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Kinetic and kinematic evaluation of compensatory movements of the head, pelvis and thoraco-lumbar spine associated with asymmetrical weight bearing of the pelvic limbs in dogs

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To the Graduate Council:

I am submitting herewith a dissertation written by David Alan Hicks entitled "Kinetic and kinematic evaluation of compensatory movements of the head, pelvis and thoraco-lumbar spine associated with asymmetrical weight bearing of the pelvic limbs in dogs." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Comparative and Experimental Medicine.

Darryl L. Millis, Major Professor

We have read this dissertation and recommend its acceptance:

Joseph P. Weigel, H. Steven Adair, Jonathan S. Wall

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Kinetic and kinematic evaluation of compensatory movements of the head, pelvis and thoraco-lumbar spine associated with asymmetrical weight bearing of the pelvic limbs in dogs

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

David Alan Hicks
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Acknowledgements

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Abstract

The purposes of this dissertation were to 1) determine ground reaction forces of dogs with mild asymmetrical weight-bearing of the pelvic limbs while trotting and 2) use three-dimensional motion analysis to identify compensatory vertical motion of the head and pelvis, and lateral motion of the thoraco-lumbar spine in dogs with mild asymmetrical weight-bearing of the pelvic limbs while trotting, and 3) use this information to introduce a subjective grading system for the pelvic limbs in dogs. Our hypotheses were that dogs with asymmetric weight bearing demonstrate compensatory motions of the head, pelvis and thoraco-lumbar spine while trotting, and that these motions would have a positive correlation with the degree of weight bearing asymmetry.

Twenty-seven dogs were included in the study. Nine were normal dogs, which had no surgical intervention, 9 dogs had a cranial cruciate ligament transection and tibial plateau leveling osteotomy 3 ± 0.5 years prior to study start, and 9 dogs had a cranial cruciate ligament transection and extracapsular lateral fabellar-tibial suture (modified retinacular imbrications technique) 7 ± 0.5 years prior to study start. A kinematic model was created so that reflective markers placed on the sagittal crest of the skull, the ischiatic tuberosity and 3 points along the thoraco-lumbar spine of each test subject could be tracked over time while trotting. Kinetic and kinematic data were used to characterize weight-bearing asymmetry between the left and right pelvic limbs, and to describe linear vertical displacement of the head and pelvis, and lateral angular displacement of the thoraco-lumbar spine. Maximum, minimum and range of motion values were analyzed for any differences between the pelvic limbs.

Dogs with subtle asymmetric weight bearing of the pelvic limbs demonstrated a greater range of pelvis linear vertical displacement (PLVD) on the side with a greater peak vertical force, and greater thoraco-lumbar lateral angular displacement (TL-LAD) toward the side with a lower peak vertical force while trotting. No differences in mean head linear vertical displacement (HLVD) were detected, and there were no significant correlations between the magnitude of HLVD, PLVD and TL-LAD and the degree of asymmetrical weight bearing of the pelvic limbs.

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LIST OF ABBREVIATIONS

EMG – Electromyography
TPLO – Tibial plateau leveling osteotomy
LFS – Lateral Fabellar Suture
DLM – Darryl L. Millis
DAH – David A. Hicks
PVF – Peak vertical force
VI – Vertical impulse
OSG – Objective symmetry grade
HLVD – Head linear vertical displacement
PLVD – Pelvis linear vertical displacement
T-L – Thoraco-lumbar
T-L LAD – Thoraco-lumbar lateral angular displacement
DJD – Degenerative Joint Disease
OA – Osteoarthritis
CCLR – Cranial cruciate ligament rupture

CHAPTER 1

INTRODUCTION

Subjective Gait Analysis in Veterinary Medicine

Locomotion can be defined as the translation of a body from one point to another by means of characteristic movements.[1] These movements, in reference to terrestrial locomotion, can be described as the dynamic activity of synchronized, repetitive, multi-planar rotational movements of body segments around joints.[2] The precise neuro-muscular actions that produce motion at the joints of a bipedal or quadrupedal animal result in a regular, cyclic manner of locomotion or characteristic gait.[3] Gaits, by one definition, are designed to minimize unwanted displacements or energy costs, while translating a body from one point to another in space at a certain range of velocity.[1] Whether referring to a symmetric gait (i.e. trot, pace, amble or running walk) or an asymmetric gait (i.e. gallop, canter, or bound),[4] alterations or asymmetries in these synchronized movements can be perceived visually as abnormal (i.e. lameness). Such gait alterations or lameness can result from diseased or ineffective interactions between muscles, tendons, bones, ligaments, joints, and central or peripheral nervous tissues.[5] Several basic gait analysis techniques may be necessary to elucidate the underlying neuro-musculoskeletal tissues involved, classify the resulting abnormalities as focal or multifocal, and determine if any of the motions being observed result from compensatory efforts by the subject.

Gait analysis, by definition, is the systematic measurement and assessment of characteristics of locomotion that either subjectively describes or objectively quantifies the forces that affect motion (i.e. kinetics) and the temporal and geometric properties of motion (i.e. kinematics).[6-8] Subjective evaluation of gait for an asymmetry or lameness by watching a human or animal in motion is common in clinical practice.[9] However, subjective assessment of lameness assumes both observational acuity, as well as the ability of the clinician or owner to reliably interpret signs of pain or disability before or after treatment for disease.[10] Variations among breeds, severity of underlying disease, the skill of the evaluator, and the types of subjective lameness grading systems used have contributed to inconsistencies resulting from traditional evaluation schemes.[5,11,12] For example, observations of normal vs. abnormal motion in equine patients have included subjective evaluations of lameness and descriptions of compensatory movements of the head[13] and pelvis[14,15] (i.e. "head nod", and "hip hike" or "gluteal rise", respectively), as well as subtle lateral or ventral-dorsal motions of the thoraco-lumbar spine.[16] Such motions may be associated with the animal's efforts to distribute body weight away from the affected limb during the swinging and weight-bearing phases of gait, presumably to reduce pain and discomfort.[17-19] However, several recent studies have reported the low agreement between equine clinicians for subjective scoring of mild to moderate lameness and have concluded that subjective scoring of lameness in horses is either only 'moderately reliable' or 'just within acceptable limits'.[20-22] Considering the suggestions of these authors, compensatory movements of the subject may further skew the reliability of lameness scores during clinical lameness examinations.

Subjective evaluation of canine gait has been used for many years as well. However, our ability to perceive or interpret subtle motions during the gait cycle can be very difficult and in some respects impossible even for experienced gait specialists.[23] The validity of owner, trainer and clinician subjective lameness scores as a reliable indicator of limb function and as a means of quantifying the long term success of treatments for many conditions is unknown.[10] Systematically determining the primary source of the lameness, characterizing associated compensatory motions, and classifying the gait following a subjective grading system used to evaluate asymmetry or lameness in the pelvic limb at a trot may allow for an earlier, more comprehensive approach to the underlying condition, its progression, and potential response to treatments.

Lameness has been reported to be the most economically important medical condition affecting horses,[9] and subclinical disorders of the locomotor system are the most frequent causes (74%) of poor performance.[24] Osteoarthritis is a common sequelae to a number of orthopedic conditions in dogs, including rupture of the cranial cruciate ligament, patella luxation, meniscal injuries, and hip dysplasia, and is characterized by pathologic changes of diarthrodial joints accompanied by clinical signs of pain and disability.[25] It has been estimated that up to 20 percent of the canine population over one year of age is affected with osteoarthritis.[25,26] Several techniques are available for evaluating outcome after treatment of orthopedic disease.[27] These include subjective evaluation of pain or lameness, force platform analysis, and radiographic scoring.[28-33] Lameness grade is commonly used to evaluate function and pain in orthopedic patients; however, this is subjective and may be confounded by evaluator bias.[27] Several examples of proposed lameness grading schemes have been described in the veterinary literature,[12,34-37] however they are very general in nature and focus mainly on consistency of weight bearing of either the forelimb or the hind limb, degree of discomfort, and variations of 'gait abnormalities'.

Movements of the head, spine, pelvis and extremities of a quadruped are a dynamic, coordinated process that result from symmetrical neuro-muscular actions on the musculoskeletal system. These motions are best described by making multiple observations over time, rather than by observing single discrete events.[38] Visually identifying alterations or asymmetries in these coordinated movements over time can prove difficult even to the trained observer, not to mention when the abnormality (i.e. lameness) is subtle. Conditions such as congenital abnormalities, trauma, degenerative joint disease (DJD) or osteoarthritis (OA), neuromuscular conditions, infectious diseases or neoplasia have been reported as resulting in varying degrees of thoracic or pelvic limb lameness.[5] Without early recognition and intervention for these disorders, irreversible damage to the musculoskeletal system may result, allowing potential treatments to be less effective if the disease continues to progress. Quantifying and characterizing the asymmetry of an animal's body weight distribution and compensatory movements during locomotion may prove clinically significant by allowing for earlier recognition of underlying disorders. This earlier recognition may allow for initiation of earlier treatment, a more comprehensive assessment of response to therapies, and a potential overall reduction in the progression of secondary OA. Therefore, competence in evaluating animals with a lameness early in the course of the disease process is vital to initiate early therapy,[5] and has been considered the driving force behind the development of more objective, quantitative kinetic and kinematic gait analysis techniques.

Kinetic Gait Analysis in Veterinary Medicine

Objective measures of musculoskeletal function have been available since the late 1800s.[23] Increasing interest in clinical methods of gait analysis for both humans and animals has been rapidly evolving over the last 40 years and has brought together various technological advances in single and serial force platforms, electro-goniometric devices, computerized two- and three-dimensional kinematic systems, electro-myography, and a variety of 'bio-feedback' instruments.[1,23] Such objective modalities can be found in modern gait laboratories in both medical and veterinary research institutions, and have aided our ability to quantitatively define temperospatial gait characteristics.[39] Force platform gait analysis is a valuable method to obtain objective data on limb loading in dogs, and is increasingly being used to evaluate the outcome of surgical or medical treatments for orthopedic conditions.[40] Kinetic analysis of canine gait can be performed using methods introduced in 1987 by Budsberg et al[1,41] which measure orthogonal ground reaction forces (i.e. mediolateral [x direction], craniocaudal [y direction], and vertical [z direction]) resulting from paw impact during the stance phase of gait.[42] This technique can accurately assess normal and abnormal weight bearing, identify features of specific gait alterations, and quantify weight distribution so that numeric comparisons can be made within or between animals over time;[6,43] these methods have become the gold standard to objectively assess lameness. The ground reaction forces obtained represent the summation of truncal and limb forces transmitted through one limb to the ground during the stance phase of the stride, and have been viewed as an objective, quantitative measure of weight bearing for individual limbs.[6,42] The peak vertical force, and vertical impulse, which is the vertical force integrated over time during the stance phase of gait, most directly measure dynamic weight bearing in both humans and animals, and are decreased, relative to 'normal', when an asymmetry or lameness is present.[1,42,44,45]

Objective analysis tools, such as the force platform, allow for a more accurate assessment of functional weight bearing, and may also reduce or eliminate subjective influence, error, or bias. Anecdotal observations suggest that dogs can have up to a 5-10% difference in weight bearing on force platform analysis prior to visualizing subtle clinical lameness in affected dogs in the pelvic limbs, and up to a 25-30% difference in the thoracic limbs. To date, kinetic assessment has been extensively used to examine the gait and gait-associated abnormalities in horses, in dogs that are considered normal, and in dogs following coxofemoral excision arthroplasty, total hip replacement, cranial cruciate ligament rupture repair, hip dysplasia, induced acute synovitis, and osteoarthritis.[1,3,41,44-63] With the continuing advances in computer technology, biomechanical researchers have developed systems that integrate methodologies using kinetic (force) analysis, two- and three-dimensional kinematic (motion) analysis, and electromyography (EMG) all at the same time.[23]

Kinematic Gait Analysis in Veterinary Medicine

Kinematic gait analysis is one of the oldest methods of evaluating movement, dating back to the late 19th century. This aspect of gait analysis describes the motion of objects, quantifies the positions, velocities, accelerations, and angles of anatomical points, segments, and joints in space.[23] It is performed using a series of cameras and non-reflective or reflective markers placed on the subject's skin over specific anatomic landmarks used for reference points, approximating centers of joint motion, indicating bony prominences, or points measured a specified distance from a specified landmark.[38,64-66] Two popular techniques that have laid the foundation for studying kinematics involve the use of analog- or digital-based analysis systems that are combined with commercially available video or optical capture computer software programs that detect and process two- or three-dimensional coordinates of the markers that emit a reflection when exposed to infrared or visible light.[8,23] A number of recent studies have used software programs to quantify two- and three-dimensional representations of animal movements that have provided joint angular motion, angular velocities, and angular accelerations; patterns of stride, including stride lengths, stance times, and swing times; and linear velocities and accelerations during normal and abnormal musculoskeletal conditions.[38,39,62,65,67-86] However, limited published data exist regarding evaluation and measurement of head, pelvic, and thoraco-lumbar spinal movements in dogs with asymmetrical weight bearing of the pelvic limbs. Also, there is little evidence regarding the sensitivity of these movements and their association with the degree of asymmetry or lameness being evaluated.[19] Regardless of the absence of objective characterization of gait and compensatory movements in the veterinary literature, anecdotal descriptions of such movements have historically influenced subjective assessments of pelvic limb lameness in dogs. To our knowledge positive correlations between these movements and the severity of observed clinical lameness have only been suggested.

Problem Statement

The purposes of the study reported here were to 1) measure ground reaction forces of dogs with mild asymmetrical weight-bearing of the pelvic limbs while trotting, 2) use kinematic analysis to characterize vertical motion of the head and pelvis, and lateral motion of the thoraco-lumbar spine in dogs with mild asymmetrical weight-bearing of the pelvic limbs while trotting and 3) use this information to introduce a subjective grading system for the pelvic limbs in dogs.

Hypothesis

We hypothesized that compensatory movements of the head, pelvis and thoraco-lumbar spine occur during asymmetrical weight bearing of the pelvic limbs in dogs, and that the magnitude of these dynamic measurements would positively correlate with the degree of weight-bearing asymmetry while trotting. We postulated that this information would be instrumental in designing a subjective grading system for the pelvic limb in dogs and in aiding the clinician or owner during clinical gait examinations of dogs with suspect pelvic limb lameness.

CHAPTER 2

MATERIALS AND METHODS

Facilities

The Veterinary Orthopedic Laboratory (VOL) at The University of Tennessee College of Veterinary Medicine was used for collection of kinetic and kinematic data.

Subjects

Twenty-seven adult research hound-type dogs were evaluated. Mean body weight was 21.5 ± 2.5 kg (47.3 ± 5.5 lbs.). All dogs were random source animals, which had reached skeletal maturity at the time of acquisition. Therefore their ages were estimated based on length of time at our research facility from time of purchase. Estimated mean age was 5.3 ± 3.3 years. These dogs were used as part of an ongoing study that grouped the dogs into three categories. The control group (Group 1; n=9) included dogs free of any orthopedic or neurologic abnormalities. Physical examination of these dogs by the same investigator (DLM) revealed no gait deficiencies, orthopedic or neurologic problems and all were assigned a subjective lameness grade of 0. The two treatment groups consisted of dogs that had received either a TPLO (Group 2, n=9) or LFS (Group 3, n=9) surgery previously. Surgery was performed on average 48 ± 5 months prior to the start of this study for Group 2 and on average 84 ± 5 months for Group 3. For both surgical groups of dogs, the CCL was surgically transected immediately prior to the stabilization procedure. The TPLO surgery was performed as previously described.[87] Briefly, an osteotomy of the proximal tibia was created using a biradial saw blade. The proximal tibial component was rotated caudally so that the tibial plateau angle was approximately 5 degrees to the long axis of the tibia. The two tibial components were held in place with a 6 holed TPLO plate (Figures 1 and 2). The LFS group was stabilized with two nylon sutures passed around the lateral femoral fabella and through a hole created in the proximal tibial tuberosity (Figure 3). Once recovered from surgery, all surgical dogs were allowed the same amount of leash restricted activity and were kept in the same controlled kennel-type environment. The control group was similarly housed. Thorough physical and orthopedic examinations were performed on Groups 2 and 3 by the same investigator (DLM) and no significant gait, clinical or orthopedic abnormalities, other than the stifle surgeries, were detected. All 18 dogs in Groups 2 and 3 were assigned a subjective lameness grade of 0, and all 27 dogs were considered fit and capable to trot consistently along a designated gait runway measuring 10.7 meters in length. The Institutional Animal Care and Use Committee approved the study.

