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Three-dimensional movements of the pelvis and the lumbar intervertebral joints in walking and trotting dogs

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ABSTRACT

Current knowledge of the physiological range of motion (ROM) in the canine axial system during locomotion is relatively limited. This is particularly problematic because dogs with back-related dysfunction frequently present for routine consultations. To collect detailed kinematic information and describe the three-dimensional motions of the pelvis and the lumbar spine (i.e. intervertebral joints S1/L7–L2/L1), we recorded ventro-dorsal and latero-lateral X-ray videos of three walking and trotting dogs and reconstructed their pelvic and intervertebral motions using X-ray reconstruction of moving morphology and scientific rotoscoping.

Pelvic roll displayed a monophasic motion pattern and the largest ROM with on average 13° and 11° during walking and trotting, respectively. Pelvic yaw had the smallest ROM with on average 5° (walk) and 6° (trot). A biphasic pattern was observed for pelvic pitch with a mean ROM of 8°. At both gaits, the greatest intervertebral motions occurred either in S1/L7 or L7/L6. The intervertebral motions were mono- or biphasic in the horizontal and the transverse body planes and biphasic in the sagittal plane. Cranial to L6/5, the ROM tended to decrease from 3° to <1.5° in all three planes. Our results confirm that pelvic displacement and intervertebral joint movements are tightly linked with pelvic limb action at symmetrical gaits. The overall small movements, particularly cranial to L5, are consistent with the epaxial musculature globally stabilising the spine against the external and internal limb forces acting on the pelvis and the trunk during walking and trotting.

Introduction

Dogs with back-related dysfunction or problems frequently present for routine consultations in veterinary practice. The reasons for their presenting signs may be multifaceted and of musculoskeletal, neurological or traumatic origins (Besalti et al., 2005; Bali et al., 2009; Marsh et al., 2010; Bergknut et al., 2013a and b). Diagnosis of the primary cause is often complicated and usually requires extensive orthopaedic and neurological examinations. Diagnostic imaging such as X-ray, CT or MRI may facilitate diagnosis by identifying soft and hard tissue abnormalities (e.g. pathologies of the vertebrae, intervertebral discs or pelvis). However, they are static representations and often give no indication of whether functional impairments of the spinal system exist.

To identify locomotor dysfunctions such as lameness, computer assisted gait analysis has become a key diagnostic tool (Budsberg et al., 1987; DeCamp, 1997; Gillette and Angle, 2008; Bockstahler et al., 2012; Abdelhadi et al., 2013). By attaching reflective markers to the skin at prominent anatomical landmarks, motion capture technologies allow for the non-invasive measurement of in-vivo joint kinematics. However, compared with the large body of knowledge on canine limb motion (DeCamp et al., 1993; Gillette and Zebas, 1999; Marsolais et al., 2003; Colborne et al., 2006; Feeney et al., 2006; Gillette and Angle, 2008; Kim et al., 2008; Holler et al., 2010; Bockstahler et al., 2012; Miqueleto et al., 2013), data on the three-dimensional (3D) movements of the pelvis and the thoracolumbar spine and particularly the intervertebral joints (IVJs) are rare (Jenkins and Camazine, 1977; Wood et al., 1992; Schendel et al., 1995; Benninger et al., 2004, 2006). One reason for this might be that skin and soft tissue movements introduce artefacts, which particularly impact the analyses of proximal body parts such as the hip or the IVJs (Van Den Bogert et al., 1990; Van Weeren et al., 1990a and b; Khumsap et al., 2004; Sha et al., 2004).

Hitherto, only one study described the locomotor kinematics of the thoracolumbar spine in sound dogs (Gradner et al., 2007). In that study, kinematic data for sagittal and lateral trunk bending were collected, but long-axis rotations and the movements at the level of individual IVJs were not quantified. Motions between adjacent vertebrae during walking and sit-to-stand motions were analysed in a highly invasive manner using bone implants instrumented with

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spatial linkages (Buttermann et al., 1992; Wood et al., 1992; Schendel et al., 1995). Furthermore, in-vitro measurements showed that the mobility of the spine varied among body planes and along the vertebral column (Buerger and Lang, 1992, 1993; Benninger et al., 2004). However, the maximum range of motion (ROM) of a joint (i.e. its mobility) is rarely used during locomotion (Jenkins and Camazine, 1977; Scherrer et al., 1979). Therefore, not only the extent but also the timing of IVJ motions that occur during locomotor activities such as walking or trotting remain unknown.

