

Load redistribution in walking and trotting Beagles with induced forelimb lameness

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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 vertical 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;74:34–39)

In healthy dogs, the forelimbs bear approximately 60% of the body weight and the hind limbs bear approximately 40% of the body weight, independent of gait (eg, walking^{1–4} or trotting^{5–9}). Differences among

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ABBREVIATIONS

GRF	Ground reaction force
IFz	Vertical impulse
MFz	Mean vertical force
PFz	Peak vertical force
SI	Symmetry index

breeds attributable to the relative distribution of body mass and body conformation have been described.^{10,11} For example, Greyhounds apply 55% of their body weight to the forelimbs and 45% to the hind limbs.^{6,12} However, the symmetry or asymmetry between the proportion of body weight supported by both forelimbs or both hind limbs is used to identify whether a dog is clinically sound or lame.^{13–20}

In an attempt to unload an injured limb, an animal will alter the load distribution among the limbs. Most studies have focused on the limb contralateral to the affected limb, and it has been established that the load is shifted to the contralateral limb.^{21–23} Although a substantial unloading of a limb likely affects the entire body, only 2 studies^{12,24} have been conducted to investigate forelimb lameness in dogs by including all 4 limbs in the data collection. In one of those studies,¹² a compensatory shift of load to both the contralateral forelimb and hind limb was detected, whereas in the other study,²⁴ there was an increase in PFz of only the

contralateral hind limb. The lack of more detailed information on the kinetic changes in all 4 limbs hinders understanding of the load redistribution and thus the specific load shifting mechanisms used by lame dogs.

The purpose of the study reported here was to determine specific kinetic changes in all 4 limbs that are associated with forelimb lameness. To directly compare data for the sound and lame conditions, we obtained data before and after inducing lameness in dogs. The method used to induce lameness allowed for the systematic study of compensatory mechanisms in relatively controlled conditions, thereby reducing the number of factors (eg, severity, duration, or cause of lameness) that could introduce variation into the results. Because walking and trotting are mechanically fundamentally different²⁵ and lameness may be visible during trotting but not walking,^{19,26,27} which implies that the load redistribution depends on gait, we evaluated dogs while walking and trotting. In addition to the commonly analyzed PFz,²⁴ we also analyzed MFz and IFz. Furthermore, footfall patterns were evaluated because an increase in ground contact time is 1 means of decreasing PFz while maintaining IFz.²⁸ Because naturally occurring and induced lameness may differ with regard to the manner in which limb loading changes, we compared the results for the study reported here with published results for orthopedic patients with clinically relevant lameness.

Materials and Methods

Dogs—Seven healthy adult Beagles (3 males and 4 females) that were (mean \pm SD) 6 \pm 3 years old and had a mean body weight of 16.3 \pm 3.7 kg were used in the study. The dogs were part of the Beagle population of the Small Animal Clinic of the University of Veterinary Medicine Hannover and were housed and fed in accordance with standard institutional protocols. All dogs received a complete physical examination before the study and were considered clinically sound (ie, free of lameness and orthopedic abnormalities). Before the study, all dogs were trained to walk and run comfortably on a treadmill. All experiments were performed in accordance with the animal welfare guidelines of the State of Lower Saxony, Germany (No. 12/0717).

Study design—All dogs ambulated on a horizontal treadmill at a slow and running walk²⁹ at their preferred speed. Although both can be considered walking gaits from a kinematic point of view (ie, relative stance dura-

tion $>$ 0.5, except for the hind limbs in the faster gait), they mechanically (ie, on the basis of their energy exchange mechanisms) represented walking and trotting (ie, using inverted-pendular mechanics vs spring-mass mechanics, respectively²⁵). Therefore, these 2 gaits were referred to as walking and trotting for this study. Walking speed ranged between 0.7 and 0.9 m/s; trotting speed was 1.2 to 1.4 m/s.

