Accepted Manuscript

Title: Vertical head and pelvic movement symmetry at the trot in dogs with induced supporting limb lameness

Authors: C.B. Gómez Álvarez, P. Gustås, A. Bergh, M. Rhodin

PII: S1090-0233(17)30193-4
DOI: https://doi.org/10.1016/j.tvjl.2017.10.011
Reference: YTVJL 5047

To appear in:

Accepted date: 17-10-2017

Please cite this article as: C.B.Gómez Álvarez, P.Gustås, A.Bergh, M.Rhodin, Vertical head and pelvic movement symmetry at the trot in dogs with induced supporting limb lameness (2010), https://doi.org/10.1016/j.tvjl.2017.10.011

Original Article

Vertical head and pelvic movement symmetry at the trot in dogs with induced supporting limb lameness

C.B. Gómez Álvarez [a,*], P. Gustås [b], A. Bergh [b], M. Rhodin [b]

[a] *School of Veterinary Medicine, Faculty of Health and Medical Sciences, University of Surrey, Guildford GU2 7AL, United Kingdom*
[b] *Faculty of Veterinary Medicine and Animal Husbandry, Swedish University of Agricultural Sciences, Uppsala SE-750 07, Sweden*

* Corresponding author. Tel.: +44 1483 689399.
E-mail address: c.gomezalvarez@surrey.ac.uk (C.B. Gómez Álvarez).

Highlights

- Induction of supporting forelimb lameness in dogs affected the lowest level of displacement of the head at the trot.
- Induction of supporting hind limb lameness in dogs affected the lowest level of displacement of the pelvis at the trot.
- Asymmetry of the lowest vertical positions of the head or pelvis is a potential indicator of induced supporting lameness.
- Compensatory movements of the ipsilateral and contralateral limbs in induced canine lameness are similar to those of lame horses.

Abstract

Compensatory limb loading has been studied in lame dogs; however, little is known about how these compensations relate to motion of the head and pelvis, assessment of which is an important component of lameness examinations. The aim of this study was to describe the patterns of vertical head and pelvic motion symmetry at the trot in dogs with induced supporting limb lameness in the forelimbs or hind limbs. Ten sound dogs were trotted on a treadmill before and after temporary induction of moderate lameness (grade 2/5) in each limb. Reflective markers were located on the head, pelvis and right forelimb, and kinematic data were captured with a motion capture system. Upper body symmetry parameters were calculated, including differences between the highest (HDmax) and lowest (HDmin) positions of the head, and between the highest (PDmax) and lowest (PDmin) positions of the mid-pelvis, with a value of zero indicating symmetry. The head was lowered more during the sound limb stance phase and lowered less during the lame limb stance phase in supporting forelimb lameness (HDmin: 4.6 mm in dogs when sound, -18.3 mm when left limb lameness was induced and 20.5 mm when right limb lameness was induced). The mid-pelvis was lowered more during the sound limb stance phase and lowered and lifted less during the lame limb stance phase in supporting hind limb lameness (PDmin: 1 mm in dogs when sound, -10.1 mm in left limb lameness and 8.4 mm in right limb lameness). The hip of the lame side, measured at the level of the greater trochanter, had an increased downwards displacement during the lame limb swing phase (-21 mm in left hind limb lameness, $P = 0.005$; 23.4 mm in right hind limb lameness, $P = 0.007$). Asymmetry in the lowering of the head or mid-pelvis is a more sensitive indicator of supporting forelimb and hind limb lameness, respectively, than asymmetry in the raising of the head. Increased displacement of the hip (‘hip drop’ of the lame side during its swing phase) is a good indicator of hind limb lameness in dogs.

Keywords: Canine; Gait analysis; Kinematics; Lameness; Compensation

Introduction

Lameness is a common problem in dogs, affecting welfare and requiring veterinary intervention. Houlton (2006) defined supporting limb lameness as '*reluctance or inability to place full weight on the limb*' and swinging limb lameness as '*lameness seen when the affected limb is in flight*'. Evaluation of canine lameness has a low inter-observer agreement (Quinn et al., 2007; Waxman et al., 2008). Since identification of the lame limb or limbs is a requisite for successful diagnosis and treatment, precise assessment of lameness is important.

Studies using force plates have shown that loading of the affected limb may decrease substantially in different orthopaedic conditions (Budsberg et al., 1996; Theyse et al., 2000; Evans et al., 2005), while there is increased loading of the contralateral limb, confirming the existence of lameness adaptation mechanisms (Budsberg et al., 1988; Rumph et al., 1995; Fanchon and Grandjean, 2007; Voss et al., 2007; Ragetly et al., 2010). During forelimb lameness, there are changes in braking and propulsion forces, weight shifting towards the contralateral side and increased loading in the ipsilateral hind limb (Abdelhadi et al., 2012, 2013; Bockstahler et al., 2012). During hind limb lameness, there is a weight shift to the contralateral hind limb and to the ipsilateral forelimb (Katic et al., 2009; Fischer et al., 2013), suggesting a compensatory mechanism triggered by the painful limb.

