Lameness is the most common and expensive medical problem of horses.1 The present standard of practice for detection and evaluation of lameness involves observing horses in motion and then grading lameness severity with an interval scale, such as the American Association of Equine Practitioners grading scale of 0 to 5. However, when horses have mild lameness, agreement among veterinarians performing subjective lameness evaluations is poor and subject to bias.2–5 Bilateral or multiple limb involvement likely contributes to variability in findings. Objective methods of lameness evaluation may be used as an alternative.

Various methods of objective lameness evaluation have been proposed during the past 15 years, but use of a stationary force plate is the most commonly reported method.6–16 Stationary force plates are considered a reference (gold) standard for detection and evaluation of equine lameness. For that purpose, stationary force plates provide repeatable and accurate results with high sensitivity and specificity by measuring the reduction in ground reaction forces of a horse’s limbs. Reduction of vertical ground reaction force to less than established thresholds for breed and subject velocity can be used as an indicator of lameness.

Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness

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Objective—To assess the analytic sensitivity of an inertial sensor system for detection of the more severely affected forelimb in horses with bilateral lameness.

Animals—18 adult horses with forelimb lameness.

Procedures—Horses were fitted with inertial sensors and evaluated for lameness with a stationary force plate as they were trotted in a straight line. Inertial sensor–derived measurements for vertical head movement asymmetry (HMA) and vector sum (VS) of maximum and minimum head height differences between right and left halves of the stride were used to predict differences in mean peak vertical force (PVF) as a percentage of body weight between the right and left forelimbs. Repeatability was compared by calculation of the intraclass correlation coefficient (ICC) for each variable. Correct classification percentages for the lamer forelimb were determined by use of a stationary force plate as the standard.

Results—SEs of the prediction of difference in PVF between the right and left forelimbs from HMA and VS were 6.1% and 5.2%, respectively. Head movement asymmetry (ICC, 0.72) was less repeatable than PVF (ICC, 0.86) and VS (ICC, 0.84). Associations were positive and significant between HMA ($R^2 = 0.73$) and VS ($R^2 = 0.81$) and the difference in PVF between the right and left forelimbs. Correct classification percentages for HMA and VS for detecting the lamer forelimb were 83.3% and 77.8%, respectively.

Conclusions and Clinical Relevance—Results suggested that an inertial sensor system to measure vertical asymmetry (HMA and VS) due to forelimb lameness in horses trotting in a straight line has adequate analytic sensitivity for clinical use. Additional studies are required to assess specificity of the system. (Am J Vet Res 2012;73:368–374)

Abbreviations

HDmax  Maximum head height difference
HDmin  Minimum head height difference
HMA  Head movement asymmetry
ICC  Intraclass correlation coefficient
PVF  Peak vertical force
VS  Vector sum
as an absolute indicator of lameness severity in a given limb, such that bilateral lameness conditions can be quantified.\textsuperscript{13} Also, it has been suggested that stationary force plates can be used to identify subclinical lameness in horses.\textsuperscript{33}

Inertial sensors, such as accelerometers and gyroscopes, are widely used in the aerospace and automotive industry for flight stabilization and navigation. Inertial sensors in microelectromechanical systems are miniaturized combinations of electrical and mechanical sensing components in 1 device. Several studies\textsuperscript{17–23} have been reported in which systems that make use of inertial sensors were used as the basis for motion analysis to detect and evaluate lameness in horses. A basic premise is that vertical movement of the torso, which can be measured with body-mounted inertial sensors, will mirror vertical ground reaction forces and that asymmetry in vertical torso movement between right and left halves of the stride can be quantified and associated with severity of lameness. However, a limitation of any kinematic system that quantifies lameness as a function of left to right asymmetry is a reduced ability to accurately detect and measure severity of bilateral lameness conditions. Additionally, measurement of lameness based on right to left asymmetry may lead to overlooking the natural causes of asymmetry unrelated to lameness, such that estimation of thresholds of asymmetry between soundness and lameness may be difficult.

Despite the aforementioned limitations and because of their small size and the potential for wireless transmission of data, inertial sensor–based systems offer the potential for development into a clinically useful, objective method of lameness evaluation by equine practitioners, justifying further investigation of the characteristics of such systems. The purpose of the study reported here was to compare the results of a recently described inertial sensor–based lameness evaluation system\textsuperscript{18,24,25} with results of stationary force plate analysis for detection and evaluation of forelimb lameness in horses with a high likelihood of bilateral involvement.

