

University of Veterinary Medicine Hannover

**Computerized gait analysis of dogs during normal gait and with
induced forelimb lameness**

Thesis

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Dedicated to

My parents and my family

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List of abbreviations

BW	Body weight
C7	Seventh cervical vertebra
CoM	Centre of body mass
D	Relative stance duration (Duty factor)
Fc	Contralateral forelimb
Fi	Ipsilateral forelimb
Fig.	Figure
Fy	Craniocaudal force
Fy-	Braking force
Fy+	Propulsive force
Fz	Vertical force
GRF	Ground reaction force
Hc	Contralateral hindlimb
Hi	Ipsilateral hindlimb
I	Impulse
L1	First lumbar vertebra
L7	Seventh lumbar vertebra
M	Mean (force)
P	Peak (force)
ROM	Range of motion
S	Summed (force)
SI	Symmetry index
S1	First sacral vertebra
Tab.	Table
T1	First thoracic vertebra

T13 Thirteenth thoracic vertebra

TFy- Duration of braking force in percent of stance duration

1. Introduction

Gait is defined by the manner the limbs move, i.e., it is characterized by a distinctive, coordinated, and repetitive pattern of limb motions (DECAMP 1997). The gait of dogs can be divided into two main groups: symmetrical and asymmetrical gaits. Symmetrical gaits include the walk, trot, and pace and are characterized by the mirrored movements of the limbs of the two body sides. Asymmetrical gaits include the gallop and the canter; thereby, each limb has its own specific function and the limb movements on both body sides are not symmetrical opposites (DECAMP 1997). Because of the symmetry in motion and loading between the limbs of the same girdle in sound animals, most gait analyses focus on the walk or the trot to discern asymmetries as an indicator of lameness.

Lameness can be defined as an alteration of the normal gait pattern caused by a functional or structural disorder in the locomotor system. Animals suffering from fore- or hindlimb lameness reduce the load in the affected limb to avoid further damage, relieve the pain and allow healing. Asymmetry in head movements, i.e., dropping of the head when the sound limb is in stance and head rising when the lame limb is on the ground, is a typical sign of forelimb lameness (BUCHNER et al. 1996). Assessment of lameness usually depends on visual observations and the experience of the clinicians to detect alterations in the movements (WAXMAN et al. 2008). However, the human eye cannot identify all the possible changes at the same time, and recognition of deviations from the norm is highly subjective. Therefore, gait analysis has increasingly been used to detect alterations in the movements and determine the compensatory mechanisms in lame animals. Gait analysis is a quantitative method offering a greater reproducibility, higher spatio-temporal resolution and depends less on the experience of the clinician.

The primary goal of this thesis was to contribute to the understanding of the compensatory mechanisms animals use when lame. An improved understanding of the biomechanical changes can help to refine therapeutic and rehabilitative measures and clarify the short- and long-term perspectives of orthopedic patients. For this, the compensatory mechanisms used by lame dogs were studied by two means. First, kinetic changes were investigated; that is alterations in the forces exerted by the dogs during locomotion. Second, kinematic evaluations informed on changes in posture and the range of motion.

Kinetics: Kinetic analysis is achieved using force plates to obtain the forces exerted by the limbs during the ground contact. Thereby, the forces recorded are the ground reaction forces (GRF). The GRF are described by orthogonal vectors: vertical (Fz), craniocaudal (Fy) and mediolateral (Fx). The component most commonly determined is Fz, which is described by its peak (PFz) and mean values (MFz) as well as the vertical impulse (IFz). Among other things, it informs about the body weight distribution among the limbs. The craniocaudal (braking/propulsive) component of the GRF is used to quantify the forces that affect forward progression. Braking is defined as the impulse required to decrease the momentum of the dog during the early stance phase, while the propulsive force is defined as the impulse required to increase the momentum of the dog in the late stance phase. Mediolateral forces have the smallest magnitude and because they are more susceptible to small changes in the animal's direction of motion, this component has not been evaluated often in studies (DECAMP 1997; GILLETTE and ANGLE 2008). However, most studies that have used the GRF to describe the changes due to lameness focused only on the injured and the contralateral limbs (BUDSBERG et al. 1996; THEYSE et al. 2000; BUDSBERG 2001; GORDON et al. 2003; BRADEN et al. 2004; BÖDDEKER et al. 2012; DRÜEN et al. 2012). So far, only very few studies evaluated the compensatory mechanisms to forelimb lameness using the changes in the GRFs (dogs: GRIFFON et al. 1994; THEYSE et al. 2000; KIRPENSTEIJN et al. 2000; BOCKSTAHLER et al. 2009, horse: WEISHAUPT et al. 2004). Thereby, all previous reports described only the changes in Fz. Only one previous study reported changes in Fy in dogs suffering from unilateral fragmented coronoid process (THEYSE et al. 2000). The only other study that was concerned with changes in the fore-aft forces investigated dogs with a total loss of the forelimb's function (i.e., amputation: KIRPENSTEIJN et al. 2000).