The use of pressure sensitive walkways has facilitated studies of vertical loading in consecutive strides of all limbs, confirming that these loading shifts not only exist during treadmill locomotion, but also over ground (Oosterlinck et al., 2011). The adaptive changes in limb loading shown in these studies suggest that changes in motion patterns must occur in order to achieve these weight shifts. The symmetries of the vertical movements of the head and pelvis (i.e. 'head nod' and 'hip hike') are variables indicative of lameness used in subjective clinical gait assessment in dogs (Houlton, 2006). Several studies have demonstrated alterations in kinematics of the limbs or individual joints during lameness (Korvick et al., 1994; Tashman et al., 2004; Bockstahler et al., 2009; Sanchez-Bustinduy et al., 2010; Druen et al., 2012). Hicks and Millis (2014) showed that subtle hind limb lameness in clinically lame dogs is associated with vertical movement asymmetries of the pelvis. However, these movement patterns have not been described in detail or quantified in dogs in experimental studies.

The aim of the present study was to determine the patterns of vertical head and pelvic movements in dogs at trot after induced supporting limb lameness in the forelimbs and in the hind limbs. We hypothesised that changes in symmetry of vertical head and pelvis displacement would be sensitive indicators of induced forelimb and hind limb lameness.

Materials and methods

Study animals

Ten clinically sound dogs (owned pet dogs) were included in the study, comprising five Labrador retrievers and one each of Flat coated retriever, Australian shepherd, Dalmatian, Lagotto Romagnolo and Irish terrier; there were two neutered males, one intact male and seven intact females). Dogs were aged 5.1 ± 1.2 years (mean ± standard deviation, SD), with a mean ± SD body mass of 23.4 ± 6.0 kg and a mean ± SD height at the withers of 53.0 ± 5.5 cm. Visual gait assessment and orthopaedic examinations were performed. None of the dogs had a history of orthopaedic disease or orthopaedic surgery. Eight dogs had previous negative radiographic screening for hip and elbow dysplasia; the other dogs had not been screened. The sample size selection was based on kinematic or kinetic studies previously performed in dogs or horses (i.e. 7-10 animals). A power calculation was not possible in this study because of the large number of parameters analysed and because no previous studies of lameness induced in all four limbs had been performed previously. The study was approved by the Ethical Committee for Animal Experiments, Swedish University of Agricultural Sciences, Uppsala, Sweden (approval number C283/12; date of approval 1 February 2013) and the study was performed with informed consent of the owners.

Motion capture system

A motion capture system consisting of eight infrared high speed cameras (Oqus, Qualisys Medical AB), recording at 240 Hz, was used to capture the movement of the dogs trotting on a treadmill (Rodby, Innovation AB) at their preferred speed; the same speed was used for all measurements of each dog. Prior to the experiment, the dogs were accustomed to treadmill locomotion (Gustås et al., 2013). Five clusters of three reflective markers, each 7 mm in diameter, were attached to five inertial sensors (synchronised for a parallel study on lameness detection) and located using double sided tape on the top of the head, the dorsal aspect of the metacarpus of the right forelimb, both greater trochanters and the midline pelvis (median sacral crest) (Fig. 1). Data were collected before and after induction of transient lameness.

Induction and measurement of lameness

Moderate lameness, distinctly visible at the trot (grade 2 on a scale of 0-5), was induced in a random order in all four limbs; dogs were randomly assigned to one of 10 different orders of induction by drawing a number from a container. The desired degree of lameness was achieved by adjusting the size and position of a cotton wad secured with elastic wrap under the paw (Fig. 2).

Prior to measurements, dogs had a ‘warm up’ period on the treadmill of 10 min. Motion was recorded for 20 s for each lameness event. Trial results were only included when dogs trotted at an even pace whilst looking straight ahead. A sound trial was recorded for each dog before any lameness was induced and between each lameness induction to ensure that the dogs returned to soundness after removal of the cotton wad.

Data analysis

Data were processed and three-dimensionally reconstructed using motion analysis software (Qualisys Track Manager) and a custom made script in Matlab (The MathWorks) was used for further analyses. Raw data were filtered using a Savitzky-Golay FIR filter (order 10 and frame size 59), which was a numerically optimised setting to preserve the amplitude and temporal information from the raw data for the two minimum and maximum peaks within each stride. The vertical position signal for each cluster was split into strides and normalised to 100% by identifying the maximal protraction of the left metacarpal marker. The marker with the best quality data from each cluster was selected and two local maximum and minimum displacements were identified for each marker and for all strides per trial.

The following parameters were calculated: (1) differences between the two highest vertical displacements of the head (HDmax), between the two highest vertical displacements of the mid-pelvis (PDmax), between the two lowest vertical displacements of the head (HDmin) and between the two lowest vertical displacements of the mid-pelvis (PDmin), measured in mm; (2) differences between the two upward movements of the head (range up 1 - range up 2 = range up HD), differences between the two upward movements of the mid-pelvis (range up 1 - range up 2 = range up PD), differences between the two downward movements of the head (range down 1 - range down 2 = range down HD) and differences between the two downward movements of the mid-pelvis (range down 1 - range down 2 = range down PD), measured in mm; (3) hip asymmetry, representing the differences between the vertical displacements of the greater trochanters, measured in mm; (4) stride duration in ms; and (5) symmetry indices of head and pelvis vertical range up (SI up) and vertical range down (SI down) (Keegan et al., 2011, Starke et al., 2012) (Fig. 3). Values of zero indicate perfect symmetry, whilst negative or positive values for HDmax, PDmax, HDmin, PDmin, range up HD, range up PD, range down HD, range down PD and hip asymmetry indicate head or pelvic motion asymmetries during left or right limb stances, respectively. Symmetry indices were calculated by using the following formulas, modified from Starke et al. (2012):

SI up = (Range up 1 – Range up 2)/Max Range up

SI down = (Range down 1 – Range down 2)/Max Range down

where, SI = 0 indicates perfect symmetry and MAX range up/MAX range down are the largest range values (i.e. range up or down 1 and range up or down 2).