Data collection—Ground reaction forces were measured on a 4-belt treadmill system^a with a force plate implemented underneath each belt. The GRF data were obtained with data collection software^b and processed with data analysis software.^c

At least 5 trials were recorded for each dog and both gaits (control data). The duration of each trial was between 25 and 30 seconds, and dogs performed 36 to 42 strides while walking and 45 to 54 strides while trotting. Dogs were allowed to rest for at least 15 minutes. Then, a moderate and reversible lameness was induced in each dog with a small sphere (9.5 or 16 mm in diameter) coated with cotton, which was taped to the ventral surface on the paw of the right forelimb (Figure 1). The dogs then repeated walking and trotting on the treadmill under the same conditions and at the same locomotor speeds as used during the control trials.

Data analysis—Of the 5 trials recorded for each condition and gait, the trial with the most regular gait and



Figure 1—Photograph of a small sphere (diameter, 9.5 mm) coated with cotton and taped to the ventral surface on the paw of the right forelimb of a Beagle to induce a reversible lameness. Inset—The small sphere without the cotton coating. Marks are at intervals of 1 mm.

Table 1—Load distribution in all 4 limbs of 7 Beagles for the sound (control) condition and after lameness was induced in the right forelimb (ipsilateral forelimb).

Gait	Variable	Contralateral forelimb		Ipsilateral forelimb		Contralateral hind limb		Ipsilateral hind limb	
		Sound	Lame	Sound	Lame	Sound	Lame	Sound	Lame
Walking	PFz	31.8 \pm 1.7	33.0 \pm 1.3	31.3 \pm 1.3	20.7 \pm 1.3*	18.7 \pm 1.3	26.8 \pm 2.4*	18.2 \pm 1.7	19.5 \pm 2.1
	MFz	31.9 \pm 1.6	36.3 \pm 2.3*	30.5 \pm 1.1	20.7 \pm 1.3*	18.8 \pm 1.1	23.6 \pm 1.4*	18.7 \pm 1.3	19.4 \pm 1.8
	Ifz	32.4 \pm 1.8	38.4 \pm 2.9*	31.6 \pm 1.3	20.3 \pm 1.8*	17.9 \pm 1.3	23.0 \pm 2.4*	18.0 \pm 1.5	18.2 \pm 2.5
Trotting	PFz	30.7 \pm 1.1	35.7 \pm 2.2†	30.7 \pm 1.4	20.3 \pm 3.8*	19.3 \pm 1.3	24.2 \pm 2.6†	19.3 \pm 1.1	19.8 \pm 1.9
	MFz	30.4 \pm 0.8	36.6 \pm 2.7*	30.4 \pm 1.2	20.7 \pm 3.1*	19.5 \pm 0.9	23.1 \pm 1.8†	19.7 \pm 0.7	19.5 \pm 1.4
	Ifz	31.5 \pm 0.7	39.3 \pm 3.2*	31.9 \pm 1.6	21.1 \pm 3.5*	18.0 \pm 1.1	22.0 \pm 1.7†	18.5 \pm 1.2	17.6 \pm 2.0

Values reported are mean \pm SD percentage of body weight.
 ,†Within a limb, value differs significantly (P < 0.01; † P < 0.05) from the value for the sound condition.

the greatest number of consecutive valid strides (ie, without overstepping) was selected for each dog for further analyses. Variables evaluated were PFz, MFz, and IFz. Additionally, SIs were determined for the forelimbs and hind limbs, and stride cycle durations as well as durations of the stance and swing phases were analyzed.

The GRF data were filtered with a low-pass 10-Hz finite-impulse response filter.^c Touchdown and lift-off of paws were manually defined. The GRF data were exported to a spreadsheet^d and standardized for each dog on the basis of that dog's body weight by use of the following equation:

$$\text{GRF} = \text{Fz}100/(\text{body mass} \cdot 9.81)$$

Mean \pm SD values were calculated for 10 valid consecutive steps. Load bearing characteristics (ie, PFz, MFz, and IFz) for each limb as well as shifts among the 4 limbs as a result of lameness were calculated as a percentage of body weight by use of the following equation³⁰:

$$\text{percentage of body weight borne by a limb} = \text{Fz of the limb} / \text{total Fz of all limbs} \cdot 100$$

where Fz is the vertical force.

