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Ground reaction force adaptations to tripedal locomotion in dogs

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ABSTRACT

To gain insight into the adaptive mechanisms to tripedal locomotion and increase understanding of the biomechanical consequences of limb amputation, this study investigated kinetic and temporal gait parameters in dogs before and after the loss of a hindlimb was simulated. Nine clinically sound Beagle dogs trotted on an instrumented treadmill and the ground reaction forces as well as the footfall patterns were compared between quadrupedal and tripedal locomotion.

Stride and stance durations decreased significantly in all limbs when the dogs ambulated tripedally, while relative stance duration increased. Both vertical and craniocaudal forces were significantly different in the remaining hindlimb. In the forelimbs, propulsive force increased in the contralateral and decreased in the ipsilateral limb, while the vertical forces were unchanged (except for mean force in the contralateral limb). Bodyweight was shifted to the contralateral and cranial body side so that each limb bore ~33% of the dog's bodyweight. The observed changes in the craniocaudal forces and the vertical impulse ratio between the fore- and hindlimbs suggest that a nose-up pitching moment occurs during the affected limb pair's functional step. To regain pitch balance for a given stride cycle, a nose-down pitching moment is exerted when the intact limb pair supports the body. These kinetic changes indicate a compensatory mechanism in which the unaffected diagonal limb pair is involved. Therefore, the intact support pair of limbs should be monitored closely in canine hindlimb amputees.

Introduction

Limb amputation is a controversial topic among both pet owners and veterinarians. Although several studies have shown that pet owners were very satisfied with the outcome after amputation (Withrow and Hirsch, 1979; Carberry and Harvey, 1987; Kirpensteijn et al., 1999), when confronted with the decision, owners often react reluctantly and are concerned about the animal's quality of life. Emotional, social and financial aspects as well as concerns that the dog will not adapt to the tripedal situation are among the prevalent issues raised (Withrow and Hirsch, 1979; Carberry and Harvey, 1987; Kirpensteijn et al., 1999).

To facilitate an informed and evidence-based decision for owners and veterinarians and to gain insight into potential sequelae in canine amputees, it is necessary to understand the biomechanical adaptations to tripedal locomotion and its consequences for the musculoskeletal system. Only few studies have performed gait analyses in amputees to discern gait adaptations. Kirpensteijn et al. (2000) compared various kinetic and temporal parameters from amputees with data from a control group. Several kinetic and kinematic differences between amputee and control dogs have also been reported in two recent studies (Hogy et al., 2013; Jarvis et al., 2013). While the dogs walked in the earlier study (Kirpensteijn et al., 2000), they trotted along a walkway in the two later studies, which may, at least in part, explain some of the differences observed.

All three studies compared data between patients and control dogs that were more or less matched regarding body size, age and/or physical condition. Only one study so far has allowed for the direct comparison of kinetic data before and after amputation in the same individual (Galindo-Zamora, 2012). In this longitudinal study, however, no significant kinetic changes were observed, most likely because the dogs were severely lame before surgery.

To further our understanding of the biomechanical adaptations to tripedal locomotion in dogs and circumvent some of the caveats by directly comparing data from the same individuals under the same experimental conditions, we collected kinetic and temporal gait data from nine healthy dogs before and after the loss of a hindlimb was simulated (i.e. the leg was tied up to the body). Because hindlimbs act like levers and exert net-propulsive forces during locomotion (Gray, 1968; Budsberg et al., 1987; Lee et al., 1999), the loss of a hindlimb represents first and foremost a loss of propulsive force. Additionally, the vertical impulse of the affected diagonal limb pair of a trotting quadruped shifts to the forelimb due to the lack of the hindlimb's vertical force. Without a compensatory mechanism for balance, any step involving a net fore–aft acceleration and/or a fore- vs. hindlimb shift of the vertical impulse also involves a moment