Materials and Methods

**Animals**—Eighteen adult Quarter Horse and Quarter Horse–type horses (mean ± SD age, 14.1 ± 4.1 years; body weight, 548 ± 48 kg) owned by the Oklahoma State University College of Veterinary Medicine were used in the study. All horses were previously trained during prior use in other clinical trials to trot across a stationary force plate. Seventeen of the 18 horses had a known chronic forelimb lameness of at least 4 months’ duration. One horse had no history of forelimb lameness but was determined to have mild forelimb lameness on the basis of data collected from the force plate. Fifteen of the 18 horses with forelimb lameness had a previous diagnosis of navicular disease determined on the basis of findings of clinical examination, diagnostic nerve blocks, and radiographic examination. One horse had a diagnosis of navicular disease and sesamoiditis, and another horse had a diagnosis of sesamoiditis. Other than lameness, the horses were in good general health. The Oklahoma State University Institutional Animal Care and Use Committee approved the study protocol.

**Data acquisition**—A single-axis accelerometer was applied to the head of each horse, and a single-axis gyroscope was applied on the dorsal surface of the right forelimb pastern. The head accelerometer was attached with tape to the most dorsal aspect of the crown piece of the head halter. The right forelimb gyroscope sensor was held in place with elastic cloth tape.\textsuperscript{a} Each sensor consisted of a surface-mounted, microelectromechanical systems device (accelerometer\textsuperscript{b} or gyroscope\textsuperscript{c}); radio transceiver (open wireless technology standard) and antenna\textsuperscript{d}; 4.2-V lithium-polymer battery\textsuperscript{e} microcontroller\textsuperscript{f}; and associated circuitry. Each sensor was encased in epoxy for protection. Finished sensors were 1.5 × 1 × 0.5 inches in size and weighed approximately 30 g. The sensors composed a local area network of 2 slave nodes wirelessly connected to a master node (a universal serial bus receiver) on a portable personal computer.

Sensor data were digitally recorded (8 bits) at 200 Hz in real time when horses were moving. The 2 channels were synchronized by use of an onboard 40-MHz crystal with an accuracy of 10 ppm, providing a timing accuracy of 5 ns/sample. Data acquisition and analysis software were custom written for this motion analysis system.\textsuperscript{6,b}

Each horse was then evaluated for lameness by means of the inertial sensor system and force plate simultaneously. Each session consisted of 6 valid trials for each forelimb in which a handler led the horse at a trot across the floor-mounted force plate. Trials were deemed valid when the hoof of the desired forelimb struck squarely on the force plate and the velocity of the horse moving across the force plate was between 2.50 and 2.90 m/s, as measured with a millisecond timer and 2 photoelectric switches placed 3 m apart and spanning the force plate surface.\textsuperscript{c} A dedicated observer watched the surface of the force plate as each horse's foot struck the plate's surface and determined whether the strike was valid. Invalid strikes were strikes in which the entire foot did not land within the confines of the force plate surface or strikes in which subject velocity was not between 2.50 and 2.90 m/s.

**Force plate data**—For each valid strike, PVF (expressed as a percentage of body weight) was measured and recorded. Body weight was assessed with an electronic digital scale\textsuperscript{3} just prior to each force plate evaluation. Mean PVF from the 6 valid trials for each forelimb was determined, and the difference between mean PVFs for the right and left forelimbs was calculated for each horse. Positive values for differences in PVF between the right and left forelimbs indicated that the left forelimb mean PVF was greater than right forelimb mean PVF. Negative values for differences in PVF between the right and left forelimbs indicated that right forelimb mean PVF was greater than left forelimb mean PVF.

**Inertial sensor data**—For each valid trial, data for vertical acceleration of the head and angular velocity of the distal aspect (proximal phalanx) of the right forelimb were collected, processed, and analyzed as described elsewhere.\textsuperscript{18,24,25} Lameness was detected and quantified by analyzing the patterns of vertical head...
movement. Angular velocity values for the right forelimb were used to determine stride frequency and timing of right forelimb stance and swing phases. Vertical head acceleration was double integrated and further processed by use of an integration error correction algorithm. The signal was then convoluted into 3 components (2 harmonic and 1 random) by means of a moving-window, curve-fitting approach. The 2 harmonic components were summed to recreate gross vertical head movement without a moving mean. Timing of gross vertical head movement to the stride cycle was determined by overlaying on the angular velocity signal of the right forelimb.