Statistical analysis

Medians and ranges for all variables before and after induction of lameness were calculated. Data were analysed using Friedman’s test and Dunn’s post-hoc test in GraphPad Prism. Significance was set at $P < 0.05$.

Results

Kinematic data were analysed from nine trials per dog, with a mean ± SD of 39.9 ± 2.7 strides per trial and a mean ± SD speed of 1.9 ± 0.1 m/s (Table 1). There were no significant differences in stride duration between trials when dogs were sound versus when dogs had induced lameness.

Differences in maximum and minimum displacements

Starting with a baseline value for the differences in vertical displacement of 4.6 mm when dogs were sound, HDmin increased significantly after inducing forelimb lameness (-18.3 mm in left limb lameness, $P = 0.004$; 20.5 mm in right limb lameness, $P = 0.006$). Similarly, from a baseline value of 1.0 mm determined when dogs were sound, PDmin increased significantly after inducing hind limb lameness (-10.1 mm in left limb lameness, *P* = 0.03; 8.4 mm in right limb lameness, *P* = 0.03).

Induction of lameness in the left forelimb was associated with a compensatory effect in the contralateral hind limb, as indicated by a significant increase in PDmin (3.5 mm, *P* = 0.39). Similarly, induction of left hind limb lameness was associated with a compensatory effect in the ipsilateral forelimb, as indicated by a significant increase in HDmin (-1.8 mm, *P* = 0.05). After induction of right forelimb and right hind limb lameness, no significant compensatory effects were seen. Differences between the highest displacements (HDmax and PDmax) were not significant.

Range up and down and symmetry indices

Starting with a baseline value of 4.4 mm determined when dogs were sound, induction of forelimb lameness resulted in a significant increase in range up HD (-24.7 mm in left limb lameness, *P* = 0.007; 23.6 mm in right limb lameness, *P* = 0.04). Starting with a baseline value of 2.9 mm determined when dogs were sound, induction of forelimb lameness resulted in a significant increase in range down HD (-16.2 mm in left limb lameness, *P* = 0.039; 20.5 mm in right limb lameness, *P* = 0.046). Starting with a baseline value of 4.4 mm when dogs were sound, induction of hind limb lameness resulted in a significant increase in range up PD (-15.1 mm in left limb lameness, *P* = 0.003; 14.1 mm in right limb lameness, *P* = 0.031). Starting with a baseline value of -1.9 mm when dogs were sound, induction of hind limb lameness resulted in a significant increase in range down PD (-4.4 mm in left limb lameness, *P* = 0.044; 5.4 mm in right limb lameness, *P* = 0.034).

These effects resulted in changes in the symmetry indices of the upward and downward movements of the head (SI up: 0.6 and -0.7 for left and right limb lameness, respectively; SI down: 0.5 and -0.5 for left and right limb lameness, respectively) and mid-pelvis (SI up: 0.4 and -0.3 for left and right limb lameness, respectively; SI down: -0.1 and -0.2 for left and right limb lameness, respectively). No compensatory mechanisms related to these parameters (e.g. ipsilateral or contralateral changes in the head motion during hind limb lameness) were observed.

Hip asymmetry

Starting with a baseline value of -1.6 mm when dogs were sound, the symmetry of the vertical range of motion of the pelvis during the swing phase decreased significantly during hind limb lameness related to increased vertical movement of the greater trochanter on the lame side (21 mm in left limb lameness, $P = 0.005$; -23.4 mm in right limb lameness, $P = 0.007$). No significant differences in hip asymmetry were observed during forelimb lameness (-9.8 mm in left limb lameness, $P = 0.11$; -1.2 mm in right limb lameness, $P = 0.078$).

Discussion

This study determined the pattern of vertical head and pelvic movements in dogs at the trot after induced supporting limb lameness in the forelimbs and in the hind limbs, and confirmed the hypothesis that changes in symmetry of vertical head and pelvis displacement are sensitive indicators of induced forelimb and hind limb lameness.