The SIs were determined by use of the following equation³¹:

$$\text{SI} = 100 \cdot (X_i - X_c) / (0.5 \cdot [X_i + X_c])$$

where X_i is the mean value of PFz, MFz, or IFz of the ipsilateral limbs and X_c is the mean value of PFz, MFz, or IFz of the contralateral limbs.

To evaluate changes in the temporal gait variables attributable to lameness, mean \pm SD of the duration of the 10 stride cycles as well as mean duration of the

stance and swing phases of each limb were calculated for the step events determined via the vertical GRF. A stride cycle started when the right forelimb (the reference limb) touched down and ended when the same limb touched down again (force threshold was set at 13 N). Thus, 1 stride comprised 1 complete stance and 1 complete swing phase with their respective durations (ie, stance phase duration and swing phase duration). Stance phase duration was then expressed as a percentage of the total stride cycle duration (ie, relative stance duration).

Statistical analysis—Normal distribution of the data was assessed via the Kolmogorov-Smirnov test. A 1-way ANOVA for repeated measures followed by a post hoc Tukey test was used to detect differences in PFz, MFz, and IFz between the sound (control) and lame conditions. Paired *t* tests were used to compare relative stance phase durations between sound and lame conditions. Values were considered significant at $P < 0.05$. All analyses were performed with a statistical program.^e

Results

Load distribution for the control condition and induced forelimb lameness—For the control condition, no significant differences were found between the 2 forelimbs or between the 2 hind limbs for PFz, MFz, and IFz during walking or trotting (Table 1). In contrast, in the forelimb in which lameness was induced (ipsilateral forelimb), all 3 variables were significantly decreased during both walking and trotting. In the contralateral forelimb, PFz, MFz, and IFz were significantly increased during trotting, whereas only MFz and IFz were increased significantly during walking. Independent of gait, no significant changes were detected for the ipsilateral hind limb, but all evaluated variables were significantly increased in the contralateral hind limb.

SI—No asymmetry was detected between the 2 forelimbs or between the 2 hind limbs for PFz, MFz, and IFz for the sound condition when the dogs walked or trotted (Table 2). Asymmetry significantly increased for all variables in the forelimbs and hind limbs and during walking and trotting when lameness was induced, except for IFz of the hind limbs during walking.

Temporal gait variables—The relative stance durations of the forelimbs and those of the hind limbs did not differ significantly when dogs walked or trotted during the control condition (Table 3). When lameness was induced, the relative stance durations increased significantly in the contralateral forelimb and hind limb

Table 2—The SI values of 7 Beagles for the sound (control) condition and after lameness was induced in the right forelimb.

Gait	Variable	Forelimbs		Hind limbs	
		Sound	Lame	Sound	Lame
Walking	PFz	-1.4 \pm 2.2	-46.1 \pm 5.4*	-3.0 \pm 4.7	-31.6 \pm 17.0†
	MFz	-4.4 \pm 5.0	-54.8 \pm 11.5*	-0.7 \pm 4.3	-19.7 \pm 13.0†
	IFz	-2.4 \pm 6.1	-61.6 \pm 13.7*	0.1 \pm 7.7	-23.3 \pm 21.3
Trotting	PFz	-0.3 \pm 2.8	-55.8 \pm 19.6*	0.1 \pm 2.3	-19.7 \pm 12.7*
	MFz	-0.0 \pm 4.3	-55.7 \pm 20.2*	0.9 \pm 2.8	-16.4 \pm 10.8†
	IFz	1.3 \pm 4.3	-60.3 \pm 23.0*	2.5 \pm 5.2	-22.4 \pm 14.0†

Values reported are mean \pm SD.

