Inertial sensor-based system for lameness detection in trotting dogs with induced lameness

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Abstract

Lameness detection can be challenging in dogs, as reflected in the reported low inter-rater agreement when visually assessing lameness. The aim of this study was to use an inertial sensor-based system to detect and quantify induced distal and proximal limb disturbances mimicking supporting and swinging limb lameness in dogs trotting on a treadmill by measuring vertical head and pelvic movement symmetry. Ten clinically sound dogs were equipped with inertial measurement units that were attached to the head, pelvis and right distal forelimb. Vertical head and pelvic movement symmetry were measured while dogs trotted on a treadmill, before and after the induction of moderate support or swinging fore- and hindlimb lameness. Four symmetry variables were calculated: the differences in displacement between the two lowest and between the two highest values of the head and pelvis per stride, respectively. These variables were defined as minimum head difference (HDmin), maximum head difference (HDmax), minimum pelvic difference (PDmin) and maximum pelvic difference (PDmax). Induction of supporting forelimb and hindlimb lameness produced significant changes in HDmin and PDmin, respectively. Swinging forelimb and hindlimb lameness produced significant changes in HDmax and PDmax, respectively. Additional compensatory ipsilateral forelimb and contralateral hindlimb movements were detected. Based on our findings, inertial sensor-based systems can be used to detect and quantify induced moderate lameness and differentiate between supporting and swinging limb lameness in dogs trotting on a treadmill. Further studies are needed to evaluate this method in dogs presented for clinical lameness evaluation and in overground locomotion.

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Introduction

Lameness evaluation can be challenging in dogs. It aims to identify the lame limb(s), by scoring the degree of lameness and localising the origin of the pain or discomfort. Lameness can be classified as supporting or swinging limb lameness, as defined by Houlton (2006) as ‘reluctance or inability to place full weight on the limb’ and ‘lameness seen when the affected limb is in flight’, respectively. Waxman et al. (2008) measured ground reaction forces in dogs with induced supporting lameness, after visual scoring by three small animal orthopaedic surgeons and three first year veterinary students. The agreement between the visual assessment and the force platform data was low (0–39% agreement), depending on the degree of lameness. The authors concluded that subjective evaluation of lameness varied greatly between observers and that it agreed poorly with objective measures of limb function, such as ground reaction forces.

These results are confirmed by those of another study, where clinically lame dogs were studied after tibial osteotomy repair (Quinn et al., 2007). In light of these findings, there is an increased interest in better understanding canine lameness by using more precise and objective methods of assessment. Several kinetic and kinematic studies have recently been performed in dogs with induced lameness (Waxman et al., 2008; Bockstahler et al., 2009; Katic et al., 2009; Abdelhadi et al., 2012, 2013; Fischer et al., 2013) and in lame canine patients (Hicks and Millis, 2014). A recent kinematic study in dogs with experimentally induced lameness, performed with a motion capture system, demonstrated that symmetry measurements of vertical head and pelvic movement, which are clinical variables commonly used in visual lameness assessment, were enough to identify the lame limb (Gómez Álvarez et al., 2017). The study also identified, for the first time in dogs, additional head and pelvic compensatory lameness mechanisms (i.e. head motion for hindlimb lameness and pelvic motion for forelimb lameness). These compensatory movements may further contribute to the marked variability between clinicians during visual evaluation of canine lameness (Waxman et al., 2008).
The optical-based systems used in the studies above are generally limited to treadmill locomotion in a laboratory environment involving time consuming and complicated analysis, rendering them less useful in clinical practice. For these reasons, inertial measurement unit (IMU) systems have been developed for objective lameness evaluations in horses, and these are based on sensor technology comprising gyroscopes, accelerometers and magnetometers (Keegan et al., 2011; Starke et al., 2013). The systems are wireless, user-friendly and include software for rapid data analysis. Additionally, measurements can be made outside the laboratory, indoors or outdoors, aiding lameness assessments in clinical situations. Currently, to the authors’ knowledge, this technology has not been evaluated for lameness detection in dogs.

The aim of this study was to use an inertial sensor-based system to detect and quantify induced distal and proximal limb disturbances mimicking supporting and swinging limb lameness in dogs trotting on a treadmill by measuring vertical head and pelvic movement symmetry.