Induction of lameness resulted in increased differences between the lowest positions of the head (HDmin) during induced forelimb lameness and of the mid-pelvis (PDmin) during induced hind limb lameness. This was confirmed by changes in the range up HD/PD and range down HD/PD, and symmetry indices. Our results demonstrate that head and pelvic vertical motion and, especially, the differences in the lowest position (HDmin, PDmin) are sensitive lameness indicators during supporting limb lameness in dogs, as described in horses (Buchner et al., 1996; Uhlir et al., 1997; Kramer et al., 2004; Kelmer et al., 2005; Keegan et al., 2011, 2012; Rhodin et al., 2013; Maliye et al., 2015). Thus, during forelimb lameness, the head is lowered more during the sound limb stance phase and lowered less during the lame limb stance phase, in agreement with the observation of a downward head ‘nod’ coinciding with the sound limb stance phase in this type of lameness (Houlton, 2006). Similarly, in hind limb lameness, the mid-pelvis was lowered more during the sound stance phase, and was lowered and lifted less during the lame stance phase.

Descriptions of canine lameness usually do not include vertical motion of the median sacral crest (i.e. mid-pelvis), but do include ‘hip hike’, which is described as ‘hiking up’ (elevation) of the gluteal region on the lame side during weight bearing in hind limb lameness (Houlton, 2006). In our study, the latter was evident by an asymmetrical vertical range of movement of the greater trochanters. However, instead of ‘hiking up’, the hip of the lame side had a larger range of displacement, by dropping further down during weight bearing of the sound limb and during the lame side swing phase; this shows that the hip of the lame side does not always rise above the level of the hip of the sound limb, as described in horses by Pfau et al. (2016).

The lack of significant changes in the highest displacements of the head or pelvis after induction of lameness demonstrated that the symmetry indices of head and pelvis movements and the lowest displacements of the head and pelvis are more sensitive parameters than the highest displacements in identifying supporting limb lameness.

Similar to the compensatory changes described in horses (May and Wyn-Jones, 1987; Kelmer et al., 2005; Rhodin et al., 2013), our study has shown that lameness in the forelimb was associated with a compensatory effect in the contralateral hind limb and that induction of hind limb lameness was associated with a compensatory effect in the ipsilateral forelimb. However, compensatory mechanisms were not observed after induction of lameness in the right forelimbs. This might be due to variation on the degree of lameness induced and differences in the pain threshold that triggers compensatory mechanisms in individual dogs with primary lameness. The clinical relevance of these findings needs to be further investigated in dogs with different degrees and causes of lameness.

Changes in the motion of the head have been reported in hind limb lameness of dogs, but these may be difficult to detect and quantify (Renberg, 2005). In our study, consistent compensatory head movements were detected during moderate hind limb lameness, however, their magnitude is very small compared to the changes due to the primary lameness making them irrelevant.

Kinetic compensatory mechanisms to reduce the load on the painful limb have been described in dogs (Waxman et al., 2008; Bockstahler et al., 2009; Katic et al., 2009; Abdelhadi et al., 2012, 2013; Fischer et al., 2013). These changes in vertical and horizontal forces cause dynamic postural adaptations of the body, resulting in the changes in the head and pelvic motion patterns described in this study. In a kinematic study in dogs with subtle lameness after transection of the cranial cruciate ligament and surgical repair, Hicks and Millis (2014) found asymmetries in the vertical displacement of the pelvis, but only found small and non-significant changes in the vertical displacement of the head. In our study, we detected asymmetry in pelvic and head motions in hind limb lameness. These discrepancies may be explained by differences in the degree of lameness (mild versus moderate) and differences in experimental design (clinical cases versus experimentally induced lameness; over ground locomotion versus constant speed on a treadmill). Further experimental and clinical studies are warranted to better understand the kinetics and kinematics of different degrees and sources of lameness.

Although none of the dogs in this study were deemed to be lame before the study on the basis of visual gait assessment, kinematic analysis revealed small asymmetries in the head and pelvic movements. This mild asymmetry in non-lame dogs is in agreement with previous studies

(Budsberg et al., 1993; Besancon et al., 2003; Fanchon and Grandjean, 2007; Colborne, 2008; Oosterlinck et al., 2011).

The treadmill speed was adjusted to the preferred speed of each dog. The dogs participating in the study were breeds of medium size, achieving a mean ± SD speed of 1.9 ± 0.1 m/s, which is similar to another study reporting a mean ± SD speed of 1.97 ± 0.04 m/s in 31 breeds (Voss et al., 2010). It is uncertain if different findings would be obtained during over ground locomotion, as is usual for visual evaluation of gait. Previous studies have shown similar hind limb kinematics (Torres et al., 2013) and similar peak vertical forces (Brebner et al., 2006) in over ground versus treadmill based gait in dogs. In contrast, with over ground locomotion, speed is constant on a treadmill, unless there are intra-stride belt speed variations (Savelberg et al., 1998). It would be useful to perform further research on canine lameness during over ground locomotion, combining kinematic techniques with force plate or pressure sensitive walkways.

Conclusions

Asymmetries of the vertical amplitude of the head and pelvis, particularly the lowest vertical positions, are potentially useful variables for objective evaluation of lameness in dogs. Compensatory lameness mechanisms observed in pelvic motion pattern during forelimb lameness and in head motion during hind limb lameness appear to be similar to those described in horses.

Conflict of interest statement

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

Acknowledgements

The authors would like to thank the owners of dogs included in the study, Lars Roepstorff for help with the data analysis, Agria Sweden for funding the study and Alex Humphries for proofreading the article. Preliminary results were presented as an Abstract at the International Conference on Canine and Equine Locomotion, London, United Kingdom, 17-19 August 2016.

