Lameness is the most common medical problem of horses and has a high economic cost. Lameness evaluation typically includes observation of a horse in motion and subjective grading of the severity of a lameness via a scoring method, such as the AAEP lameness grading scale. Objective methods of lameness evaluation may increase sensitivity for detection of lameness.

Comparison of a body-mounted inertial sensor system–based method with subjective evaluation for detection of lameness in horses

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Objective—To compare data obtained with an inertial sensor system with results of subjective lameness examinations performed by 3 experienced equine veterinarians for evaluation of lameness in horses.

Animals—106 horses.

Procedures—Horses were evaluated for lameness with a body-mounted inertial sensor system during trotting in a straight line and via subjective evaluation by 3 experienced equine practitioners who performed complete lameness examinations including lunging in a circle and limb flexion tests. Agreement among evaluators regarding results of subjective evaluations and correlations and agreements between various inertial sensor measures and results of subjective lameness evaluations were determined via calculation of Fleiss’ κ statistic, regression analysis, and calculation of 95% prediction intervals.

Results—Evaluators agreed on classification of horses into 3 mutually exclusive lameness categories (right limb lameness severity greater than left limb lameness severity, left limb lameness severity greater than right limb lameness severity, or equal right and left limb lameness severity) for 58.8% (κ = 0.37) and 54.7% (κ = 0.31) of horses for forelimb and hind limb lameness, respectively. All inertial sensor measures for forelimb and hind limb lameness were positively and significantly correlated with results of subjective evaluations. Agreement between inertial sensors measures and results of subjective evaluations was fair to moderate for forelimb lameness and slight to fair for hind limb lameness.

Conclusions and Clinical Relevance—Results of lameness evaluation of horses with an inertial sensor system and via subjective lameness examinations were significantly correlated but did not have strong agreement. Inertial sensor–based evaluation may augment but not replace subjective lameness examination of horses. (Am J Vet Res 2013;74:17–24)
mechanical and electrical components that measure acceleration (accelerometers) or angular velocity (gyroscopes). Body-mounted devices with such inertial sensors have been used for evaluation of lameness in horses. Vertical movement of the head and torso of a horse can be measured with such devices; head and torso movements of horses can affect and be affected by vertical ground reaction forces of limbs. Asymmetry of vertical head and torso movements between right and left portions of a stride can be quantified, and associations between such data and severity of lameness in horses can be determined. Because of their small size and potential for wireless transmission of data, body-mounted inertial sensor devices are being commercially developed for objective evaluation of lameness in horses. Potentially, such devices could be routinely used by equine practitioners in the field for evaluation of lameness in horses.

The objective of the study reported here was to compare data obtained with an inertial sensor system with results of subjective lameness examinations performed by 3 experienced equine veterinarians for evaluation of lameness in horses. We hypothesized that data obtained by use of an inertial sensor system would be correlated with results of subjective lameness examinations performed by experienced equine veterinarians. If data obtained with an inertial sensor system and results of subjective lameness examinations of horses are strongly correlated, then threshold values of inertial sensor measures for detection of lameness in horses can be estimated via association of such data with mean subjective lameness scores of experienced equine veterinarians.