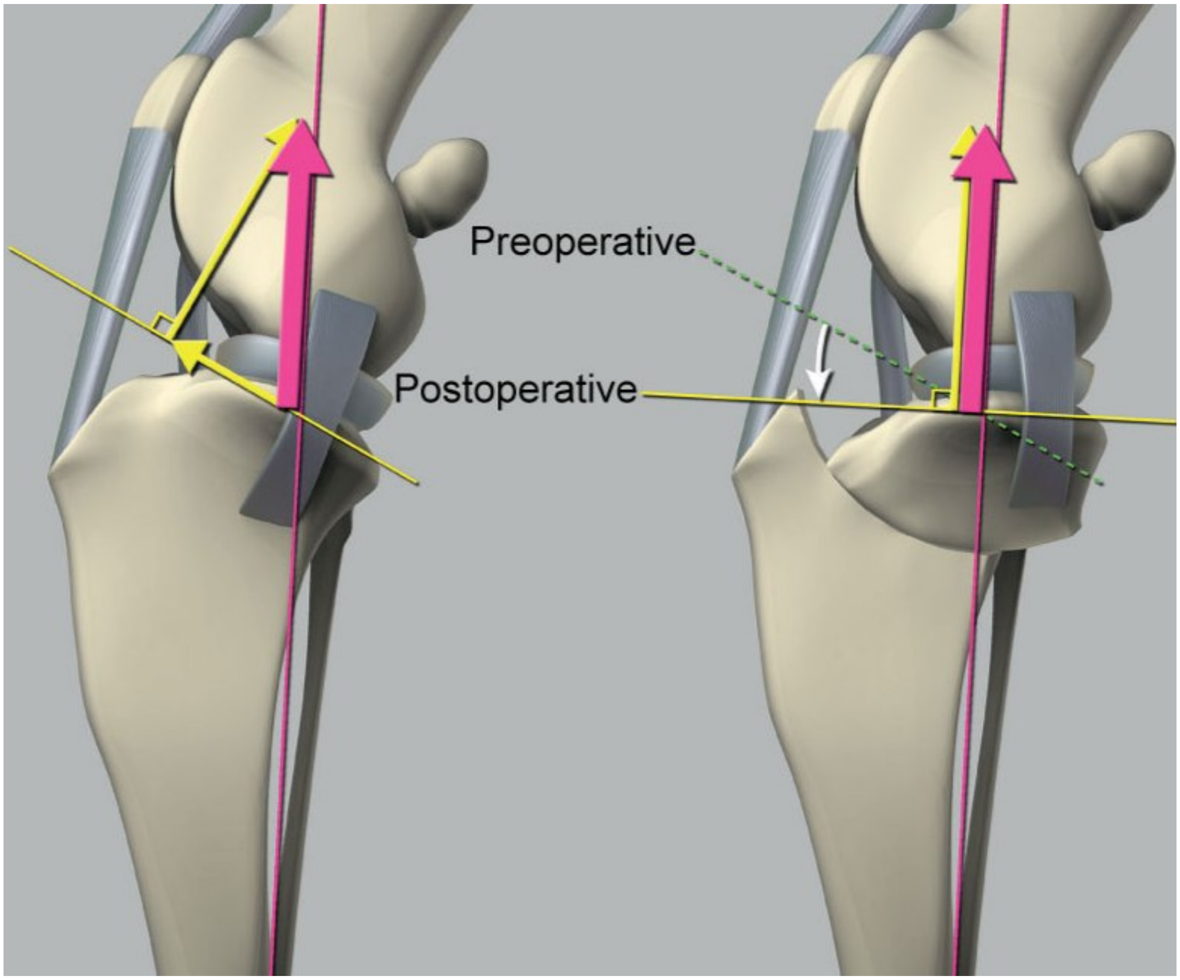

Figure 1. A representation of a tibia before and after the proximal tibial osteotomy for the tibial plateau leveling osteotomy. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

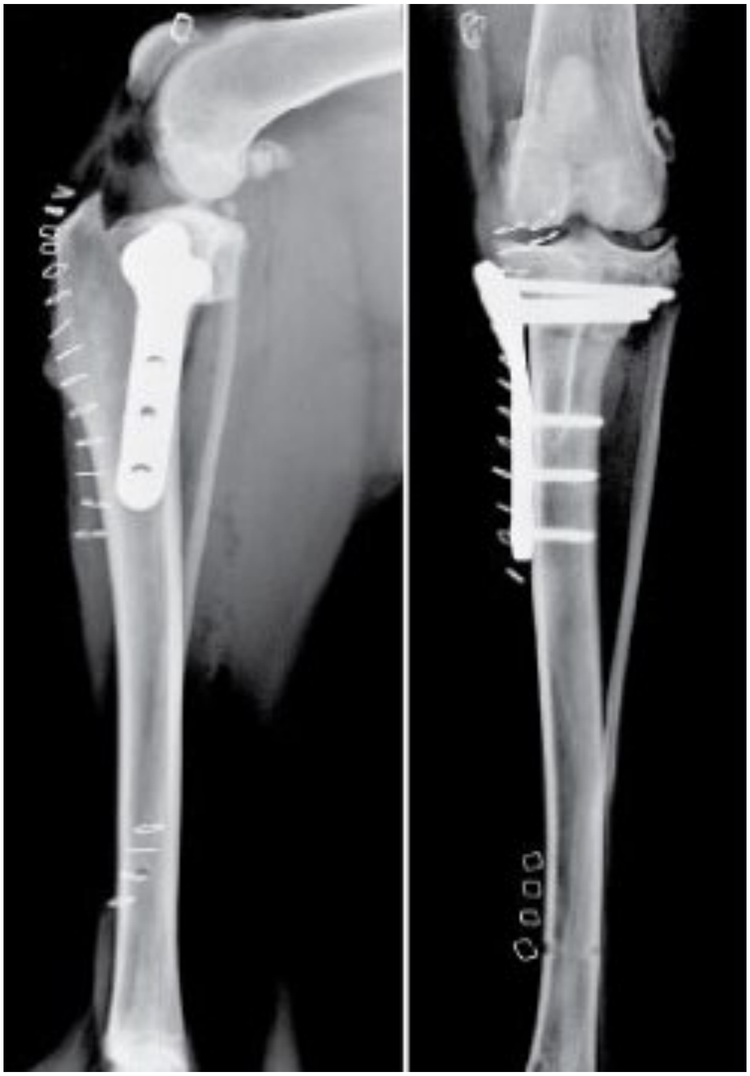

Figure 2. Post-operative radiographic images of a TPLO procedure. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

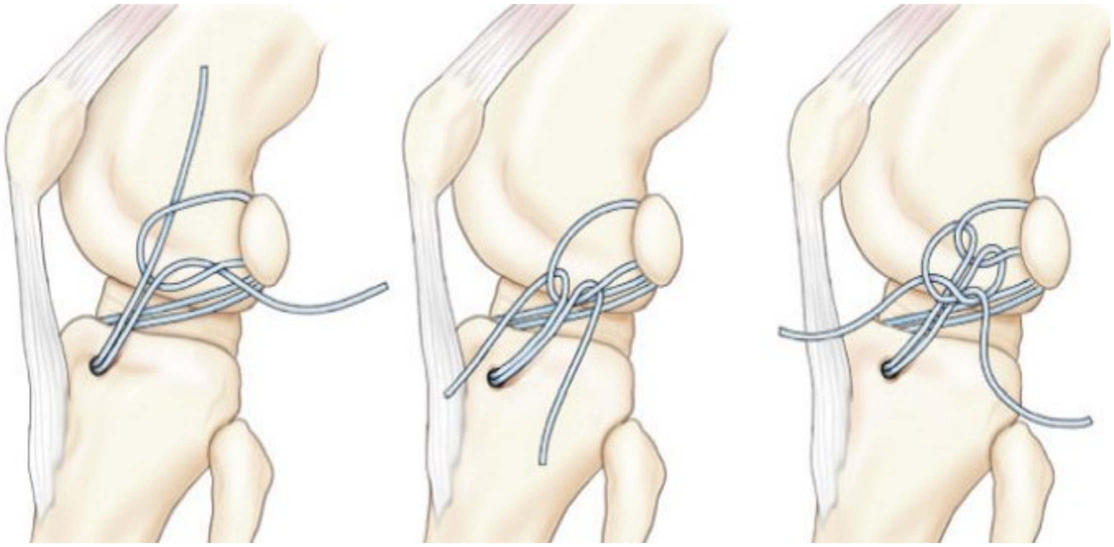

Figure 3: Representation of lateral fabellar suture procedure. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

Ground Reaction Force Measurement and Limb Designation Protocol

Kinetic data were obtained using a force platform (OR 6-6, Advanced Medical Technology Inc., Watertown, MA). The force platform was mounted in the center of and level with the surface of the designated gait runway. The signal from the force platform was processed through an analog to digital convertor board and stored by use of a specialized computer software program (Acquire 7.3, Sharon Software, Inc., Dewitt, MI). As each dog trotted along the gait runway and across the force platform, velocity and acceleration were recorded by use of 5 photoelectric cells, each placed 50 centimeters apart, and a start-interrupt timer system. Care was taken to ensure that the dog triggered the photoelectric cells and that a relatively constant speed with minimal acceleration or deceleration was maintained across the force platform during each trial. Forward velocity of the dog was controlled by the same investigator (DAH) and maintained between 1.7 to 2.1 meters/second (m/s) [(3.8 to 4.7 miles/hour)]. Forward velocity was also verified by kinematic analysis of a reflective sphere placed on the sagittal crest of the skull. The acceptable range of acceleration and deceleration was maintained at ± 0.50 meters/second/second (m/s^2) [(± 0.003 $miles/second^2$)], respectively. An evaluation was considered valid if the velocity and acceleration were within the described parameters, and a thoracic limb followed immediately by the ipsilateral pelvic limb contacted the force platform while the dog trotted along the gait runway. If the dog was distracted during an evaluation, or if any portion of a contralateral paw hit the force platform, the data were considered invalid. Five valid evaluations were collected for both left and right pelvic limbs, and vertical ground reaction forces were used to mark initiation and termination of the stance phase. Peak vertical force (PVF) and vertical impulse (VI) were recorded, and these values were expressed as a percent of body weight for each limb at 1-millisecond intervals for 650 milliseconds after each foot strike. The mean velocity, acceleration, PVF and VI values for each dog for the 5 valid trials were calculated for both pelvic limbs while trotting. Mean PVF values were used to identify weight-bearing asymmetry in all study dogs. For study purposes, the pelvic limb that demonstrated the lowest mean PVF was designated the limb with 'lower' degree of weight bearing, and the contralateral pelvic limb, which demonstrated the greater mean PVF, was designated as the limb with 'greater' degree of weight bearing.

Objective Symmetry Grade Assignment

A simplified method for determining a mean vertical symmetry index was used by calculating the ratio between the lower and greater PVF values. The resulting value was multiplied by 100, and then subtracted from 1 to yield the percent difference in weight bearing (i.e. degree of weight bearing asymmetry) between the pelvic limbs with lower and greater PVF values. Objective symmetry grades ranging from 0 – 5 were proposed based on the percentage of weight bearing asymmetry calculated between the pelvic limbs with lower and greater degrees of weight bearing (Table 1). For example, a weight bearing difference between 0.0 and 7.9% using the symmetry index represents near perfect symmetry between the 2 measured limbs (i.e. no lameness) and would be assigned an objective symmetry grade of 0. A weight bearing difference between 27.0 and 45.9% objectively would be an objective symmetry grade of 2.

Table 1–Proposed objective symmetry grade (OSG) based on percent difference of the mean lower and greater peak vertical force values.

Percent Difference of Mean Affected / Unaffected Pelvic Limb PVF	OSG
0.00-7.9%	0
8.0-26.9%	1
27.0-45.9%	2
46.0-64.9%	3
65.0-83.9%	4
84.0-100% (Non-weightbearing)	5

Kinematic Measurement Protocol

Kinematic gait analysis was performed simultaneously with kinetic data recording using a commercially available motion analysis system (Peak Performance Technologies, Inc., Centennial, CO). The commercial software system used an absolute reference frame based on the global Cartesian system, in which the x-axis corresponded to the principal cranial-caudal direction, the y-axis corresponded to the medial-lateral direction, and the z-axis corresponded to the vertical direction (Figure 1).

The system was calibrated before each recording session by capturing 4 stationary and 2 dynamic reflective spheres on a reference frame and a reference wand, respectively (2 cm diameter; Peak Performance Technologies, Inc., Centennial, CO). This calibration process yielded a designated three-dimensional test space (an area measuring 6.3m x 6.3m x 6.3m) that was centered directly over the force platform. The 4 stationary spheres represented the origin, the x-axis and the y-axis. The 2 x-axis spheres measured 40 cm and 80 cm from the origin, respectively, and the 1 y-axis sphere measured 70 cm from the origin. The 2 dynamic spheres on the wand measured 90 cm apart. All measurements were made from the center of all spheres. The 6 reflective spheres represented known coordinates for calibration of the designated three-dimensional test space and were recorded for 1 minute while the wand was moved throughout the test space. The calibration process reported error measurements at a distance of 500 millimeters within a field of view of the 6 spheres with known coordinates, and was considered adequate if the error measurements were $\leq$ 1 millimeter for each sphere (0.2% error).

An area of hair (5 cm^2) was clipped from each dog at specific anatomic landmarks. These landmarks included the sagittal crest of the skull, bilateral dorsal aspects of the scapular spine, bilateral scapulohumeral joints, bilateral humeroulnar joints, bilateral lateral antebrachiocarpal joints, bilateral lateral metacarpal-phalangeal joints, a dorsal midline point measured 8 cm cranial to the thoraco-lumbar spinal junction, the thoraco-lumbar spinal junction, a dorsal midline point measured 8 cm caudal to the thoraco-lumbar spinal junction, bilateral cranial dorsal iliac spines, bilateral ischiatic tuberosities, bilateral greater trochanters, bilateral femorotibial joints, bilateral tarsocrural joints and bilateral lateral metatarsal-phalangeal joints**.** The reflective spheres were securely attached to the anatomic landmarks of each dog by the same investigator (DAH) with nonirritant adhesive (Figure 2). Four digital infrared cameras (Philips LTC-5000; Philips, Inc., Centennial, CO) were used to capture marker locations on each dog as they trotted along the designated gait runway, crossing directly over the force platform. Each camera had 48 annularly placed light-emitting diodes around the lens for improved brightness and uniformity of light. Sample frequency of each camera was 60 Hz. Marker locations were recorded by use of the motion analysis program and software (KineCalc for Motus 8.3, Peak Performance Technologies, Inc., Centennial, CO) was used to calculate all of the defined variables. Three-dimensional coordinates of marker trajectories were smoothed by a Butterworth 4^{th}-order low-pass filter at a cut off frequency of 6 Hz according to the manufacturer's recommendations (KineCalc for Motus 8.3, Peak Performance Technologies, Inc., Centennial, CO).

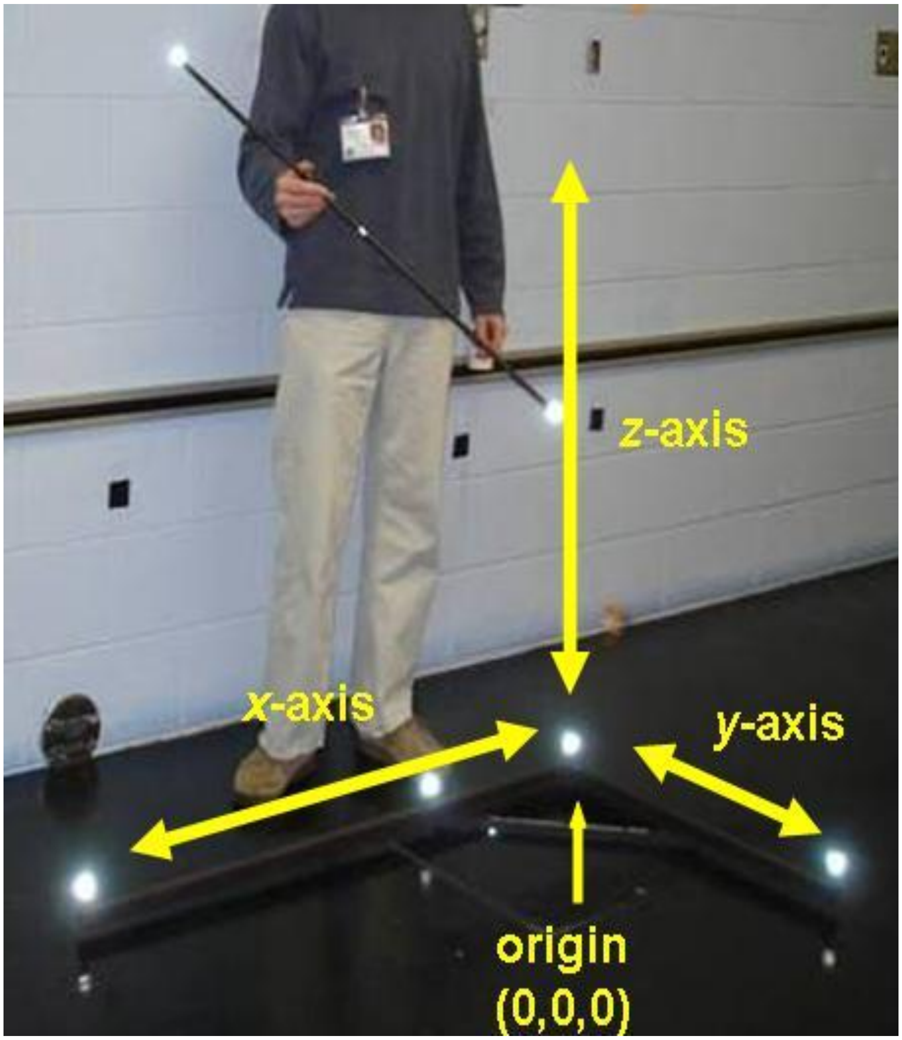

Figure 4 – Picture of reference frame and reference wand indicating calibration test space directly over the force platform. The small yellow arrow indicates the origin and the large yellow arrows represent the *x*-axis, *y*-axis, and *z*-axis, respectively.