References

Abdelhadi, J., Wefstaedt, P., Galindo-Zamora, V., Anders, A., Nolte, I., Schilling, N., 2013. Load redistribution in walking and trotting beagles with induced forelimb lameness. American Journal of Veterinary Research 74, 34-39.

Abdelhadi, J., Wefstaedt, P., Nolte, I., Schilling, N., 2012. Fore-aft ground force adaptations to induced forelimb lameness in walking and trotting dogs. PLoS One 7, e52202.

Besancon, M.F., Conzemius, M.G., Derrick, T.R., Ritter, M.J., 2003. Comparison of vertical forces in normal greyhounds between force platform and pressure walkway measurement systems. Veterinary and Comparative Orthopaedics and Traumatology 16, 153-157.

Bockstahler, B.A., Prickler, B., Lewy, E., Holler, P.J., Vobornik, A., Peham, C., 2012. Hind limb kinematics during therapeutic exercises in dogs with osteoarthritis of the hip joints. American Journal of Veterinary Research 73, 1371-1376.

Bockstahler, B.A., Vobornik, A., Müller, M., Peham, C., 2009. Compensatory load redistribution in naturally occurring osteoarthritis of the elbow joint and induced weight-bearing lameness of the forelimbs compared with clinically sound dogs. The Veterinary Journal 180, 202-212.

Brebner, N.S., Moens, N.M.M., Runciman, J.R., 2006. Evaluation of a treadmill with integrated force plates for kinetic gait analysis of sound and lame dogs at a trot. Veterinary and Comparative Orthopaedics and Traumatology 19, 205-212.

Buchner, H.H., Savelberg, H.H., Schamhardt, H.C., Barneveld, A., 1996. Head and trunk movement adaptations in horses with experimentally induced fore- or hindlimb lameness. Equine Veterinary Journal 28, 71-76.

Budsberg, S.C., Jevens, D.J., Brown, J., Foutz, T.L., DeCamp, C.E., Reece, L., 1993. Evaluation of limb symmetry indices, using ground reaction forces in healthy dogs. American Journal of Veterinary Research 54, 1569-1574.

Budsberg, S.C., Verstraete, M.C., Soutas-Little, R.W., Flo, G.L., Probst, C.W., 1988. Force plate analyses before and after stabilization of canine stifles for cruciate injury. American Journal of Veterinary Research 49, 1522-1524.

Budsberg, S.C., Chambers, J.N., Lue, S.L., Foutz, T.L., Reece, L., 1996. Prospective evaluation of ground reaction forces in dogs undergoing unilateral total hip replacement. American Journal of Veterinary Research 57, 1781-1785.

Colborne, G.R., 2008. Are sound dogs mechanically symmetric at trot? No, actually. Veterinary and Comparative Orthopaedics and Traumatology 21, 294-301.

de Medeiros, M., Bustinduy, M.S., Radke, H., Langley-Hobbs, S., Jeffery, N., 2011. Early kinematic outcome after treatment of cranial cruciate ligament rupture by tibial plateau levelling osteotomy in the dog. Veterinary and Comparative Orthopaedics and Traumatology 24, 178-184.

Drüen, S., Böddeker, J., Meyer-Lindenberg, A., Fehr, M., Nolte, I., Wefstaedt, P., 2012. Computer-based gait analysis of dogs: Evaluation of kinetic and kinematic parameters after cemented and cementless total hip replacement. Veterinary and Comparative Orthopaedics and Traumatology 25, 375-384.

Evans, R., Horstman, C., Conzemius, M., 2005. Accuracy and optimization of force platform gait analysis in Labradors with cranial cruciate disease evaluated at a walking gait. Veterinary Surgery 34, 445-449.

Fanchon, L. and Grandjean, D., 2007. Accuracy of asymmetry indices of ground reaction forces for diagnosis of hind limb lameness in dogs. American Journal of Veterinary Research 68, 1089-1094.

Fischer, S., Anders, A., Nolte, I., Schilling, N., 2013. Compensatory load redistribution in walking and trotting dogs with hind limb lameness. The Veterinary Journal 197, 746-752.

Gustås, P., Pettersson, K., Honkavaara, S., Lagerstedt, A.S., Byström, A., 2013. Kinematic and temporospatial assessment of habituation of Labrador retrievers to treadmill trotting. The Veterinary Journal 198, 114-119.

Hicks, D.A. and Millis, D.L., 2014. Kinetic and kinematic evaluation of compensatory movements of the head, pelvis and thoracolumbar spine associated with asymmetric weight bearing of the pelvic limbs in trotting dogs. Veterinary and Comparative Orthopaedics and Traumatology 6, 453-460.

Houlton, J., 2006. An approach to the lame dog or cat. In: Houlton J.E.F., Cook J.L., Innes J.F., Langley-Hobbs S.J. (Eds). BSAVA Manual of Canine and Feline Musculoskeletal Disorders. British Small Animal Veterinary Association, Gloucester, UK, p. 6.

Katic, N., Bockstahler, B.A., Mueller, M., Peham, C., Ing, T.D., 2009. Fourier analysis of vertical ground reaction forces in dogs with unilateral hind limb lameness and in dogs without lameness. American Journal of Veterinary Research 70, 118-126.