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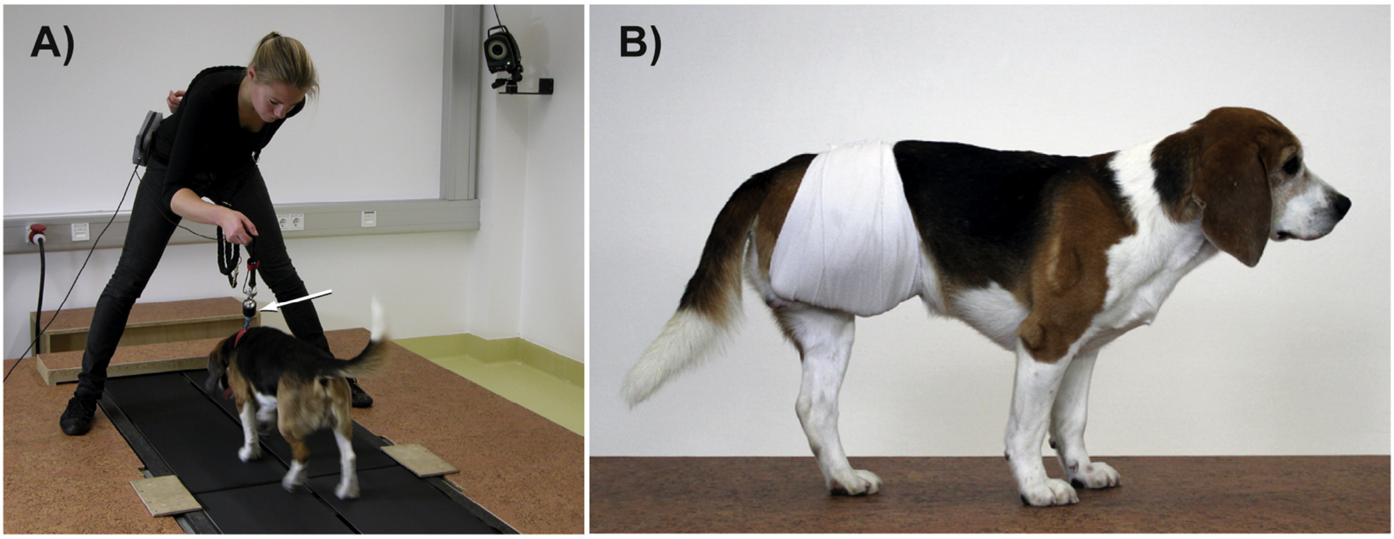

Fig. 1. A. Data collection during quadrupedal locomotion (i.e. control data). Note the force transducer in series with the leash to verify steady state locomotion of the dog during recordings (arrow). B. Subject with the modified Ehmer sling: the right hindlimb is tied up to the dog's body to simulate the loss of that limb.

exerted about the pitch axis of the body and thus a net rotation about the body's transverse axis (Gray, 1968; Lee et al., 1999).

The goals of this study were: (1) to improve our knowledge about the kinetic and temporal gait adaptions to tripedal locomotion in dogs; (2) to compare our results with previously published data from amputees; and (3) to investigate how dogs maintain pitch stability when locomoting tripedally.

Materials and methods

Animals

Nine clinically sound Beagle dogs participated in this study. The six male and three female dogs had a bodyweight (BW) of 15.0 ± 0.8 kg (mean ± SD) and were 4.4 ± 1.4 years old. All dogs were owned by the Small Animal Clinic of the University of Veterinary Medicine Hannover (Germany) and underwent a standard orthopaedic examination before data collection. All experiments were in strict accordance with the German Animal Welfare Regulations and approved by the Ethics Committee of the State of Lower Saxony (protocol No 12/0717).

Data collection

Data from quadrupedal and tripedal locomotion were collected in the same session for each dog. Prior to data collection, the dogs were habituated to locomoting quadrupedally on the instrumented four-belt treadmill (Model 4060-08, Bertec). The treadmill was equipped with force plates underneath each belt to obtain single limb ground reaction forces (GRF) (Fig. 1A).

Tripedal data were acquired by simulating amputation of the right hindlimb (referred to as the ipsilateral hindlimb). To do this, the leg was tied up to the body using a modified Ehmer sling (Fig. 1B). To familiarize the dogs to wearing the sling, each dog was trained to locomote tripedally on the laboratory floor first before it was introduced to ambulating on the treadmill. Depending on the individual's performance, the dogs underwent training sessions of 30 min two to three times a week for 12–20 weeks. On average, the dogs had 19 sessions for the tripedal condition, of which only the first three included tripedal training on the laboratory floor exclusively. Data collection started when the dog was fully adept at locomoting tripedally on the treadmill: i.e. when it showed a fluent and regular motion pattern without any tripping or skipping and the same regular GRF patterns were observed throughout the whole session.