Materials and methods

The Ethical Committee for Animal Experiments, Uppsala, Sweden (No. C283/12; 1 February 2013) approved the study, which was performed with the informed consent of the dog owners.

Dogs

Ten clinically sound dogs were included in the study (five Labrador retrievers, one flatcoated retriever, one Australian shepherd, one Dalmatian, one Lagotto Romagnolo and one kooikerhondje). There were three males (two neutered, one intact) and seven intact females. Mean age was 5.1 ± 1.2 years, mean body mass was 23.4 ± 6.0 kg and mean height at the withers was 53.0 ± 5.5 cm. The dogs were assessed as clinically sound after orthopaedic examination performed by one clinician (PG). None of the dogs had a history of orthopaedic conditions or joint surgery. Eight of the dogs had previous radiographic screening for hip and elbow dysplasia with negative findings, according to the clinical history given by the owner.

Treadmill

Before the commencement of the study, dogs were acclimatised to treadmill locomotion according to published guidelines (Gustäsfors et al., 2013). Gait analysis was performed on a rubber-belt treadmill (Rodby, Innovation AB) in all dogs. The dogs had a warm-up period of approximately 10 min at walk and trot before recordings commenced. The speed of the treadmill was individually set at each dog's pre-performed on a rubber-belt treadmill (Rodby, Innovation AB) in all dogs. The dogs developed for lameness detection in horses, was used in this study (Keegan et al., 2011; Starke et al., 2013). The systems are wireless, user-friendly and include software for rapid data analysis. Additionally, measurements can be made outside the laboratory, indoors or outdoors, aiding lameness assessments in clinical situations. Currently, to the authors’ knowledge, this technology has not been evaluated for lameness detection in dogs.

The aim of this study was to use an inertial sensor-based system to detect and quantify induced distal and proximal limb disturbances mimicking supporting and swinging limb lameness in dogs trotting on a treadmill by measuring vertical head and pelvic movement symmetry.

Fig. 1. Inertial sensor placement. Three sensors were attached to: (1) the midline of the top of the head; (2) the midline of the spinous processes of the second sacral vertebra; and (3) the dorsal surface of the metacarpal bones of the right forelimb, respectively.

Lameness induction

Reversible distal limb disturbance was induced, mimicking supporting limb lameness, in all dogs by placement of a cotton wool wad under the paw, secured with cohesive bandage. The size of the wad was adjusted to each dog to induce lameness of 2 degrees (on a scale 0–5; moderately lame, distinctly visible at the trot). A proximal limb disturbance, mimicking swinging limb lameness, was reversibly induced by placement of a custom-made weight (200 g) above the carpus and tarsal joint, respectively. Lameness inductions were carried out in randomised order and evaluated by the same person (AB). Ten different orders of lameness induction were created and each dog was randomly assigned to one of the 10 induction schemes manually by drawing one of the 10 numbers from a box.

Instrumentation

Lameness Locator (Equinosis), an IMU system comprising three inertial sensors developed for lameness detection in horses, was used in this study (Keegan et al., 2011). Each sensor consisted of two single-axis accelerometers, oriented with their sensitive axis aligned with gravity (positive upwards), positioned in the midline of the top of the head and the midline of the spinous processes of the sacral vertebra 2 (Fig. 1). The accelerometers were attached to the dogs using custom made elastic wrap accessories secured with double-sided adhesive tape. To determine the timing of stride phases, a single-axis gyroscope was strapped to the dorsal surface of the metacarpal bones of the right forelimb. An extra sensor (not for data collection) was also placed in the same position on the left forelimb to identify left or right stance or swing phase. Despite the system being designed for horses, no species adjustment for dogs was required to achieve good stride splitting. From the displacement signal, local maxima and minima were established (two per stride). Differences between the two lowest head displacements (HDmin), and between the two lowest pelvic displacements (PDmin) during the left and right stance phase and differences between the two highest head displacements (HDmax) and between the two highest pelvic displacements (PDmax) during the left and right limb swing phase were computed per stride, as described elsewhere for horses (Keegan et al., 2011). The mean amplitude and sign (negative values for left limb and positive values for right limb asymmetry, as defined in our parallel study; Gómez Álvarez et al., 2017) for each variable for all strides per trial were calculated. A value of zero indicates perfect symmetry. For each variable, positive values denoted lameness and motion asymmetry attributed to the right limb, and negative values to the left limb (DMin, DMax, DMinleft, DMaxleft, DMinright, DMaxright; Table 1).

