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Compensatory load redistribution in walking and trotting dogs with hind limb lameness

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ABSTRACT

This study evaluated adaptations in vertical force and temporal gait parameters to hind limb lameness in walking and trotting dogs. Eight clinically normal adult Beagles were allowed to ambulate on an instrumented treadmill at their preferred speed while the ground reaction forces were recorded for all limbs before and after a moderate, reversible, hind limb lameness was induced. At both gaits, vertical force was decreased in the ipsilateral and increased in the contralateral hind limb. While peak force increased in the ipsilateral forelimb, no changes were observed for mean force and impulse when the dogs walked or trotted. In the contralateral forelimb, the peak force was unchanged, but the mean force significantly increased during walking and trotting; vertical impulse increased only during walking. Relative stance duration increased in the ipsilateral hind limb when the dogs trotted. In the contralateral fore and hind limbs, relative stance duration increased during walking and trotting, but decreased in the ipsilateral forelimb during walking. Analysis of load redistribution and temporal gait changes during hind limb lameness showed that compensatory mechanisms were similar regardless of gait. The centre of mass consistently shifted to the contralateral body side and cranio-caudally to the side opposite the affected limb. These biomechanical changes indicate substantial short- and long-term effects of hind limb lameness on the musculoskeletal system.

Introduction

More than half of the musculoskeletal problems in dogs are caused by joint diseases affecting the hind limb (i.e. hip and knee; Johnson et al., 1994) and are commonly associated with alterations in the gait (i.e. lameness) due to the animal's effort to unload the affected limb. The biomechanical consequences of orthopaedic diseases, such as hip dysplasia and cranial cruciate ligament rupture, have been evaluated by investigating the load bearing characteristics of either the affected hind limb only (Gordon et al., 2003; Hoelzler et al., 2004; Conzemius et al., 2005; Evans et al., 2005; Madore et al., 2007) or both hind limbs (Budsberg et al., 1988; Voss et al., 2008; Ragetly et al., 2010; Böddeker et al., 2012; Seibert et al., 2012). Fewer studies have evaluated the effects of hind limb lameness on the forelimbs (Rumph et al., 1993, 1995; Dupuis et al., 1994; Jevens et al., 1996; Katic et al., 2009). Nevertheless, unloading one limb causes biomechanical adaptations in all remaining limbs and results in an irregular gait pattern and a compensatory redistribution of limb loading.

During the standard orthopaedic examination, dogs are usually ambulated at different speeds and gaits to diagnose lameness. Since locomotor forces increase with speed and depend on gait (Riggs et al., 1993; McLaughlin and Roush, 1994; Renberg et al., 1999; Evans et al., 2003; Voss et al., 2010), not only may lameness be more apparent during trotting compared to walking (Quinn et al., 2007; Voss et al., 2007), but the compensatory mechanism used by the animal may differ. Additionally, the fundamental biomechanical differences between walking and trotting (i.e. legs behaving like inverted pendula vs. 'pogo sticks'; Cavagna et al., 1977) may result in differences in the locomotor adaptations to lameness. Previous studies have evaluated induced hind limb lameness in trotting dogs (O'Connor et al., 1989; Rumph et al., 1993, 1995; Dupuis et al., 1994) or clinical lameness in walking dogs (Budsberg et al., 1988; Katic et al., 2009; Böddeker et al., 2012). It is uncertain if dogs show the same locomotor adaptations to hind limb lameness when walking and trotting.

In dogs, as in most quadrupedal mammals, fore and hind limbs play different functional roles during locomotion (Gray, 1968). The forelimbs exert a net-braking force, while the hind limbs exert a net-propulsive force during steady state locomotion (Budsberg et al., 1987; Riggs et al., 1993; Bertram et al., 1997; Lee et al., 1999). Forelimbs function as compliant struts (Carrier et al.,

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2008), whereas hind limbs function as levers (Schilling et al., 2009). Regardless of gait, the forelimbs bear a greater proportion of the dog's bodyweight (BW) in comparison with the hind limbs (Budsberg et al., 1987; Rumph et al., 1994; Bertram et al., 2000; Bockstahler et al., 2007; Voss et al., 2010). Therefore, when the function of a limb is partially lost, the dog's mechanism to cope with this loss has been expected to differ depending on whether a fore or a hind limb is affected (Roy, 1971; Leach et al., 1977).

