. Other workers attempted to determine cut-off values with ROC analysis for pelvic limb symmetry indices (SI) of PVF, VI, PCP (paw contact pressure) and PCA (paw contact area) using large breed dogs with lameness due to naturally occurring rupture of the cranial cruciate ligament.[9] All SI's had 100% sensitivity and specificity. An underlying assumption of both these studies is that all dogs, independent of body weight, body size and body shape, have the same gait variable values. However, studies with normalized gait variables indicate that this is not true and there also are no reports of this being true for SIs.[41] Therefore, without such proof, these findings should not be applied to dogs of different breeds with different body weight, body size, body shape, or gait. Another question is whether these findings can be applied to dogs with lameness due to other causes than ruptured cranial cruciate ligament.

Intuitively, one would think that gait variable changes that occur with cranial cruciate ligament rupture (CCLR) will not be the same as with for instance fractures, hip dysplasia, or forelimb conditions.

A third approach is by establishing normal values for gait variables using normal dogs free of lameness or neurological deficits, and comparing these variables to those of lame animals. In a recent study, kinetic gait variables of 90 normal dogs of different body weight (BW; ranging from 1.5-60 kg), different body size and body shape were evaluated.[29] First, gait variables that were constant or a function of bodyweight across all weight groups were identified and then 95% confidence intervals of selected gait variables were determined. It was suggested that such 95% confidence intervals may serve as normative ranges that may be used to detect lameness and neurological deficits in *individual* dogs of any body weight, body size and body shape. An advantage of this approach is that it can be used for dogs with lameness due to any etiology. Even though the normal ranges are for dogs of any body weight, body size and body shape, use of appropriately normalized gait variables will be advantageous, as they most likely will have a narrower normal range than non-normalized variables. A limitation of this approach is that these normative ranges have not been validated and that the sensitivity and specificity of the normative ranges to detect thoracic or pelvic limb lameness in individual dogs has not been determined. An additional limitation of this approach is that a 95% confidence interval of the mean provides very conservative minimum and maximum range values, at least theoretically resulting in an increased number of false negative results. Unfortunately, statistical calculations show that a population of 90-120 dogs would be needed to establish a true normal range. Nevertheless, pilot studies using the proposed normal ranges demonstrated that they may be used successfully to identify lameness in dogs with CCLR and neurological deficits due to cervical or thoracolumbar spinal cord lesions.[29,42]

Several studies have tried to establish the relationship between OGA and IGA in an attempt to determine how accurate each method truly is.[10,16] One study using both numerical rating scales and VAS by trained veterinarians, compare lameness scores in dogs with induced pelvic limb lameness with force plate analysis.[10] Agreement between observer and force plate was calculated using correlation coefficients and was found to be low ($r = 0.3 – 0.58$) unless the lameness was severe, regardless of scoring technique used. Another study compared VAS scores to force plate data.[16] Correlations ranged from 0.69 to 0.90 when compared to PVF and 0.68 to 0.89 when compared to VI. They concluded that agreement between OGA and IGA was low.

The true relationship between OGA and IGA has not been well characterized. Although current literature suggests these two do not correlate very well, the search remains for which method can be considered the superior method. This becomes important when a gold standard is needed on which to base lameness findings. Because the agreement between different observational scoring systems is low and subjectivity is high, it is hard to support OGA as a true gold standard. From a scientific viewpoint it would make sense that IGA would make a better gold standard because it is more objective. However, criteria for detecting lameness using IGA have not been properly validated. Additionally, IGA equipment is not readily available in many practices, making it difficult to give it such an important title as gold standard. The truth is that a gold standard may not exist yet.

Both OGA and IGA use the same criteria to evaluate lameness: force, temporo-spatial, and joint angle variables. With OGA, observations are made by a single or multiple observers to determine whether or not an animal is lame. Observations are qualitative and subjective, mainly because of observer bias. This form of bias is difficult to eliminate, but OGA can be made less subjective by applying numerical scales to the observations. Even though many criteria for lameness have been reported, there is only scant information on definitions of the severity of deviation required to differentiate normal from abnormal gait. Nevertheless, OGA is the most commonly used type of gait analysis as it is an easy and fast method of detecting lameness.

Instrumented gait analysis is a more objective way of evaluating lameness than OGA. Gait variables that can be used to differentiate normal from abnormal gait, such as decreased PVF or %WD, have been proposed. However, changes of variable values that constitute lameness have not been defined. Several approaches to discriminate abnormal gait have been reported and include normalization of gait variable values, use of ROC analysis to determine cut-off values using gait data of lame dogs, and by determining normal values for gait variables using sound dogs. These approaches are promising, but hitherto have not provided robust and reliable definitions of lameness. Compared with

OGA, IGA has the advantages of being quantitative. However, IGA takes more time, requires a significant investment, and is technically more demanding than OGA.

For IGA to become a useful tool to determine lameness in individual dogs, gait variable criteria to discriminate normal from abnormal gait will have to be defined. First, more normalization techniques for KVs, TSVs, and KMVs, valid for dogs of any body weight, body shape, body size, and perhaps also velocity and symmetric gait, will have to be developed. Then, cut-off values can be determined, either by ROC analysis of normalized gait data from known lame dogs or by normal ranges of normalized gait variables from known sound dogs. Part of this work already has been completed, but it will take more time and effort before a set of defined criteria to discriminate between normal and abnormal canine gait will be available for researchers and clinicians.