Compensatory lameness mechanisms were assessed by quantifying asymmetries in the pelvic displacement (PDmin, PDmax) for induced forelimb lameness, and in the head displacement (HDmin, HDmax) for induced hindlimb lameness.

Statistics

For descriptive purposes and to illustrate both magnitudes and left–right directions of asymmetry, signed means (positive or negative) and standard deviations (SDs) were calculated for each trial, before and after induction of lameness. For all 10 dogs pair-wise comparisons were performed for each of the four displacement/ asymmetry variables between the sound measurement and each lameness induction, using Wilcoxon signed rank tests (Graphpad Prism, Graphpad Software) with a significance level of P ≤ 0.05.

Results

Data collection

All dogs successfully trotted on the treadmill after habituation. One control (sound) measurement and the two types of lameness induced (supporting or swinging limb) in four limbs per dog yielded...
Table 1
Descriptive statistics for fore- and hindlimb lameness parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>n(^a)</th>
<th>Mean (mm)(^b)</th>
<th>SD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDminleft</td>
<td>7</td>
<td>3.8</td>
<td>2.4</td>
</tr>
<tr>
<td>HDminright</td>
<td>3</td>
<td>−8.0</td>
<td>5.4</td>
</tr>
<tr>
<td>HDmaxleft</td>
<td>5</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>HDmaxright</td>
<td>5</td>
<td>−2.0</td>
<td>3.9</td>
</tr>
<tr>
<td>PDminleft</td>
<td>8</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>PDminright</td>
<td>2</td>
<td>−1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>PDmaxleft</td>
<td>7</td>
<td>1.9</td>
<td>2.3</td>
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<tr>
<td>PDmaxright</td>
<td>3</td>
<td>−3.9</td>
<td>3.8</td>
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<tr>
<td>LF HDminleft</td>
<td>3</td>
<td>−8.0</td>
<td>5.4</td>
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<tr>
<td>LF HDmaxleft</td>
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<tr>
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<td>5</td>
<td>3.1</td>
<td>3.1</td>
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<tr>
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<td>5</td>
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<tr>
<td>RH PDmaxright</td>
<td>3</td>
<td>−3.9</td>
<td>3.8</td>
</tr>
</tbody>
</table>

SD, standard deviation; HDmin, minimum head difference; HDmax, maximum head difference; PDmin, minimum pelvic difference; PDmax, maximum pelvic difference.

\(^a\) Number of dogs from the total of 10 with either a left (−) or right (+) limb asymmetry for each variable.

\(^b\) Positive (right) or negative (left) values for sound and after lameness induction.

90 trials, each with four asymmetry values measured, with a mean number of strides of 34 ± 7.3. Small pre-existing asymmetries of different signs were detected (positive or negative values of the differences in displacement). These were not clinically observable (Table 1).

Supporting limb lameness

The Lameness Locator successfully identified the induction of supporting limb lameness for all limbs in all dogs by measuring changes in the forelimb (HDmin) or the hindlimb (PDmin) lameness parameters with the expected sign (negative for left and positive for right limb lameness induction), with absolute values significantly greater than before induction in nine of the 10 dogs (Table 1). There was a significant increase in amplitude for HDmax (negative in the left, −40 ± 21.1; positive in the right, 36 ± 15.1) (forelimb lameness; P = 0.002) in dogs with swinging limb lameness in the forelimbs. The induction of swinging limb lameness in the hindlimbs significantly increased the amplitude of PDmax (i.e. negative for left, −11 ± 9.3; positive for right, 11 ± 12.2; P = 0.002). Box plots were drawn, where the median, lowest (HDmax) or hindlimb (PDmax) lameness parameters with the expected sign (negative for left and positive for right limb lameness induction), with absolute values significantly greater than before induction in nine of the 10 dogs (Table 1). There was a significant change in HDmin (mean ± SD) in dogs with supporting lameness in the forelimbs when left (−40 ± 25.7) and right (43 ± 27.0) forelimb lameness was induced (P = 0.002). Induction of supporting lameness in the left hindlimb significantly increased the amplitudes of PDmin (−12 ± 7.9) and PDmax (−9.1 ± 14.1; P = 0.03) and induction in the right hindlimb also increased the amplitude of PDmin (11 ± 7.6) significantly (P = 0.002). Box plots were drawn, where the median, lowest