Kinematics: Kinematics gait analysis (i.e., the spatio-temporal description of motion) can be performed using various techniques. One is to track the animal's movements using a set of cameras, which are connected to a computer and detect reflective markers placed on the dog's skin over specific anatomic landmarks. The obtained kinematic data allow for example the determination of the flexion and extension angles or the range of motion of the joints. Previous kinematic studies have described first and foremost the joint angles of the limbs in sound dogs and assessed for example the kinematic changes in dogs with stifle or hip joint diseases (BENNETT et al. 1996; DECAMP et al. 1996; MCLAUGHLIN 2001;

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CLEMENTS et al. 2005). Kinematic changes of the head and trunk motions in adaptation to forelimb lameness have been studied in horses (BUCHNER et al. 1996; VORSTENBOSCH et al. 1997; GOMEZ ALVAREZ et al. 2007). These studies suggested that the changes in the motion pattern of the head facilitate the reduction of the load in the affected limb (BUCHNER et al. 1996; KEEGAN et al. 2000). No previous study has evaluated changes in head, neck and trunk motions to compensate for forelimb lameness in dogs. In summary, the exact mechanisms of load redistribution and balance of body as well as their effects on head, neck and trunk movements during walking and trotting in dogs with forelimb lameness remain open.

In order to better understand how dogs compensate for the lameness of a forelimb when walking and trotting, a moderate and reversible lameness was induced in Beagles, and selected kinetic and kinematic parameters were systematically studied using computer-assisted gait analyses techniques. The comparison between Beagles without and with forelimb lameness allowed for the detection of the specific adaptations in the selected parameters. Because many factors can influence the results, among them are breed, speed, gait, degree, duration, or cause of lameness, using this induced lameness model allows for the systematic study of the compensatory mechanism under relatively controlled conditions. The collected information will be useful to extend our understanding of the basic compensatory mechanisms in liming dogs. Thus, this work can improve diagnosis and the treatment of lame dogs.

2. Studies

2.1. Study I:

The following study was published on 01.01.2013 in American Journal of Veterinary Research.

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Load redistribution in walking and trotting Beagles with induced forelimb lameness

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STUDY I

This manuscript represents a portion of the Doctoral thesis submitted by the first author as partial fulfillment of the requirements for a Dr med vet degree.

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2.1.1. Summary

Objective—To evaluate the load redistribution mechanisms in walking and trotting dogs with induced forelimb lameness.

Animals—7 healthy adult Beagles.

Procedures—Dogs walked and trotted on an instrumented treadmill to determine control values for peak and mean vertical force as well as impulse for all 4 limbs. A small sphere was attached to the ventral pad of the right forelimb paw to induce a reversible lameness, and recordings were repeated for both gaits. Additionally, footfall patterns were assessed to test for changes in temporal gait variables.

Results—During walking and trotting, peak and mean vertical force as well as vertical impulse were decreased in the ipsilateral forelimb, increased in the contralateral hind limb, and remained unchanged in the ipsilateral hind limb after lameness was induced. All 3 variables were increased in the contralateral forelimb during trotting, whereas only mean vertical force and vertical impulse were increased during walking. Stance phase duration increased in the contralateral forelimb and hind limb during walking but not during trotting.

Conclusions and Clinical Relevance—Analysis of the results suggested that compensatory load redistribution mechanisms in dogs depend on the gait. All 4 limbs should be evaluated in basic research and clinical studies to determine the effects of lameness on the entire body. Further studies are necessary to elucidate specific mechanisms for unloading of the affected limb and to determine the long-term effects of load changes in animals with chronic lameness.

(Am J Vet Res 2013;73:34–39)

2.2. Study II:

The following study was published on 26.12.2012 in „Plos One“. Manuscript Number: PONE-D-12-28281

Fore-aft ground force adaptations to induced forelimb lameness in walking and trotting dogs

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2.2.1. Abstract

Animals alter their locomotor mechanics to adapt to a loss of limb function. To better understand their compensatory mechanisms, this study evaluated the changes in the fore-aft ground forces to forelimb lameness and tested the hypothesis that dogs unload the affected limb by producing a nose-up pitching moment via the exertion of a net-propulsive force when the lame limb is on the ground. Seven healthy Beagles walked and trotted at steady speed on an instrumented treadmill while horizontal force data were collected before and after a moderate lameness was induced. Peak, mean and summed braking and propulsive forces as well as the duration each force was exerted and the time to reach maximum force were evaluated for both the sound and the lame condition. Compared with the sound condition, a net-propulsive force was produced by the lame diagonal limbs due to a reduced braking force in the affected forelimb and an increased propulsive force in the contralateral hindlimb when the dogs walked and trotted. To regain pitch stability and ensure steady speed for a given locomotor cycle, the dogs produced a net-braking force when the sound diagonal limbs were on the ground by exerting greater braking forces in both limbs during walking and additionally reducing the propulsive force in the hindlimb during trotting. Consistent with the proposed mechanism, dogs maximize their double support phases when walking. Likely associated with the fore-aft force adaptations to lameness are changes in muscle recruitment that potentially result in short- and long-term effects on the limb and trunk muscles.

Keywords: craniocaudal, ground reaction force, kinetic, *Canis*

2.3. Additional study:

The data collection as well as most of the analyses for the following study are completed. The manuscript for this part of the work is currently in preparation.