The in-vivo approach of scientific rotoscoping (Gatesy et al., 2010) is a non-invasive, markerless method of X-ray reconstruction of moving morphology (XROMM; Brainerd et al., 2010) which combines the 3D reconstruction of skeletal elements from CT scans with biplane high-speed X-ray videography. The resulting kinematic data set provides the most detailed information about the pelvic and lumbar spine movements in walking and trotting dogs to date and thus may stimulate new diagnostic and therapeutic approaches for back-related dysfunctions in canine patients.

The aim of this study was to use detailed 3D kinematics of the pelvis and the lumbar IVJs to investigate the in-vivo motions of the spine and the functional integration between limb and back movements during walking and trotting in sound dogs. For this, lumbar IVJ motions and pelvic displacements were analysed and compared with the footfall patterns. Based on previous studies of pelvic and intervertebral movements of various mammals, we hypothesised that: (1) axial and lateral rotations would show a monophasic motion pattern with one minimum and one maximum per stride cycle associated with the lift-off and touch-down events of the pelvic limbs (Faber et al., 2000, 2001; Haussler et al., 2001; Licka et al., 2001a and b; Wennerstrand et al., 2004, 2009; Nyakatura and Fischer, 2010); (2) sagittal rotations would display a biphasic pattern with two minima and two maxima per stride associated with touch-down and lift-off, as well as mid-stance and mid-swing of the pelvic limbs (Faber et al., 2000, 2001; Haussler et al., 2001; Licka et al., 2001a and b; Wennerstrand et al., 2004, 2009; Nyakatura and Fischer, 2010); and (3) the greatest intervertebral ROM would occur in the last presacral IVJ (Buerger and Lang, 1993; Benninger et al., 2004).

Materials and methods

Animals

Three dogs from the Beagle population of the Small Animal Clinic at the University of Veterinary Medicine Hannover participated in this study (Table 1). Orthopaedic and clinical examinations and evaluation of the CT-scans (see below) confirmed that the dogs were sound and without any orthopaedic abnormalities. All experiments were carried out in strict accordance with the German Animal Welfare Regulations and approved by the Ethic Committees of Lower Saxony (No.: 10A078; 11 October 2010) and Thuringia (No.: 02–136/10; 6 October 2010).

Study design

The dogs walked (1.0 ± 0.2 m/s) and trotted (1.5 ± 0.3 m/s) on a horizontal motorised treadmill (Appendix: Supplementary Fig. S1). Duty factors were 0.6 ± 0.01 and 0.5 ± 0.01 for the walk and the trot, respectively (see below for sample sizes of walking and running trials). Biplane X-ray videos of each dog walking and trotting were recorded using a digital high-speed videography system (Neurostar Siemens). Both image intensifiers (diameters: 40 cm) were equipped with high-speed cameras (Visario Speedcam, Weinberger) to synchronously record the dogs from two perspectives (image resolution: 1.536 × 1.024 pixels; 500 frames per second). X-ray settings were 90 kV and 70 mA with the shutter set at 500 µs. Touch-down and lift-off events were determined using standard high-speed video cameras, which filmed the dogs synchronously with the X-ray videos at separate angles from the front and the back (SpeedCam MiniVis, High Speed Vision).

CT-scans of the complete spine and pelvis of each dog were obtained with a 64-slice scanner (Brilliance 64, Philips Medical Systems). For this, the dogs were sedated according to standard anaesthetic protocols; isoflurane inhalation narcotic 1.5–2.5%, premedication with diazepam 0.1 mg/kg and propofol 6 mg/kg. Scan settings were 120 kV and 275 mA; voxel size was 0.2 mm (x, y) and 0.1 mm (z).