To gain a better understanding of the compensatory load shifting mechanisms in lame dogs, we induced a moderate, reversible, load-bearing hind limb lameness in Beagles while they were walking and trotting on an instrumented treadmill, and evaluated the changes in the ground reaction force (GRF) and temporal gait parameters. Force plate analysis was used because it is an accurate and objective way of evaluating limb function and provides a reproducible measurement of the load bearing characteristics of the limbs. Inducing hind limb lameness allowed for a direct comparison of the gait parameters between sound and lame dogs and the precise determination of the degree and cause of lameness.

The aims of this study were: (1) to determine changes occurring in the vertical GRF, i.e. peak vertical forces (PFz), mean vertical forces (MFz) and vertical impulse (IFz), as well as the temporal gait parameters (i.e. footfall pattern, relative stance duration) in all four limbs; (2) to determine whether the observed locomotor adaptations differed between the gaits; and (3) to determine whether the compensatory mechanisms in response to hind limb lameness differed from the ones used to cope with forelimb lameness. To address the latter, we compared our results with the ones from a previous study (Abdelhadi et al., 2013), which used the same experimental design and therefore allowed for a direct comparison of load redistribution strategies.

Materials and methods

Animals

Eight Beagles aged 4 ± 1 years (mean ± standard deviation, SD) were used in this study. The sample size sufficient for this study was determined using Win Episcope 2.0 with a level of confidence of 95%, a power of 80% and the outcome measures PFz, MFz and IFz (Thrusfield et al., 2001). The BW (mean ± SD) of the two females and six males was 15.2 ± 1.1 kg. All dogs belonged to the Beagle population of the Small Animal Clinic of the University of Veterinary Medicine, Hannover, Germany. Inclusion criteria were absence of lameness (see results) and orthopaedic abnormalities in the previous clinical examination. Before data collection, the dogs were habituated to ambulating on the treadmill. Data collection started as soon as the dogs were walking and trotting smoothly and comfortably. All experiments were carried out in accordance with the German Animal Welfare guidelines of the State of Lower Saxony (approval number 12/0717).

Study design

To allow for comparison of the compensatory load redistribution mechanisms in forelimb vs. hind limb lameness, the same experimental protocol as in Abdelhadi et al. (2013) was used in the current study, but lameness was induced in the right hind limb (i.e. ipsilateral hind limb, H_i). Before inducing lameness, each Beagle walked (0.9 m/s) and trotted (1.4 m/s) on a horizontal treadmill. Despite the short temporal overlap in ground contacts between the forelimbs at the faster gait (duty factor, $D > 0.5$; i.e. running walk according to Hildebrand (1966); Fig. 1), from a mechanical point of view, this gait represented a trot (i.e. using spring-mass mechanics; Cavagna et al., 1977) and will subsequently be referred to as trot. The selected speeds were determined during the habituation sessions, as were the preferred speeds for the dogs at the respective gait. At these speeds, the dogs ambulated smoothly and comfortably matched the treadmill speed, which allowed us to record single limb forces (see below).

After recording the control trials, a moderate and reversible hind limb lameness was induced using a small sphere, which was coated with cotton gauze and taped under the paw with adhesive tape and bandages. The size of the sphere (9.5 or 16.0 mm in diameter) depended on the degree of lameness it induced in a given dog. The degree of lameness was evaluated based on the GRF data. To be able to compare our data with previous results (Abdelhadi et al., 2013), we aimed at an unloading of ~30–40% with regard to PFz (in %BW) compared with the sound condition.