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CHAPTER 3: CUT-OFF VALUES FOR DETERMINING LAMENESS

Introduction

Lameness is a common presentation of musculoskeletal disease.[1,2] Decreased lameness severity is often seen as a sign of healing or success of treatment.[1] Therefore, recognition of lameness and the severity of lameness is an essential part of the evaluation process and diagnosis of canine orthopedic diseases.

The gait of lame dogs can be evaluated by one of two methods. The first, known as observational gait analysis (OGA), relies on an observer to make a visual assessment of lameness. Observed lameness can be described in terms of visual changes including: decreased loading of the affected limb and shifting of the load to the unaffected limbs, decreased length of the swing phase, decreased duration of the stance phase, alterations in joint angle and thus a combination of kinetic and kinematic changes.[1] A major limitation of OGA is its inherent subjectivity and limited repeatability both by the same observer and between observers. Several techniques such as numerical lameness scoring, the use of visual analog scales, and the use of multiple observers with or without video analysis have been used in an attempt to make this technique less subjective and more repeatable.[3–5]

The second method to evaluate canine gait is instrumented gait analysis (IGA) which uses electronic equipment to capture forces (kinetic analysis) and movement (kinematic analysis) related to an animal's locomotion. It has been proposed as a more objective quantitative way to define lameness in dogs.[6,7] However, criteria used to define lameness based on IGA are lacking. The most commonly used variable to report lameness is peak vertical force (PVF), the maximum force perpendicular to the ground during stance.[8–10] Variables can be calculated from PVF and include the derivatives PVF normalized for body weight (%PVF), dynamic weight distribution (%WD; the PVF of a limb as a fraction of the total PVF of all four limbs), and vertical impulse (VI; the total vertical force generated during the stance phase), left-right symmetry indices (SI), and the limb's rate of loading and unloading.[11] Even though lameness has been reported as a decrease of the affected limb's PVF and derivatives, it is not known (or defined) how much decrease constitutes lameness as opposed to normal variability. Not having established criteria defining lameness is a major limitation of IGA and inhibits widespread implementation of the technique.

Several approaches towards definition of lameness criteria in individual dogs have been reported.[12–14] To make future criteria applicable to dogs of all breeds, bodyweights, body sizes and body shapes, normalization of gait variables, for instance normalization by body weight or body size has been proposed.[13] However, this approach has not yet resulted in a recommended and generally accepted set of gait variables that can be used for comparisons between dogs of different body weight, body size and body shape.

Approaches aimed at defining criteria to discriminate lame from sound individual dogs include development of cut-off values, either by receiver operating curve analysis (ROC) of gait data from known lame dogs or by defining normal ranges of gait variables from known sound dogs. Recently, two groups have used ROC cut-off values to define lameness criteria.[12,15] With ROC analysis, optimal cut-off values as well as their sensitivity and specificity are determined using the so-called area under the curve (AUC). These cut off values may then be used to identify lameness. Evans et al evaluated individual and combined variables in dogs with hind limb lameness due to ruptured cranial cruciate ligament (RCCL) to come up with combinations of the most sensitive and specific variables.[15] They reported that a combination of PVF-FS (falling slope) had the greatest AUC (0.98), indicating the test's almost perfect ability to discriminate lame from sound dogs. Others used ROC analysis to evaluate the ability of symmetry indices (SIs) of kinetic variables (KVs) to differentiate between sound dogs and dogs with hind limb lameness due to RCCL.[12] They concluded that using symmetry indices of each variable could produce sensitivities of up to 100%. Both studies show the promise of this approach, but both only used large breed dogs with ruptured cranial cruciate ligament. Thus, it is unknown whether these criteria can be used with dogs of different body weight or lameness caused by other conditions than ruptured cranial cruciate ligament.

Other workers established normal ranges for kinetic variables of sound (normal) walking dogs of any body weight, body size or body shape.[14] These normal ranges have not been evaluated in a larger population of lame dogs, but results of a preliminary study of 30 dogs with hind limb lameness due to ruptured cranial cruciate ligament rupture suggested that normal ranges may be used as cut-off values to discriminate sound from lame dogs.[16]

Reports on the values of normal and abnormal forelimb gait variables are limited. Information does exist, however, describing joint motion of normal dogs of different breeds, undergoing different activities.[17–22] Recently, alterations in IGA variables from dogs with forelimb lameness were described.[22] Beagles were evaluated at walk and at trot before and after induction of lameness by attaching a round sphere to one paw. They found that during walking and trotting, PVF and VI decreased in the ipsilateral forelimb, increased in the contralateral hind limb, and remained unchanged in the ipsilateral hind limb after lameness was induced.[22] Those variables increased in the contralateral forelimb at a trot. This information is useful in characterizing changes that may occur in forelimbs during lameness, but it is unknown whether these changes also are associated with naturally occurring forelimb lameness or lameness of different etiology.

The goal of the present is study is to characterize kinetic and kinematic variables in dogs with orthopedic forelimb lameness and to determine cut-off values of gait variables for lameness detection using ROC analysis with OGA as the reference standard. Our hypothesis is that cut-off values with an AUC greater than 0.7 can be established for selected IGA variables.