Keegan, K.G., Kramer, J., Yonezawa, Y., Maki, H., Pai, P.F., Dent, E. V., Kellerman, T.E., Wilson, D. A., Reed, S.K., 2011. Assessment of repeatability of a wireless, inertial sensor-based lameness evaluation system for horses. American Journal of Veterinary Research 72, 1156-1163.

Keegan, K.G., MacAllister, C.G., Wilson, D. A., Gedon, C. A., Kramer, J., Yonezawa, Y., Maki, H., Frank Pai, P., 2012. Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness. American Journal of Veterinary Research 73, 368-374.

Kelmer, G., Keegan, K.G., Kramer, J., Wilson, D.A., Pai, F.P., Singh, P., 2005. Computer-assisted kinematic evaluation of induced compensatory movements resembling lameness in horses trotting on a treadmill. American Journal of Veterinary Research 66, 646-655.

Korvick, D.L., Pijanowski, G.I., Schaeffer, D.J., 1994. Three-dimensional cranial cruciate kinematics of the intact and ligament-deficient stifle of dogs. Journal of Biomechanics 27, 77-87.

Kramer, J., Keegan, K.G., Kelmer, G., Wilson, D. A., 2004. Objective determination of pelvic movement during hind limb lameness by use of a signal decomposition method and pelvic height differences. American Journal of Veterinary Research 65, 741-747.

Maliye, S., Voute, L.C., Marshall, J.F., 2015. Naturally-occurring forelimb lameness in the horse results in significant compensatory load redistribution during trotting. The Veterinary Journal 204, 208-213.

May, S.A., Wyn-Jones, G., 1987. Identification of hindleg lameness. Equine Veterinary Journal 19, 185-188.

Oosterlinck, M., Bosmans, T., Gasthuys, F., Polis, I., van Ryssen, B., Dewulf, J., Pille, F., 2011. Accuracy of pressure plate kinetic asymmetry indices and their correlation with visual gait assessment scores in lame and nonlame dogs. American Journal of Veterinary Research 72, 820-825.

Pfau, T., Fiske-Jackson, A., Rhodin, M., 2016. Quantitative assessment of gait parameters in horses: Useful for aiding clinical decision making? Equine Veterinary Education 28, 209-215.

Quinn, M.M., Keuler, N.S., Lu, Y., Faria, M.L.E., Muir, P., Markel, M.D., 2007. Evaluation of agreement between numerical rating scales, visual analogue scoring scales, and force plate gait analysis in dogs. Veterinary Surgery 36, 360-367.

Ragetly, C.A., Griffon, D.J., Mostafa, A.A., Thomas, J.E., Hsiao-Wecksler, E.T., 2010. Inverse dynamics analysis of the pelvic limbs in Labrador retrievers with and without cranial cruciate ligament disease. Veterinary Surgery 39, 513-522.

Renberg, W.C., 2005. Pathophysiology and management of arthritis. Veterinary Clinics of North America: Small Animal Practice 35, 1073-1091.

Rhodin, M., Pfau, T., Roepstorff, L., Egenvall, A., 2013. Effect of lungeing on head and pelvic movement asymmetry in horses with induced lameness. The Veterinary Journal 198 (Suppl. 1.), e39-e45.

Rumph, P.F., Kincaid, S.A., Visco, D.M., Baird, D.K., Kammermann, J.R., West, M.S., 1995. Redistribution of vertical ground reaction force in dogs with experimentally induced chronic hindlimb lameness. Veterinary Surgery 24, 384-389.

Sanchez-Bustinduy, M., de Medeiros, M.A., Radke, H., Langley-Hobbs, S., McKinley, T., Jeffery, N., 2010. Comparison of kinematic variables in defining lameness caused by naturally occurring rupture of the cranial cruciate ligament in dogs. Veterinary Surgery 39, 523-530.

Savelberg, H., Vorstenbosch, M., Kamman, E., van de Weijer J.G, Schambardt, H., 1998. Intra-stride belt-speed variation affects treadmill locomotion. Gait and Posture 7, 26-34.

Starke, S.D., Willems, E., May, S.A., Pfau, T., 2012. Vertical head and trunk movement adaptations of sound horses trotting in a circle on a hard surface. The Veterinary Journal 193, 73-80.

Tashman, S., Anderst, W., Kolowich, P., Havstad, S., Arnoczky, S., 2004. Kinematics of the ACL-deficient canine knee during gait: Serial changes over two years. Journal of Orthopaedic Research 22, 931-941.

Theyse, L.F.H., Hazewinkel, H.A.W., Van Den Brom, W.E., 2000. Force plate analyses before and after surgical treatment of unilateral fragmented coronoid process. Veterinary and Comparative Orthopaedics and Traumatology 13, 135-140.

Torres, B.T., Moëns, N.M.M., Al-Nadaf, S., Reynolds, L.R., Fu, Y.C., Budsberg, S.C., 2013. Comparison of overground and treadmill-based gaits of dogs. American Journal of Veterinary Research 74, 535-541.

Uhlir, C., Licka, T., Kübber, P., Peham, C., Scheidl, M., Girtler, D., 1997. Compensatory movements of horses with a stance phase lameness. Equine Veterinary Journal Suppl. 23, 102-105.