Materials and Methods

Animals—One hundred six horses were evaluated during the study. Age range for 98 of the horses was 1 to 24 years (mean ± SD age, 8.5 ± 6.2 years). Age was not recorded and could not be retrospectively determined for 8 of the horses. Horses included 58 geldings, 46 mares, and 2 sexually intact males. Breeds included American Quarter Horse or Quarter Horse-type (n = 43), warmblood (30), mixed breed (7), Thoroughbred (6), Missouri Fox Trotter (2), pony (1), draft (1), and mule (1). Breed was not recorded and could not be retrospectively determined for 15 horses. Horses included in the study had been trained to trot while being led by a handler with a lead shank. Most of the horses were brought by their owners to the University of Missouri Veterinary Medical Teaching Hospital for evaluation of lameness or poor performance (n = 56) or for prepurchase or preseason (ie, before training started) evaluation (7). Some horses were evaluated for lameness at private training stables (n = 6). Additionally, horses that belonged to the University of Missouri College of Veterinary Medicine teaching herd (n = 10) or 1 of 2 local college riding stables (15 and 12) were evaluated. Seven of the horses that belonged to the University of Missouri College of Veterinary Medicine teaching herd had a history of moderate chronic lameness. Some of the horses that belonged to the local college riding stables were suspected by the students or their mentors to have mild lameness that did not preclude exercise; however, complete histories were not obtained and medical records were not retrieved for those horses. The horses included in this study were a heterogeneous population of horses without lameness and horses with mild to moderate forelimb or hind limb lameness. Horses for which an AAEP lameness grade of 4 or 5 was assigned by any veterinary evaluator in the study were not included. Use of horses owned by the University of Missouri was performed in accordance with institutional animal care and use policies. Permission for instrumentation and collection and use of data of client-owned horses was obtained from owners or assigned agents.

Data acquisition and analysis—Three inertial sensors were attached to each horse. One single-axis accelerometer (head-mounted accelerometer) was attached with tape to the most dorsal aspect of the crown piece of the halter or to a head bumper attached to the halter. One single-axis accelerometer (pelvic-mounted accelerometer) was attached to the skin between the right and left tuber sacrale via a hook-and-loop fastener and duct tape. One single-axis gyroscope was attached with elastic tape to the dorsal aspect of the region between the metacarpophalangeal joint and the coronary band (ie, pastern) of the right forelimb. Each sensor consisted of a microelectromechanical systems device (accelerometer or gyroscope), a radio transceiver and antenna, a 4.2-V lithium-polymer battery, and a microcontroller and associated circuitry encased in epoxy. Each sensor measured 3.7 × 2.5 × 1.3 cm and weighed approximately 30 g. The sensors comprised a local area network of 3 slave nodes wirelessly connected to a master node (universal serial bus receiver) in a portable personal computer. Sensor data were digitally recorded (8 bits) at 200 Hz as horses were trotting. The 3 channels were synchronized by use of an on-board 40-MHz crystal oscillator with an accuracy of 10 ppm; timing accuracy was 5 ns/sample. Data acquisition and analysis software were custom-written for this application.

Each horse was simultaneously evaluated with inertial sensors and via observation by 3 experienced equine veterinarians (including KGK, DAW, JK, SKR, or other evaluators who were not authors) during trotting in a straight line. Then, veterinarians performed additional evaluations such as lunging of horses on soft and hard surfaces and limb flexion tests. Each veterinarian determined subjective lameness scores for each limb of each horse by use of the AAEP lameness grading scale. During lameness evaluation of horses, veterinarians were not aware of results determined with the inertial sensor system or those determined by the other veterinarians. Horses were trotted on asphalt or a hard-packed dirt surface during evaluation in a straight line and limb flexion tests. Lunging of horses was performed on various types of surfaces.

Inertial sensor data—Two separate trials of inertial sensor data collection were performed during trotting in a straight line for each horse. For each trial, data regarding vertical acceleration of the head and pelvis and angular velocity of the right forelimb pastern were obtained, processed, and analyzed as previously de-
Forelimb and hind limb lameness of horses was quantified via analysis of patterns of vertical movements of the head and pelvis, respectively. Data obtained with the gyroscopic sensor on the right forelimb and pelvis were analyzed to determine stride frequency and timing of stance phases of the gait of the right forelimb. Data regarding vertical acceleration of the head and pelvis were double-integrated and then processed with a moving-window integration error correction algorithm. Then, data were separated into 3 components (2 harmonic and 1 random) via a moving-window curve-fitting approach. The random component of the data was removed, and the harmonic components were summed to determine relative vertical head and pelvic heights between right and left halves of the stride (in millimeters) versus time. Mean height of the second harmonic signal was set to 0. Temporal relationships between vertical head and pelvic movements and phases of the stride were determined by use of right forelimb gyroscopic sensor data for determination of the beginning and end of the stance phase of the gait for the right forelimb.