Figure 5 – Picture of reflective spheres placed on the left side of the animal representing specific anatomic landmarks. Thoracic and pelvic limb markers were not used for the current study.

Five valid trials were recorded for both left and right sides while each dog trotted along the 10.68 meter designated gait runway, passing through the calibrated three-dimensional test space and directly over the force platform. For study purposes, one pelvic limb stride was defined by one complete stance phase (i.e. from paw strike to toe off) and one complete sequential swing phase (i.e. from toe off to paw strike). Data for 2 consecutive pelvic limb strides were collected per trial. For study purposes, the sequence of the 2 complete pelvic limb strides was defined as the pelvic limb gait cycle. Both vertical ground reaction forces for the 2nd rear limb strike and digital tracking of a reflective marker secured to the lateral metatarsal-phalangeal joint region throughout the gait cycle was used to mark initiation and termination of both the stance and swing phases. After trials were obtained for each dog trotting through the test space, the digital video files were processed by use of specialized motion analysis software to identify locations of all reflective markers in 3-dimensions.

Measurements: Head Linear Vertical Displacement (HLVD)

HLVD during 2 strides per trial was established by tracking the reflective marker secured on the sagittal crest of the skull (Figure 3) in the vertical (Z coordinate) axis while trotting over ground. The HLVD in meters from the surface of the gait runway was calculated for each stride and maximal and minimal vertical displacement values were determined using specialized computer software. The mean of the maximal and minimal values for the 2 consecutive strides was calculated for each dog for the 5 valid trials, and the mean of these values (i.e. mean of the means) ± SD for maximum and minimum displacement values for HLVD were determined for the pelvic limb gait cycles with lower and greater degrees of weight bearing. Mean HVLD total motion values for the gait cycles were determined by subtracting the minimum values from the maximum values.

Measurements: Pelvis Linear Vertical Displacement (PLVD)

PLVD during 2 strides per trial was established by tracking the marker secured on the ischiatic tuberosity (Figure 3) in the vertical (Z coordinate) axis while trotting over ground. The PLVD, in meters from the surface of the gait runway, was calculated for each stride and maximal and minimal values were determined using specialized computer software. The mean of the maximal and minimal values for the 2 consecutive strides was calculated for each dog for the 5 valid trials, and the mean of these values (i.e. mean of the means) ± SD for maximum and minimum displacement values for PLVD were determined for the pelvic limb gait cycles with lower and greater degrees of weight bearing. Mean PLVD total motion values for the gait cycles were determined by subtracting the minimum values from the maximum values.

Measurements: Thoraco-Lumbar Lateral Angular Displacement (TL-LAD)

For study purposes the thoraco-lumbar joint angle (T-L Angle) was defined by the positions of the 3 reflective markers on the dorsal midline of the T-L region (Figure 4) to establish 2 distinct segments. Segment 1 was created by a computer-generated line between marker number one (8 cm cranial to the thoraco-lumbar junction) and marker number two (at the thoraco-lumbar junction). Segment 2 was created by a computer-generated line between marker number two and marker number three (8 cm caudal to the thoraco-lumbar junction). Using the Cartesian global coordinate system and computer software, the T-L angle in degrees was calculated by tracking the 2 segments (Figure 4) in the horizontal (Y coordinate) axis. A computer-generated angle of reference (Figure 5) was defined as 180^0 when the 3 markers were in a straight line from cranial to caudal, and any deviation from this angle of reference was defined as the thoraco-lumbar lateral angular displacement (TL-LAD). Based on the designated origin of the calibration reference frame (Figure 1), when TL-LAD occurred to the left side of the animal (i.e. to the left of the 180^0 reference angle), the computer-generated angular values were less than 180^0 (Figures 5 and 6). When TL-LAD occurred to the right side of the animal (i.e. to the right of the 180^0 reference angle), the computer-generated angular values were greater than 180^0 (Figures 5 and7). Maximum and minimum values were generated for 2 strides using computer software. The mean of the maximal and minimal values for the 2 consecutive strides was calculated for each dog for the 5 valid trials, and the mean of these values (i.e. mean of the means) ± SD for maximum and minimum displacement values for T-L LAD were determined for the pelvic limb gait cycles with lower and greater degrees of weight bearing. For study purposes the numerical difference from the 180^0 reference angle was calculated for each of the mean maximum and minimum displacement values for all 27 dogs and represents the T-L LAD occurring throughout the gait cycles for both pelvic limbs. Mean summary statistics for all dynamic measurements are reported in Table 2.

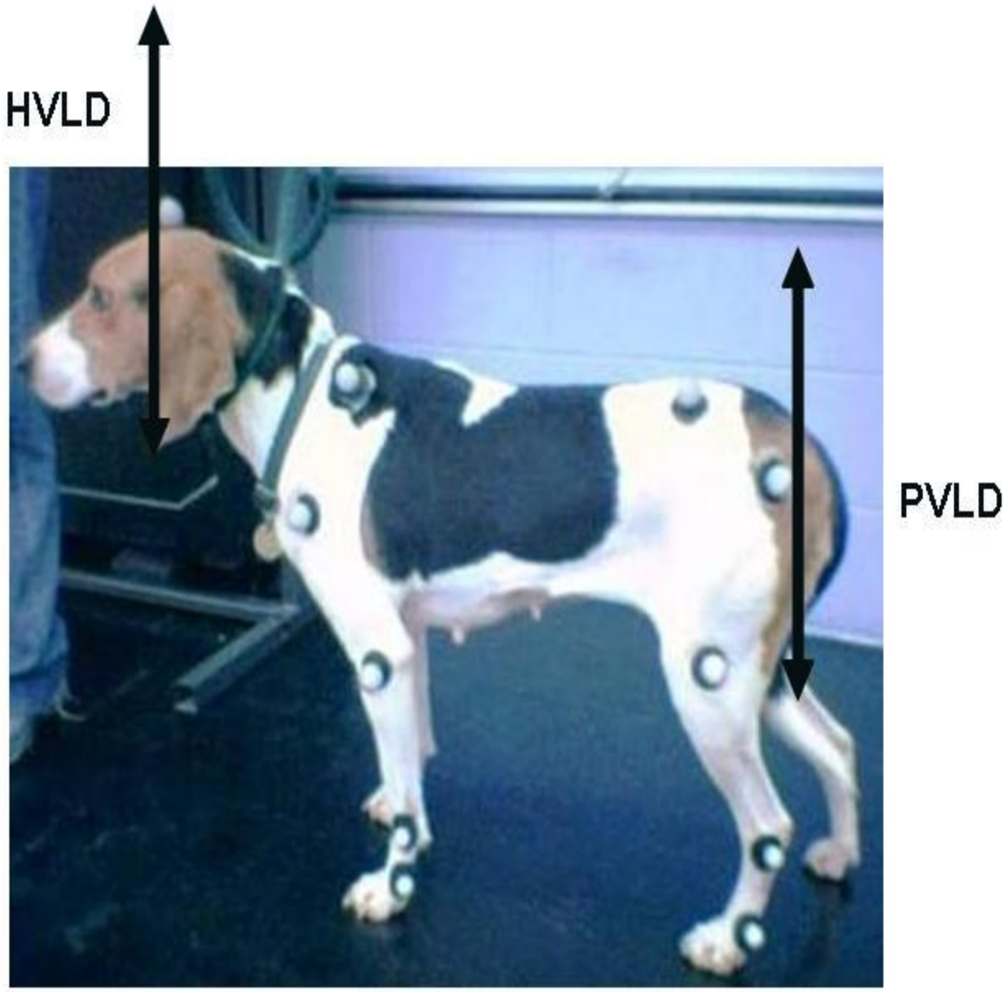

Figure 6 – Picture of reflective markers placed on the study subjects for kinematic analysis. The 2 black arrows indicate reflective markers placed on the sagittal crest of the skull and ischiatic tuberosity for tracking head linear vertical displacement (HLVD) and pelvis linear vertical displacement (PLVD), respectively. Thoracic and pelvic limb markers were not used in the current study.

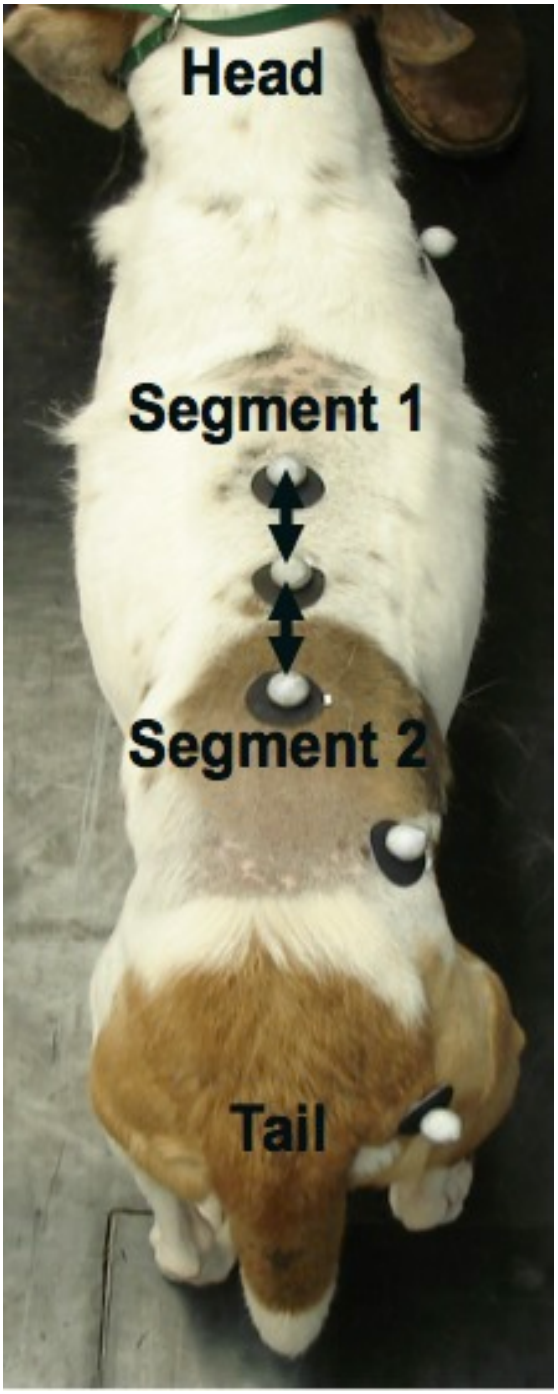

Figure 7 – Picture of reflective markers placed on the dorsal midline of the T-L region to establish computer-generated segments 1 and 2 represented by the black arrows.

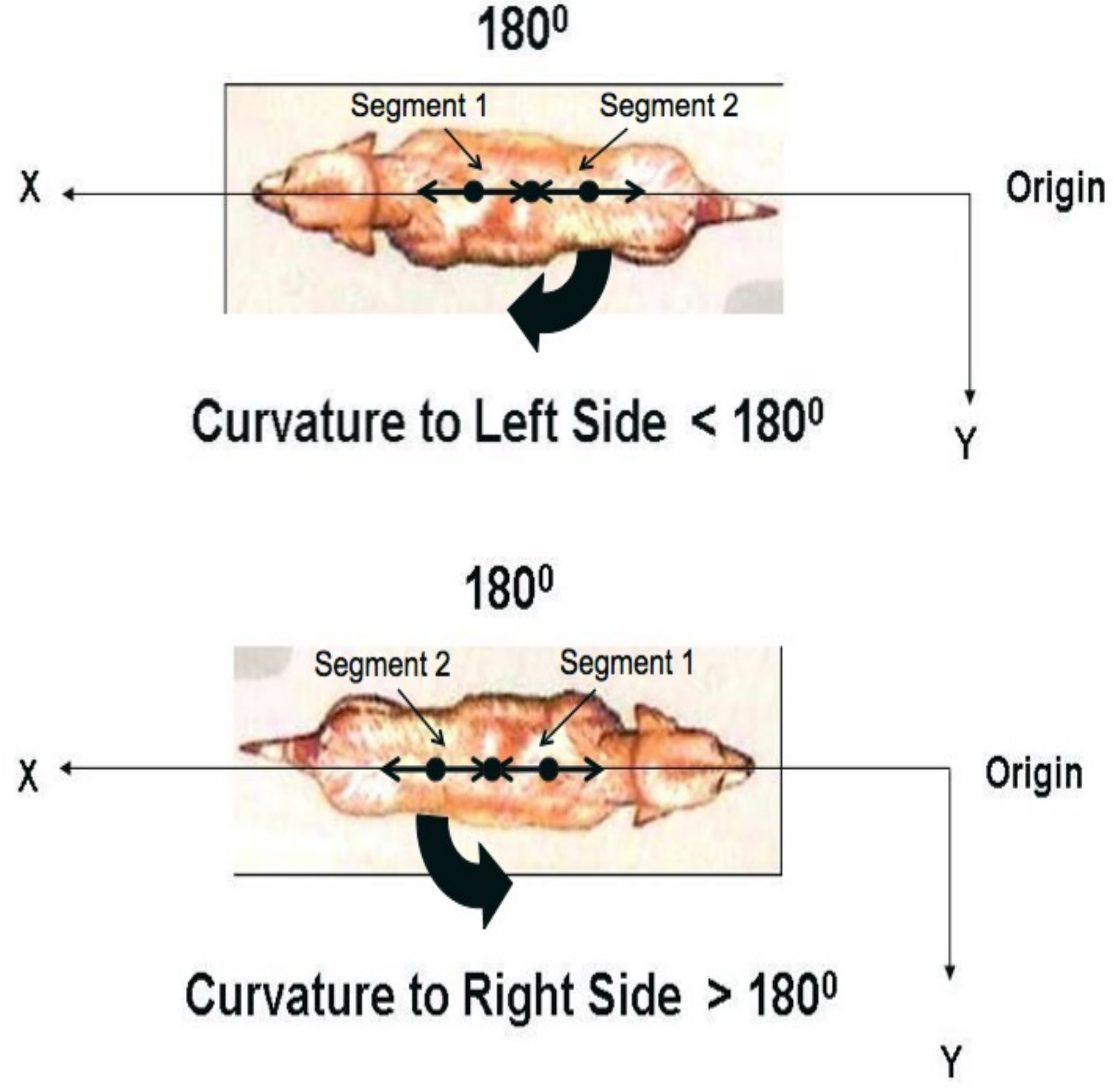

Figure 8 – Illustration of computer-generated angle of reference for thoraco-lumbar lateral angular displacement (T-L LAD). When segments 1 and 2 (large black arrows along the x-axis) are in a straight line, the computer-generated angle resulted in 180^{o} (small black arrow along the x-axis). When T-L LAD occurred to the left (top figure), the computer-generate angles were< 180^{o}. When T-L LAD occurred to the right (bottom figure), the computer-generate angles were> 180^{o}.

Figure 9 – Picture of reflective markers placed on the dorsal midline of the T-L region for kinematic analysis. The black arrows represent thoraco-lumbar lateral angular displacement (T-L LAD) to the left.

Figure 10 – Picture of reflective markers placed on the dorsal midline of the T-L region for kinematic analysis. The black arrows represent thoraco-lumbar lateral angular displacement (T-L LAD) to the right.

Table 2 – Mean + SD values for kinetic and kinematic variables for the pelvic limbs at a trot with lower and greater degrees of weight bearing.

Variable	Lower degree of weight bearing	Greater degree of weight bearing
Forward Velocity (m/s)	1.87 + 0.10	1.89 + 0.11
Acceleration (m/s/s)	0.023 + 0.17	0.021 + 0.17
Peak Vertical Force (% of body weight)	66.50 + 8.0*	71.39 + 7.88
Vertical Impulse (% of body weight)	8.46 + 0.88*	8.95 + 0.84
Maximum HLVD (meters)	0.55 + 0.09	0.53 + 0.12
Minimum HLVD (meters)	0.51 + 0.08	0.49 + 0.11
Total motion of HLVD (meters)	0.037 + 0.010	0.036 + 0.014
Maximum PLVD (meters)	0.57 + 0.09	0.57 + 0.13
Minimum PLVD (meters)	0.47 + 0.11	0.43 + 0.13
Total motion of PVLD (meters)	0.095 + 0.054	0.134 + 0.086*
Maximum T-L LAD (degrees)	8.73 + 5.25*	5.51+ 6.51
Minimum T-L LAD (degrees)	-4.98 + 4.51	-8.29 + 7.26

* Value is significantly ($P < 0.05$) different between pelvic limbs with lower and greater degrees of weight bearing.