Swinging limb lameness

The Lameness Locator also successfully identified the induction of swinging limb lameness by measuring changes in forelimb (HDmax) or hindlimb (PDmax) lameness parameters with the expected sign (negative for left and positive for right limb lameness induction), with absolute values significantly greater than before induction in nine of the 10 dogs (Table 1). There was a significant increase in amplitude for HDmax (negative in the left, −40 ± 21.1; positive in the right, 36 ± 15.1) (forelimb lameness; P = 0.002) in dogs with swinging limb lameness in the forelimbs. The induction of swinging limb lameness in the hindlimbs significantly increased the amplitude of PDmax (i.e. negative for left, −11 ± 9.3; positive for right, 11 ± 12.2; P = 0.002). Box plots were drawn, where the median, lowest

Fig. 2. Box plots of minimum head difference (HDmin) values before (sound) and after supporting limb induced lameness on each limb (left forelimb, LF; right forelimb, RF; left hindlimb, LH; right hindlimb, RH). Significant differences compared to sound measurement are indicated by *P = 0.002 for LF and RF induction and P = 0.049 for LH induction.
and highest quartiles and minimum and maximum values are presented for each variable (Figs. 6–9).

Additional compensatory lameness mechanisms detected by Lameness Locator

Induction of supporting and swinging left hindlimb lameness significantly decreased HDmin values (supporting, $-8 \pm 17.3, P = 0.049$; swinging, $−10 \pm 13.5, P = 0.020$), consistent with ipsilateral compensatory forelimb movement asymmetry. Induction of supporting left forelimb lameness significantly increased PDmin values ($8 \pm 4.9$) ($P = 0.002$), consistent with contralateral compensatory hindlimb movement asymmetry. Induction of swinging limb lameness of right hind significantly increased HDmax values ($13 \pm 10.6$) ($P = 0.002$),
consistent with ipsilateral compensatory forelimb movement asymmetry.

Discussion

In the present study, induced lameness was successfully detected from head and pelvic movements using inertial motion sensors. Changes in the symmetry between the lowest head and pelvic displacements were good indicators of supporting limb lameness and changes in the symmetry of the highest head and pelvic displacement indicated swinging limb lameness. Bell et al. (2016) reported in a study of hindlimb lame horses that the difference between the lowest pelvic positions indicated a supporting limb lameness, with decreases in loading during the first half of the stance phase, and differences between the maximum pelvic positions indicated a push off-type lameness, with decreased transfer of vertical force to horizontal force in the second half of the stance phase. We do not know how our swinging limb lameness corresponded to specific clinical diagnoses, but we can speculate that, as in horses, changes in the symmetry of the highest positions of head and pelvis could indicate a push off-type lameness. The system used was also able to detect compensatory lameness mechanisms other than those expected for the lame limb (i.e., head asymmetry for forelimb lameness and pelvic motion asymmetry for hindlimb lameness). Therefore, asymmetrical movement of the head can be considered an indicator of both hindlimb and forelimb lameness. This may contribute to the low inter-observer agreement for lameness assessment, and potentially to misdiagnosis of the correct limb, at least with inexperienced observers.

Our results agree with our parallel kinematic study, where the symmetry of vertical head and pelvic motion was described through optical-based 3D kinematic analysis that was performed simultaneously in these dogs (Gómez Álvarez et al., 2017). Differences in the lowest and highest head and pelvic displacements obtained with both sensors and optical-based kinematic analysis agreed with the lameness induced, confirming that head and pelvic displacements are important symmetry variables for objective lameness evaluation in dogs. The same variables are often used in inertial sensor-based lameness evaluations in horses (Keegan et al., 2011; Starke et al., 2013; Pfau et al., 2015).