Materials and Methods

Twenty client-owned dogs with unilateral forelimb lameness were studied. Dogs were included if they had an observable unilateral forelimb lameness of any duration and the lameness could be localized to a region of the affected limb. Age, breed, size and weight were not selection criterion. Dogs were excluded if they had bilateral or shifting forelimb lameness at the time of examination, if they had neurological disease, or if they were too aggressive or uncooperative during the orthopedic or instrumented gait exam. Written informed consent was obtained from all clients prior to inclusion and the study was approved by the Purdue Animal Care and Use Committee.

Visual lameness exams (OGA) were performed prior to instrumented gait analysis and any physical manipulation. Visual exams were performed by a board-certified small animal surgeon (Observer 1) and a small animal surgery resident (Observer 2), unaware of the side of the forelimb lameness or presumptive diagnosis. Lameness grading was performed first at the walk and then at the trot according to the following numerical scale: Grade 0: no observable lameness, Grade I: mild observable lameness, Grade II: moderate observable lameness, Grade III: significant weight bearing lameness, and Grade IV: non-weight bearing lameness. Each observer was asked to determine which forelimb was affected (left or right) and to score each dog at the walk and at the trot. The average score of the two observers for walk and for trot was calculated. Dogs were only included if lameness (defined as numerical score of >0) was documented at either the walk or the trot by one or both observers. The dog was then taken to have instrumented gait analysis performed. Upon return, a full physical, orthopedic and neurologic exam were performed. The ultimate diagnosis was based on results of radiographic and surgical evaluation (if applicable). All lame dogs were free of concurrent orthopedic and neurologic abnormalities.

Before data acquisition, dogs were conditioned by one handler to walk over a 9 m long runway. A pressure sensing walkway (3.9sensors/cm^2, Tekscan Inc, South Boston, MA, USA) was used. Trials were collected until 6 valid trials (3 on each side) were collected. A valid trial consisted of straight walking without stopping, hesitating, trotting, or swinging of the head.[11,5] Variables obtained directly included PVF, stance phase duration, gait cycle duration and stride length. The dynamic weight distribution (%WD), swing phase duration, symmetry index (SI) and duty factor were derived using the following equations.[5,11]

$$\%WD = (PVF_{\text{Limb of interest}} / \Sigma\, PVF_{\text{All four limbs}}) \times 100\%$$

Swing phase duration = gait cycle duration – stance phase duration

$$SI = (|X_R - X_L| / [0.5|X_R + X_L|\,]) \text{ x } 100\%$$

Duty factor = duration of stance phase/duration of gait cycle

For each variable, the inter-trial CV (coefficient of variation), a measure of inter-step variability also was calculated.[5,11]

Reflective spheres were placed on the thoracic limb (dorsal aspect of the scapular spine, acromion, lateral epicondyle of the humerus, ulnar-carpal joint, distal aspect of the 5th metacarpal bone). Motion was digitized using cameras and specialized software (MaxTRAQ® and MaxMATE®; Innovision Systems Inc, MI, USA, MathLab®). A full gait cycle was defined as one of the thoracic limb paw pads hitting the floor and contacting the pressure walkway (beginning of stance phase) and ending when the same forelimb contacted the walkway during the subsequent gait cycle.[11] For each forelimb joint, the peak extension, peak flexion and range of motion (ROM) was obtained and of each variable the SI and inter-trial CV was calculated.[5,11]

Mean and standard deviation (SD) were used to summarize the distribution of the kinetic and kinematic variables in the study sample. A paired t-test was performed to compare variables of affected and unaffected forelimbs. Significance between limbs for each variable was set at $p < 0.05$. Correlation between the scores of the observers and between walk and trot OGA score were determined via Spearman’s Rank Correlation. Correlations between OGA score and IGA variables of the affected limb were also calculated. The AUC from the ROC analysis was generated to quantify the overall performance of the instrumented gait analysis variables on discriminating forelimb lameness. In addition, the optimal cut-off values for the selected kinetic and kinematic variables based on the Youdon’s index were identified.[9] Sensitivity and specificity using the optimal cut-offs identified from the ROC analysis were also reported. Statistical analyses were performed using MedCalc for Windows, version 12.6 (MedCalc Software, Ostend, Belgium).

Results

Of the 20 lame dogs (mean age 42 months, range 9-100 months), 14 were male and 6 were female. Mean body weight was 39.2 kg (range 13.2 – 50.5 kg). Breeds included: Labrador Retriever (n= 4), mixed breed (n=3), German Shepherd (n=2), Golden retriever (n=2), Bernese Mountain Dog (n=1), English Setter (n=1), American Bulldog (n=1), English bulldog (n=1), Goldendoodle (n=1), Border Collie (n=1), Boston terrier (n=1), Great Dane (n=1) and Borzoi (n=1). Final diagnoses included bicipital tenosynovitis (n=3), shoulder osteochondritis dessicans (n=3), chronic elbow osteoarthritis (n=2), elbow dysplasia including; fragmented coronoid process (n=2), elbow subluxation (n=1), ununited anconeal process (n=1); other (n=2), carpal valgus (n=1), brachial myositis (n=1), carpal DJD (n=1), supraspinatus mineralization (n=1) and in two patients lameness localized but undiagnosed.