CHAPTER 3

Data Analysis

Statistics

All computations were performed using a commercially available statistical software program (SAS, version 9.1, SAS Inc., Cary, NC). All data were tested by the Shapiro-Wilk test and were normally distributed. The mean PVF and VI values for 5 valid trials for each dog was calculated and used to identify weight-bearing asymmetry between right and left pelvic limbs at a trot. These mean values were compared using a paired Student's *t*-test to determine significance. Mean maximum, minimum and total range of motion HLVD, PLVD, and T-L LAD values of the 5 valid trials were calculated for each dog. These mean values were then used to compare differences between the pelvic limbs with lower or greater degrees of weight bearing using a paired Student's *t*-test. Simple linear regression was used to determine if a relationship existed between mean lower and greater peak vertical force (PVF) and vertical impulse (VI) of the pelvic limbs and the mean HLVD, PLVD, and T-L LAD values. Values of $P < 0.05$ were considered significant.

CHAPTER 4

RESULTS

Ground Reaction Forces and Limb Designation

All 27 dogs completed the study. Mean body weight was 21.5 ± 2.5 kg (47.3 ± 5.5 lbs.) and estimated mean age was 5.3 ± 3.3 years. The mean PVF value for 5 valid trials for each dog was calculated and used to identify weight-bearing asymmetry between right and left pelvic limbs at a trot. The pelvic limb that had the lower mean PVF value was designated the limb with a ‘lower’ degree of weight bearing, and the contralateral pelvic limb was designated as the limb with a ‘greater’ degree of weight bearing. Twelve of the 27 dogs evaluated had lower weight bearing on the right pelvic limb. The remaining 15 dogs had lower weight bearing on the left pelvic limb. Mean PVF in the lower weight bearing limbs (66.50 ± 8.0) was significantly different (Figure 11) than that of the greater weight bearing limbs (71.39 ± 7.88; $P < 0.001$), and mean vertical impulse was significantly different (Figure 12) in the lower weight bearing limb (8.46 ± 0.88) compared to the greater weight bearing limb (8.95 ± 0.84; $P < 0.003$).

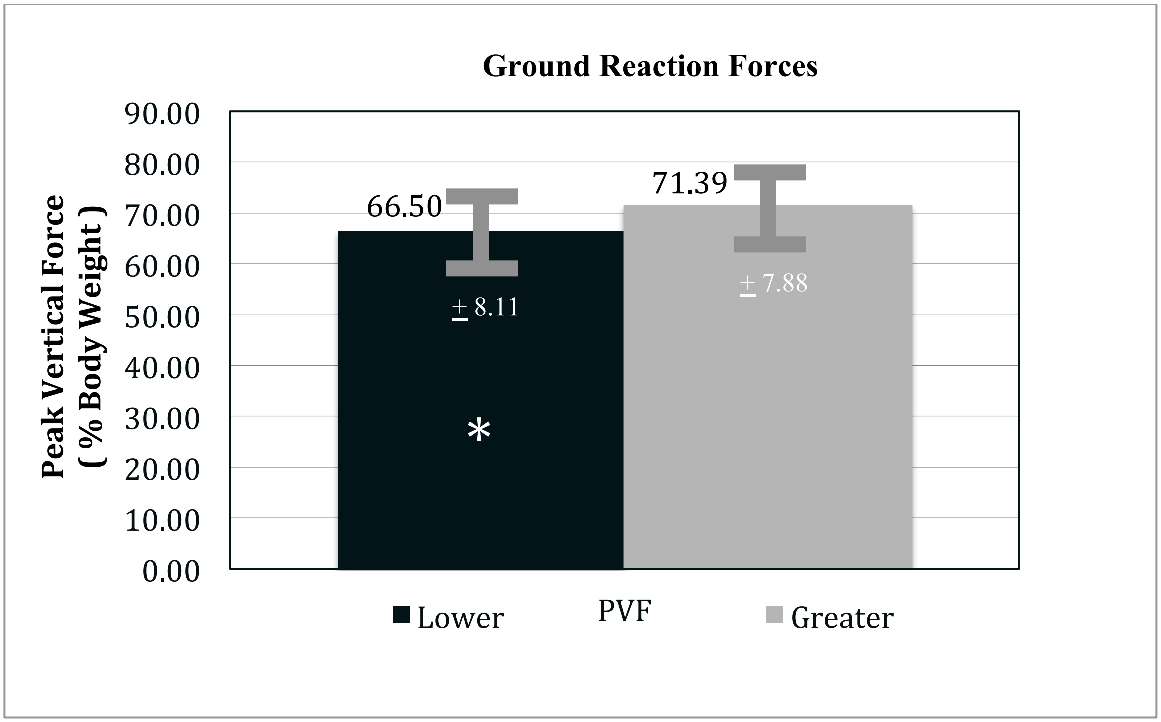

Figure 11 – Bar graph of mean peak vertical force (PVF) values with standard deviation bars reported during the stance phase of the gait cycle for lower and greater weight bearing in the pelvic limbs of all 27 dogs. *Significant difference ($P < 0.001$).

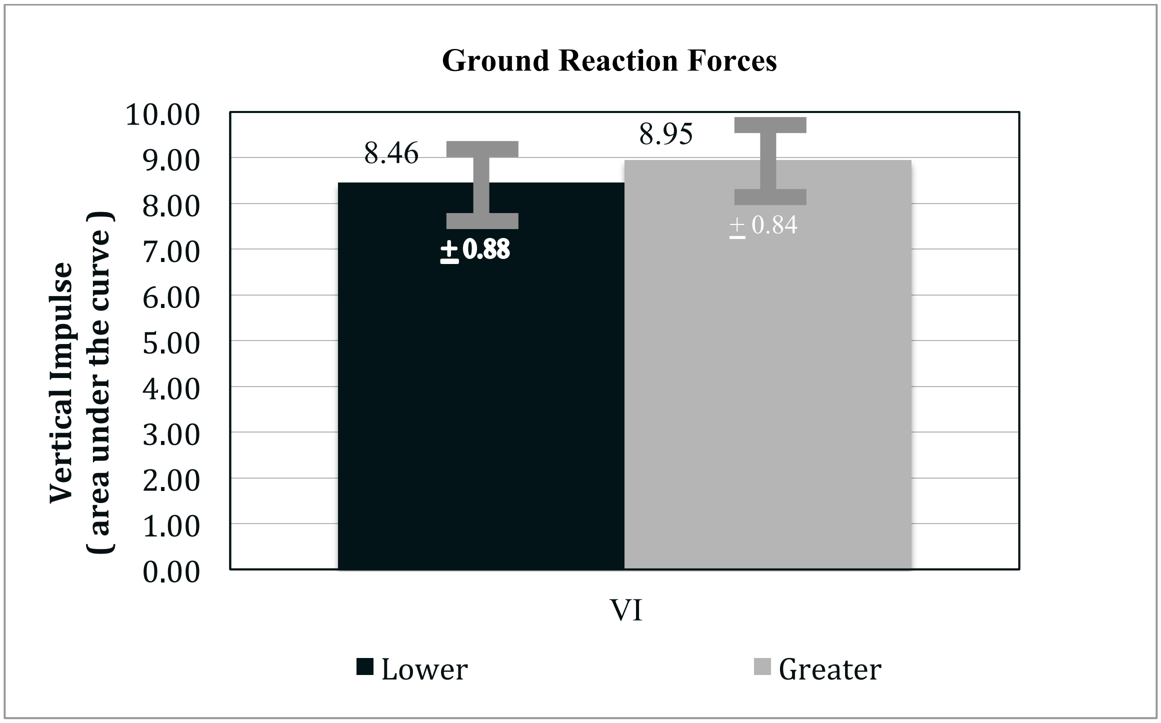

Figure 12 – Bar graph of mean vertical impulse (VI) values with standard deviation bars reported during the stance phase of the gait cycle for the for the lower and greater weight bearing in the pelvic limbs of all 27 dogs. *Significant difference (P < 0.03).

Objective Symmetry Grade Assignments

Objective symmetry grades (OSG) for all 27 dogs are provided in Table 3. Fourteen of the 27 dogs evaluated were assigned an OSG of 0, which represents an 0.0 – 7.9% difference in weight bearing symmetry between the pelvic limbs, and 13 of the 27 were assigned an OSG of 1, which represents an 8.0 – 26.9% difference in weight bearing symmetry. None of the 27 dogs had greater than 26.9% difference in weight bearing symmetry and were not assigned an OSG greater than 1.

Table 3–Objective symmetry grade (OSG) for all 27 dogs.

	Mean PVF				
Dog*	Affected	Unaffected	Ratio	Percent Asymmetry (1 - Ratio)	OSG
1	60.42	72.14	0.84	16	1
2	63.59	71.32	0.89	11	1
3	67.28	68.81	0.98	2	0
4	54.77	59.48	0.92	8	1
5	70.70	79.36	0.89	11	1
6	76.08	76.57	0.99	1	0
7	85.26	88.79	0.96	4	0
8	62.13	65.12	0.95	5	0
9	75.19	78.03	0.96	4	0
10	57.96	66.36	0.87	13	1
11	59.32	62.06	0.96	4	0
12	77.89	85.42	0.91	9	1
13	62.85	65.86	0.95	5	0
14	52.69	58.96	0.89	11	1
15	64.65	68.90	0.94	6	0
16	61.62	62.10	0.99	1	0
17	67.17	73.97	0.91	9	1
18	59.62	65.40	0.91	9	1
19	67.79	69.48	0.98	2	0
20	59.29	59.88	0.99	1	0
21	69.77	78.07	0.89	11	1
22	69.70	75.38	0.92	8	1
23	68.46	71.55	0.96	4	0
24	70.80	78.91	0.90	10	1
25	74.33	76.04	0.98	2	0
26	57.55	69.20	0.83	17	1
27	78.89	80.40	0.98	2	0

*Dogs 1-9 were the normal group, dogs 10-18 were the TPLO group and dogs 19-27 were the LFS group.

Head Linear Vertical Displacement (HLVD)

Mean maximum, minimum and total motion values for HLVD for the pelvic limbs with a lower degree of weight bearing were 0.55 ± 0.09, 0.51 ± 0.08, and 0.037 ± 0.010 meters, respectively, and 0.53 ± 0.12, 0.49 ± 0.11, and 0.036 ± 0.014 meters, respectively, for the pelvic limbs with a greater degree of weight bearing. There were no significant differences in any mean HLVD values between the pelvic limbs with lower and greater degrees of weight bearing (Figure 13). Figure 14 is a graph of head linear vertical displacement (HLVD) of a dog during one stance phase and one swing phase of the right pelvic limb with a lower degree of weight bearing and an objective symmetry grade of 1, demonstrating a sinusoidal pattern over time.

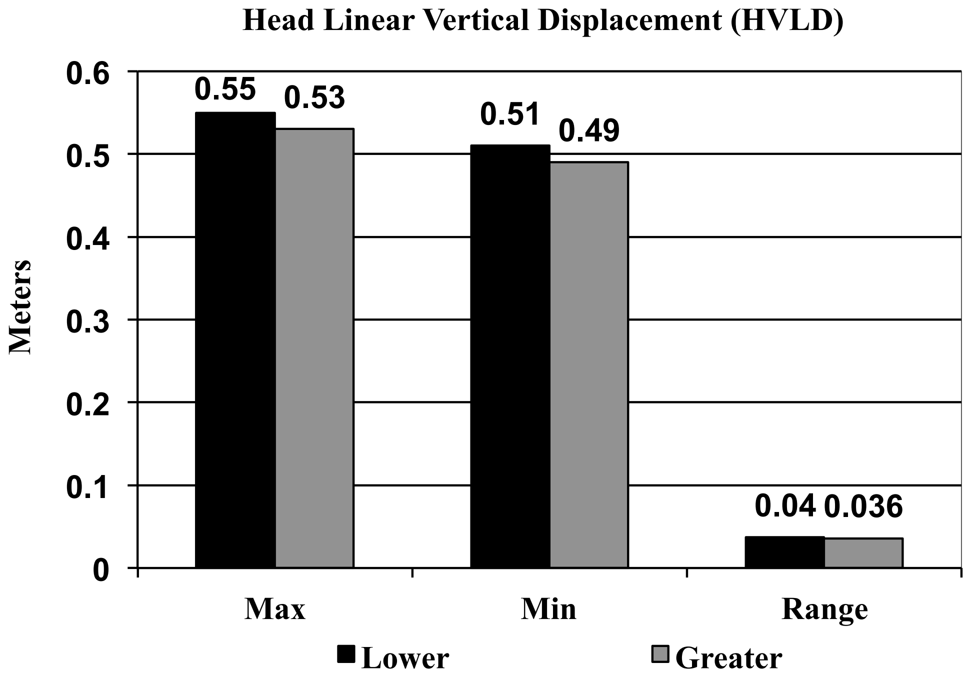

Figure 13– Bar graph of mean maximum, minimum and total motion values for head linear vertical displacement (HVLD) reported during the gait cycle of the pelvic limbs with lower and greater degrees of weight bearing for all 27 dogs. No significant differences detected (P > 0.05).

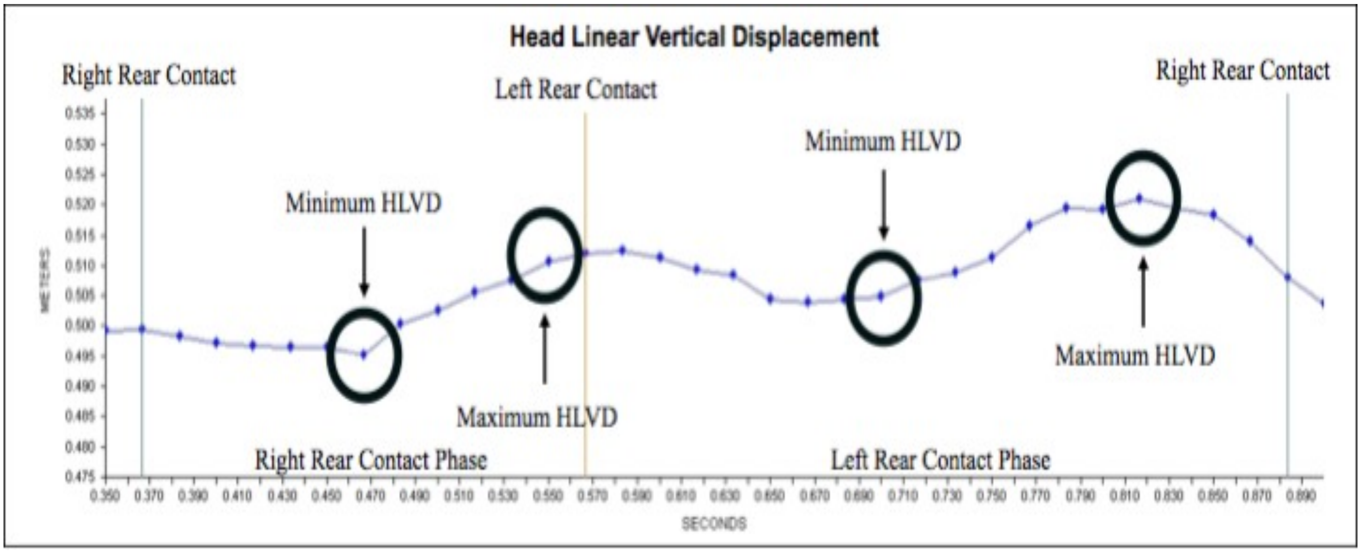

Figure 14 – Graph of head linear vertical displacement (HLVD) of a dog during right contact phase (i.e. left swing phase) and left contact phase (i.e. right swing phase) with an objective symmetry grade of 1, demonstrating a sinusoidal pattern over time. Circles with arrows indicate minimum and maximum HLVD values from the gait runway surface, respectively, occurring at midstance of the contact phase and just before initiation of the respective swing phase.

Pelvis Linear Vertical Displacement (PLVD)

Mean maximum, minimum and total motion values for PLVD values for the pelvic limbs with a lower degree of weight bearing were 0.57 ± 0.09, 0.47 ± 0.11, and 0.095 ± 0.054 meters, respectively, and 0.57 ± 0.13, 0.43 ± 0.13, and 0.134 ± 0.086 meters, respectively, for the pelvic limbs with a greater degree of weight bearing. Mean total motion for PLVD was significantly greater on the side with the greater degree of weight bearing ($P < 0.05$), however no significant differences in mean maximum or minimum PLVD values between the pelvic limbs with lower or greater degrees of weight bearing were detected (Figure 15). Nine of the 27 dogs evaluated (33%) demonstrated a 2- to 4-fold increase in total motion for PVLD on the side with a greater degree of weight bearing compared to the contralateral side. The mean total motion for PVLD for these 9 dogs was 0.20 ± 0.11 meters for the side with a greater degree of weight bearing and 0.06 ± 0.03 meters for the contralateral side. Maximum and minimum PVLD values between pelvic limbs in one dog with an objective symmetry grade of 1 is represented schematically in Figures 16 and 17, respectively.