Asymmetries of vertical movements of the head and pelvis between right and left portions of strides were determined via calculation of MXH, MXP, MNH, and MNP (Figure 1). Differences in maximum and minimum head and pelvic heights between right and left forelimbs and hind limbs were calculated via subtraction of the second minimum or maximum value from the first minimum or maximum value; the first minimum or maximum value was designated as the value detected closest in time to the beginning of the stance phase of the gait of the right forelimb.

The MXH was a measure of the asymmetry between right and left forelimbs of horses regarding upward movement of the head during the second half of the stance phase of the gait of the forelimbs. The MNH was a measure of the asymmetry between right and left forelimbs regarding downward movement of the head during the first half of the stance phase of the gait of the forelimbs. The mechanical model that best explained head movement of horses with lameness was a free body influenced by gravity and purposeful extensor muscle activity. This model predicted that the pelvis of a horse with lameness would have less downward movement during the first half of the stance phase of the gait of the lame hind limb, less upward movement during the second half of the stance phase of the gait of the lame hind limb, or both, compared with the sound (ie, nonlame) hind limb; such changes in movement would reduce forces on a lame hind limb during motion. Therefore, MXP and MNP were independent variables in this model and could have the same or opposite signs (positive or negative), depending on the part (first half or second half) of the stance phase of the gait during which changes in gait attributable to hind limb lameness occurred.

The theoretically expected value of MXP and MNP for a trial with perfect right to left hind limb symmetry (ie, no lameness) was 0; positive or negative values of these variables would increase in magnitude with increasing severity of lameness. Because MXP and MNP were independent variables, the sum of MXP and MNP was a measure of overall right versus left asymmetry in vertical movement of the pelvis that included asymmetry in both upward and downward movements. Therefore, the sum of MXP and MNP was a measure of hind limb lameness severity.

The vector sum of MXH and MNH (for evaluation of forelimb lameness) and the sum of MXP and MNP (for evaluation of hind limb lameness) were calculated for each straight line trial for each horse. A positive value indicated right forelimb or hind limb lameness and a negative value indicated left forelimb or hind limb lameness.

Subjective lameness examination scores—Differences in each evaluator’s subjective lameness scores between right and left forelimbs and between right and left hind limbs for each horse were determined by subtracting the score for the left forelimb from the score for the right forelimb and by subtracting the score for the left hind limb from the score for the right hind limb. Values were positive for horses with greater right limb versus left limb lameness scores, and values were negative for horses with greater left limb versus right limb lameness scores. Agreement among evaluators for classification of horses into 3 mutually exclusive lameness categories (right limb lameness scores greater than left limb lameness scores, left limb lameness scores greater than right limb lameness scores, or equal right and left limb lameness scores) for forelimbs and hind limbs was determined via calculation of Fleiss’ κ statistic. The in-
terevaluator, within-horse SDs for differences in subjective lameness scores between right and left forelimbs and between right and left hind limbs were calculated. The MDSSF and MDSSH were determined for each of the 3 evaluators for each horse.

Correlation between inertial sensor measures and subjective lameness scores—Correlations between raw (MXH, MNH, MXP, and MNP) and calculated (vector sum of MXH and MNH and sum of MXP and MNP) inertial sensor measures of lameness and MDSSF and MDSSH were determined via Pearson's product-moment correlation coefficients. Correlations between variables were considered significant when values of $P$ were <0.05. The 95% prediction intervals for forelimb and hind limb lameness scores for each inertial sensor measure were calculated via regression analysis of subjective lameness scores and values of inertial sensor measures.