Table 1
Details of the Beagles enrolled in the study.

	Sex	Age (years)	Bodyweight (kg)	Height at withers (cm)	Height of croup (cm)
Dog #1	Male	3	16	39	39
Dog #2	Female	3	13	38	39
Dog #3	Female	3	15	39	39

XROMM/scientific rotoscoping

The scientific rotoscoping workflow used in this study followed the XROMM recommendations[1] and is described in detail, including an example of animation, in the supplementary materials (Appendix: Supplementary Fig. S1, Table S1).

Data analyses

Of the recorded trials, consecutive strides of walking ($n = 6$) and trotting ($n = 5$) were selected for the scientific rotoscoping. The 3D movements of the pelvis and the IVJs are defined as follows: axial rotations occurred about the long-axis of the body in the transversal body plane (i.e. roll, rx); lateral rotations were rotations about the ventro-dorsal body axis in the horizontal plane (i.e. yaw, ry); and sagittal rotations occurred about the latero-medial axis in the sagittal plane of the body (i.e. pitch, rz) (Fig. 1). For these three rotations of the pelvis and the lumbar IVJs S1/L7–L2/1, means ± standard deviations (M ± SD) of the ROM were determined for each dog and for all dogs as a group. The IVJs were presented in a caudo-cranial order; that is, the motion of a cranial vertebra was described relative to the vertebra immediately caudal to it (Haussler et al., 2001).

Additionally, the timing of when the direction of rotational motion changed was determined as the percentage of the stride cycle of the reference limb. These changes in motion direction were determined whether negative rotations became positive or not. Thus, the changes in motion direction were not related to whether they represented a minimum or a maximum, because that information varied among the vertebral levels, dogs and gaits. Instead, the moment when motion directions changed during a stride was more or less consistent and therefore quantifiable and comparable among vertebral levels, dogs and gaits. Note that due to the small sample size (i.e. individuals, strides), this study is first and foremost descriptive.

To allow for the comparison of the angular movements across strides and dogs and with reference to the footfall events, stance and swing phases were separately time-normalised (i.e. 'phase-normalisation'; Deban et al., 2012) using Matlab (TheMathWorks, Matlab R2010b). As a result, walking data for the stance and swing phases covered 60% and 40% of the stride cycle, respectively (i.e. lift-off of the reference limb at 60% of the stride cycle). During trotting, both stance and swing phases covered 50% of the stride cycle. The footfall patterns are plotted with the respective kinematic data (Figs. 2–4). Note that the right pelvic limb is the reference limb in this study.

Results

Pelvic rotations

Independent of gait, pelvic roll showed a monophasic pattern with the direction of rotation changing just before the touch-downs of the pelvic limbs (Fig. 2). As a result, the hip joints were positioned near the substrate during touch-down. During walking, direction of motion changed after 36 ± 4% and 92 ± 4% of the stride cycle of the reference limb. During trotting, the direction of rotation changed slightly later during the stride (42 ± 4%, 94 ± 3%; Table 2). Compared with lateral and sagittal rotations, pelvic roll showed the greatest ROM during both walking and trotting with 12.6 ± 1.3° and 10.9 ± 0.8°, respectively (Fig. 2, Table 3).

During walking and trotting, pelvic yaw also exhibited a monophasic motion pattern (Fig. 3). Maximum and minimum values were associated with the touch-down and lift-off events of the pelvic limbs. That is, the hip joint faced cranially ipsilateral to the pelvic limb touching the ground and caudally ipsilateral to the limb lifting off. Pelvic yaw changed its direction of rotation after 42 ± 9% and 94 ± 5% of the stride cycle of the reference limb when the dogs walked and after 56 ± 6% and 102 ± 6% when they trotted (Table 2). With a mean ROM of 4.6 ± 1.1° (walk) and 5.8 ± 0.9° (trot), pelvic yaw was smaller than the rotations in the other two body planes (Fig. 3, Table 3).

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[1] See: http://www.xromm.org (accessed 17 December 2015).