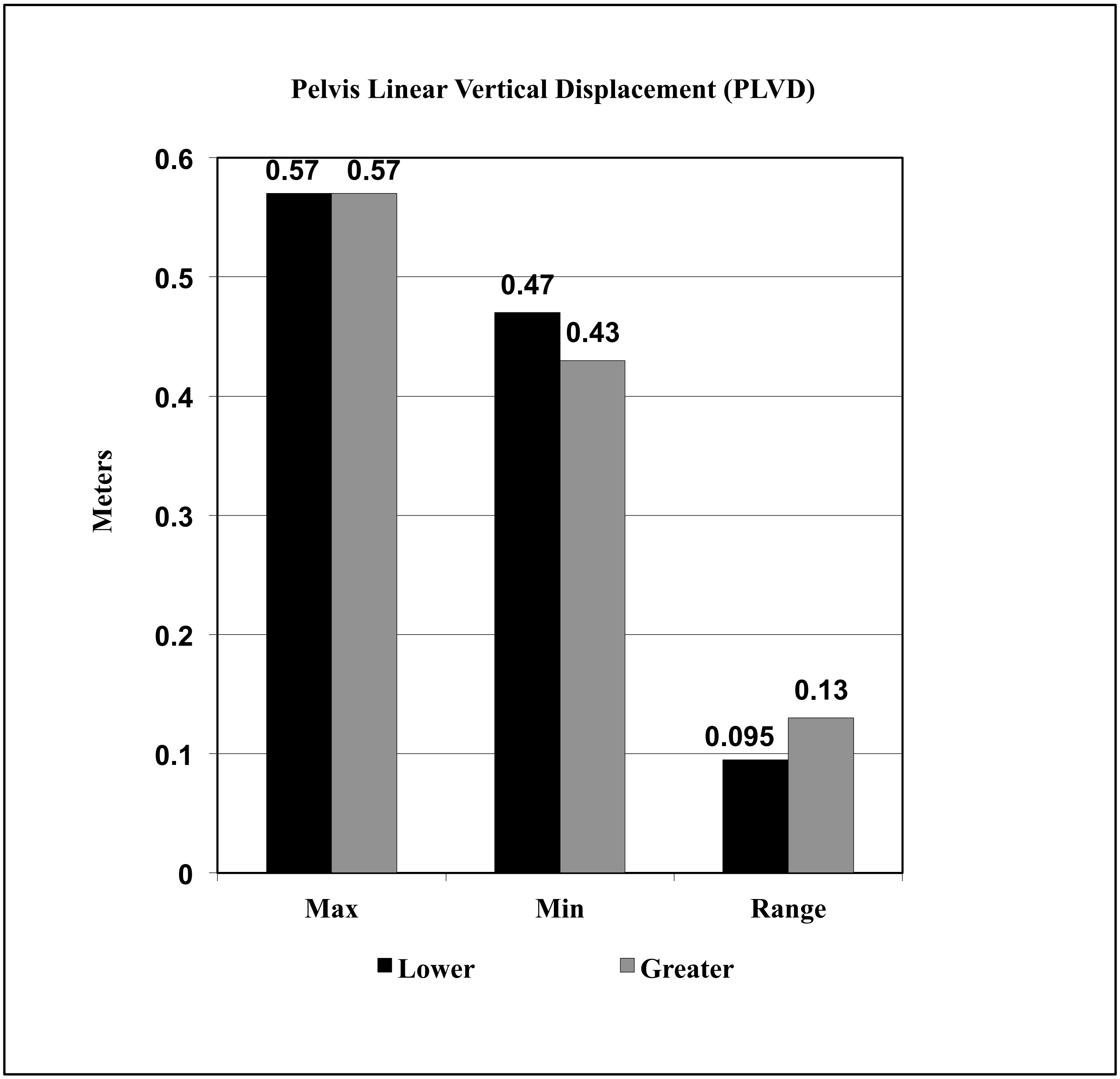

Figure 15 – Bar graph of mean maximum, minimum and total motion values for pelvis linear vertical displacement (PVLD) reported during the gait cycle of the pelvic limbs with lower and greater degrees of weight bearing for all 27 dogs. *Significant difference detected ($P < 0.05$).

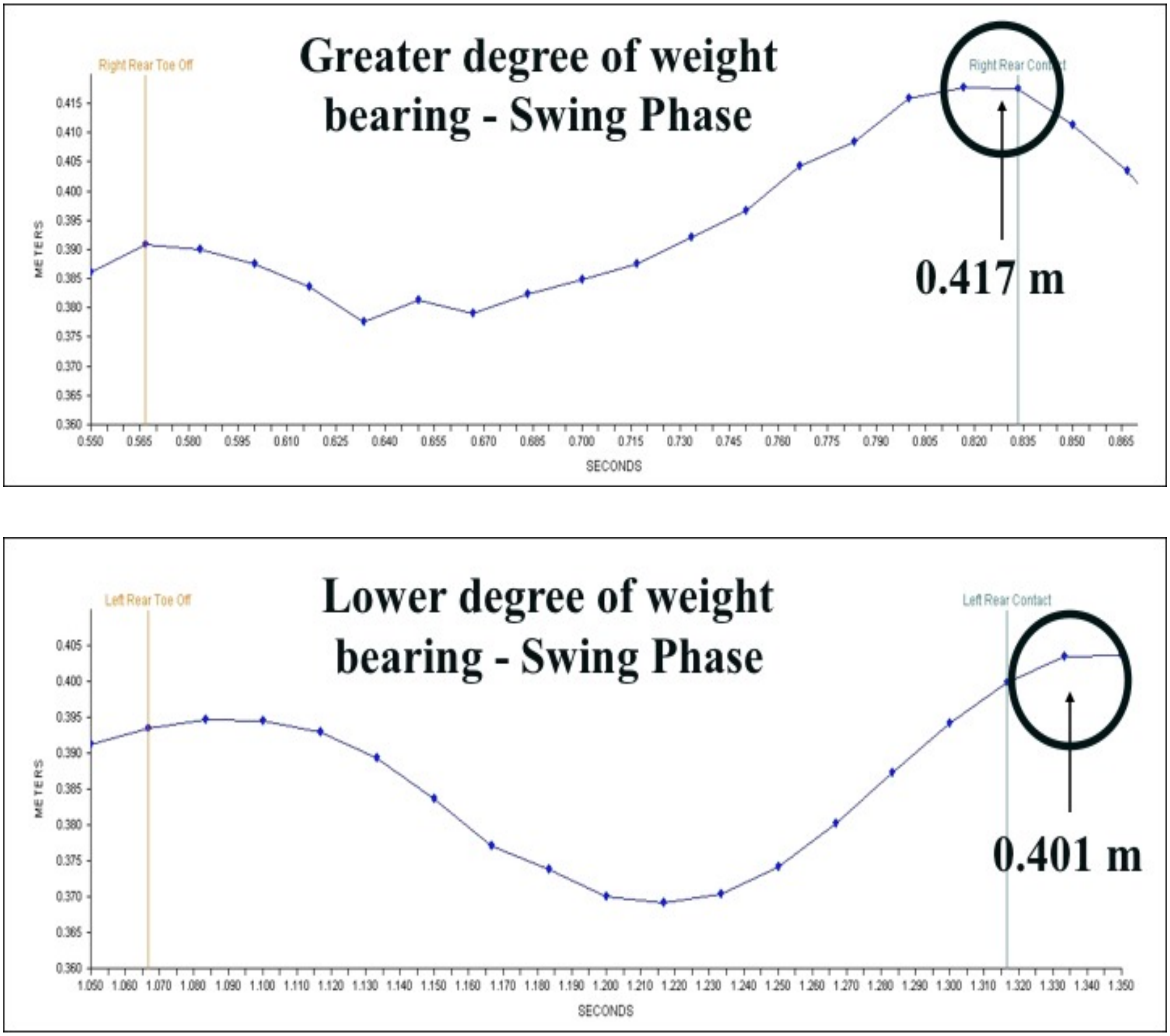

Figure 16 – Graphs of pelvis linear vertical displacement (PLVD) during one swing phase of the pelvic limb with greater and lower degrees of weight bearing, respectively, in a dog with an objective symmetry grade of 1. Circles with arrows indicate maximum PLVD values occurring near the initiation of the contact phase of the respective limb.

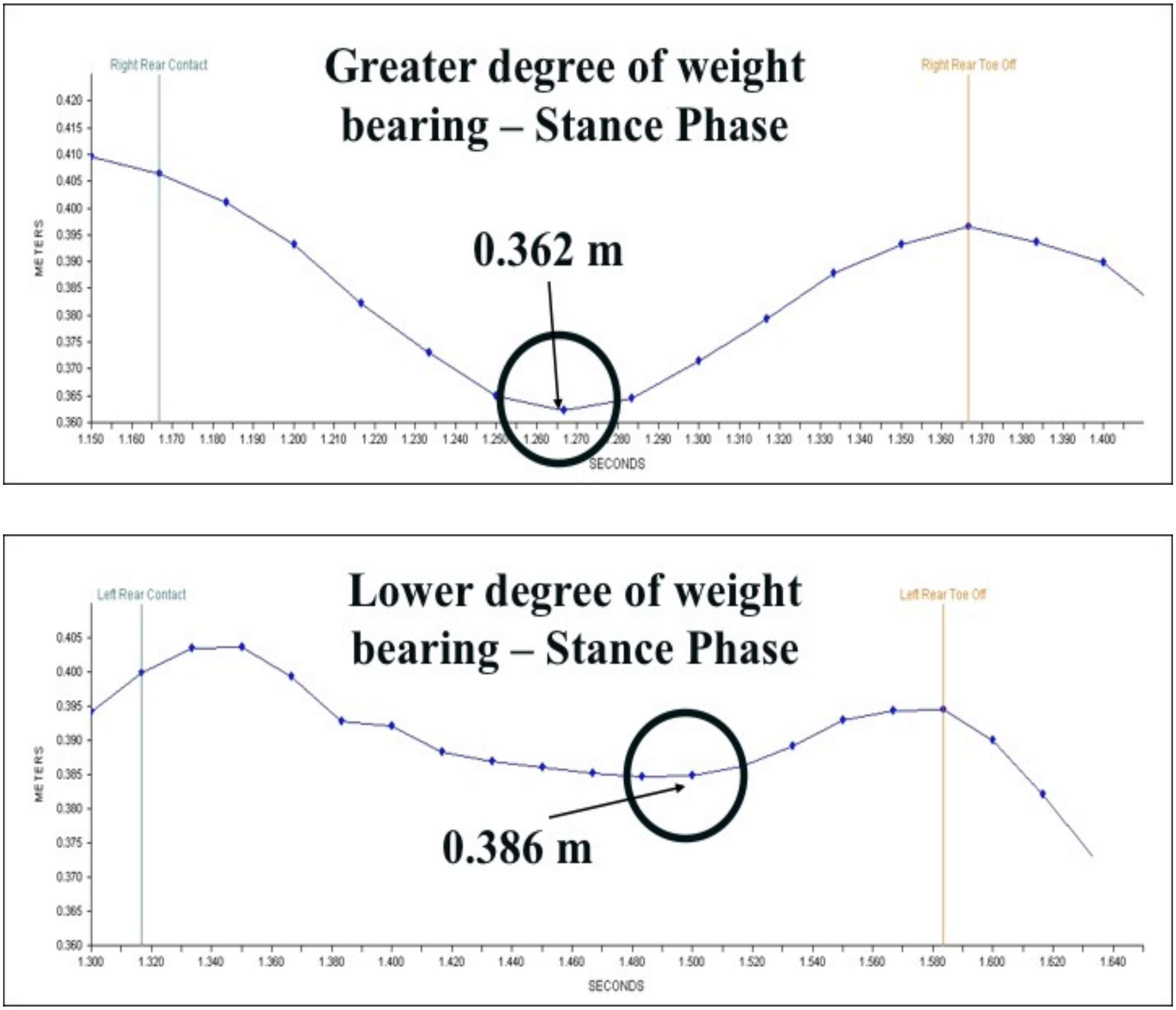

Figure 17– Graphs of pelvis linear vertical displacement (PLVD) during one stance phase of the pelvic limb with greater and lower degrees of weight bearing, respectively, in a dog with an objective symmetry grade of 1. Circles with arrows indicate minimum PLVD values occurring near mid-stance of the respective limb.

Thoracо-Lumbar Lateral Angular Displacement (T-L LAD)

Maximum and minimum values for T-L LAD were 8.73 ± 5.25 and -4.98 ± 4.51, respectively, for the pelvic limb with a lower degree of weight bearing. Maximum and minimum values for T-L LAD were 5.51 ± 6.51, -8.29 ± 7.26, respectively, for the limb with a greater degree of weight bearing. Maximum T-L LAD values were significantly different (P value < 0.05) between the pelvic limbs and the degree of weight bearing (Figure 18). Mean T-L LAD from 180^0 values between the limbs with the lower and greater degrees of weight bearing in one dog with an objective symmetry grade of 1 is represented schematically in Figure 19.

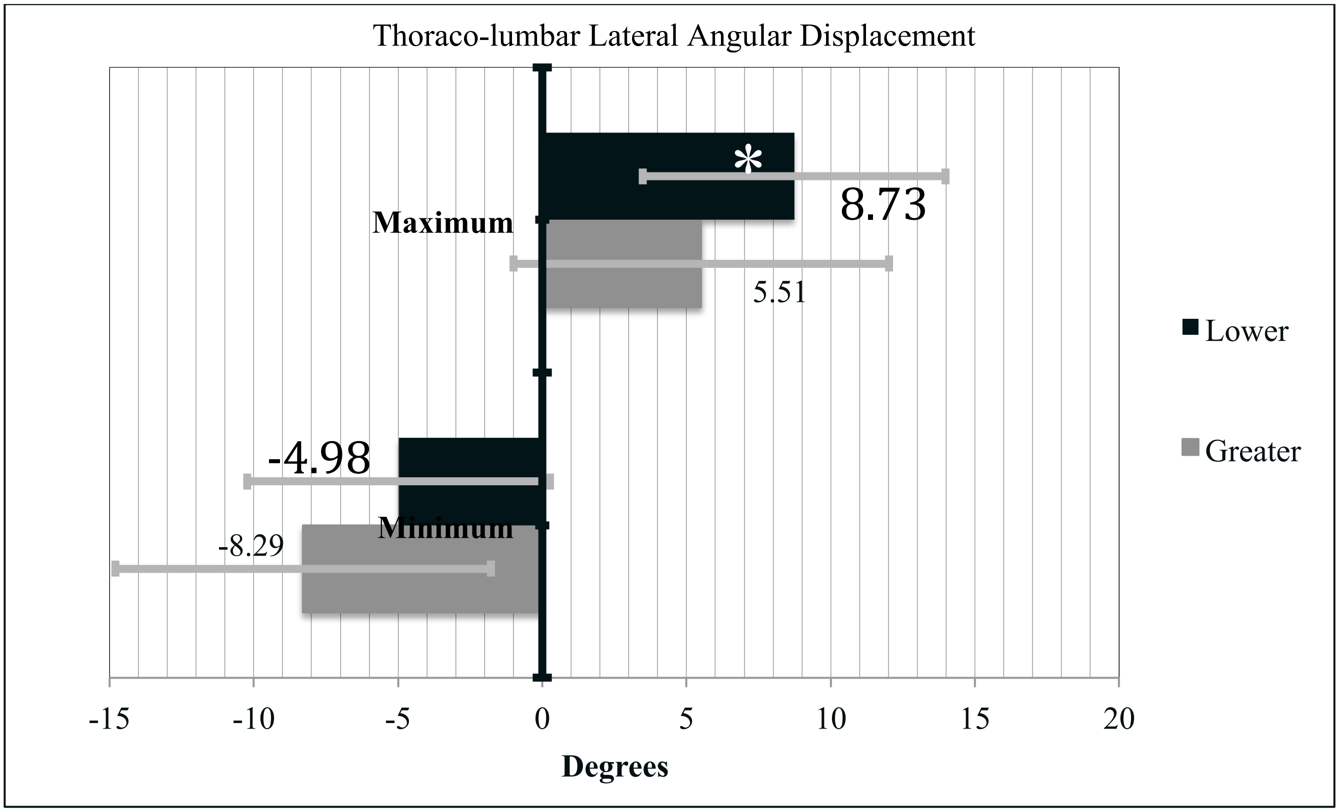

Figure 18 – Bar graph of mean maximum and minimum values with standard deviation bars for thoraco-lumbar lateral angular displacement (T-L LAD) reported during the gait cycle for the pelvic limbs with lower and greater degrees of weight bearing for all 27 dogs. *Significant difference ($P < 0.05$).