Preferred locomotor speed varied slightly among dogs and ranged between 1.3 and 1.5 m/s. Each dog's preferred speed was determined during the habituation period and represented the speed at which the dog, particularly tripedally, matched the treadmill speed effortlessly. For each dog, however, locomotor speed was the same during tripedal and quadrupedal trials. We refer to the dogs' gait as a trot based on its mechanics (i.e. using spring-mass vs. inverted pendulum mechanics) (Cavagna et al., 1977). According to its footfalls, this gait represents a 'running walk' with short temporal overlaps of the ground contacts of the forelimbs (Hildebrand, 1966) (Fig. 2).

All GRF data were collected using Vicon Nexus (Vicon Motion Systems; force threshold: 13 N; sampling rate: 1000 Hz). For each dog, at least five quadrupedal (control) trials were recorded. Each trial lasted up to 30 s and covered between 60 and 69 stride cycles. After a break of at least 15 min, the Ehmer sling was applied using gauze and bandage. The dogs were then allowed to run on the floor to verify that the sling was appropriate in tightness (e.g. preventing leg motions inside the bandage) and to ensure that dogs showed no signs of discomfort. After a few seconds of ambulating on the treadmill, at least five trials were recorded for the tripedal condition. Tripedal trials also lasted up to 30 s and covered between 66 and 78 strides. Of the recorded data, 10 consecutive valid strides of one of the trials recorded per dog and condition were selected for further analysis. A stride was considered valid if the dog ran at steady state (i.e. mean fore–aft acceleration of the body is 0) and single limb GRF were collected (i.e. strides without overstepping).

To verify that the dogs ambulated unrestrained and at steady state, all dogs were handled by the same experimenter (AF) and were led by a customized leash equipped with a force transducer (KMM30-200N Z/D, signal amplifier IA 2, DMS 24 V, 0-10 V; Inelta Sensors Systems). The force transducer signal was recorded synchronously with the GRF using Vicon Nexus. Only trials with a leash force of less than 0.2 N were included in the data analysis.

Data analysis

Two of the three orthogonal components of the GRF were analyzed (i.e. Fz-vertical force; Fy-craniocaudal, fore–aft or braking and propulsive force). For this, first touch-down and lift-off events of all limbs were marked manually in Vicon Nexus using the vertical force traces. Then, the data were time normalized to 100% of the stance duration of the respective limb and exported to Microsoft Excel 2003. All force data were normalized to the dog's BW.

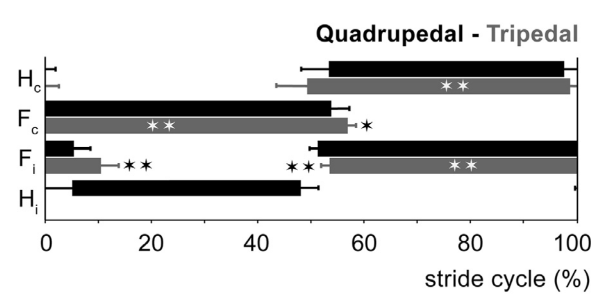

Fig. 2. Averaged footfall patterns from all nine Beagle dogs ambulating quadrupedally (black) and tripedally (grey). Bars represent means ± standard deviation of the stance duration of each limb relative to the stride cycle of the forelimb contralateral (Fc) to the right hindlimb (Hi). Filled asterisks indicate significant differences in the timing of the touch-down or lift-off events during tripedal locomotion compared with the quadrupedal condition (see Table 1). Open asterisks indicate significant changes in relative stance duration. Fc, contralateral forelimb; Fi, ipsilateral forelimb; Hc, contralateral hindlimb; Hi, ipsilateral hindlimb (hindlimb for which the amputation was simulated). *$P < 0.05$; **$P < 0.01$.