The mean OGA lameness score for the dogs at the walk was 1.2 out of 4 for both Observer 1 (sd 0.77; range 0 -3) and Observer 2 (sd 0.82; range 0-3); the mean lameness score of the 2 observers for dogs at walk was 1.2 (sd 0.75). At the trot, the mean OGA lameness scores for Observer 1 and Observer 2 were 1.4 (range 0 - 2) and 1.3 (range 0 - 2) respectively; the mean lameness score of the 2 observers for dogs at trot was 1.35 (sd = 0.78). Correlation between the two observers was 0.79 for scores at the walk and 0.71 for scores at the trot. Correlation between the mean scores obtained at walk and scores obtained at trot was 0.86. Side of observed lameness correlated 100% of the time between observers.

The mean duty factor was 0.63 (range 0.55-0.67), indicating that all dogs were walking during the data acquisition. Significant differences between affected and unaffected limbs were only found for PVF ($p < 0.0001$), %WD ($p < 0.0001$) and CV of peak elbow extension ($p = 0.04$). Even though no quantitative differences between KMVs of affected and unaffected were found, qualitative differences in the shape of the joint angle-gait cycle curves were seen (see Fig 1). A summary of the descriptive statistics of KVs, TSVs and KMVs can be found in Table 1, 2 and 3.

The AUC and associated 95% CI of PVF, %WD, CV of carpal joint extension and CV of elbow peak extension exceeded 0.5, indicating discriminatory ability. Only the AUC of PVF and %WD exceeded 0.7 (0.727 and 0.922, respectively). Optimal cut-off values for PVF and %WD, based on Youden's index, yielded ≤10.6 kgf for PVF and ≤29.7% for %WD. Associated sensitivity and specificity for PVF were 70% and 75%, and for %WD they were 90% and 85% respectively. The results of the ROC analysis are listed in Table 4 and 5.

The lame forelimb as chosen by the observers during OGA always corresponded with the lame side based on gait variable values obtained with IGA. The correlation between the mean OGA lameness score of the 2 observers of the walking dogs and KVs of the affected limb was only > 0.60 for the PVF-SI (0.65) and %WD-SI (0.65). Correlation coefficients of TSVs > 0.6 were the stance phase duration SI (0.64), swing phase duration SI (0.65), and stance phase duration CV of the affected limb (0.63). Overall, correlation coefficients for KMVs were smaller than those for KVs and TSVs, and all were < 0.52.

Discussion

The results of the OGA study suggest a moderate inter-observer correlation for forelimb lameness (walk r = 0.79, trot r = 0.71) and a moderate scoring agreement of dogs with forelimb lameness at walk and at trot (r=0.86). The results of the IGA study suggest that in walking dogs only the mean PVF, mean %WD and the mean inter trial CV of maximum elbow extension were significantly different when gait variables of affected and unaffected forelimbs were compared. Using ROC analysis, cut off values for PVF (≤10.6 kgf; sensitivity 70% specificity 75%) and %WD (≤29.7%; sensitivity 90% specificity 85%) to discriminate between lame and sound individual walking dogs were determined. Only a modest correlation between OGA results of walking dogs and IGA results of the affected forelimb was found.

The combined results of the comparison of mean gait variable values of the affected and unaffected forelimb and the ROC analysis suggest that the PVF and %WD may be the most useful gait variables to identify forelimb lameness. The utility of PVF for the detection of forelimb lameness had been reported before by others.[5,8,23] The discriminatory power of PVF is remarkable because PVF is not a normalized variable and at walk is mostly a function of body weight[14] which had a wide range in this study. The superior discriminatory power of %WD compared with PVF was expected, because in walking dogs %WD is independent of body weight and the same for dogs with different body weight.[14]

In this dataset TSVs and KMVs did not appear to facilitate the differentiation between sound dogs and dogs with forelimb lameness. This is surprising because decrease of stance phase and swing phase duration, as well as changes in joint angles have been mentioned as lameness criteria for OGA.[1,2] Both TSVs and KMVs were not normalized, as normalization techniques for these variables, except for step length, have not been reported. The lack of normalization may be a major factor why TSVs and KMVs are not discriminatory in this study. Even though no quantitative differences in mean peak extension, mean peak flexion and mean ROM were found, qualitative evaluation of the graphic evaluations of the joint angle changes during the gait cycle (Fig. 2) revealed shape differences when curves of affected and unaffected joints, suggesting that even though a significant difference was not detected, subtle changes are present. These differences may signify differences in timing or in amplitude of activation of one or more muscles in the joint angles of interest. Thus, present quantitative analysis techniques of joint angles during locomotion may be insufficient to detect actual differences. Clearly, further studies will be needed to determine the full effect of lameness on TSVs and KMVs.

The lack of discriminatory power of SIs was also unexpected. Firstly, although it only has been demonstrated for SIs of KVs, it is assumed that the SI of gait variables is independent of body weight and velocity..[13] Thus, one would expect that the SI would be an excellent variable to detect lameness. Secondly, asymmetry has been mentioned as a lameness criterion with OGA, and other workers reported a very high AUC and sensitivity for the SIs of PVF and other KVs in dogs with hind limb lameness due to CCL rupture.[15] A possible explanation for the differences between the results of that study and the present one may be due to the mild lameness of the patients in this study compared with the studies with hind limb lameness due to RCCL. The relationship between limb function and SI is non-linear, thus it indeed may be that more severe lameness will be relatively more detectable. It also may be that shifting of the body weight to the hind limb in the patients of the present study limited the increase of the SIs of forelimb gait variables. The effect of lameness severity on the weight distribution among the four limbs and on utility of the SI should be further explored.