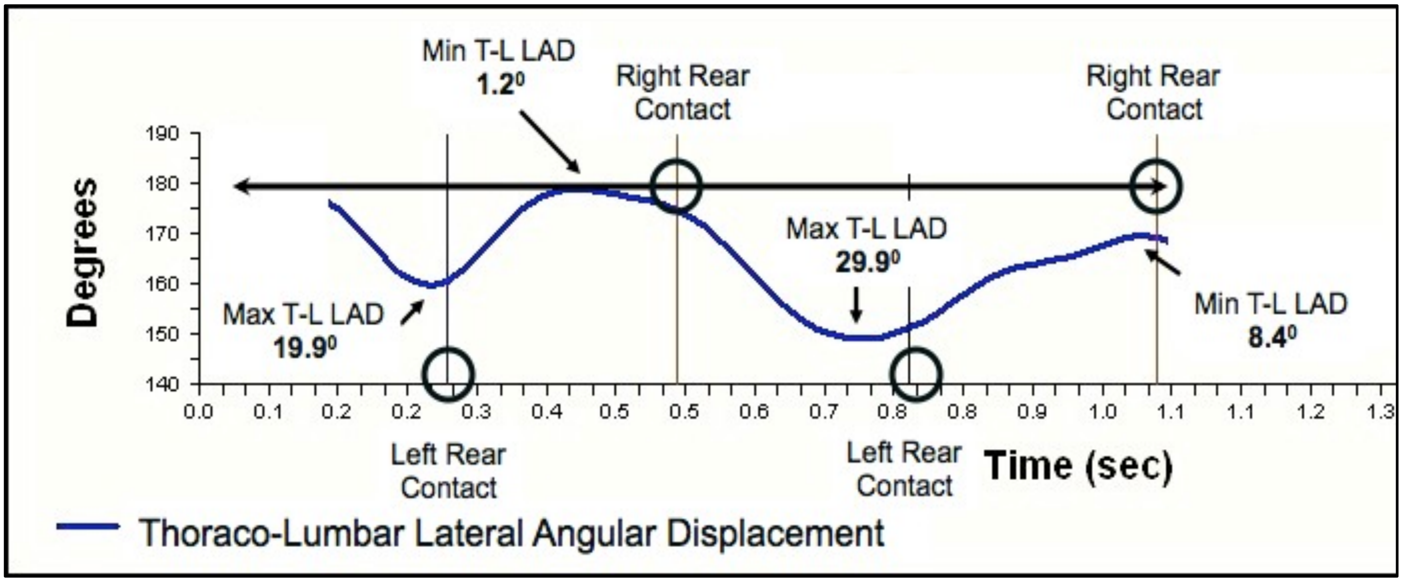

Figure 19 – Graph of thoraco-lumbar lateral angular displacement (T-L LAD) from 180° (horizontal arrow) throughout two contact phases of the left pelvic limb in one dog with an objective symmetry grade of 1. Black circles indicate left and rear contacts, respectively. Black arrows indicate T-L LAD values for the left limb (lower degree of weight bearing) just prior to contact phases and right limb (greater degree of weight bearing) just prior to the contact phase.

Eleven of the 27 dogs evaluated (41%) demonstrated a 2- to 10-fold increase in the mean T-L LAD from 180^0 on the side with a lower degree of weight bearing compared to the side with a greater degree of weight bearing during the swing phase of the gait cycle. The mean T-L LAD values from 180^0 for these 11 dogs were 11.16 ± 3.83 degrees for the side with a lower degree of weight bearing and 0.63 ± 3.46 degrees for the side with a greater degree.

No significant correlations were detected between mean PVF and VI of the pelvic limbs with lower or greater degrees of weight bearing and mean HLVD, PLVD, and T-L LAD values.

CHAPTER 5

DISCUSSION

We evaluated mild asymmetrical weight bearing of the pelvic limbs in trotting dogs using force platform analysis. We also used kinematic analysis to characterize vertical motion of the head and pelvis, and lateral motion of the thoraco-lumbar spine throughout the gait cycle. Our findings support our hypothesis that dogs with subtle asymmetric weight bearing of the pelvic limbs demonstrate compensatory motions, including a greater range of pelvis linear vertical displacement (PLVD) on the side with a greater degree of weight bearing, and greater thoraco-lumbar lateral angular displacement (TL-LAD) toward the side with a lower degree of weight bearing while trotting. No differences in mean head linear vertical displacement (HLVD) were detected, however. We also hypothesized that the magnitude of these compensatory movements would positively correlate with the degree of weight-bearing asymmetry while trotting. However, there were no significant correlations between the magnitude of HLVD, PLVD and TL-LAD and mean peak vertical force (PVF) or vertical impulse (VI) in dogs with subtle asymmetrical weight bearing of the pelvic limbs. To our knowledge the study reported here is the first to evaluate vertical linear displacement of the head in dogs with subtle weight bearing asymmetry of the pelvic limbs while trotting. We chose the sagittal crest of the skull as an anatomic landmark for uniform identification and relative ease to evaluate head movement. Considering that head and pelvic movements have been considered to be most important in diagnosing lameness is horses,[14] we were interested in determining if the head follows a similar pattern of vertical displacement and if it demonstrates similar compensatory motions during gait as compared with horses. Due to the large mass of the head and neck and the length from the body center of mass in horses, head movements are thought to influence load distribution to the limbs to minimize pain associated with the lameness and possibly prevent further damage to tissues.[88,89] Dropping the head when the sound foot lands and raising it when weight is placed on the lame limb is an indicator of forelimb lameness in horses.[14] However, the contribution of head movements in the overall compensation of lameness is difficult to determine; various explanations regarding how head movements influence limb loading have been suggested.[88] Most authors agree that a head nod may be associated with a pelvic limb lameness, but there is disagreement as to when this occurs.[90] Several studies have developed methods to objectively quantify the severity of equine lameness using head and trunk kinematic data.[11,13-15,90-94] One study in particular, by Buchner et al[14], evaluated kinematics of the head and trunk with various degrees of lameness. Maximum vertical displacement, velocity and acceleration of head, withers, tuber sacrale and both tuber coxae were quantified during different phases of gait. Their analysis indicated that the amplitude and symmetry of head movements significantly change with increasing lameness, and lameness-induced head movements are compensatory mechanisms. They suggested that horses could develop upward kinetic energy by exaggerated back rotation during the stance phase of the sound limb and reduce the lifting effort during the lame stance phase. In addition to the effect of exaggerated back rotation, they suggested that the head movements they observed may help the horse unload the lame pelvic limb during weight bearing. However, unlike a forelimb lameness, they stated the changes in head movement noted during a pelvic limb lameness were small and not significant before a lameness *degree* 2.[14] This leads us to the question of the importance of compensatory head movements associated with pelvic limb weight bearing asymmetry in dogs. The results of our study revealed that movement of the head in trotting dogs follows a sinusoidal pattern of vertical displacement over time (Figure 10). However, we were unable to detect a significant difference in mean maximum, minimum, or total motion for HLVD during asymmetrical weight bearing of the pelvic limbs in trotting dogs. One explanation for the findings in our study could be the inherent differences in conformation of the horse compared to the dog, especially regarding the distribution of mass among various body parts (i.e. head, trunk and extremities). The large mass of the head and neck and their protruding position relative to the body center of mass in horses may contribute to natural differences in head movement between the two species during ambulation. Studies similar to the 2-segment 2-dimensional inverse dynamic model of trotting horses by Vorstenbosch et al[88] would be indicated to determine if the static and dynamic effects of head movement play a major role in lameness compensation in dogs as well. Such studies could be faced with several limitations considering the variability of size and conformation inherent among different canine breeds. Another explanation for the lack of significance in our study is that we evaluated mild asymmetric weight bearing of the pelvic limbs. Vertical movements of the head may not be a sensitive indicator of pelvic limb weight bearing asymmetry, especially if only mild asymmetry is present. However, differences in vertical head movement during pelvic limb asymmetry may become more pronounced as the severity of asymmetry increases. Carefully designed studies evaluating vertical head movements in a similar population of dogs with objective symmetry grades ranging from 0 to 5 would be necessary to address this question.

Significant differences in the mean range of pelvic linear vertical displacement (PLVD) were detected between the degrees of weight bearing of the pelvic limbs in the study reported here (Figure 12). We chose to evaluate pelvic movement in dogs with subtle asymmetric weight bearing of the hind limbs by comparing vertical displacement of the right and left ischiatic tuberosities. Several studies have evaluated asymmetry of pelvic movement in horses to detect and measure forelimb and hind limb lameness.[11,14,89,93,95,96] However, to our knowledge, this is the first study to evaluate vertical movement of the pelvis in dogs while trotting. We chose the ischiatic tuberosity as our anatomic landmark, compared to the sacrum or tuber coxae chosen in horses, due to the overall differences in muscle mass, ease of identification, and the relative visibility of the landmark during clinical gait analysis. We felt that it was a consistently palpable anatomic landmark in the pelvic limb and would be the most representative marker of pelvic movement in dogs throughout the gait cycle and different movements might be associated with potential weight bearing asymmetry.

Analysis of vertical pelvic movement using the sacrum as a marker of pelvic position has been suggested as an optimum method for detecting hind limb lameness in horses,[14] in contrast to our choice of using the ischiatic tuberosity in the dog. Vertical movement of the sacrum in trotting horses has a sinusoidal pattern during gait, in which two minimum and maximum movement cycles occur during one complete stride. The first minimum height is reached during the middle of the stance phase and the first maximum is reached immediately after the end of one limb's stance phase (i.e. at toe off). The second minimum and maximum heights occur during the middle and at the end of the contralateral limb's stance phase, respectively. In an ideal sound horse, the minimum and maximum heights reached near midstance and after toe off (immediately after stance) of one hind limb are equal to the subsequent minimum and maximum heights of the contralateral hind limb.[97] Our data support that vertical movement of the ischiatic tuberosity in trotting dogs also has a sinusoidal pattern during gait, in which a cycle of movement occur in each limb during one complete stride. Although the pattern of ischiatic tuberosity movement reaches its minimum height during midstance (Figure 14), which is similar to tuber sacrale motion in the horse, the maximum height occurs near the initiation of stance phase (i.e. at the end of the swing phase; Figure 13) for both pelvic limbs and their respective degree of weight bearing. This difference in maximum pelvic heights reached in horses at push off (i.e. initiation of swing phase) and in dogs at initial contact (i.e. at the end of swing phase) may be a plausible explanation of what occurs during kinematic and visually-assessed lameness examinations between horses and dogs. For example, in a kinematic study by Kramer et al, pelvic movements in sound horses and in horses with induced hind limb lameness were described.[97] They found that induction of a transient, shoe-induced lameness in horses at two different levels of intensity consistently resulted in less downward movement of the pelvis during stance phase of the affected limb and less upward movement of the pelvis after toe off of the affected limb. They stated that the hip or pelvic hike (discussed in many descriptions of visually-assessed lameness) may actually be the result of propulsion of the sound limb that elevates the pelvis to a higher degree than propulsion by the lame limb and occurs immediately before weight bearing of the lame limb. In our study we did not find a significance difference between the two limbs in the maximum or minimum pelvic heights while trotting. However, we did find a significant difference in the total pelvic motion that occurs on the side with a greater degree of weight bearing compared to the side with a lower degree of weight bearing during gait, with most of this difference due to the minimum pelvic height (Figure 12). These data suggest that more downward movement of the pelvis occurs during the stance phase and more upward movement of the pelvis occurs at the end of the swing phase of the limb with a greater degree of weight bearing. This greater total pelvic motion supports our suggestion that a ‘hip drop’ on the side with a greater degree of weight bearing versus a ‘hip hike’ on the side with a lower degree of weight bearing occurs in dogs while trotting and may be visually detected during clinical lameness evaluation. Less downward movement of the pelvis during stance phase of the lower degree limb and less upward movement of the pelvis right after contact explains the fact that there was less total motion detected throughout the gait cycle of the lower degree limb. However, pelvic movement in the horse using the sacrum as a marker and pelvic movement in the dog using the ischiatic tuberosity may not be comparable. To our knowledge no lameness studies of the equine species have been conducted using the ischiatic tuberosity as a marker of pelvic movement. We could postulate that the kinematics of gait between the two species is fundamentally different during a trot, but without equivalent studies to evaluate the same anatomic points under similar study conditions, comparisons between the two species remain speculative at best.

Evaluation of pelvic movement with hind limb lameness of horses by comparing right and left tuber coxae displacement has been reported.[14,15,90] Tuber coxae displacement is affected by rotation of the pelvis relative to the vertebral column as well as by translational displacement of the trunk. The rotational movement of the pelvis around the vertebral column results in the pelvis rotating away from the weight-bearing limb. The vertical displacement of each tuber coxae during one stride in sound horses is normally symmetrical. In addition, the minimum height reached by the left tuber coxae during right hind limb stance is lower than the minimum height the left tuber coxae reaches during left hind limb stance and vice versa.[97] We believe that rotation of the pelvis relative to the vertebral column and translational displacements of the trunk occur during weight bearing in dogs. However it is unknown whether or not asymmetry of the ischiatic tuberosity in dogs mimics asymmetry in the tuber coxae described for horses, but it is likely. The degree of weight bearing asymmetry (i.e. lameness) necessary in dogs to cause significant pelvic height differences of right and left ischiatic tuberosities is unknown. We did not detect any significant differences in maximum or minimum PLVD values between the pelvic limbs, although minimum PLVD tended to be less on the side with a greater degree of weight bearing. This could possibly be explained by the small study population and that none of the 27 dogs had an objective symmetry grade greater than 1. However, we did find a significant difference in the total motion for PLVD between the pelvic limbs and their degree of weight bearing (Figure 12). Furthermore, 6 of the 27 dogs evaluated (22%) demonstrated a 2- to 4-fold increase in the total motion for PVLD on the side with a greater degree of weight bearing compared to the contralateral side throughout the gait cycle. The mean range of motion for PVLD for these 6 dogs was 0.20 m for the greater degree and 0.06 m for the lesser degree. This information could be useful in describing pelvic movement in dogs with subtle weight bearing asymmetry, and could be viewed as the initial step in characterizing compensatory movements associated with mild pelvic limb lameness.

A plausible explanation of why dogs with subtle asymmetric weight bearing of the pelvic limbs (mild pelvic limb lameness) demonstrate a ‘hip drop’ on the side of the pelvis with a greater degree of weight bearing of the respective limb during trotting is perhaps a compensatory spring loading to increase propulsion from that limb to make up for less propulsion from the side with a lower degree of weight bearing. This explanation of changes in forward propulsion between the limbs with lower or greater degrees of weight bearing is supported in a study reported by DeCamp et al, which described alterations in patterns of pelvic limb movement secondary to lameness in dogs that were one, three and six months after having their cranial cruciate ligament experimentally transected.[74] They explained that the differences observed in pelvic limb movements likely developed as adaptive responses to painful stimuli from an unstable joint. Femorotibial joint adaptation, with increased flexion angle and decreased extension during stance phase, was thought to be the animal’s compensatory response to a ruptured cranial cruciate ligament. Less extension of the femorotibial joint at the end of the stance phase was proposed to be a result of reduced limb propulsion and be a protective adaptation to pain and joint instability. Greater extension of the coxofemoral and tarsal joints was also thought to compensate for the altered femorotibial joint, and therefore, maintain gait.[74] These changes in movement are supported by our findings of greater total pelvis linear vertical displacement (PLVD) on the side with a greater degree of weight bearing to help compensate for abnormal femorotibial joint function on the affected side. All 27 dogs in the study reported here demonstrated significantly less propulsion on the limb with a lower degree of weight bearing throughout the gait cycle compared to the limb with a greater degree of weight bearing. This greater propulsion and altered flexion and extension of the joints on the limb with a greater degree of weight bearing may manifest as a 'hip drop' during the stance phase of the gait cycle, compared to the limb with a lower degree of weight bearing. However, the scope of our study was not to compare normal dogs and dogs with previous surgery following stifle stabilization.