Perfect symmetry is represented by SI = 0. Negative values indicate the respective variable was greater for the left limb than the right limb, and positive values indicate the variable was greater for the right limb than the left limb.

*Within a pair of limbs, value differs significantly ($P < 0.01$; † $P < 0.05$) from the value for the sound condition.

Table 3—Relative stance duration of 7 Beagles for the sound (control) condition and after lameness was induced in the right forelimb (ipsilateral forelimb).

Gait	Contralateral forelimb		Ipsilateral forelimb		Contralateral hind limb		Ipsilateral hind limb	
	Sound	Lame	Sound	Lame	Sound	Lame	Sound	Lame
Walking	65.6 \pm 2.1	71.8 \pm 2.1*	66.1 \pm 1.5	63.3 \pm 3.7	60.4 \pm 1.7	66.0 \pm 4.0*	61.1 \pm 2.2	57.6 \pm 4.8
Trotting	55.6 \pm 3.2	66.9 \pm 9.6	56.8 \pm 4.8	58.2 \pm 4.0	47.6 \pm 3.8	48.0 \pm 6.0	48.4 \pm 3.8	45.4 \pm 9.8

Values reported are mean \pm SD percentage of the stride cycle.
*Within a limb, value differs significantly ($P < 0.05$) from the value for the sound condition.

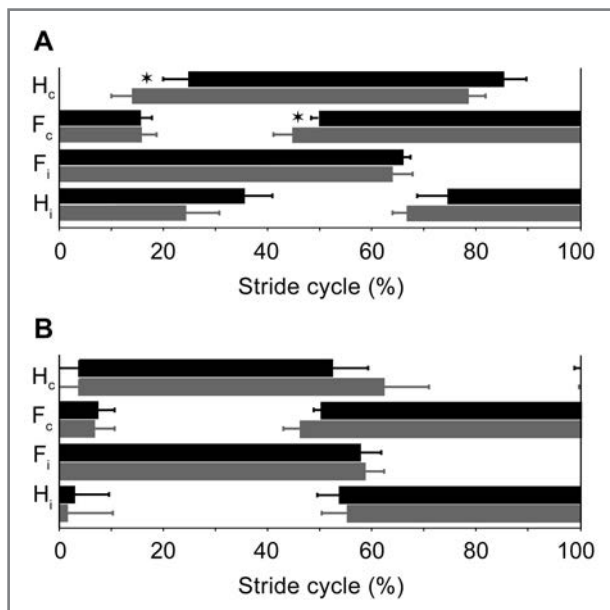


Figure 2—Mean \pm SD stance duration for footfall patterns of all 7 Beagles during walking (A) and trotting (B) for the sound (control) condition (black bars) and after lameness was induced (gray bars) in the right forelimb (ipsilateral forelimb). Stance duration was the interval from touchdown to liftoff of a paw. *During walking, touchdown of the paw in a limb after induced lameness was shifted significantly ($P < 0.05$), compared with results for that same limb in the sound condition. F_c = Contralateral forelimb. F_i = Ipsilateral forelimb (reference limb). H_c = Contralateral hind limb. H_i = Ipsilateral hind limb.

during walking because of earlier touchdown (Figure 2). No differences in relative stance durations were detected during trotting.

Discussion

No significant differences in PFz, MFz, and IFz were detected between the 2 forelimbs and between the 2 hind limbs during walking or trotting for the sound condition. Accordingly, the load distribution between the forelimbs or hind limbs was symmetric in the Beagles of the present study. These results are comparable with values for walking and trotting dogs of other studies.^{1-7,9} Consistently, each forelimb bore approximately 30% of a dog's body weight, and each hind limb bore approximately 20% of a dog's body weight. The SIs determined in the study reported here were comparable with results for dogs in other studies.^{13,16} Thus, the dogs enrolled in the present study were healthy and the collected data can serve as control data.