Voss, K., Galeandro, L., Wiestner, T., Haessig, M., Montavon, P.M., 2010. Relationships of body weight, body size, subject velocity, and vertical ground reaction forces in trotting dogs. Veterinary Surgery 39, 863-869.

Voss, K., Imhof, J., Kaestner, S., Montavon, P.M., 2007. Force plate gait analysis at the walk and trot in dogs with low-grade hindlimb lameness. Veterinary and Comparative Orthopaedics and Traumatology 20, 299-304.

Waxman, A.S., Robinson, D.A., Evans, R.B., Hulse, D.A., Innes, J.F., Conzemius, M.G., 2008. Relationship between objective and subjective assessment of limb function in normal dogs with an experimentally induced lameness. Veterinary Surgery 37, 241-246.

Figure legends

Fig. 1. Clusters of reflective markers attached to inertial sensors were located at the midline of the top of the head (sagittal crest of the parietal bone), the dorsal aspect of the metacarpus of the right forelimb, both greater trochanters and the midline pelvis (median sacral crest).

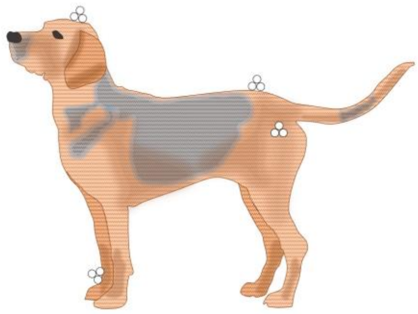

Fig. 2. Picture of a cotton wad secured with elastic wrap under a dog's paw to induce a moderate lameness, distinctly visible at the trot (score 2 on a scale from 0 to 5) by adjusting the size and position of the cotton wad under the paw.

Fig. 3. Schematic representation of the vertical displacement of the head during one stride at the trot in a dog with right forelimb lameness. The first lowest displacement of the head (Min 1) occurred during the sound left forelimb stance and the second lowest displacement of the head (Min 2) occurred during lame right forelimb stance. The differences between Min 1 and 2 are shown as HD min. The first highest displacement of the head (Max 1) occurred after the sound left forelimb stance and the second highest displacement of the head (Max 2) occurred after the lame right forelimb stance. There were no significant differences between Max 1 and 2 (HD max). The range up 1 and 2, and range down 1 and 2 of the head (vertical motions used to calculate the range up HD, range down HD) are also depicted. A similar motion pattern was seen in the pelvic vertical motion during hind limb lameness.