In essence, IGA is a sophisticated way of recording phenomena that are also evaluated and observed with OGA. With both techniques loading and unloading of limbs (kinetic variables), timing (temporo-spatial variables), and joint angles (kinematic analysis) are evaluated. In this study, the highest correlation was found between mean lameness score during walking and the IGA variables PVF-SI (0.65), %WD-SI (0.65), stance phase duration-SI (0.64), and swing phase duration-SI (0.65). Thus, in dogs with forelimb lameness evaluated using OGA asymmetry may be the most important visual cue. This is consistent with work from other workers reporting a moderate correlation between observational lameness scores and SIs of kinetic variables in dogs with hindlimb lameness.[12]

A major limitation of this study is the limited number of enrolled dogs. An initial power calculation suggested that 20 dogs would be sufficient for this study, but a follow-up power calculation indicated that a population of 50 dogs would be necessary to adequately evaluate all KV, TSP and KMV values. Such a study is in progress. Another limitation is that most dogs exhibited only mild to moderate (grade 0 – 2) forelimb lameness. As suggested above, this may have affected the interpretation of asymmetry with the SIs. In future studies we will try to include cases with a wider range of lameness severity.

This study is significant because it is the first study simultaneously evaluating KVs, TSVs and KMVs in canine lameness and the first study evaluating naturally-occurring canine forelimb lameness with the aid of IGA. The results suggest that in walking individual dogs PVF, and %WD are the most important variables for identification of forelimb lameness. Even though the study has a relatively small number of enrolled dogs, the results give important insights in gait variable changes associated with forelimb lameness, identify weaknesses in the present approach to IGA of individual patients, and will provide guidance for future studies focused on gait analysis of individual dogs.

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Table 1: Mean, standard deviation, range and 95% CI of KVs of the affected and unaffected forelimbs. Values of Affected and Unaffected variables with the same symbols (* or #) are statistically different ($p<0.05$).

KV		Mean	SD	Range	95% CI
PVF	**Affected**	9.3*	2.8	4.5 - 14.1	7.9 - 10.6
(kgf)	**Unaffected**	11.5*	2.9	6.3 - 17.9	10.2 - 12.9
	CV-Affected	0.08	0.04	0.02 - 0.19	0.06 - 0.09
	CV-Unaffected	0.07	0.03	0.02 - 0.11	0.06 - 0.08
	SI	22.75	21.64	2.90 - 83.90	12.60 - 32.90
% WD	**Affected**	25.8$^{\#}$	4.2	16.1 - 32.0	23.8 - 27.7
	Unaffected	32.2$^{\#}$	3.1	27.6- 41.2	30.7 - 33.6
	CV-Affected	0.08	0.04	0.02 - 0.19	0.06 - 0.09
	CV-Unaffected	0.07	0.03	0.02 - 0.11	0.06 - 0.08
	SI	22.75	21.64	2.90 - 83.90	12.60 - 32.90

Table 2. Table 1: Mean, standard deviation, range and 95% CI of TSVs of the affected and unaffected forelimbs.

TSV		Mean	SD	Range	95% CI
Gait Cycle Duration (s)	**Affected**	0.71	0.10	0.57 - 0.95	0.66 - 0.76
	Unaffected	0.71	0.10	0.58 - 0.95	0.66 - 0.76
	CV-Affected	0.04	0.02	0.02 - 0.10	0.03 - 0.05
	CV-Unaffected	0.04	0.01	0.03 - 0.07	0.04 - 0.05
	SI	1.06	0.76	0 - 2.70	0.69 - 1.43
Stance Phase Duration (s)	**Affected**	0.45	0.06	0.3 - 0.54	0.41- 0.47
	Unaffected	0.46	0.07	0.3 - 0.62	0.42 - 0.49
	CV-Affected	0.06	0.03	0.02- 0.12	0.04-0.07
	CV-Unaffected	0.06	0.02	0.03 - 0.10	0.05-0.07
	SI	4.13	4.73	0 - 18.40	1.9-6.3
Swing Phase Duration (s)	**Affected**	0.27	0.05	0.22 - 0.43	0.25 - 0.29
	Unaffected	0.26	0.03	0.2 - 0.32	0.24 - 0.27
	CV-Affected	0.06	0.02	0.02-0.1	0.05 - 0.07
	CV-Unaffected	0.06	0.03	0.01 - 0.1	0.05 - 0.07
	SI	7.04	6.77	0 - 27.90	3.87-10.20
Stride Length (cm)	**Affected**	80.02	12.30	51.4 - 101.27	72.98 - 84.83
	Unaffected	80.27	13.10	50.05 -105.83	72.62 - 85.23
	CV-Affected	0.03	0.01	0.01-0.06	0.03-0.04
	CV-Unaffected	0.03	0.01	0.01-0.60	0.02-0.03
	SI	1.34	1.17	0.10 - 4.40	0.79-1.88

Table 3 Table 1: Mean, standard deviation, range and 95% CI of KMVs of the affected and unaffected forelimbs. Values of Affected and Unaffected variables with the same symbols are statistically different (p<0.05).