Vertical HMAs between the right and left strides were determined by use of 2 general approaches. The first approach involved determination of the ratio of the amplitudes of the first to the second head harmonic by use of the entire processed signal from the trial. The second approach involved calculation of the HDmax and HDmin (in mm) between the right and left sides for every stride in the trial and then calculation of the VS of HDmax and HDmin as follows:

\[ VS = \sqrt{\text{HDmax}^2 + \text{HDmin}^2} \]

The first approach generates an overall measurement of HMA during an entire trial, with 0 as a minimum value signifying perfect symmetry (soundness) and increasing values signifying increasing asymmetry (increasing forelimb lameness). The second approach calculates asymmetry for every stride in the trial and then distributes asymmetry to right and left sides for every stride, depending on whether HDmin is a positive or negative value.

The HDmax is a measurement of the upward HMA after the end of the stance of the forelimbs. Positive HDmax indicates that a horse thrust its head upward to a higher position after pushoff of the left versus right forelimb, and negative HDmax indicates that a horse thrust its head up to a higher position after pushoff of the right versus left forelimb. Horses with signs of pain predominant in the second half of the stance will thrust the head upward more, so right forelimb lameness will have a negative HDmax and left forelimb lameness will have a positive HDmax. Horses with signs of pain predominant in the first half of the stance will have a positive HDmax for right forelimb lameness and negative HDmax for left forelimb lameness (ie, opposite in numeric sign to that for pushoff lameness).

The HDmin is a measurement of the downward HMA during the first half of the stance of the forelimbs. A positive HDmin indicates that the horse's head moves downward less (to a higher position) during the stance phase of the right versus left forelimb, and a negative HDmin indicates that the horse's head moves downward more (to a lower position) during the stance phase of the right versus left forelimb. A positive HDmin always indicates right forelimb lameness, and a negative HDmin always indicates left forelimb lameness (ie, HDmin can never be negative for right forelimb lameness or positive for left forelimb lameness).

An expected value of HDmax and HDmin for a trial with perfect right to left symmetry (ie, total lack of lameness) is 0, with increasingly negative values or positive values depending on the magnitude of right or left asymmetry. The VS of HDmax and HDmin provides an overall measurement of vertical HMA that accounts for both upward and downward movement asymmetries.

The HDmin is always positive for right forelimb lameness and always negative for left forelimb lameness, whereas HDmax may be positive or negative for both right and left forelimb lameness. Therefore, in the second approach, distribution of lameness to the more affected forelimb side was determined on the basis of the sign (positive or negative) of the HDmin value.

For force plate evaluations, inertial sensor data were collected from the beginning of a horse's run up to the force plate and continued for 4 to 6 strides after successfully striking the force plate. The first 2 strides at the beginning and last 2 strides at the end of the force plate run were extracted and discarded. This resulted in collection of a minimum of 4 and a maximum of 6 contiguous strides of data/trial, inclusive of the stride that struck the force plate.

Statistical analysis—For prediction of force plate results from inertial sensor data, force plate results (differences in PVF between the right and left forelimbs) were regressed on inertial sensor results (HMA and VS). Standard errors of force plate results as predicted from inertial sensor results were calculated from the regression equations and compared with typical error of calculation of the difference in PVF between the right and left forelimbs directly from PVF. Because the difference in PVF between the right and left forelimbs was calculated from the difference in mean PVF for the right and left limbs, typical error of the difference in PVF between the right and left forelimbs was calculated as the square root of the sum of squares of the within-subject SD of PVFs for the right and left limbs.

To compare repeatability between the inertial sensors and force plate results, the ICC was calculated for the raw force plate measurement (PVF) and for each inertial sensor raw measurement (HMA and VS). Associations among the difference in PVF between the right and left forelimbs, HMA, and VS were estimated by calculating the Pearson product moment correlations (r). Correct classification percentages were calculated for each inertial sensor measurement for detecting the lamered forelimb (ie, the limb with the lower PVF).

Results

Horses—For measurement of PVF, 36 trials were completed (2 trials/horse [1 for right and 1 for left forelimb]) with 6 repeats/trial. For HMA and VS, there were 18 trials (1 trial/horse) with 12 repeats/trial.

PVF, HMA, and VS—Raw force plate findings (mean PVF as a percentage of body weight) for right and left forelimbs and the inertial sensor findings (HMA and VS) for all 18 horses were summarized (Table 1). The within-subject SD of stride rate for all strides collected was 0.11 strides/s, with a maximum SD of 0.23 strides/s and a minimum SD of 0.04 strides/s. The within-subject SD of the stride rate between left and right strides was 0.05 strides/s. The SEs
The within-subject SD of PVF was 3.2%, resulting in a typical error for calculation of the difference in PVF between the right and left forelimbs of 4.5%.