Compared with results for the sound condition, PFz was significantly decreased in the forelimb in which lameness was induced (ipsilateral forelimb) during both walking and trotting. This is consistent with results for other studies of walking dogs^{12,32,33} and trotting horses.³⁴ However, these results are in contrast with those of another study²⁴ in which investigators detected no change in PFz, possibly because they induced a milder degree of lameness. In the contralateral forelimb, PFz was unchanged in the present study, which is consistent with results

of another study.²⁴ However, PFz was significantly increased during walking in other studies.^{12,32,33} The PFz was significantly increased during trotting in the present study, but remained unchanged in another study.³⁴ In the ipsilateral hind limb, no significant changes of PFz were detected in the study reported here or in another study.²⁴ In contrast, investigators detected a significant decrease in PFz in walking dogs¹² and trotting horses.³⁴ In the present study as well as previous studies,^{12,24,34} PFz was significantly increased in the contralateral hind limb.

Compared with results for the sound condition, MFz was significantly decreased in the forelimb with induced lameness in the dogs of the present study. These results are consistent with those of another study.²⁴ In the contralateral forelimb and contralateral hind limb, MFz was significantly increased for both gaits, whereas there was not a significant change in the ipsilateral hind limb. These findings are in agreement with results of that other study.²⁴

In the present study, IFz was significantly decreased in the ipsilateral forelimb during both walking and trotting, compared with results for the sound condition. This is consistent with results reported for walking dogs^{24,33} and trotting horses.³⁴ In the contralateral forelimb, IFz was significantly increased in the present study and 2 other studies.^{33,34} However, investigators in another study²⁴ detected no significant difference in IFz. Although we did not detect significant changes in IFz of the ipsilateral hind limb in the present study, which is consistent with results of 1 study,²⁴ investigators in another study³⁴ detected a decrease in IFz. The IFz of the contralateral hind limb was significantly increased during both walking and trotting in the study reported here, which is in agreement with the results of 1 study³⁴ but differs from results of another study²⁴ (investigators in that study²⁴ detected no changes in IFz of the contralateral hind limb).

Compared with results for the sound condition in the present study, relative stance duration was decreased in the ipsilateral forelimb during walking but increased during trotting, although neither the increase nor decrease was significant (Figure 2). This differs from results of another study³⁴ in which researchers detected a significant increase in the relative stance duration in trotting horses. In the contralateral forelimb, relative stance duration was significantly increased during walking but remained unchanged during trotting in the present study. In contrast, a significant increase in relative stance duration in the contralateral forelimb was detected in trotting horses in another study.³⁴ Relative stance duration was not significantly changed in the ipsilateral hind limb during either gait in the present study, which is similar to results of other studies.^{24,34} During walking, the relative stance duration was significantly increased in the contralateral hind limb, but there was no change during trotting; these results are similar to results in horses.³⁴

A significant decrease in PFz in the ipsilateral forelimb, significant increase in PFz in the contralateral hind limb, and no change in PFz in the contralateral forelimb and ipsilateral hind limb in the present study are in agreement with results of a study²⁴ of dogs that

were clinically lame because of dysplasia of the elbow joint. In the dogs with induced lameness in the present study and the dogs with clinical lameness in that other study,²⁴ MFz significantly decreased in the ipsilateral forelimb, remained unchanged in the ipsilateral hind limb, and significantly increased in the contralateral hind limb. However, results for our dogs with induced lameness differ from those of the dogs with clinical lameness in that MFz was unchanged in the contralateral forelimb in the clinically lame dogs. Similar to results for the induced lameness in the study reported here, IFz was significantly decreased in the ipsilateral forelimb but was unchanged in the ipsilateral hind limb during walking in dogs with lameness attributable to dysplasia of the elbow joint.²⁴ In contrast to results for clinical lameness in that study,²⁴ IFz was significantly increased in the contralateral forelimb and the contralateral hind limb in the dogs of the present study. Similar to our results for dogs with induced lameness, there was no change in the relative stance duration in the ipsilateral forelimb and the ipsilateral hind limb and relative stance duration was significantly increased in the contralateral forelimb in walking dogs with lameness attributable to dysplasia of the elbow joint.²⁴