Adaptations in axial kinematics to forelimb lameness in walking and trotting Beagles

2.3.1. Introduction:

Asymmetry in head movements, i.e., dropping of the head when the sound limb is in stance and head rising when the lame limb is on the ground, is a typical sign of forelimb lameness in horses (BUCHNER et al. 1996). Most likely, other spinal regions than the neck will show kinematic changes in adaptation to forelimb lameness. For example, alterations in the kinematic patterns of the thoracic region –the trunk region near the affected limb– can be expected. An understanding of the compensatory mechanisms is the key to preventing further damage, improving rehabilitation and providing a realistic estimate of the long-term outcome of orthopedic patients. In this study, the kinematics of the head, neck and trunk will be investigated in walking and trotting dogs and compared between the sound and the lame condition. For this, the same technique of inducing a moderate and reversible forelimb lameness will be applied as used in the aforementioned studies. This study aims at extending our understanding of the dog's changes in the spinal motions in compensation of a forelimb lameness and particularly of the role of the spinal motions in shifting the instantaneous location of the CoM.

2.3.2. Animals:

Seven adult and clinically sound Beagles (four females, three males) with an age of 6.3 ± 2 years (mean \pm SD) and a body mass of 16.3 ± 3.7 kg were used. All experiments were carried out in accordance with the German Animal Welfare guidelines and approved by Ethics committee of Lower Saxony, Germany (No. 12/0717). All dogs received a complete physical examination before data collection and were considered clinically sound (i.e., free of lameness

and orthopedic abnormalities). Before the study, all dogs were trained to walk and run comfortably on the treadmill (Fig. 1).

2.3.3. Study design:

The dogs moved on a horizontal treadmill at their preferred speeds. Walking speed ranged between 0.7 and 0.9 m/s; trotting speed was 1.2 to 1.4 m/s. The trot was defined mechanically (i.e., according to (CAVAGNA et al. 1977); for further details see Abdelhadi et al., in press). A moderate and reversible forelimb lameness was induced after the control data were collected and the measurements were repeated. To induce lameness, a small sphere of 9.5 to 16 mm in diameter coated with cotton taped under the paw of the right forelimb (F_1).

2.3.4. Data collection:

The kinematic data were collected by means of spherical reflective markers (16 mm in diameter). The markers were placed on 11 anatomical landmarks along the head, neck, thoracic and lumbar regions as well as the pelvis with adhesive tape. The following anatomic positions were used: one marker on each side of the zygomatic arch, one marker on the occipital area, one marker on [C7/T1], one marker on [T13/L1] thoracolumbar junction, one marker on [L7-S1] lumbosacral junction (Fig. 1A). Additionally, four accessory markers were used: one marker on each side of thoracic wall and one marker on each side of the flank region. Six infrared high-speed cameras (MX3+, Vicon Motion Systems Ltd, Oxford, UK) arranged around the treadmill recorded the three-dimensional position of the markers during motion at 100 Hz. Before each measurement, the infrared and the video cameras were calibrated. When the dogs walked and trotted smoothly and comfortably at their preferred speed, at least five trials were recorded per dog and gait (i.e., control data). The duration of each trial was between 25 and 30 seconds walking and trotting respectively. Then, the dogs were allowed to rest for at least 15 minutes. After that, measurements were repeated but with lameness induced in the right forelimb. From the five trials recorded per condition, for each dog and gait, trials with the most regular gait and the greatest number of consecutive valid strides were selected for further analyses.

2.3.5. Data analysis:

In the selected trials, the markers were labelled using Vicon Nexus (Vicon Nexus, Vicon Motion Systems Ltd, Oxford, UK) and thereby identified as head, neck and trunk markers

according to the previously defined spinal model (Fig. 1B). In this model, the various angles are defined as both three-dimensional angles as well as angles projected in the sagittal, horizontal and the transverse planes. After determination of the stride events (i.e., touchdown, liftoff), the kinematic data were exported as time-normalized data series to Microsoft Excel (2003) for further analysis. Then, maximum and minimum angular excursions and the range of motion (ROM) for each spinal segment as well as for the angles between the respective regions were determined.