To our knowledge, the study reported here is the first to investigate thoraco-lumbar (T-L) spinal kinematics of the dog with asymmetrical weight bearing of the pelvic limbs while trotting. Although there are extensive data about kinematics of the extremities, we are unaware of such data for the canine spine. A comprehensive review of the veterinary literature revealed that kinematics of the vertebral column are related to motion of normal dogs.[98] Vertebrae can rotate in 3 planes, resulting in flexion-extension, lateral bending, and axial rotation. The amount of rotation that is possible varies along the vertebral column, depending on the size, shape, and orientation of anatomic structures such as the intervertebral discs, articular facets, lateral joints, dorsal spinous processes, and ligaments.[99]

Several in vitro techniques using isolated dissected thoracolumbar vertebral columns of the horse have been reported.[100-102] For those studies, it was concluded that the amount of rotation is limited ($< 5^0$) for most intervertebral joints, except in the cranial thoracic and lumbosacral joint ($> 20^0$).[102] Faber et al[103] studied movements of the vertebral column of horses trotting on treadmill and suggested that movements of the vertebral column and pelvic limbs are closely associated. Kinematics of 8 vertebrae and both tuber coxae were determined using bone-fixated markers. They found that flexion-extension and axial rotation were characterized by a double sinusoidal pattern of motion during one stride cycle, whereas lateral bending was characterized by one peak and one trough. Ranges of motion for all vertebrae were: flexion-extension, 2.8^0 to 4.9^0; lateral bending, 1.9^0 to 3.6^0; axial rotation, 4.6^0 to 5.8^0; except for thoracic vertebrae 10 and 13, where the amount of axial rotation decreased from 3.1^0 and 3.3^0, respectively. They suggested that their findings were in agreement with a kinematic study of the vertebral column in humans,[104] which stated that the more caudal vertebrae start to rotate and the more cranial vertebrae follow as a result of the direct linkage between the pelvic limbs and the vertebral column. This mechanism was explained as a conservation of angular momentum generated by the pelvic limbs. For comparison a study by Benninger[105] et al evaluated the 3-dimensional motion pattern including main and coupled motions of the caudal lumbar and lumbosacral portions of the vertebral column of dogs. They concluded that coupled axial rotation and lateral bending are similar at all levels in vertebral columns of dogs and range between 1^0 and 2^0. A study by Faber et al[106] determined the validity of using skin-fixated markers to assess kinematics of the thoraco-lumbar vertebral column in horses. Kinematics of 8 vertebrae and both tuber coxae were determined by use of bone-fixated and skin-fixated markers. They found that data from skin-fixated markers were accurate for determining lateral bending at the walk in the mid-thoracic and lower lumbar portion of the vertebral column only. However, at the trot, data from skin-fixated markers were valid for determining lateral bending for all thoracolumbar vertebrae.[106] We believe the results of these studies support our suggestion that thoraco-lumbar lateral angular displacement (T-L LAD) in the dog results from direct linkage of the vertebral column to the pelvic limb in dogs while trotting. However, the ability to identify coupling of axial rotation and lateral bending or the evaluation of flexion-extension, lateral bending and axial rotation of individual vertebral bodies or specific intervertebral joints in our dogs using skin-fixated markers was beyond the scope of our study. Furthermore, we are uncertain if data from skin-fixated markers in dogs would have similar results compared to data derived from horses.

We were aware of assumptions that must be made when skin-fixated markers are used in kinematic studies of the vertebral column.[106] First, analysis of movements within the vertebral column can only be performed in 2-dimensions, because at least 3 markers per vertebrae are required for 3-dimensional analysis. In a 2-dimensional approach, data are determined in the sagittal, horizontal or frontal plane. Such an approach is viable when out-of-plane motions are not expected (i.e. when anatomical constraints prevent such motions or when the activity has a planar nature.[106] However, out-of-plane motions of the vertebral column can be expected, because these motions are 3-dimensional in origin.[102] Second, angles are usually calculated between 2 motions segments, in which each segment is defined by 2 markers.[107,108] In the vertebral column, each motion segment includes several vertebrae and thus several intervertebral joints.[106] Consequently, the motion segments will not behave like rigid bodies, thus violating the rigid-body requirement, which is one the fundamental assumptions of the kinematic procedure.[109] Finally, the use of skin-fixated markers assumes that these markers reflect movement of the underlying vertebrae, which is not necessarily true.[106] However, the use of skin markers was adequate for our study. We were not interested in determining 3-dimensional kinematics of the vertebral column, but we wished to describe lateral angular displacement of the thoraco-lumbar spine in the horizontal plane during subtle weight bearing asymmetry of the pelvic limbs. We agree that flexion-extension, axial rotation, and lateral bending likely occur during normal and abnormal canine locomotion and that some degree of coupling of these motions is inherent. However, we are unaware of any study in the literature describing these physiologic movements in of the thoraco-lumbar spine in dogs while trotting. Thus, our study was the first to describe this.

We were also aware of a well known, but hard to eliminate source of error attributable to skin movement artifact.[110] Most kinematic studies of canine extremities have used noninvasive methods, with skin markers positioned over bony prominences on the extremities.[77,111] However, the validity of results determined by use of spherical markers attached to the thoracolumbar skin during trotting studies in dogs has not been evaluated. In a study of anesthetized dogs in which piezoelectric accelerometers were attached to the bone and skin, passive manipulation of the adjacent vertebrae was used to move the spine. Artifactual error associated with translation of movement between the skin marker and the underlying bone was <2%.[112] Several other studies have used skin-fixated markers positioned over dorsal spinous processes of vertebrae to determine kinematics of the vertebral column in horses.[102,107,113] These studies suggest that relative motion of the skin with respect to the underlying bony structure can be distorted by inertial effects attributable to the non-rigid attachment of the skin to the bony structure, and the movement caused by muscle contraction beneath the skin. Additional studies to quantify skin motion artifact in dogs under a multitude of conditions is needed to fully understand the relationship between skin movement and the underlying musculature and bony structures. However, the use of skin markers may be suitable for noninvasive clinical studies even though they may not reflect the true movement of the vertebral spine.[110]

Finally we felt it would be paramount to have a basic understanding of epaxial muscular function in dogs under normal conditions to fully understand the motions of the T-L spine during asymmetrical weight bearing of the pelvic limbs. A number of studies have described the function of the epaxial muscles in dogs while walking, trotting and galloping.[114-116] These studies evaluated normal dogs using surgically implanted EMG electrodes and proposed that axial muscles in mammals serve three potential functions during locomotion. First, they mobilize the trunk and can contribute to propulsion through the production of mechanical work. Second, they can control or counteract movements passively induced by gravitational and inertial forces. Third, they link the vertebrae and ensure the integrity of the spine, thereby allowing polysegmental muscles to act on larger units of the spine.[116] The authors reported that the epaxial muscles studied showed a biphasic EMG activity pattern during the stride cycle. The greater activity (main burst) was associated with the second half of the ipsilateral pelvic limb stance and the lower level EMG activity occurred during the ipsilateral pelvic limb swing phase.[116] Compared with walking, the integrated activity of the epaxial muscles increased when dogs trotted. Greater accelerations and decelerations are required to swing the limbs back and forth during each trotting stride and therefore the locomotor forces acting on the trunk are likely greater. The greatest increase in muscle recruitment occurred at mid-trunk (thoracic vertebra 13) and this gait-associated change in activity was significantly greater at thoracic vertebra 13 than at lumbar vertebra 6.[116] They concluded that the timing in recruitment of the epaxial muscles functions to stabilize the trunk against extrinsic pelvic limb muscle action and long-axis torsion during trotting. Trotting data showed that the timing of the epaxial muscle EMG activity is also appropriate to produce lateral bending of the trunk. This muscle activity was expected to occur around toe off of the ipsilateral pelvic limb and produce lateral bending.[116]

This information was vital to help with interpretation of our study because we were interested in evaluating thoraco-lumbar lateral angular displacement (T-L LAD) at a trot using skin-fixated markers. We proposed that the described lateral bending in horses would be similar to our description of T-L LAD in dogs and data derived by use of skin-fixated markers would be plausible in describing the motion of the thoraco-lumbar spine of dogs. We evaluated motion of the thoraco-lumbar spine between the described segments (Figure 7) and found a significant difference in the amount of maximum T-L LAD between limbs with a lower degree of weight bearing and a greater degree of weight bearing (Figure 18). Eleven of the 27 dogs evaluated (41%) demonstrated a 2- to 10-fold increase in the maximum T-L LAD on the side with a lower degree of weight bearing compared to the contralateral side. This increased motion occurred just before the contact phase (Figure 19) and could be considered a compensatory effort by the animal to maintain progressive motion during gait. Painful extension of the hip or stifle joint leading to asymmetric weight bearing may lead to inadequate propulsion of the pelvic limb with a lower degree of weight bearing. The pronounced lateral angular displacement of the thoraco-lumbar spine toward the limb with a lower degree of weight bearing may be a compensatory effort by the animal to maintain comfortable, progressive momentum by using the epaxial muscles to pull the pelvis forward. The conclusions by Schilling et al[116] support our suggestions in that a burst of EMG activity of the epaxial muscles occurring around toe off of the ipsilateral pelvic limb in normal dogs could produce the exaggerated lateral bending we observed during asymmetrical weight bearing while trotting. A possible explanation for why the maximum amount of T-L motion occurred just before initiation of the stance phase instead of toe off could be due to differences in muscle contraction that occur during symmetrical weight bearing compared to asymmetrical weight bearing while trotting. A lower degree of weight bearing potentially alters the normal, synchronous actions between the pelvic limb and axial skeleton, resulting in altered muscle activity that manifests as increased lateral bending toward the side with a lower degree to conserve gait. It is unknown what degree of asymmetric weight bearing would result in reduced propulsion of the lame limb and altered muscle activity to result in asymmetric spinal motion The active or passive role of the epaxial muscles of the thoracolumbar spine in dogs experiencing asymmetrical weight bearing of the pelvic limbs remains debatable until a carefully designed study integrating EMG, force platform analysis and kinematic analysis of the T-L spine can be conducted.

One concern is that altered or abnormal spinal motion in dogs with pelvic limb lameness may predispose them to developing secondary osteoarthritis of the intervertebral joints. Spinal arthritis could worsen alterations in gait and perhaps result in clinical problems from subsequent compression of associated neural structures.[117] This is an important point because dysfunction of the back is a well-known cause of poor performance and lameness in equine athletes.[103] Similar to horses, dogs with back problems often have reduced performance.[118] Considering that a high number of canine patients with pelvic limb conditions also have degenerative changes in their vertebral column, describing normal and abnormal motion of the canine T-L vertebral column during subtle asymmetrical weight bearing of the pelvic limbs may be crucial to understanding how altered spinal motion may lead to back pain. These data may provide an initial understanding of the T-L spine and supporting tissues during canine locomotion and may allow earlier identification of underlying pelvic limb conditions leading to these secondary changes. Furthermore, with as much as a 2-fold difference in thoraco-lumbar spinal motion toward the pelvic limb with a lower degree of weight bearing while trotting, visual detection of asymmetrical thoraco-lumbar spinal movements may improve gait evaluation by owners, trainers and clinicians. Finally, this information was considered essential for developing and clarifying the criteria proposed in our subjective lameness grading scale (Table 4).

For study purposes, mean PVF values were used to designate the pelvic limbs with a lower degree or greater degree of weight bearing of all 27 dogs. Possible causes of the asymmetry may be variation between trials, or previous TPLO or LFS procedures in 18 of the 27 dogs. Symmetry has been examined in healthy dogs while trotting and no significant difference was detected between sides,[3,79,81] but none of the dogs had perfect right-to-left symmetry as measured by use of kinetic data.[3] We found a difference between pelvic limbs in the dogs used in our study and this information was the basis for our assignment. The described lack of perfect right-to-left symmetry may help explain why we detected subtle weight bearing asymmetry in 9 of the 27 dogs, which were normal; however, this may not be applicable to the remaining 18 dogs that had known histories of TPLO or LFS procedures.

Several veterinary studies have compared post-operative ground reaction forces of TPLO and LFS to stabilize the stifle in patients with cranial cruciate ligament rupture. One study by Conzemuis et al[82] evaluated dogs receiving these procedures for six months after surgery and evaluated peak vertical force differences between them at a walk. They found no differences between the two surgical groups, and few dogs returned to normal function in the 6-month post-operative evaluation period. Approximately 15% of the lateral suture dogs and 11% of the TPLO dogs returned to normal function at a walk based on ground reaction forces and impulses.[82] We evaluated dogs at a trot, which may result in even fewer dogs having normal weight bearing because of the additional force placed on the limb while trotting. Another study by Au et al[83] compared the same two procedures at a walk up to 2 years post-operatively. They did not compare to healthy controls, but found that at all time points up to and including the 2 year post-operative time, there was no difference in peak vertical force between these groups. A similar study by Ballagas et al[84] found that one group of dogs that had experimentally transected CCLs and repair of stifle instability with a TPLO procedure had no significant differences at a trot between 18 week post-operative and pre-operative peak vertical forces and impulses. However, there was still a notable difference in weightbearing between the surgical and nonsurgical limbs and the lack of significance was likely due to low power of the study as a result of small numbers. Another similar study by Jevens et al[85] found similar results when comparing the lateral suture technique in trotting dogs.All of these studies evaluated dogs in the short-term, whereas we evaluated dogs 4-6 years after surgery. During this time, in addition to any surgical effects, arthritis may have progressed and contributed to the asymmetry in weight bearing.

In light of these studies that compared different surgical techniques, an important difference in our study was that we were not interested in comparing PVF values between normal dogs and dogs with previous surgery following experimental cranial cruciate ligament transection. Rather than repeating similar studies we were interested in evaluating a population of dogs that demonstrated subtle weight bearing asymmetry between the pelvic limbs while trotting. Our goal was to determine if compensatory motions of the head, pelvis and thoracolumbar spine occur during subtle weight bearing asymmetry and if such motions correlate with the degree of asymmetry. If these motions are present with subtle weight bearing asymmetry, then perhaps they would become more pronounced with increasing severity of asymmetry. The 18 dogs that had stifle surgery had a mean time after surgery of 5 years, and these dogs demonstrated subjective gait characteristics similar to the 9 normal age-matched dogs and were given a lameness grade of 0 by the same investigator (DLM) during subjective clinical assessments. However, we found a significant difference in mean PVF between the pelvic limbs (Figure 8). One explanation of the contrasting findings between our and previous studies is perhaps the length of time that had lapsed between the initial surgery and the initiation of the different studies. To our knowledge no study has published findings with greater than 2 years after surgery with objective data; our study evaluated dogs that were on average 5 years after surgery.

An answer that remains unknown is whether or not the previous surgery influenced the differences between PVF of the pelvic limbs. Not all dogs had surgery on the limb with a lower degree of weight bearing in this study. In some dogs, the nonsurgical limb was the limb with a lower degree of weight bearing for purposes of our study. Therefore, our results indicate that surgical intervention of the stifle joint did not always coincide with our pelvic limb assignment in this subset of dogs. Six of the 9 dogs that underwent TPLO and 3 of the 9 LFS dogs demonstrated lower PVF on the non-surgical limb. Three of the TPLO dogs that demonstrated a lower PVF on the non-surgical limb were assigned an OSG of 1, which represents an 8-26.9% difference in weight bearing between the pelvic limbs. A potential explanation for these findings is that these dogs may have been experiencing subclinical pathology in the non-surgical limb at the time of this study that was not detected on physical examination, and this resulted in assigning the non-surgical limb as the limb with a lower degree of weight bearing. It is possible that compensatory movements in chronically affected patients remain for a long time because of inherent muscle memory as a result of an acute condition. Another potential explanation could be that these dogs were experiencing pathology in both limbs at the time of study, especially with the history of previous surgery, and compensation for bilateral lameness lead to asymmetrical weight bearing. Perhaps a larger study following the same criteria as the study reported here would be necessary to truly discern whether or not dogs with long-term follow up (i.e. greater than 5 years) for cranial cruciate ligament disease would demonstrate similar findings of PVF asymmetry and associated compensatory changes.

We chose peak vertical force (PVF) as our primary criterion for detecting weight-bearing asymmetry between the pelvic limbs, and used a simplified method for determining a mean vertical symmetry index by calculating the ratio of the mean PVF values between the limb with a lower degree of weight bearing and the limb with a greater degree of weight bearing. The resulting value was multiplied by 100, then subtracted from 1 to obtain the percent asymmetry and subsequent objective symmetry grades for all 27 dogs (Tables 1 and 3). Previous studies have indicated minor asymmetry in temporal and kinetic components, which were not the result of any pathologic state, but may simply represent variations of gait in normal dogs.[3,86,87] A study by Budsberg et al[3] evaluated limb symmetry by identifying and quantifying asymmetries between fore- and hind-limb ground reaction forces of healthy dogs at a trot. They evaluated three methods for calculating symmetry indices and reported that the mean vertical symmetry indices, regardless of calculation method, deviated < 8% from perfect symmetry for all variables in normal dogs. The most consistent values of symmetry were for the vertical axis, as compared with craniocaudal and mediolateral axes. We felt the findings in that study were similar to our findings of percent differences in weight bearing symmetry and used this information to establish cutoff points for our proposed objective symmetry grades (OSG) ranging from 0 – 5 (Tables 1 and 3). For example, a weight bearing difference between 0.0 and 7.9% would represent near perfect symmetry between the 2 measured limbs objectively (i.e. no lameness) and would be equivalent to an objective symmetry grade of 0. A weight bearing difference between 27.0 and 45.9% objectively would be equivalent to an objective symmetry grade of 2. Fourteen of the 27 dogs in our study deviated <7% from perfect symmetry based on mean PVF values and were assigned an OSG of 0. The remaining 13 of 27 dogs demonstrated a weight bearing difference of 8.0 – 26.9% and were assigned an OSG of 1. The mean vertical symmetry index for all 27 dogs in our study deviated < 17% from perfect symmetry and none were assigned an OSG of greater than 1. Following these proposed cutoff values based on quantitative force platform data may allow for easier categorization of a dog's weight bearing symmetry to a nominal 0 – 5 grading scale by assignment of an objective symmetry grade.