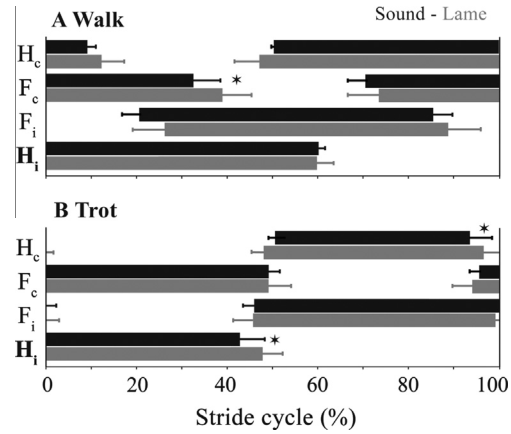

Fig. 1. Stride cycle with mean ± standard deviation (SD) stance duration for footfall patterns of all eight Beagles during walking (A) and trotting (B) for the sound (control) condition (black bars) and after lameness was induced (grey bars) in the right hind limb (ipsilateral hind limb, H_i). Stance duration was the interval between touch-down to lift-off of a paw. *Touch-down of the paw of a limb after induced lameness was shifted significantly during walking (F_c, $P < 0.05$) and trotting (H_c, $P < 0.05$; H_i, $P < 0.01$) in comparison with the results for that same limb in the sound condition. Stride cycle was the interval between touch-down to next the touch-down of the same limb. F_c, contralateral forelimb; F_i, ipsilateral forelimb; H_c, contralateral hind limb; H_i, ipsilateral hind limb (i.e. affected limb, bold).

Data collection and analysis

Data collection and analysis are described in detail in Abdelhadi et al. (2013). A treadmill with four separate belts and force plates underneath each belt (Model 4060-08, Bertec) was used to record single limb GRF (sampling rate 1000 Hz). Data were recorded and evaluated to ensure a sufficient number of valid steps using Vicon Nexus (Vicon). Control data comprising at least 5–10 trials, each lasting up to 30 s and covering between 48 and 65 strides, were recorded for each dog while walking and trotting comfortably at the selected speed. After a break of approximately 15 min, lameness was induced and the data collection repeated. To evaluate kinetic changes, 10 valid consecutive strides were selected for each dog, gait and condition.

Mean ± SD for PFz, MFz and IFz were calculated for all four limbs. Additionally, relative stance duration (i.e. duration of stance phase as percentage of total stride duration = D), as well as symmetry indices for the vertical forces of the fore and hind limbs, were determined. After manual identification of the footfall events in Vicon Nexus using the GRF, the force data were time-normalised to 100% of the stance duration of the respective limb and transferred to Microsoft Excel for further analysis. The vertical force parameters were then normalised to the dog's BW using the following equation:

$$\text{GRFs}\ (\%\text{BW}) = \text{Fz} \times 100/(\text{BM} \times 9.81).$$

These BW-normalised data were used to compare the load-bearing characteristics among the four limbs before and after lameness was induced (Steiss et al., 1982):

$$\%\text{BW bearing} = \text{Fz of the limb}/\text{total Fz of all limbs} \times 100.$$

Symmetry in the vertical force and temporal variables was quantified using the following equation (Herzog et al., 1989):

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

In this equation, X represents the mean value of PFz, MFz or IFz of the ipsilateral (i) and the contralateral (c) limbs from the 10 steps. Footfall patterns and D were evaluated to test for significant differences in the temporal gait parameters due to lameness. A stride cycle begins with the contact of the affected limb (ipsilateral hind limb, H_i) and ends with its subsequent touch-down. Therefore, one locomotor cycle comprises one complete stance and one complete swing phase of the reference limb.

Statistical analysis

Data were tested for normal distribution using the Kolmogorov–Smirnov test. The significance of the differences in PFz, MFz and IFz between the sound and lame conditions was determined using one-way analysis of variance (ANOVA) for repeated measures, followed by a post hoc Tukey test. Paired t tests were used to compare relative stance durations between sound and lame conditions. P values <0.05 were considered to be significant. All statistical tests were performed in GraphPad Prism (version 4).