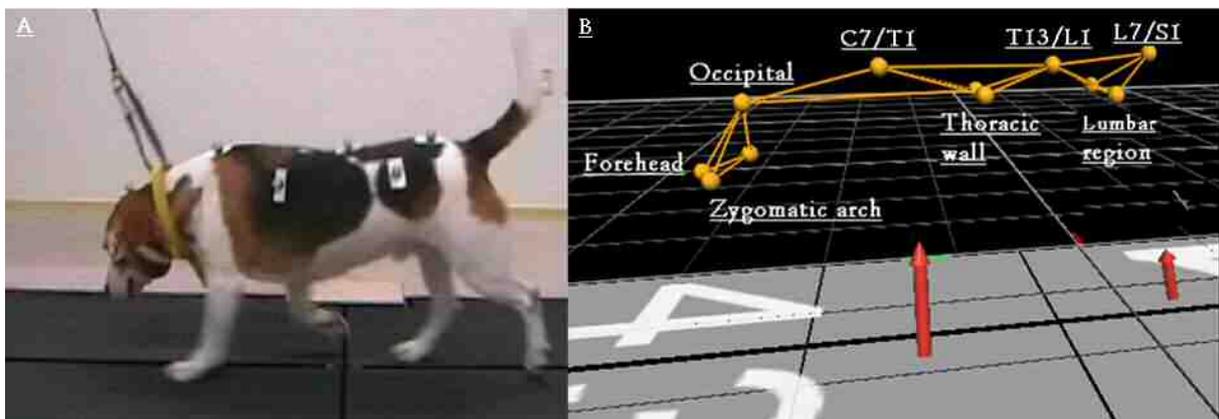


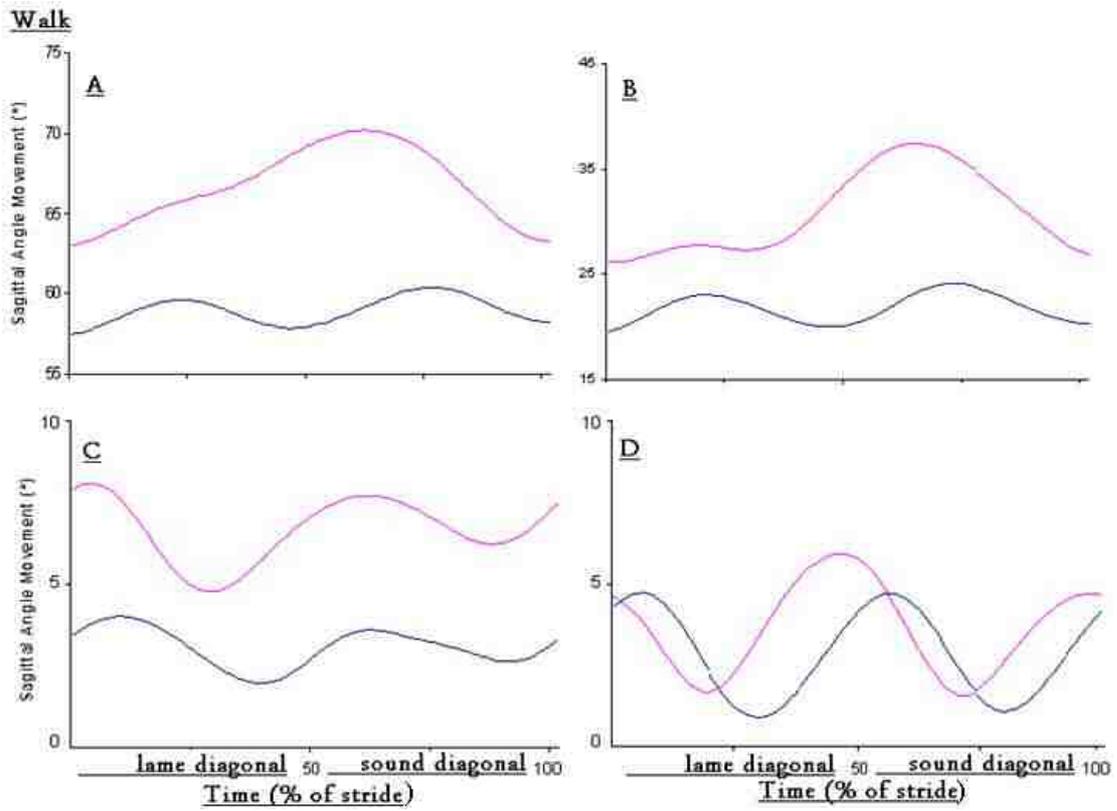
Fig. 1: Dog trotting on the treadmill with markers (A), kinematic model after labeling the 11 head, neck and trunk markers (B).

2.3.6. Preliminary results:

All four spinal segments studied showed a symmetrical, biphasic motion pattern in the sagittal plane during walking and trotting, i.e., between spinal segments, two dorso-ventral flexions and extension per locomotor cycle were observed. After lameness was induced, this biphasic pattern was substantially changed, resembling more a uniphasic pattern. Thereby, the peak associated with the stance phase of the lame limb was reduced (Fig. 2). The ROM was significantly increased during both walking and trotting but was increased more during walking than during trotting. The comparison among the spinal segments shows that the changes in the ROM were greater for the neck than the head (Tab. 1). In the thoracic segment, the ROM was increased significantly during walking. In the horizontal plane, spinal motions were characterized by a monophasic pattern (Fig. 3). The ROM increased in the head, neck and lumbar segments, but decreased in thoracic segment (Tab. 1). However, the changes in

ADDITIONAL STUDY

horizontal plane were not significant for either trunk segment.