Kinetic compensatory lameness mechanisms have been described in dogs (Waxman et al., 2008; Rokstahler et al., 2009; Katic et al., 2009; Abdelhadi et al., 2012, 2013; Fischer et al., 2013), demonstrating that compensation occurs by changing the ground reaction forces of the ipsilateral and contralateral limbs, specifically braking, propulsion, peak vertical force and vertical impulse during fore- and hindlimb lameness. These changes unload the painful limb, and they can only be achieved by dynamic postural adaptations of the head, trunk and limbs, with subsequent changes in their motion patterns. This was shown in experimentally induced lameness by Gómez Álvarez et al. (2017), where an ipsilateral compensatory forelimb asymmetry was observed during supporting hindlimb lameness induction. If the same mechanisms exist in clinical cases, there could be a risk of the clinician targeting the evaluation towards a ‘false’ forelimb lameness. Therefore, when an ipsilateral forelimb and hindlimb lameness is seen concurrently, with no obvious clinical findings to explain a true forelimb lameness, the forelimb lameness signs might be merely compensatory. However, subtle contralateral hindlimb asymmetry, observed during forelimb supporting lameness, would not lead to confusion or misdiagnosis, because of the large differences in the magnitudes of the asymmetries of the head and pelvis.

Small pre-existing asymmetries were observed in the dogs before any lameness had been induced, similar to previous findings in sound dogs evaluated with a diverse array of methods, confirming that some degree of asymmetry is evident even in non-lame dogs (Budsberg et al., 1993; Besancon et al., 2003; Fanchon and Grandjean, 2007; Colborne, 2008; Oosterlinck et al., 2011). When using the motion analysis system in horses, there are established threshold values for asymmetry, i.e. +/- 6 mm for the head movement (HDmin or HDmax) and +/- 3 mm for the pelvic movement (PDmin or PDmax). Corresponding canine values require further investigation. Whether the asymmetry is caused by pain can only be determined by a thorough clinical examination. Further studies in larger populations of sound and lame dogs are needed to investigate the biological variation of motion asymmetries in dogs.

The lameness score of 2 used in the dogs we studied was chosen based on the inter-observer variability that exists in dogs during the clinical assessment of mild to moderate lameness. Moreover, this IMU system uses all the strides recorded and averages them to produce the results, in contrast with visual lameness scoring in dogs, which by definition does not necessarily include all strides (i.e. dogs might not be lame in all strides). In a kinematic study performed in dogs with subtle clinical lameness by Hicks and Millis (2014), only the pelvis showed significant vertical displacement, not the head. An IMU system should be able to detect more subtle lameness than the moderate lameness induced in our study, as it detected small asymmetries in sound limbs; however, further studies on subtle lameness are needed to fully explore this.

In the present study, all dogs were measured during steady state locomotion with very regular motion on a treadmill at a constant speed that yielded measurements with low variability of the head and pelvic vertical displacement. Sensors can also be used for overground measurements, however, it is possible that the regularity of speed and motion will be more difficult to achieve in dogs during overground measurements compared to horses, but this is yet to be established. The dogs used in the study were all medium to large size and there were no indications of that gait affected by the additional weight of each sensor (30 g). However, this might not be the case in small dog breeds.

Our findings with induced lameness in dogs suggest that similar motion patterns might occur in clinical cases, both for supporting and swinging limb lameness. Further studies are needed to investigate whether using IMUs during overground locomotion in clinical settings with lame canine patients will yield the same results.

Conclusions

Inertial sensor-based systems can successfully be used to detect and quantify moderate induced lameness and differentiate between supporting and swinging limb lameness in dogs trotting on a treadmill. If concurrent ipsilateral fore- and hindlimb lameness is observed, it is possible that the forelimb lameness is a compensatory lameness rather than a primary lameness. Therefore, the use of IMUs might help improve the diagnosis of lameness in dogs and also provide a wireless and portable device for the objective quantification of lameness.

Conflict of interest statement

None of the authors of this paper has financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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