We felt this information was consistent with our subjective clinical evaluations prior to the study and represented a population of dogs with mild asymmetrical weight bearing of the pelvic limbs. None of the dogs had obvious clinical, orthopedic or gait abnormalities, other than the previous stifle surgeries described in 18 of the dogs. Additionally, we found no correlation between normal dogs or previous surgical dogs and the assignment of an objective symmetry grade. We were interested in evaluating the kinetics and kinematics of dogs that had minimal or no obvious clinical lameness, but had subtle weight bearing asymmetry between the pelvic limbs while trotting. We were especially interested in this sub-set of dogs that, despite being seemingly clinically sound, may demonstrate some compensatory movements of the head, pelvis and T-L spine that could indicate mild asymmetrical weight bearing of the pelvic limbs. If such subtle compensatory movements occur in dogs with subclinical rear limb lameness, identification and classification of mild pelvic limb lameness would perhaps be less challenging to clinicians, trainers or owners during subjective clinical evaluations, and allow earlier diagnosis and intervention to treat lameness.

We chose the trotting gait for evaluation in our study because of its symmetric nature, in which diagonal limbs have an even cadence over time[3], and because it is routinely used during clinical evaluations of dogs to discern alterations in movement that may indicate a pathologic condition. We reviewed the literature and several sources can be found describing subjective lameness grading systems in dogs.[12,35-37] One study by Shires et al[12] evaluated an intra-articular cruciate ligament replacement technique in a series of dogs. Two subjective grading systems were introduced for owners to evaluate the frequency of lameness prior to surgery and the type of lameness post-operatively. The frequency of lameness scale had grades from 0 to 4, and the type of lameness scale had grades from 0 to 5.[12] We were interested in taking the basic criteria described in the 5- and 6-point lameness grading systems by Shires and others[35-37] and expand the descriptions to be more specific for pelvic limb lameness in dogs at a trot. Apart from general visual descriptions of lameness, such as degree of discomfort and a lower or greater degree of weight bearing, we chose to introduce 3 additional descriptors of compensatory motion based on our hypotheses. We hypothesized that motion of the head (HVLD or vertical head nod), pelvis (PLVD or vertical hip drop), and thoraco-lumbar spine (T-L LAD) occurs in dogs with asymmetrical weight bearing of the pelvic limbs while trotting, and that this information would improve our ability to evaluate clinical lameness and be instrumental in designing a subjective grading system for the pelvic limb in dogs. Our data supported the hypothesis that compensatory movements of the pelvis and thoraco-lumbar spine occur with subtle weight bearing asymmetry of the pelvic limbs in dogs and that our proposed descriptors may be valid. However, no significant differences were found in mean vertical head motion. It may be possible that head motion does not indicate subtle weight bearing asymmetry, but it may be an indicator of more severe asymmetrical weight bearing. We cannot confirm this based on our study because our dogs did not have severe asymmetries in weight bearing, but this appears to be supported in clinical patients with increasing degrees of weight bearing asymmetry.

Our subsequent intention was to use the discrete value objective symmetry grading system introduced in Table 1 and compare this to a proposed subjective lameness scale introduced in Table 4. We felt this would be the first step in using quantitative information concerning subtle weight bearing asymmetry and the associated compensatory motions in dogs, and extrapolate this information to a subjective lameness grading system for the pelvic limb. The application of quantitative data to a qualitative, subjective format would allow potential identification of specific compensatory movements and potentially improve subjective clinical evaluation of dogs with suspected pelvic limb lameness. We suggest that if such compensatory movements are evident in dogs with subtle asymmetric weight bearing of the pelvic limbs, these may become more pronounced with more severe pelvic limb lameness. However, further studies with a larger study population and a broader range of lameness severity would be necessary to validate our proposed subjective lameness grading system for application to clinical patients.

Table 4- Proposed subjective lameness grading system for the pelvic limb in dogs at a trot.

Grade	Descriptors
0	-No Lameness Present
1	-Lameness Is Difficult To Observe -No Discomfort Noted -Weight Bearing Fairly Consistent On Affected Pelvic Limb -Vertical Head Nod Is Not Observed -Vertical Hip Drop Is Subtle -Lateral T-L Spinal Displacement Towards The Affected Pelvic Limb Is Subtle
2	-Mild, Subtle Lameness Is Observed -Mild Or Inconsistent Discomfort Noted -Vertical Head Nod Is Inconsistent When Affected Pelvic Limb Contacts The Ground -Vertical Hip Drop May be Observed When Unaffected Pelvic Limb Contacts The Ground -Lateral T-L Spinal Displacement Towards The Affected Pelvic Limb Is Observed
3	-Moderate Lameness Is Observed -Moderate Discomfort Noted -Subtle Vertical Head Nod Is Consistent When Affected Pelvic Limb Contacts The Ground -Vertical Hip Drop Is Consistently Observed When Unaffected Pelvic Limb Contacts The Ground -Lateral T-L Spinal Displacement Towards The Affected Pelvic Limb Is Consistent
4	-Marked Lameness Is Observed -Marked Discomfort Noted -Intermittent Non-Weight Bearing On Affected Pelvic Limb -Vertical Head Nod Is Pronounced When Affected Pelvic Limb Contacts The Ground -Vertical Hip Drop Is Pronounced When Unaffected Pelvic Limb Contacts The Ground -Lateral T-L Spinal Displacement Towards The Affected Pelvic Limb Is Pronounced
5	-Non-Ambulatory At Times -Non-Weight Bearing On All Strides On Affected Pelvic Limb -Severe Discomfort Noted -Prefers To Sit Or Become Recumbent -Inability To Move

Our results indicate that surgical intervention of the stifle joint did not coordinate with our pelvic limb assignment in this subset of dogs. Six of the 9 dogs that underwent TPLO and 3 of the 9 LFS dogs demonstrated lower PVF on the non-surgical limb. One question that arose as a result of our study is if femorotibial adaptation of the limbs is a permanent modification to the biomechanics of gait in dogs with previous stifle surgery, or is it a temporary adjustment in relation to joint pain and instability? Because our population of dogs had surgery on average of 5 years prior to study start, we suggest that these changes may not be permanent modifications to the stifle joint pathology and perhaps associated with the progression of osteoarthritis or subclinical pathology in the designated affected limb at the study start. Further studies with long-term follow up (i.e. greater than 5 years) for cranial cruciate ligament disease are necessary to truly discern whether or not dogs experience permanent modifications to the stifle joint associated with the suggested femorotibial adaptation.

There are other limitations to our study. The population of subjects we evaluated was relatively small and this may have reduced the opportunity to detect statistical differences among some of the variables. The subtle degree of weight bearing asymmetry in the dogs may have also reduced the ability to demonstrate differences in some parameters. A larger study population with a broader range of weight bearing asymmetry in the pelvic limbs may have addressed these limitations. The use of 4 cameras limited us to evaluating one side at a time. This required the handler (DAH) to lead the dog on the left side going one way and from the right side going the other way. Although it is usual to handle horses from the left side,[63] dogs are often handled from both sides. Therefore, we believe that this did not affect the gait measurements. A limited number of strides evaluated during each trial were a concern in our study. Due to the constraints of our gait laboratory, we were only able to evaluate 2 strides per gait cycle. Previous studies[14,15,90,93,96,119] of equine pelvic limb movement have analyzed only a limited number of strides (3 to 15) per condition. In some instances, these strides have not been consistent. Analysis of larger numbers of strides per trial would allow for a better representation of a horse's overall movement pattern. Evaluation of a large number of strides is particularly important in horses in which the degree of lameness is mild or the nature of the lameness is intermittent. In this situation the likelihood of misrepresenting a horse's overall movement pattern is decreased.[97] The use of serial force platforms or a treadmill with an embedded force platform would have allowed evaluation of additional consecutive strides. Maximum and minimum values were used for all kinematic variables instead of continuous waveforms. We analyzed discrete portions of the kinetic and kinematic waveforms in order to compare differences between the pelvic limbs. Although this resulted in a large amount of data, there are other methods to analyze waveforms. Principal component analysis[120], polynomial equations[75,76], Fourier analysis[74,77-79], and generalized indicator function analysis (GIFA),[121] have all been used to study gait waveforms successfully. It is possible that these methods may have identified differences that were undetectable by our method. Inaccurate placement of skin marker may affect kinematic data. The markers in our study were easy to place on the sagittal crest of the skull and ischiatic tuberosity, where bony landmarks were easy to palpate. The thoraco-lumbar segments were less easy to locate, however, because of the differences in muscle mass covering the T-L junction. In the present study, one individual (DAH) placed all of the markers, which should reduce variations caused by placement error. Regarding skin movement artifact, we are in agreement Gradner et al[110] and believe that the use of skin markers may be suitable for noninvasive clinical studies even though they may not reflect the true movement of the vertebral spine. Further studies to quantify skin motion artifact in dogs under a multitude of conditions is necessary to fully understand the relationship between skin movement and the underlying musculature and bony structures.

In conclusion, we found that dogs with subtle asymmetric weight bearing of the pelvic limbs demonstrate greater total motion of the pelvis (PLVD) on the side with a greater degree of weight bearing, and greater thoraco-lumbar lateral angular displacement (TL-LAD) toward the side with a lower degree of weight bearing while trotting. Description of these compensatory movements is valuable when evaluating in dogs with subtle weight bearing asymmetry in the pelvic limbs and may improve the sensitivity of lameness detection during subjective clinical lameness examinations. This information could prove useful for owners, trainers and clinicians to enhance our ability to identify early changes in the gait of dogs to allow earlier intervention.

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APPENDICES

Appendix A: Mean PVF and VI values for statistical analysis

Dog	Group	Lower PVF	Greater PVF	Lower VI	Greater VI
1	N	60.4200	72.1140	7.2780	9.1540
2	N	63.5900	71.3240	9.0520	9.4760
3	N	67.2840	68.8080	8.5780	8.1300
4	N	54.7700	59.4880	7.1380	8.0100
5	N	70.7000	79.3580	9.3220	10.6700
6	N	76.0840	76.5680	8.4380	9.4620
7	N	85.2560	88.7900	9.5360	9.3960
8	N	62.1340	65.1180	7.7060	8.1040
9	N	75.1880	78.0340	7.8720	7.7260
10	T	57.9580	66.3640	7.5760	7.6000
11	T	59.3220	62.0600	8.8520	8.5900
12	T	77.8940	85.4240	9.6430	9.2560
13	T	62.8520	65.8580	8.2580	8.6140
14	T	52.6900	58.9600	6.7950	7.8440
15	T	64.6480	68.9020	9.9180	9.6600
16	T	61.6220	62.0880	8.6280	8.5420
17	T	67.1680	73.9680	7.7680	8.4580
18	T	59.6280	65.3980	8.5980	9.2120
19	S	67.7940	69.4780	9.1380	9.0060
20	S	59.2940	59.8780	8.7640	9.0300
21	S	69.7720	78.0720	8.1340	8.8280
22	S	69.7020	75.3820	8.0360	9.3560
23	S	68.4560	71.5520	8.0720	8.9720
24	S	70.8020	78.9120	10.6320	10.6280
25	S	74.3320	76.0420	8.6320	8.1820
26	S	57.5480	69.2000	8.0180	10.6640
27	S	78.8860	80.4000	7.9420	9.0540

*N = Normal; T = TPLO; S = Suture.

Appendix B: Mean HLVD values for statistical analysis

Dog	Group	Lower PVF HLVD Maximum	Lower PVF HLVD Minimum	GreaterPVF HLVD Maximum	GreaterPVF HLVD Minimum
1	N	0.5508	0.5076	0.5272	0.4650
2	N	0.3132	0.2848	0.3612	0.3136
3	N	0.6010	0.5544	0.5790	0.5460
4	N	0.4796	0.4540	0.4834	0.4588
5	N	0.5576	0.5278	0.1104	0.1018
6	N	0.4804	0.4498	0.6196	0.5782
7	N	0.4866	0.4398	0.4908	0.4306
8	N	0.5826	0.5532	0.6204	0.5900
9	N	0.5374	0.4892	0.5340	0.4884
10	T	0.2840	0.2650	0.3266	0.2726
11	T	0.5982	0.5700	0.6234	0.5970
12	T	0.6122	0.5640	0.5932	0.5382
13	T	0.5070	0.4782	0.4778	0.4364
14	T	0.5966	0.5614	0.3898	0.3794
15	T	0.6490	0.5988	0.6324	0.5982
16	T	0.5256	0.4968	0.5384	0.5092
17	T	0.6082	0.5796	0.6060	0.5706
18	T	0.5352	0.4770	0.5630	0.5218
19	S	0.5648	0.5358	0.5576	0.5364
20	S	0.6532	0.6088	0.6506	0.5872
21	S	0.6585	0.6223	0.6550	0.6133
22	S	0.5668	0.5228	0.5424	0.5098
23	S	0.6212	0.5910	0.6132	0.5874
24	S	0.6106	0.5656	0.5905	0.5610
25	S	0.6063	0.5715	0.6246	0.5952
26	S	0.5550	0.5102	0.5494	0.5208
27	S	0.5448	0.5168	0.4264	0.3958

*N = Normal; T = TPLO; S = Suture.

Appendix C: Mean PLVD values for statistical analysis

Dog	Group	Lower PVF PLVD Maximum	Lower PVF PLVD Minimum	Greater PVF PLVD Maximum	Greater PVF PLVD Minimum
1	N	0.5384	0.3306	0.5518	0.3876
2	N	0.3362	0.2364	0.3664	0.2448
3	N	0.6076	0.4678	0.5940	0.4810
4	N	0.4860	0.4196	0.4934	0.4598
5	N	0.5628	0.5144	0.1642	0.1030
6	N	0.5106	0.3256	0.6832	0.5092
7	N	0.4912	0.3390	0.5674	0.4308
8	N	0.6022	0.4436	0.6660	0.5672
9	N	0.5292	0.3172	0.5568	0.3600
10	T	0.2930	0.2745	0.3690	-0.0038
11	T	0.6232	0.5698	0.6408	0.5618
12	T	0.6070	0.5380	0.7668	0.4816
13	T	0.5302	0.4572	0.5196	0.4422
14	T	0.6012	0.5668	0.4814	0.4052
15	T	0.6524	0.5410	0.6350	0.5128
16	T	0.5466	0.4054	0.5434	0.4720
17	T	0.6280	0.5698	0.6154	0.5240
18	T	0.6142	0.5330	0.5430	0.4222
19	S	0.5834	0.5192	0.5656	0.5070
20	S	0.6732	0.5528	0.5996	0.3954
21	S	0.6753	0.6260	0.6735	0.4770
22	S	0.5868	0.5290	0.5714	0.3988
23	S	0.6402	0.6012	0.6322	0.5932
24	S	0.6430	0.5302	0.8720	0.5495
25	S	0.6140	0.5755	0.6458	0.5692
26	S	0.5838	0.5030	0.5460	0.4446
27	S	0.5606	0.4600	0.4392	0.3940

*N = Normal; T = TPLO; S = Suture.

Appendix D: Mean T-L LAD values for statistical analysis

Dog	Group	Lower PVF T-L LAD Maximum	Lower PVF T-L LAD Minimum	Greater PVF T-L LAD Maximum	Greater PVF T-L LAD Minimum
1	N	10.8995	-5.1824	2.2041	-11.8020
2	N	12.5117	-4.1849	1.9799	-5.3890
3	N	11.3068	1.2677	-3.0689	-10.7454
4	N	9.2194	-5.5412	3.9464	-5.0691
5	N	9.5866	0.4892	-6.4125	-14.6990
6	N	1.4022	-11.9667	12.6896	-9.2621
7	N	10.0591	-5.0057	8.1043	-14.4243
8	N	21.1035	-3.7634	18.6272	-15.0921
9	N	7.4336	-3.6921	0.4104	-5.2432
10	T	16.1695	-10.1408	18.4933	-0.7351
11	T	2.7373	-5.9762	6.5403	-25.2240
12	T	13.1596	-1.6103	6.2650	-9.1425
13	T	12.3561	-6.8088	4.7793	-25.3478
14	T	4.0945	-7.6853	9.3565	-2.7206
15	T	11.3351	-5.3661	10.4058	-2.8860
16	T	7.4906	-9.2329	9.2002	-2.3965
17	T	10.8485	-0.1692	1.2606	-5.4168
18	T	3.7470	-3.4785	4.4333	-7.2250
19	S	8.8500	1.1058	-3.0191	-14.3041
20	S	14.9531	-10.2351	7.9638	-5.9468
21	S	4.1387	-1.9768	3.5655	-4.5714
22	S	4.9054	-6.9515	7.9636	-2.3951
23	S	0.5428	-4.3639	-4.2714	1.1134
24	S	4.0128	-0.8029	2.4983	-16.6631
25	S	4.9484	-10.3370	11.6038	1.7988
26	S	1.2456	-16.1044	14.6292	1.6198
27	S	16.5740	3.1600	-1.3922	-11.5714

*N = Normal; T = TPLO; S = Suture.

VITA

Dr. David A. Hicks is originally from Cleveland, Tennessee. He attended Cleveland State Community College where he received an Associates Degree in Chemistry in 1994. He earned his doctor of veterinary medicine degree from the University of Tennessee in 2000. His veterinary training continued with a rotating internship at the Animal Medical Center in New York City and an orthopedic fellowship at the University of Tennessee. He remained at the University of Tennessee to pursue his residency training in small animal surgery and a doctorate in comparative and experimental medicine with a concentration in biomechanics.