ADDITIONAL STUDY

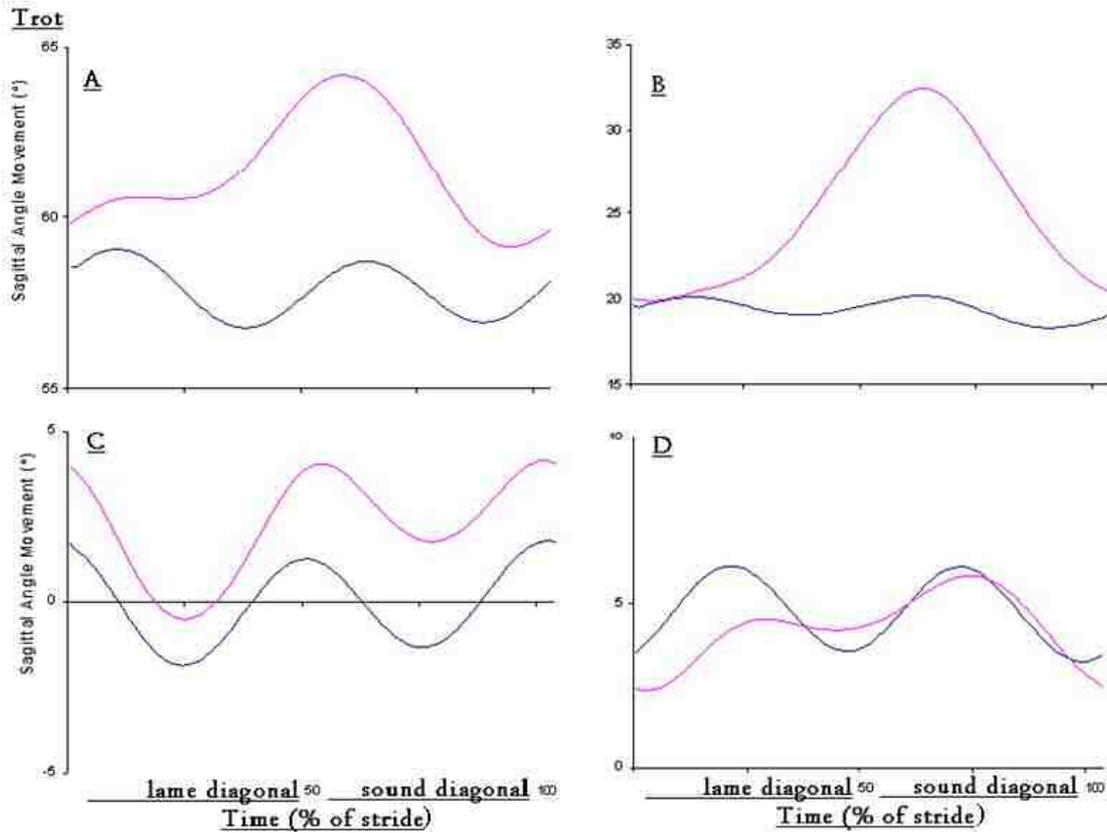


Fig. 2: Averaged spinal motion projected in the sagittal plane and time-normalized to one complete stride cycle for the head (A), neck (B), thoracic (C) and the lumbar segments (D). Blue line = sound condition, pink line = lame condition. The respective stride cycle (x-axis) starts with the touchdown of the reference limb (lame) and ends with its subsequent touchdown; liftoff is at 50% of the cycle.

ADDITIONAL STUDY

Tab. 1: Range of motion (ROM) values (mean±SD in °), head, neck, thoracic and lumbar segments at walk and trot in beagle with and without induced forelimb lameness. Significant differences between sound and lame conditions at * p<0.05.

ROM	Sagittal plane		Horizontal plane	
	sound	lame	sound	lame
Head				
trot	2.1±0.6	6.8±3.5*	6.0±2.2	9.3±5.0
walk	2.9±1.0	7.9±3.9*	7.9±4.4	11.1±6.0
Neck				
trot	1.8±1.0	13.8±5.0*	6.1±1.2	7.8±1.4
walk	3.9±1.4	13.2±4.8*	10.2±2.8	9.1±1.9
Thoracic				
trot	3.5±1.0	4.0±0.7	8.8±5.0	6.7±1.8
walk	1.8±0.9	2.8±0.5*	10.2±3.3	10.0±2.5
Lumbar				
trot	2.8±1.1	2.8±0.9	9.4±2.1	9.7±4.7
walk	4.2±1.2	4.4±0.6	9.3±2.5	11.1±2.9

3. General Discussion

Compensatory mechanisms allow animals to change the loading regime in the affected limb, while redistributing the body weight, maintaining the forward velocity and the direction of body progression. This work was designed to investigate the changes in selected kinetic and kinematic parameters to better understand how dogs compensate for forelimb lameness. For this, adult Beagles were trained to walk and trot on the treadmill and the temporal gait parameters, the vertical and craniocaudal components of the GRF as well as the kinematics of the head, neck and trunk were investigated before and after lameness was induced in the forelimb.

In healthy walking and trotting dogs, about 60% of the body weight is supported by the forelimbs, while the hindlimbs bear about 40% of the body weight (BUDSBERG et al. 1987; RUMPH et al. 1994; BERTRAM et al. 2000; MCLAUGHLIN 2001; FANCHON et al. 2006; LASCELLES et al. 2006; BOCKSTAHLER et al. 2007; KATIC et al. 2009; VOSS et al. 2010); only some small differences in load distribution among breeds due to the differences in body conformation have been described (MÖLSA et al. 2010; VOSS et al. 2011). During steady-state locomotion, the function of the forelimbs differs from that of the hindlimbs. The forelimbs decelerate the body, while the hindlimbs generate forward momentum of the body. Thereby, the fore-aft forces exerted by the diagonal limb pair should be equal and opposite to provide pitch stability of the body for a given locomotor cycle (Abdelhadi et al. acc.; 2.2.). In contrast to steady-state locomotion, all limbs are involved in both acceleration and deceleration when dogs change their speed. However, if one limb does not perform at its full function, the remaining limbs must accept increased responsibility of load bearing (LEACH et al. 1977).