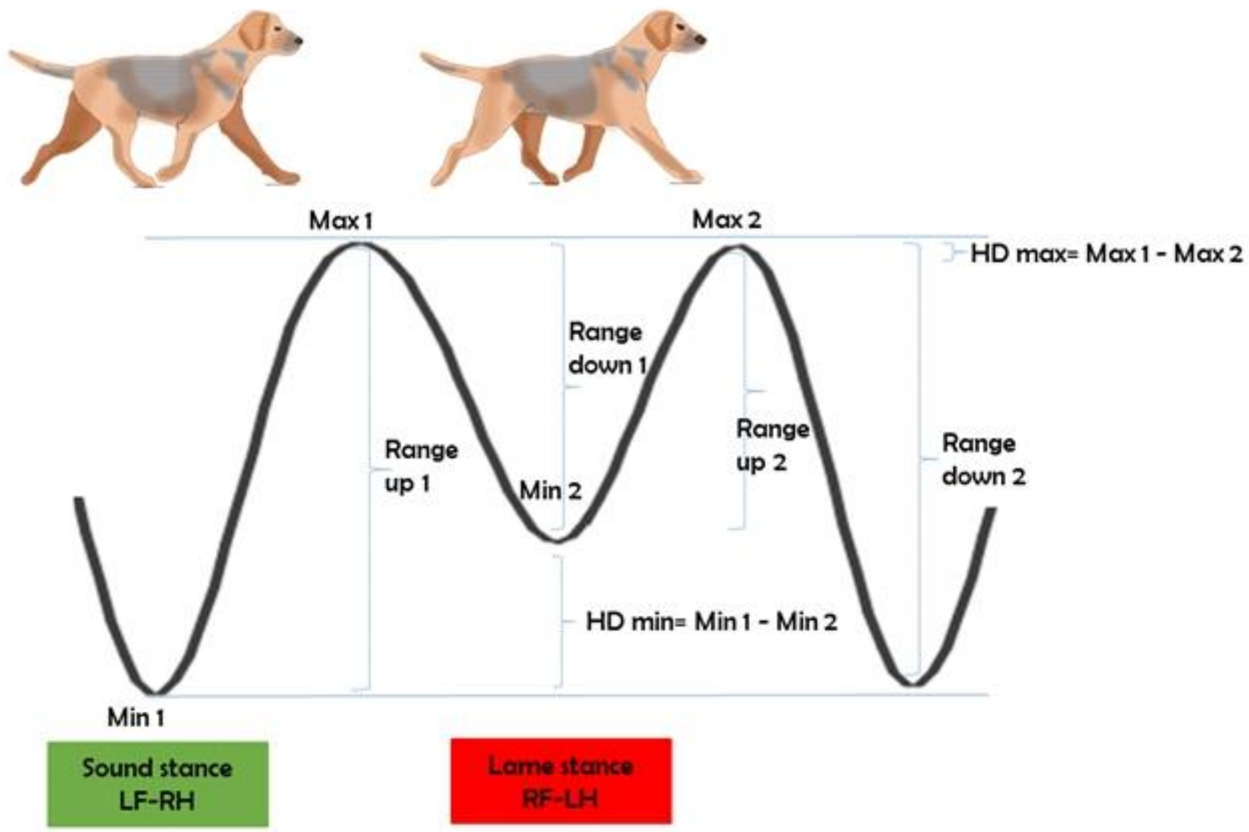

Table 1
Median (range) lameness parameters in 10 dogs with induced forelimb and hind limb lameness at a mean ± standard deviation trotting speed of 1.9 ± 0.1 m/s.

		Forelimb lameness		Hind limb lameness	
Parameter	Sound	Left forelimb	Right forelimb	Left hind limb	Right hind limb
HDmin	4.6 (-5.6 to 11)	-18.3 (-57.5 to 1.3)*	20.5 (2.5 to 40)*	-1.8 (-23.1 to 9.2)*	1.8 (-3.2 to 10.9)
HDmax	1.3 (-4.7 to 3.1)	-2.9 (-15 to 5.3)	3.4 (-5.7 to 27.3)	-3.6 (-13.6 to 4.5)	-1.9 (-5.9 to 4.6)
PDmin	1.0 (-2.2 to 4.1)	3.5 (-1.2 to 7.3)*	-0.5 (-13.6 to 4.7)	-10.1 (-22.3 to -6.4)*	8.4 (1.7 to 14.6)*
PDmax	2.8 (-7.4 to 7.2)	1.7 (-5.1 to 8.3)	0.5 (-10.8 to 12.0)	-3.8 (-15.2 to 14.3)	5.1 (-14.8 to 18.6)
Range up HD	4.4 (-12.2 to 11.8)	-24.7 (-56.5 to -4.3)*	23.6 (10.0 to 47.6)*	-2.3 (-35.2 to 12.4)	-0.0 (-6.3 to 10.6)
Range down HD	2.9 (-4.2 to 9.8)	-16.2 (-54.8 to -0.6)*	20.5 (-12.4 to 44.7)*	3.3 (-17.9 to 6.5)	4.7 (-7.8 to 12.6)
Range up PD	4.4 (-7.6 to 10)	5.1 (-3.8 to 15.8)	-0.7 (-19.6 to 12.3)	-15.1 (-41.1 to 4.8)*	14.12 (-13.0 to 28.9)*
Range down PD	-1.9 (-5.7 to 6.4)	2.3 (-2.9 to 8.9)	-3.5 (-11.7 to 6.6)	-4.4 (-23.9 to 8.4)*	5.4 (-7.9 to 16.5)*
SI up H	-0.2 (-0.4 to 0.5)	0.6 (0.2 to 1.0)*	-0.7 (-1.0 to 0.3)*	0.1 (-0.4 to 0.8)	0.0 (-0.4 to 0.4)
SI down H	-0.1 (-0.3 to 0.2)	0.5 (0.0 to 0.9)*	-0.5 (-1.0 to 0.3)*	-0.1 (-0.3 to 0.7)	-0.2 (-0.4 to 0.3)
SI up P	-0.1 (-0.4 to 0.2)	-0.2 (-0.4 to 0.1)	0.0 (-0.4 to 0.5)	0.4 (-0.1 to 0.9)*	-0.3 (-0.6 to 0.3)*
SI down P	0.1 (-0.2 to 0.1)	-0.1 (-0.4 to 0.1)	0.1 (-0.3 to 0.4)	0.1 (-0.2 to 0.6)*	-0.1 (-0.3 to 0.2)*
Hip asymmetry during swing phase	-1.6 (-19.9 to 8.6)	-9.8 (-27.9 to 20.1)	-1.2 (-26.8 to 26.7)	-21 (-35.5 to 2.9)*	23.4 (-21.8 to 42.1)*
Stride duration (ms)	514 (426 to 568)	511 (452 to 550)	517 (471 to 543)	505 (441 to 545)	514 (446 to 561)

Difference between the two highest displacements of the head (HDmax) and mid-pelvis (PDmax); difference between the two lowest displacements of the head (HDmin) and mid-pelvis (PDmin); differences between the two upward movements of the head and mid-pelvis (range up HD, range up PD); differences between the two downward movements of the head and mid-pelvis (range down HD, range down PD); a value of zero indicates perfect symmetry, whilst negative and positive values indicate a left or right limb lameness, respectively; symmetry indices of the head and mid-pelvis upwards movement (SI up H, SI up P) and downwards movements (SI down H, SI down P), with a value of zero indicating perfect symmetry; difference between the left and right hip vertical displacement (Hip asymmetry during swing phase), where negative and positive values indicate a left or right limb lameness, respectively. Data are expressed in mm unless specified otherwise. Significant differences ($P < 0.05$) compared with sound trials are indicated with asterisks (*).