Repeatability of methods—The within-subject SD for force plate analysis of the difference in PVF between right and left forelimbs was 3.2%. That for inertial sensor analysis of HMA was 0.51 and for VS was 6.5 mm. The inertial sensor measurement, HMA (ICC = 0.72), was less repeatable than the raw force plate measurement (PVF, ICC = 0.86) and the companion inertial sensor measurement (VS; ICC = 0.84).

Comparison of methods—Associations were plotted of the inertial sensor values of lameness, HMA ($R^2 = 0.73$) and VS ($R^2 = 0.81$), with the stationary force plate difference in PVF between the right and left forelimbs (Figure 1). Associations of both inertial sensor measurements with force plate results were strongly positive and significant ($P < 0.001$).

With HMA as the measurement of interest, the inertial sensor system identified the same limb as lamer as did the force plate for 15 of 18 horses. For the 3 horses for which the inertial sensor system did not identify the same lame limb as the lamer limb when HMA was used, the differences in PVF between the forelimbs were 2.1%, 1.6%, and 0.6%. With VS as the measurement of interest, the inertial sensor evaluation identified the same limb as lamer as did the force plate for 14 of 18 horses. For the 4 horses that the inertial sensor system did not identify the same limb when the VS was used, the difference in PVF between the right and left forelimbs was 2.1%, 1.7%, 1.6%, and 0.6%. When either HMA or VS was used, the inertial sensor system identified the same limb as lamer as did the force plate in all horses (100%)}
correct classification) in which the difference in PVF between the right and left forelimbs was > 4%.

Associations between the absolute value of the inertial sensor measurements of lameness, HMA ($R^2 = 0.49$) and VS ($R^2 = 0.63$), and the absolute value of the difference in PVF between the right and left forelimbs were plotted (Figure 2). The y intercepts of HMA and VS (ie, when the predicted difference in PVF between the right and left forelimbs was equal to 0) were 1.3 and 5.6 mm, respectively. When these y intercepts were used as an estimated threshold between nonlameness and lameness, HMA and VS predicted that 14 and 16 of the 18 horses were lame, respectively. For the 4 horses that the inertial sensor system did not identify as lame according to the HMA, the mean PVFs in the right and left forelimbs were 83.1% and 84.8%, 90.3% and 91.9%, 85.4% and 92.9%, and 86.0% and 83.9%, respectively. For the 2 horses that the inertial sensor system did not identify as lame according to the VS, the mean PVFs in the right and left forelimbs were 90.3% and 91.9% and 86.0% and 83.9%, respectively. Neither inertial sensor measure identified as lame the 1 horse that did not have a history of forelimb lameness.

**Discussion**

In the present study, the sensitivity of an inertial sensor system for detecting lameness in horses was assessed to determine its usefulness in equine practice in situations where force plate analysis is not practical. The inertial sensor–based method was noninvasive, and instrumentation of horses was simple and rapidly accomplished. It allowed data collection in real time. Furthermore, data analysis was quick and involved asymmetry detection algorithms previously shown to be accurate for lameness detection in horses.

Each force plate trial in the study was considered an evaluation of lameness severity in 1 forelimb, independent of the status of the opposite forelimb. With the force plate method, horses with bilateral forelimb lameness would be judged as lame, even if the severity of lameness were equivalent in each forelimb. By contrast, the inertial sensor system measures the asymmetry of head movement between the right and left portions of a stride. Horses with bilateral forelimb lameness, in which the severity of lameness in opposite limbs is equivalent in every stride, would be judged as symmetric if inertial sensors were used. Thus, the force plate cannot measure the severity of lameness in both limbs without at least 2 separate trials, but the inertial sensor system cannot measure the absolute severity of lameness in 1 limb in any 1 stride. For these reasons, individual raw measurements obtained with each method could not be used for determining a method’s sensitivity for lameness detection. Any comparison must incorporate a measurement of asymmetry amplitude between the right and left limbs. This was accomplished for the force plate measurement (PVF) through calculation of the difference between right and left forelimbs.

The SEs for predictions of the difference in PVF between the right and left forelimbs for inertial sensor evaluation when HMA and VS were used were 6.1% and 5.2%, respectively. These values were only slightly higher than the within-subject SD for the difference in PVF between the right and left forelimbs (4.5%) that was calculated from the PVF. All study horses with a difference in mean PVF between the right and left limbs > 4% were correctly detected as lame, and that lameness was identified (right vs left) with the inertial sensor system. Use of stationary force plates as the reference standard of lameness detection and evaluation provided evidence that the inertial sensor system is sensitive for detecting forelimb lameness in horses. However, because only 1 nonlame horse was evaluated in our study, the specificity of the inertial sensor system or the likelihood of obtaining false-positive results could not be confidently determined.