In adaptation to induced forelimb lameness, the following biomechanical changes were observed in walking and trotting dogs studied: 1) The vertical force was decreased in both limbs ipsilateral to the side on which lameness was induced and increased in both contralateral limbs. This confirms previous results (GRIFFON et al. 1994; MCLAUGHLIN and ROUSH 1995; BOCKSTAHLER et al. 2009). 2) When the lame diagonal limb pair was on the ground, a net-propulsive force was exerted due to a reduced braking force in the affected forelimb and an increased propulsive force in the contralateral hindlimb. When the

sound diagonal limb pair was in ground contact, a net-braking force was produced due to an increased braking force in both the contralateral forelimb and the ipsilateral hindlimb. This agrees well with previous results in forelimb amputated dogs (KIRPENSTEIJN et al. 2000). 3) Regarding the temporal stride parameters, relative stance durations were increased in the contralateral forelimb in both walking and trotting, which is in agreement with the results of walking dogs with lameness attributable to dysplasia of the elbow joint (BOCKSTAHLER et al. 2009) and induced forelimb lameness in horses (WEISHAUPT et al. 2006). During walking, the relative stance duration was increased in the contralateral hind limb; these results are similar to results in dogs with lameness attributable to dysplasia of the elbow joint (BOCKSTAHLER et al. 2009). 4) Kinematically, a decreased vertical displacement of the head and neck was observed during the stance phase of the lame limb, while it was increased during the stance phase of the contralateral forelimb. This agrees well with previous results from horses (BUCHNER et al. 1996).

Based on these findings, the following mechanisms can be postulated that contribute to reduce the load at the affected limb and compensate for forelimb lameness. **1)** The CoM is temporarily shifted caudally by producing a torque at the hip via an increase in the retractor moment. That is, increased activity in the extrinsic hindlimb muscles that retract the leg generates a moment at the hip which, assuming that hip and trunk are stabilized, results in a nose-up pitching moment and thus in unloading the forelimb. Consistent with that, greater vertical and propulsive forces and increased stance duration were observed in the contralateral hindlimb. **2)** The net-propulsive force exerted by the lame diagonal limb pair results in a nose-up pitching moment about the CoM and unloads the forelimb. Associated with that, the CoM possibly shifts caudally facilitating the unloading of the affected forelimb. In agreement with that, increased vertical and propulsive forces were observed in the contralateral hindlimb. To restore pitch stability for a given locomotor cycle, the net-braking force produced by the sound diagonal limb pair results in a nose-down pitching moment which is consistent with the increased vertical and braking forces observed in the contralateral forelimb as well as the increased braking force exerted by the ipsilateral hindlimb. **3)** Elevation of the head and neck and the associated change in body conformation lead to a caudal shift of the CoM when the lame forelimb is in stance. This plus the momentum resulting from the upward movement of the head (LEACH et al. 1977) are likely to reduce the load on the lame leg. Accordingly, the

head and neck moved upwards during the lame forelimb's stance phase and its vertical force was decreased, while limb loading was increased in the contralateral hindlimb. During the second half of the locomotor cycle, head and neck were moved downwards which may shift CoM cranially and results in the increased vertical force observed in the contralateral forelimb. 4) Additionally to cranio-caudally shifting the CoM, the affected forelimb appears to be unloaded by a medio-lateral shift of the CoM because increased vertical forces were recorded in the contralateral fore- and hindlimbs. This may be accomplished by a change in the body configuration for example by changing the magnitude and timing of the lateral bending of neck and trunk. To test this hypothesis, more information on the kinematics of the spinal movements in the horizontal plane are needed. Additionally, long-axis rotation of the trunk may facilitate a lateral shift of the CoM and thereby unload the affected limb. This would require a change in the extrinsic muscle activity in the contralateral fore- and hindlimb (e.g., trapezius, gluteus medius muscles). However, there is currently not enough information about the activity patterns of those muscles particularly in clinical cases. Therefore, further studies using electromyography are necessary to investigate the changes in the muscle recruitment and test the proposed mechanism.

Most likely, lame dogs use a mix of these suggested compensatory mechanisms and it remains to be determined which role each mechanism plays and under which circumstances dogs favour one or the other strategy. Therefore, more studies are necessary that modify critical parameters such as locomotor speed, degree and cause of lameness or body size to evaluate the compensatory strategies of dogs. Nevertheless, as this work shows, dogs compensate forelimb lameness by shifting the CoM to the sound side and caudally and by elevating their head and neck to reduce the load placed on the lame limb. When the sound diagonal limb is on the ground, the CoM shifts cranially and head and neck drop resulting in an increased load and the stance duration of the contralateral forelimb.