KMV		Mean	SD	Range	95% CI
Carpus - Peak extension	**Affected**	182.6	4.4	174.5 - 193.7	180.5 - 184.6
	Unaffected	179.8	9.6	147.7 - 192.2	175.2 - 184.4
	CV-Affected	0.01	0.01	0 - 0.02	0 - 0.01
	CV-Unaffected	0.02	0.01	0 - 0.04	0.02- 0.05
	SI	3.8	5.2	0.1 - 22.2	1.4-6.3
Carpus - Peak flexion	**Affected**	109.3	13.1	85 - 137.6	103.2 - 115.5
	Unaffected	108.3	13. 7	84.2 - 128.8	101.9 - 114.7
	CV-Affected	0.04	0.02	0.01 - 0.12	0.03 - 0.05
	CV-Unaffected	0.04	0.02	0 - 0.09	0.02 - 0.05
	SI	8.49	5.34	1.4 - 19.2	6.0 - 11.0
Carpus - ROM	**Affected**	73.3	14.7	44.2 - 98.6	66.4- 80.1
	Unaffected	71.5	16.0	38.7 - 99.0	64.0 – 79.0
	CV-Affected	0.06	0.03	0 - 0.14	0.04 - 0.07
	CV-Unaffected	0.05	0.04	0.02 - 0.17	0.05 - 0.09
	SI	14.5	9.0	2.0 - 34.1	10.3 - 18.7

KMV		Mean	SD	Range	95% CI
Elbow - Peak extension	**Affected**	146.5	11.3	121.9 – 168.0	141.3 - 151.8
	Unaffected	147.4	7.4	133.8 - 163.2	144.0 - 150.9
	CV-Affected	0.03*	0.02	0 - 0.07	0.02 - 0.04
	CV-Unaffected	0.02*	0.01	0 - 0.05	0.01 0.02
	SI	5.9	5.6	0.20 - 20.7	3.2 - 8.5
Elbow - Peak flexion	**Affected**	91.1	10.9	69.8 - 111.3	86.1 - 96.2
	Unaffected	88.5	11.8	70.8 - 112.0	83.0 - 94.1
	CV-Affected	0.03	0.02	0 - .10	0.02- 0.04
	CV-Unaffected	0.06	0.11	0 - 0.53	0.00 - 0.10
	SI	10.1	8.3	0.1 - 30.1	6.2 – 14.0
Elbow - ROM	**Affected**	55.4	9.1	33.1 - 73.5	51.2 - 59.6
	Unaffected	58.88	10.3	38.7 - 77.2	54.1 - 63.7

	CV-Affected	0.08	0.04	0.04 - 0.18	0.06 - 0.09
	CV-Unaffected	0.08	0.10	0.01- 0.51	0.03 - 0.13
	SI	11.4	8.3	0.5 - 34.0	7.5 -15.3
KMV		Mean	SD	Range	95% CI
Shoulder - Peak extension	**Affected**	148.4	15.5	110.5 - 181.3	141.2- 155.7
	Unaffected	146.0	15.1	112.5- 171.9	131.9 - 153.0
	CV-Affected	0.02	0.01	0 - 0.04	0.01 - 0.02
	CV-Unaffected	0.02	0.01	0 - 0.05	0.01 - 0.02
	SI	7.6	6.7	1.3 - 30.5	4.5 - 10.8
Shoulder - Peak flexion	**Affected**	116.7	12.6	81.3 - 141.2	110.8 - 122.5
	Unaffected	112.8	9.8	92.2 - 128.5	108.2 - 117.3
	CV-Affected	0.02	0.01	0 - 0.03	0.01 - 0.02
	CV-Unaffected	0.02	0.01	0 - 0.04	0.01 - 0.02
	SI	7.7	6.2	0.9 - 27.3	4.8 - 10.6
Shoulder - ROM	**Affected**	31.8	6.6	22.0 - 45.8	28.7 - 34.9
	Unaffected	33.2	7.6	20.3 - 53.6	29.7 - 36.8
	CV-Affected	0.09	0.04	0 - 0.16	0.07 - 0.10
	CV-Unaffected	0.08	0.03	0.01 - 0.14	0.06 - 0.10
	SI	19.3	17.4	0.5 - 55.1	11.2 - 27.5

Table 4. Area Under the Curve (AUC) with associated 95% CI of selected gait variables. Variables with AUC and associated 95% CI > 0.5 are identified in bold.

	Variable	AUC	95% CI
KV			
	PVF	**0.727**	**0.564 - 0.856**
	PVF-CV	0.536	0.367 - 0.699
	%WD	**0.922**	**0.793 - 0.983**
TSV			
	Gait Cycle Duration	0.510	0.343 - 0.675
	Gait Cycle Duration-CV	0.543	0.374 - 0.705
	Stance Phase Duration	0.535	0.366 - 0.698
	Stance Phase Duration-CV	0.524	0.356 - 0.688
	Swing Phase Duration	0.558	0.388 - 0.719
	Swing Phase Duration-CV	0.511	0.344 - 0.676
	Stride Length	0.525	0.357 - 0.689
	Stride Length-CV	0.589	0.418 - 0.745
KMV			
Carpus	Peak Extension	0.537	0.373 - 0.696
	Peak Extension-CV	**0.675**	**0.509 - 0.814**
	Peak Flexion	0.505	0.343 - 0.667
	Peak Flexion-CV	0.517	0.354 - 0.678