Agreement between inertial sensor measures and subjective lameness scores—Threshold values of raw and calculated inertial sensor measures were determined for classification of horses into 3 mutually exclusive lameness categories (right limb lameness severity greater than left limb lameness severity, left limb lameness severity greater than right limb lameness severity, or equal right and left limb lameness severity) for forelimbs and hind limbs via regression analysis of values of inertial sensor measures and MDSSF and MDSSH values; these threshold values were the 95% confidence intervals of y-intercepts determined for values of MDSSF and MDSSH equal to 0. Likewise, threshold values of subjective lameness scores were determined for classification of horses into 3 mutually exclusive lameness categories (right limb lameness severity greater than left limb lameness severity, left limb lameness severity greater than right limb lameness severity, and equal right and left limb lameness severity) for forelimbs and hind limbs via regression analysis of values of inertial sensor measures and MDSSF and MDSSH values; these threshold values were the 95% confidence intervals of y-intercepts determined for values of inertial sensor measures (MXH, MNH, vector sum of MXH and MNH, MXP, MNP, and sum of MXP and MNP) equal to 0. By use of these threshold values for classification of lameness in horses, agreement between values of inertial sensor measures and subjective lameness scores was evaluated via calculation of Fleiss' $\kappa$ statistic.

**Results**

**Interevaluator agreement for subjective lameness scores**—Evaluators agreed on classification of horses into 3 mutually exclusive lameness categories (right limb lameness scores greater than left limb lameness scores, left limb lameness scores greater than right limb lameness scores, or equal right and left limb lameness scores) for 58.5% (62/106; $\kappa = 0.37$) and 54.7% (58/106; $\kappa = 0.31$) of horses for forelimbs and hind limbs, respectively.

![Figure 1](image1.png)

**Figure 1**—Illustration of a plot of the vertical movements of the head or pelvis of a trotting horse determined by use of an inertial sensor. Estimates of the timing of right (black bars) and left (white bars) forelimb stance phases of strides are indicated. The MXH and MXP were determined via subtracting the maximum height of the head (MXH) or pelvis (MXP) during the beginning of the left forelimb or left hind limb stance phase (C) from the maximum height of those regions during the beginning of the right forelimb or right hind limb stance phase (A). The MNH and MNP were determined via subtracting the minimum height of the head (MNH) or pelvis (MNP) during the left forelimb or left hind limb stance phase (D) from the minimum height of those regions during the right forelimb or right hind limb stance phase (B). During the study, head and pelvic heights were measured in millimeters.

![Figure 2](image2.png)

**Figure 2**—Plots of values of MDSSF (units, AAEP lameness grade) versus the vector sum of MXH and MNH (VSH; A), MXH (B), and MNH (C; in mm) for 106 horses undergoing evaluation of lameness by use of an inertial sensor system during trotting in a straight line. The $R^2$ (95% confidence interval) values are indicated in the upper left quadrant of each plot. Data for each horse (gray diamonds) and regression lines are indicated.
Correlation between inertial sensor measures and subjective lameness scores—Values of all inertial sensor measures for forelimbs (MNH, MNP, and SP; in mm) for 106 horses undergoing evaluation of lameness by use of an inertial sensor system during trotting in a straight line. The $R^2$ (95% confidence interval) values are indicated in the upper left quadrant of each plot. Data for each horse (gray diamonds) and regression lines are indicated.

Table 1—Standard errors of predicted AAEP lameness grades for various measures of lameness determined by use of an inertial sensor system for evaluation of 106 horses with various severities of lameness.

<table>
<thead>
<tr>
<th>Inertial sensor measure</th>
<th>SE of predicted lameness grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector sum of MXH</td>
<td>1.19</td>
</tr>
<tr>
<td>Vector sum of MNH</td>
<td>1.03</td>
</tr>
<tr>
<td>Vector sum of MXH and MNH</td>
<td>1.04</td>
</tr>
<tr>
<td>MXH</td>
<td>1.10</td>
</tr>
<tr>
<td>MNP</td>
<td>1.26</td>
</tr>
<tr>
<td>Sum of MXH and MNH</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Discussion

In the present study, we evaluated an inertial sensor system for evaluation of lameness in horses trotting in a straight line and compared results with those determined by 3 equine veterinarians performing lameness examinations. Results of other studies\textsuperscript{7,12} conducted during conditions similar to those of the present study indicate results of evaluation of horses with this inertial sensor system are repeatable for detection of forelimb and hind limb lameness and agree well with results obtained by use of a stationary force plate for detection of bilateral forelimb lameness.