The proposed mechanisms are associated with changes in the muscular and skeletal stress of the locomotor system, which potentially leads to short- and long-term problems. For example muscle fatigue may occur in acute cases and changes in muscle size in chronically lame dogs. The following muscles may be affected among others: protractor and anti-gravity muscles of the contralateral forelimb because of its increased loading and role in deceleration, retractor and extensor muscles of the contralateral hindlimb due to the increased propulsive

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and vertical forces and the back muscles because of their function in stabilizing the pelvis against retractor muscle action. Furthermore, changes can be expected based on the increase of force and moment at the stifle and hip joints of the contralateral hindlimb as well as at the shoulder and elbow joints of the contralateral forelimb. Likewise, back problems can be expected in acute and chronic patients due to the asymmetrical stress on the back combined with increased axial compression resulting from the for-aft changes in the CoM velocity. Therefore, the lame limb should be treated as soon as possible to prevent damage to the other limbs. Furthermore, the diagnosis and treatment of the forelimb lameness should be carried out by carefully observing and examining the animal from the cranial, lateral and caudal aspect to detect any changes in joint configuration and muscle size. Not only the changes in the affected limb, but also in the other limbs especially the contralateral limbs as well as the trunk need to be monitored to ensure that no sequelae occur.

The induced forelimb lameness model used in this project provided a comprehensive data set to quantify the kinematic and kinetic changes in adaptation to forelimb lameness and thus facilitated a better understanding of the compensatory mechanism of the locomotor system in forelimb lame dogs. Incorporation of these findings in the diagnosis and treatment of clinical cases may help to improve therapeutic and rehabilitative approaches as well as help to estimate the short- and long-term consequences of orthopedic problems on the locomotor system.

4. Summary

Jalal Abdelhadi

Computerized gait analysis of dogs during normal gait and with induced forelimb lameness

Although alterations in the gait may be visually recognizable in lame animals, the underlying compensatory mechanisms and specifically the redistribution of loading among the limbs as well as adaptations in the axial kinematics have not been studied in detail yet. Therefore, this project was designed to determine changes in selected kinetic and kinematic parameters in adaptation to a moderate forelimb lameness in Beagles. This information may facilitate the diagnosis and the treatment of orthopedic patients in the future.

In this study, adult Beagles, and thus dogs comparable in breed, size, and age, were trained to walk and trot on a treadmill and temporal gait parameters, vertical and craniocaudal GRF as well as kinematic data of the head and spine were collected before and after lameness was induced in the forelimb. Compared to the sound condition, vertical force was decreased in the affected forelimb and increased in the contralateral forelimb during both walking and trotting. While no changes were observed in the ipsilateral hindlimb, vertical force was significantly increased in the contralateral hindlimb independent from gait. When the lame diagonal limb pair was on the ground, a net-propulsive force was produced due to a reduced braking force of the affected forelimb and an increased propulsive force in the contralateral hindlimb during both walking and trotting. This results in a nose-up pitching moment and thus a temporary unloading of the affected forelimb. To regain pitch stability and ensure steady speed per locomotor cycle, a net-braking force was produced when the sound diagonal limbs were in stance by exerting greater braking forces in both limbs during walking and additionally reducing the propulsive force in the hindlimb during trotting. Consistent with these observations, dogs maximize their double support phases when walking by increasing the

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relative stance duration in the contralateral limbs. The observed changes in head and neck kinematics, such as a decreased vertical displacement when the lame limb is in stance and an increased displacement when the sound limb is on the ground, are consistent with the temporal unloading of the affected limb. The comparison among the spinal segments shows that the changes in the ROM were greater for the neck than the head and, in general, the effects of lameness on the motions of the spinal segments varied substantially along the axial system.

In summary, the results of this work suggest that the compensatory mechanisms to lameness are well-integrated processes affecting both spatiotemporal and dynamic parameters. That is, compensation of forelimb lameness in dogs affects, among other things, the vertical and the fore-aft components of the GRF, temporal gait parameters such as relative stance durations and the ROM of the spine. These strategies taken together facilitate the decrease of loading in the affected limb and allow the animal to maintain forward velocity and pitch stability of the body. The short- and long-term effects on the musculoskeletal system need further investigation for a more realistic estimate of the outcome of orthopedic patients from the various existing therapeutic and rehabilitative approaches.

5. Zusammenfassung

Jalal Abdelhadi

Computergestützte Ganganalyse von Hunden während des physiologischen Ganges und mit induzierter Vordergliedmaßenlahmheit

Obwohl Abweichungen vom physiologischen Gangbild mehr oder weniger offensichtlich sind wenn Tiere lahmen, wurden die zugrundeliegenden Mechanismen zur Kompensation des teilweisen Verlustes der Funktion einer Vorderextremität und insbesondere die Umverteilung der Last zwischen den übrigen Extremitäten sowie die Veränderungen in der axialen Kinematik bisher noch nicht detailliert untersucht. Ziel dieser Arbeit war, die Veränderungen ausgewählter kinetischer und kinematischer Parameter in Anpassung an eine Vorderbeinlahmheit am Beispiel des Beagles zu untersuchen. Die gewonnenen Erkenntnisse sollen in der Zukunft die Lahmheitsdiagnostik und v.a. die Behandlung von orthopädischen Patienten unterstützen und genauere Aussagen über die veränderte Belastungssituation im Bewegungsapparat der Patienten und insbesondere deren Folgen für chronische Erkrankung erlauben.