	ROM	0.545	0.380 - 0.703
	ROM-CV	0.583	0.416 - 0.736
Elbow	Peak Extension	0.508	0.345 - 0.669
	Peak Extension-CV	**0.693**	**0.527 - 0.828**
	Peak Flexion	0.577	0.411 - 0.732
	Peak Flexion-CV	0.515	0.352 - 0.676
	ROM	0.608	0.441 - 0.758
	ROM-CV	0.590	0.423 - 0.743
Shoulder	Peak Extension	0.532	0.368 - 0.692
	Peak Extension-CV	0.545	0.380 - 0.703
	Peak Flexion	0.607	0.441 - 0.758
	Peak Flexion-CV	0.500	0.338 - 0.662
	ROM	0.545	0.380 - 0.703
	ROM-CV	0.552	0.387 - 0.710

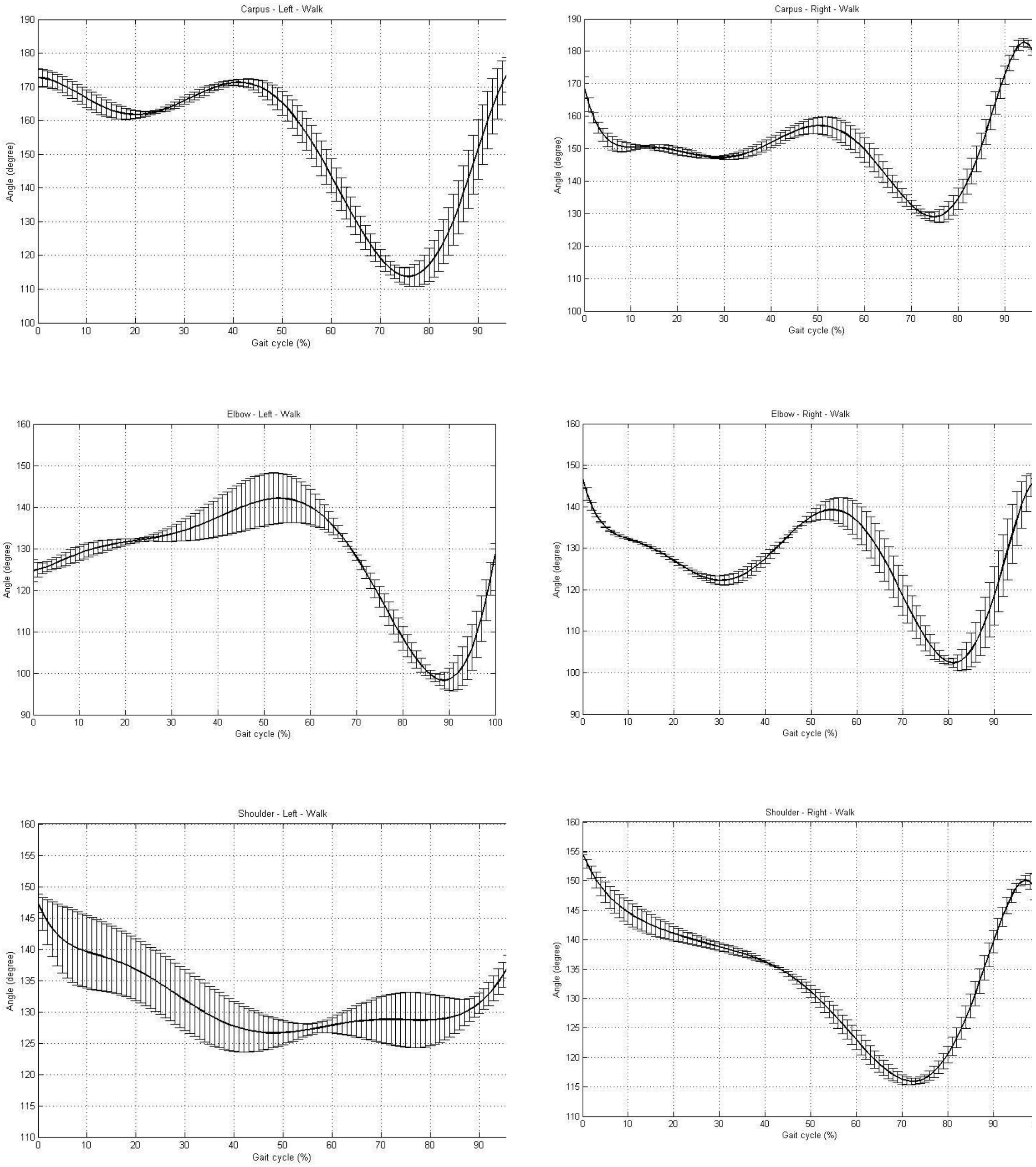

Figure 1: Graphic representation of joint angle changes during the gait cycle. Example is a dog with severe forelimb lameness (grade 3 walk, grade 4 trot). Note curve differences between joints. Graphs in the left column are from the left (affected) forelimb and graphs in the right column are from the right (unaffected) forelimb.

CHAPTER 4: CONCLUSIONS, SIGNIFICANCE, FUTURE DIRECTIONS

The purpose of the research in this thesis was to characterize kinetic and kinematic variables of dogs with forelimb lameness, and to discriminate lame from sound individual dogs using a set of normal ranges, previously established in our laboratory.

The combined results of the comparison of mean gait variable values of the affected and unaffected forelimb and the ROC analysis suggest that forelimb lameness is mostly characterized by decreased PVF and %WD, and that therefore these variables may be useful gait variables to identify forelimb lameness.