Results of the present study indicated correlations between the vector sum of MXH and MNH and MDSSF $\kappa = 0.43$) and between the sum of MXH and MNH and MDSSH $\kappa = 0.22$) and between MXP (which is an indicator of maximum pelvic height) and MDSSH $\kappa = 0.26$) was higher than the agreement between MNP (which is an indicator of minimum pelvic height) and MDSSH $\kappa = 0.17$).

Agreement between inertial sensor measures and subjective lameness scores—Agreement between values of inertial sensor measures and results of subjective lameness evaluations for classification of horses into 3 mutually exclusive lameness categories was higher for forelimbs than it was for hind limbs (Tables 2 and 3). Agreements between inertial sensors measures and results of subjective lameness evaluations for classification of forelimb lameness were fair ($0.20 \leq \kappa \leq 0.40$) to moderate ($0.41 \leq \kappa \leq 0.60$). Agreements between inertial sensors measures and results of subjective lameness evaluations for classification of hind limb lameness were slight ($0.0 \leq \kappa \leq 0.20$) to fair. For evaluation of forelimbs, agreement between MNH (which is an indicator of minimum head height) and MDSSF $\kappa = 0.43$) and between the vector sum of MXH and MNH (which includes components of upward and downward movements of the head) and MDSSH $\kappa = 0.41$) was higher than the agreement between MXH (which is an indicator of maximum head height) and MDSSF $\kappa = 0.30$). For evaluation of hind limbs, agreement between the sum of MXP and MNP (which includes components of upward and downward movements of the pelvis) and MDSSH $\kappa = 0.22$) and between MXP (which is an indicator of maximum pelvic height) and MDSSH $\kappa = 0.26$) was higher than the agreement between MNP (which is an indicator of minimum pelvic height) and MDSSH $\kappa = 0.17$).
Agreement evaluations were statistically significant but not strong. Agreements between inertial sensor system measures of lameness and results of subjective lameness evaluations and interevaluator agreement for classification of lameness of horses were higher for forelimbs than they were for hind limbs. These results may be attributable to inaccuracies in results of either method of evaluation (inertial sensor system and subjective lameness evaluation) or to the fact that the outcome measures of each of these methods were not the same. Evaluation of horses with the inertial sensor system was limited to collection of data during trotting in a straight line, whereas subjective lameness evaluations typically included performance of limb flexion tests and lunging of horses. Some lameness conditions may not be detectable during trotting of horses in a straight line; such conditions may only be detectable during lunging in a circle or after performance of limb flexion tests. Variations in surface conditions during lunging of horses may have exacerbated lameness in some horses.

Table 2—Agreement between various inertial sensor measures and MDSSF values for classification of lameness in 106 horses evaluated by use of an inertial sensor system and via subjective lameness evaluation by 3 experienced veterinarians.

<table>
<thead>
<tr>
<th>Inertial sensor measure</th>
<th>Lameness category</th>
<th>MDSSF</th>
<th>( \kappa ) Statistic value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right &gt; Left</td>
<td>Left &gt; Right</td>
<td>Right = Left</td>
</tr>
<tr>
<td>MNH</td>
<td>31</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>MXH</td>
<td>27</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>VSH</td>
<td>32</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

Data are number of horses. Horses were allocated to 1 of 3 forelimb lameness categories (right forelimb lameness severity greater than left forelimb lameness severity, left forelimb lameness severity greater than right forelimb lameness severity, and equal right and left forelimb lameness severity) on the basis of values of inertial sensor measures of head movements and subjective lameness scores determined by 3 experienced observers.

VSH = Vector sum of MXH and MNH.

Table 3—Agreement between various inertial sensor measures and MDSSH values for classification of lameness in 106 horses evaluated by use of an inertial sensor system and via subjective lameness evaluation by 3 experienced veterinarians.