Mit Hilfe der computergestützten Ganganalyse, d.h. mittels eines instrumentierten Laufbandes und eines Infrarot-Bewegungsanalyse-Systems, wurden ausgewählte kinetische und kinematische Gangparameter untersucht, um so objektive Aussagen z.B. über die Umverteilung des Körpergewichtes und damit der Belastung der einzelnen Gliedmaßen sowie über die Anpassungen in den zeitlichen Gangparametern und den Bewegungen von Kopf, Hals-, Brust- und Lendenwirbelsäule zu erhalten. Um die Variabilität aufgrund von Unterschieden in Rasse, Alter, Geschwindigkeit oder Ursache und Grad der Lahmheit zu reduzieren, wurden erwachsene Hunde der gleichen Rasse –dem Beagle– untersucht und bei diesen eine mittelgradige Lahmheit der Vordergliedmaße induziert. Damit war ein direkter Vergleich der lokomotorischen Parameter vor und nach Induktion der reversiblen Lahmheit unter den gleichen experimentellen Bedingungen und bei den gleichen Individuen möglich. Der Fokus dieser Arbeit lag dabei auf dem Vergleich 1) der vertikalen und der kraniokaudalen

Bodenreaktionskräfte (GRF), um so Aussagen über die Verteilung des Körpergewichtes sowie die Umverteilung der Funktion der Extremitäten bei der Beschleunigung des Körpermassenschwerpunktes zu treffen, 2) der Fußfallmuster für eine genauere Analyse der Veränderungen der Bodenkontaktzeiten, sowie 3) der Kinematik des axialen Systems anhand der Bewegungen der einzelnen Abschnitte in der sagittalen und horizontalen Ebene. Darüber hinaus ermöglichte die Untersuchung von Schritt und Trab einen Vergleich der Kompensationsmechanismen zwischen diesen beiden symmetrischen Gangarten.

Verglichen mit dem physiologischen Gang waren beim lahmen Hund in Schritt und Trab die vertikale Bodenreaktionskraft (maximale Kraft, mittlere Kraft, Impuls) im betroffenen Bein reduziert und signifikant erhöht im kontralateralen Vorderbein. Bezüglich der Hinterextremitäten zeigten sich keine Veränderungen in der ipsilateralen Extremität, aber eine signifikante Erhöhung aller Parameter im kontralateralen Bein. Während des gemeinsamen Bodenkontaktes des betroffenen diagonalen Beinpaars produzierten die Hunde eine (positive) Nettobeschleunigung durch eine Reduktion der Bremskraft im Vorderbein und eine Erhöhung der Beschleunigungskraft im kontralateralen Hinterbein. Diese Nettobeschleunigung des Körpers führt zu einem Moment um die Nickachse des Tieres und damit zu einer Erhöhung des Nickwinkels und Entlastung der Vordergliedmaße. In der zweiten Hälfte des Schrittzklus führt dann die erzeugte (negative) Nettobeschleunigung aufgrund erhöhter Bremskräfte beider diagonalen Gliedmaßen sowie einer reduzierten Beschleunigungskraft des Hinterbeines im Trab zur Erhaltung der über den Schrittzklus konstanten Fortbewegungsgeschwindigkeit und der Neigungsstabilität des Körpers. Übereinstimmend mit diesen Beobachtungen erhöhen Hunde mit Vorderbeinlahmheit die Dauer der gemeinsamen Stützphase beider kontralateraler Extremitäten im Schritt und verlängern damit den Zeitraum, in dem Kräfte auf den Boden ausgeübt werden können. Bezüglich der Veränderungen der axialen Kinematik zeigen sich signifikante Veränderungen in den Bewegungen in der sagittalen Ebene in allen Abschnitten, aber insbesondere von Kopf und Hals. Beispielsweise verringert sich die Amplitude der Kopf- und Halsbewegungen während der Stemmphase der lahmen Gliedmaße und erhöht sich während der Stemmphase der gesunden Gliedmaße. Diese Unterschiede waren ausgeprägter im Schritt als im Trab. Die vorläufige Auswertung der ersten Ergebnisse lassen deutliche Unterschiede in den beobachteten Bewegungsänderungen entlang der Körperachse vermuten, die auf einen

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unterschiedlichen Einfluss der Lahmheit auf die einzelnen Wirbelsäulenregionen schließen lassen.

Zusammenfassend läßt sich feststellen, daß die Kompensation eines teilweisen Verlustes der Funktion einer Vordergliedmaße ein gut integrierter und komplexer Prozess ist, der sowohl zeitlich-räumliche als auch dynamische Parameter betrifft. Dabei treten u.a. Veränderungen der vertikalen und der kraniokaudalen Bodenreaktionskräfte und der zeitlichen Gangparameter aller Extremitäten sowie der Bewegungsumfänge der zentralen Körperachse auf. In Kombination erlauben diese Mechanismen die Entlastung des betroffenen Vorderbeines.

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DECLARATION

8. Declaration

I herewith declare that I autonomously carried out the thesis entitled "Computerized gait analysis of dogs during normal gait and with induced forelimb lameness". No third party assistance has been used.

I did not receive any assistance in return for payment by consulting agencies or any other person. No one received any kind of payment for direct or indirect assistance in correlation to the content of the submitted thesis.

I conducted the project at the following institution:

Small Animal Clinic, University of Veterinary Medicine Hannover

The thesis has not been submitted elsewhere for an exam, as thesis or for evaluation in a similar context.

I hereby affirm the above statements to be complete and true to the best of my knowledge.

[date], signature