This is the first study evaluating cut-off values based on normal ranges. The normal ranges used in this study were previously established in our laboratory. They were derived from IGA data from 90 sound walking dogs of different body shape, body size and body weight (1.5 - 60 kg) and based on the 95% CI of the mean of the gait variables. The sensitivity and specificity of the normal ranges of gait variables used to detect forelimb lameness in the data set of this study was determined and found to be less than 55% and 75% respectively (see Appendix). Thus, this analysis suggested that normal ranges based on the 95% CI of the mean are not suitable for the detection of lameness.

Because the intended approach did not provide the robust criteria to discriminate dogs with forelimb lameness from sound dogs, cut-off values using the gait data of the receiver operating characteristics (ROC) analysis were established. Based on AUC, only PVF (AUC 0.73, CI 0.564 - 0.856), %WD (AUC 0.92, CI 0.793 - 0.983), peak extension of the carpus (AUC 0.68, CI 0.509 - 0.814) and peak extension of the elbow (AUC 0.69, CI 0.527 - 0.828) had discriminatory ability and only the AUC for PVF and %WD were greater than 0.70. Cut off values for PVF (≤ 10.6; sensitivity 70% specificity 75%) and %WD (≤ 29.7; sensitivity 90% specificity 85%) to be used to discriminate between lame and sound individual walking dogs were determined.

In this study, the highest correlation was found between mean lameness score during walking and the IGA variables PVF-SI (0.65), %WD-SI (0.65), stance phase duration-SI (0.64), and swing phase duration-SI (0.65). This may suggest that asymmetry is the most significant visual cue used for OGA. This moderate correlation is similar to other studies and may reflect the lack of definitive criteria linking the two methods.

The significance of this study is that it is the first study to simultaneously evaluate KVs, TSVs and KMVs in lame dogs. It is also the first time that forelimb lameness was characterized using IGA and the provided cut-off values may be an important step towards establishing robust criteria to discriminate lame from sound walking dogs.

This study has identified the need for areas of future study. The first and foremost remains the need to refine the set of normal ranges. This will need to be done by continually adding to the current set of normal dogs. Once the normal ranges have been solidified they may be used to help compile a range of normal values that could be used widely for gait analysis at multiple institutions. Cut off values could be performed, as in this study, to provide a system of checking the normal ranges and comparing specificity and sensitivity of the two systems. Ultimately, this could provide a standardized way to analyze gait and could help make the challenging process of lameness detection that much easier.

APPENDIX

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The purpose of the research in this thesis was to characterize kinetic and kinematic variables in dogs with forelimb lameness, and to discriminate lame from sound individual dogs using a set of previously established normal ranges. These normal ranges were derived from 90 normal dogs of different body weight, body shape and body size and were based on the 95% CI of the mean of the analyzed gait variables. The body weight of these dogs ranged from 1.5-60 kg.

The sensitivity and specificity of the normal values of gait variables used to detect forelimb lameness in the data set of the study group of Chapter 3 was determined and found to be less than 53% and 70% respectively. Thus, this analysis suggested that normal ranges based on the 95% CI of the mean are not suitable for the detection of lameness. The results are summarized in Table 1, 2 and 3 of the Appendix.

Because our intended approach did not provide the robust criteria to discriminate dogs with forelimb lameness from sound dogs, we established cut-off values using receiver operating characteristics (ROC) analysis. The data of that study are presented in Chapter 3.

Table 1a. Sensitivity and specificity of normal ranges for being able to detect forelimb lameness using KVs.

KV	Normal Range	Sensitivity (Affected Limb)	Specificity (Unaffected Limb)
PVF	Based on BW	0.05	1
PVF - SI	4.17-18.17	0.05	
% WD	25.37 – 34.23	0.45	1

Table 1b. Sensitivity and specificity of normal ranges for being able to detect forelimb lameness using TSVs.

TSV	Normal Range	Sensitivity (Affected Limb)	Specificity (Unaffected Limb)
GCD	0.042 – 0.048	0.53	0.53
GCD- SI	0.606 – 0.94	0.32	
Stance	0.05 – 0.058	0.25	0.75
Stance SI	1.266 – 2.072	0.3	
Swing	0.053 - 0.06	0.55	0.6
Swing SI	2.153 – 3.649	0.25	
Stride	0.03 – 0.034	0.25	0.65
Stride SI	0.658 – 1.104	0.3	

Table 1c. Sensitivity and specificity of normal ranges for being able to detect forelimb lameness using KMVs.

KMV	Normal Range	Sensitivity (Affected Limb)	Specificity (Unaffected Limb)
Shoulder Extension	149.47 – 155.09		
Shoulder Flexion	119.92 – 124.38		
Shoulder Range of Motion	28.67 – 31.58	0.4	0.7
Elbow Extension	145.55 – 149.38		
Elbow Flexion	91.67 – 95.57		
Elbow Range of Motion	52.38 – 55.31	0.25	0.75
Carpus Extension	181.76 – 184.60		
Carpus Flexion	105.70 – 110.36		
Carpus Range of Motion	72.96 – 79.07	0.5	0.5

VITA

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Jennifer Carr received her Bachelor of Science degree from the University of Delaware in 2004. She then attended veterinary school at North Carolina State University, graduating in 2008. She completed a rotating Internship in Small Animal Medicine and Surgery in 2009 at Texas A&M University. Following the completion of her internship, she completed a surgical internship in Dallas in 2010 and an orthopedic fellowship in 2011. She began a small animal surgery residency at Purdue University in 2011.