<table>
<thead>
<tr>
<th>Inertial sensor measure</th>
<th>Lameness category</th>
<th>MDSSH</th>
<th>( \kappa ) Statistic value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right &gt; Left</td>
<td>Left &gt; Right</td>
<td>Right = Left</td>
</tr>
<tr>
<td>MNP</td>
<td>28</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>MXP</td>
<td>36</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>SP</td>
<td>34</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

Data are number of horses. Horses were allocated to 1 of 3 hind limb lameness categories (right hind limb lameness severity greater than left hind limb lameness severity, left hind limb lameness severity greater than right hind limb lameness severity, and equal right and left hind limb lameness severity) on the basis of values of inertial sensor measures of pelvic movements and subjective lameness scores determined by 3 experienced observers.

SP = Sum of MXP and MNP.
ness severity in right and left limbs during every stride at a trot in a straight line would be determined to be sound by use of such methods. For horses with bilateral lameness in which the severity of lameness is worse in 1 limb than it is in the contralateral limb, results of such methods would indicate a unilateral lameness and the severity of lameness would be underestimated. In the present study, the threshold value for identification of horses as sound versus lame was estimated via calculation of the 95% prediction error for mean difference in AAEP scores between right and left limbs for all 3 evaluators when equal to 0. Asymmetry in vertical motion between right and left limbs of horses during movement may be attributable to causes other than lameness, such as neurologic dysfunction or physical asymmetry between limbs (eg, different length of right and left limbs). Such causes of asymmetrical gait can only be identified via examination by a veterinarian with accurate knowledge of the clinical history of a horse; such evaluation typically includes observation and palpation of limbs and the torso of a horse, use of local anesthetic techniques, and performance of imaging. Because the inertial sensor system used in the present study can only detect asymmetries in vertical movement between right and left limbs, results obtained with this system could only be compared with differences in subjective lameness scores between right and left limbs.

In the present study, agreement among evaluators regarding differences in subjective lameness scores between right and left limbs ($\kappa = 0.37$ and 0.31 for forelimbs and hind limbs, respectively) was slightly better than agreement among evaluators in another study in which 3 equine clinicians identified the limb with the most severe lameness in horses. In that study, when the mean AAEP lameness grade for forelimbs of horses was $< 1.5$ (ie, mild lameness), evaluators agreed on which forelimb had the most severe lameness $65.8\%$ of the time ($\kappa = 0.32$). When the mean AAEP lameness grade for hind limbs of those horses was $< 1.5$, evaluators agreed on which hind limb had the most severe lameness $57.9\%$ of the time ($\kappa = 0.14$). Results of the present study and results of that other study indicated agreement among evaluators for identifications of hind limb lameness was less than that for identification of forelimb lameness. Results of the present study and those of other studies suggested that variability in results of subjective lameness evaluations is high, even among expert equine clinicians. Such variability in results of subjective lameness evaluations may be caused by differences among evaluators regarding the variables used to identify lameness and may have decreased the strength of the correlations between subjective lameness scores and values of inertial sensor system measures in the present study.

The inertial sensor measures (MNH and the vector sum of MXH and MNP) that had the highest correlation with results of subjective lameness evaluation of horses obtained by use of a body-mounted inertial sensor system were significantly but weakly associated with results obtained via subjective lameness evaluation by expert clinicians. However, strong association between results of subjective and inertial sensor evaluations for lameness would suggest that results of an inertial sensor evaluation of lameness could not yield additional information beyond those of a standard subjective lameness evaluation. The high repeatability of results obtained by use of the inertial sensor system and the high agreement between such results and those obtained via other objective methods of lameness evaluation (such as a force plate) suggested that evaluation of lameness in horses with a body-mounted inertial sensor may provide veterinarians with useful information for evaluation of lameness in horses. Such objective measures may augment but not replace results obtained via subjective evaluation of lameness in horses, especially for evaluation of horses with mild lameness or for detection of mild improvements in severity of lameness after performance of diagnostic local anesthetic blocks or administration of treatments.

References

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