Differences in results from the various studies that have involved the use of induced lameness as a method to evaluate load redistribution strategies in quadrupeds indicate that there is variation in the ways in which loading is changed to cope with forelimb lameness. Factors likely to influence the compensatory mechanisms include species, gait, speed, body weight, location of the lesion (eg, proximal or distal aspect of a limb), degree of lameness (ie, degree of limb unloading), or a combination of these factors. Because the few studies conducted to investigate induced forelimb lameness in quadrupedal mammals have had variations in several of these factors (ie, species [horses or dogs], gait [walking or trotting], speed, body location [shoulder joint, elbow joint, or foot], and induced unloading between 3% and 36% of body mass), it remains unclear as to which factors play the more critical roles in an animal's coping mechanism. For example, comparison of the relative locomotor speed (ie, Froude number) among the studies does not reveal an obvious relationship between speed and the compensatory load redistribution during walking. Nevertheless, because locomotor forces increase with speed and depend on gait,^{1,5,6,9,10,28,35-38} effects on the mechanisms for shifting of loading can be expected.

Load alterations sometimes included the contralateral forelimb in walking dogs, and this may be related to the location of the lesion.³⁹ Studies conducted to investigate lameness in proximal joints revealed an increase in PFz in the contralateral forelimb (shoulder joint^{12,32} or elbow joint³³), whereas lameness induced at the paw did not change the PFz in the contralateral forelimb in the present study or another study.²⁴ However, all studies are in agreement with regard to a load shift to the contralateral hind limb.

The relative limb loading and thus the instantaneous location of the center of body mass in quadrupedal mammals such as horses or dogs can be changed and thereby the forelimb unloaded by at least 2 mechanisms. First, postural changes of the head, neck, and

trunk as well as of the forelimbs, hind limbs, or both may result in dynamic changes in the location of the center of body mass. For example, greater extension of a forelimb or greater flexion of a hind limb, or a combination of both, as well as greater dorsal flexion of the neck would result in a caudal shift of the center of body mass, whereas changes of trunk motions in the horizontal plane could shift the center of body mass laterally. Such postural adaptations have been observed in horses and were found to be crucial mechanisms for shifting the center of body mass and thus the redistribution of limb loading.^{40,f} Additionally, peak vertical accelerations of the center of body mass were reduced when lameness was induced in a forelimb in horses, which resulted in a reduction in the overall PFz values.⁴¹ The same mechanisms probably apply to dogs, although they have not yet been studied in detail. The second mechanism by which the center of body mass may be shifted caudally is to produce torque at the hip joint via an increase in retractor moment. This would result in a nose-up pitching moment and thus temporary unloading of the forelimb. Consistent with that, increased vertical forces, most likely attributable to a greater retractor moment at the hip joint, were observed in the contralateral hind limb in the present study. Additionally, touchdown of the contralateral hind limb was relatively earlier during the gait cycle during walking, which resulted in an increase in temporal overlap of the stance phases of the ipsilateral forelimb and the contralateral hind limb and thus relatively more time to produce torque at the hip joint. These hypotheses will provide useful areas for future studies. Furthermore, the long-term effects of the load redistribution and the shift of the center of body mass need to be established to evaluate the prospects for patients with chronic lameness.

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- a. Model 4060-08, Bertec Corp, Columbus, Ohio.
 - b. Vicon Nexus, Vicon Motion Systems Ltd, Oxford, England.
 - c. MyoResearch XP master edition, Noraxon, Scottsdale, Ariz.
 - d. Excel, Microsoft Corp, Redmond, Wash.
 - e. GraphPad Prism, version 4, GraphPad Software Inc, La Jolla, Calif.
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