The ICC of HMA, the inertial sensor variable representing overall vertical HMA for the entire trial, was less than that of the stationary force plate measurement and the companion inertial sensor measurement, indicating that HMA was less repeatable than the other 2 variables. The VS had repeatability (ie, precision) similar to that of the PVF. The VS of HDmax and HDmin was measured, and a mean was calculated for all strides in each trial. This inertial sensor measurement also had higher correct classification percentages for detecting lameness than did HMA. Results of our experiment support the use of the VS rather than HMA when the inertial sensor system is used for lameness detection in horses because of its higher precision and strength of association with force plate results.

In the present study, data on only 4 to 6 contiguous strides were collected and analyzed for each inertial sensor trial. The inertial sensor system analysis method, which incorporates a frequency-based signal convolution and decomposition into harmonic components, is better for lameness analysis when data on larger numbers of contiguous strides are available. In another study, test-retest repeatability of the inertial sensor system for detecting vertical HMA was higher (ICC range, 0.88 to 0.94) than that achieved for similar measurements in the present study (ICC range, 0.72 to 0.84). However, in the previous study, data on trials with a mean of 48 contiguous strides were collected and the trials with the least number of contiguous strides involved a mean of 21.6 strides. Higher test-retest repeatability can be expected when greater numbers of contiguous strides are analyzed up to a certain limit, at which the longer duration of trotting may increase (lameness gets worse with exercise) or decrease (gait improves with mild exercise [ie, horse warms out of lameness]) initial lameness. Given the results of the present study and the previous study, we recommend collecting data on a minimum of 20 contiguous strides when the inertial sensor system is used.

Repeatability of the raw force plate results in the present study was high. The within-subject SD of the raw force plate variable, PVF, was only 3.2%, which is equivalent to a coefficient of variation of 3.7% (mean PVF, 86.6%). Repeatability was maintained by controlling subject velocity, which can be assessed by examining the small within-subject SD of stride rate between trials by use of the right forelimb gyroscopic sensor of the inertial sensor system. In a previous in-depth study of the use of force plates to detect forelimb
lameness in horses, the within-subject coefficient of variation for PVF ranged from 4.0% for horses believed to be subclinically lame to 8.0% for horses with grade 4 lameness. Other studies also also repeatable results of the within-subject coefficient of variation < 10%.

The inertial sensor system used in the present study does not measure true head position in a 3-D space as is accomplished by use of the high-speed camera and marker systems traditionally used for kinematic analysis in horses. The accelerometers used in this inertial sensor system measure acceleration normal to the surface of the sensor. Rotation of the sensor around all 3 axes from true vertical in a 3-D space will decrease signal amplitude when measuring true vertical acceleration. This rotation may be large in the sagittal plane for the head-mounted sensor, particularly in horses that consciously raise or lower their head as when jerking the head away from the handler or lowering the head to look at or smell the ground. However, the data processing approach used for this method removes random, nonperiodic vertical movement and quantifies HMA by estimating the remaining shape of the head movement signal. It is less dependent on true head movement amplitude and more dependent on relative head height between right and left half strides. When the head rotation is equal in amplitude in each half stride (right vs left), the effect of sensor rotation will be minimized. However, when the head rotation is not equal in amplitude in each half stride, asymmetries not attributable to lameness will be recorded. Additional studies to determine the amplitude of this potential effect are needed.

For the present study, an assumption was made that measurement of that vertical ground reaction force by use of stationary force plates would be sufficiently precise and accurate for detecting forelimb lameness in horses and for use as a reference standard. Sufficient evidence exists to suggest this assumption is valid for horses with experimentally induced lameness, horses with lameness severity higher than grade 2, and detection of lameness changes after treatment. Peak vertical ground reaction force is not the only, and perhaps not the best, indicator for all types of lameness, particularly in the situation of mild lameness. Other information in the vertical ground reaction force signal, such as vertical ground reaction force impulse (area under the curve), timing-specific vertical ground reaction force characteristics, or information in the horizontal ground reaction force signal, may facilitate lameness classification.

Results of the present study suggest that HMA as measured by use of the inertial sensor system is sensitive enough to be used clinically to detect forelimb lameness in horses trotting in a straight line. Specificity of the system needs further investigation. Horses with bilateral lameness of equivalent severity may be evaluated as not lame with the inertial sensors if evaluated only when trotting in a straight line. Studies are needed to determine the sensitivity and specificity of inertial sensor systems for detection of hind limb lameness in horses.

References


