# Assessment of repeatability of a wireless, inertial sensor–based lameness evaluation system for horses

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**Objective**—To determine repeatability of a wireless, inertial sensor–based lameness evaluation system in horses.

**Animals**—236 horses.

**Procedures**—Horses were from 2 to 29 years of age and of various breeds and lameness disposition. All horses were instrumented with a wireless, inertial sensor–based motion analysis system on the head (accelerometer), pelvis (midline croup region [accelerometer]), and right forelimb (gyroscope) before evaluation in 2 consecutive trials, approximately 5 minutes apart, as the horse was trotted in a straight line. Signal-processing algorithms generated overall trial asymmetry measures for vertical head and pelvic movement and stride-by-stride differences in head and pelvic maximum and minimum positions between right and left sides of each stride. Repeatability was determined, and trial difference was determined for groups of horses with various numbers of strides for which data were collected per trial.

**Results**—Inertial sensor–based measures of torso movement asymmetry were repeatable. Repeatability for measures of torso asymmetry for determination of hind limb lameness was slightly greater than that for forelimb lameness. Collecting large numbers of strides degraded stride-to-stride repeatability but did not degrade intertrial repeatability.

**Conclusions and Clinical Relevance**—The inertial sensor system used to measure asymmetry of head and pelvic movement as an aid in the detection and evaluation of lameness in horses trotting in a straight line was sufficiently repeatable to investigate for clinical use. (*Am J Vet Res* 2011;72:1156–1163)

Lameness is the most common medical problem in horses.[1] When considering total cost of treatment and loss of use, it is also the most expensive.[1] Even lameness of mild severity, if it adversely affects the performance or use of a horse, can be costly to the owner. Ideally, veterinary practitioners should be able to reliably detect and quantify lameness in horses at all severity levels. The current standard for lameness evaluation in horses is subjective grading by use of scales with discrete levels, such as the AAEP lameness scale.[2]

**Abbreviations**

| | |
|---|---|
| AAEP | American Association of Equine Practitioners |
| CI | Confidence interval |
| HDmax | Difference in head maximum positions between right and left portions of the stride |
| HDmin | Difference in head minimum positions between right and left portions of the stride |
| HMA | Head movement asymmetry |
| PDmax | Difference in pelvis maximum positions between right and left portions of the stride |
| PDmin | Difference in pelvis minimum positions between right and left portions of the stride |
| PMA | Pelvic movement asymmetry |

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However, evidence suggests that subjective evaluation of lameness, even among experts, is only marginally acceptable for lameness of mild severity.[3–6] Therefore, a search for and development of an objective and more reliable form of lameness evaluation in horses is a worthwhile endeavor.

Camera-based kinematic evaluation of movement on a treadmill and use of a stationary force plate are 2 techniques that have been tested and provide repeatable and accurate objective evaluation of lameness in horses.[7–10] Camera-based kinematic evaluations are usually performed in a laboratory setting under carefully controlled conditions of lighting and background with predetermined locations and limited size of the field of view. The stationary force plate requires dedicated space and substantial technical expertise to use and maintain. Obtaining sufficient data for reproducible results also requires multiple hoof strikes on the small surface area of the plate, which requires time and patience. Although these techniques are useful investigative tools and are worth further study and development, they are not useful as a field-ready, objective lameness evaluation technique for use by practicing equine veterinarians at this time.

A technique that has potential for development into an objective method of lameness evaluation for use in the field is wireless transmission of data from inertial sensors attached to the horse's body. Sensors can be designed that are small enough to be inconsequential to a horse's normal movement. Data logging and downloading collected data from inertial sensors have been reported in horses as early as 1994.[11] In 2002, a method of wireless transmission of body-mounted inertial sensors for the specific purpose of lameness evaluation in horses was introduced.[12] The study reported here represents an improvement of the system first reported in 2002, with further development by collaboration between equine veterinarians and electrical and mechanical engineers. The purpose of the study reported here was to determine the system's repeatability in uncontrolled conditions for the detection of movement variables useful in evaluation of lameness in horses.

## Materials and Methods

**Animals—**A total of 236 horses were evaluated in this study. All horses were adult sized and ranged in age from 2 to 29 years (mean ± SD, 9.0 ± 5.8 years). There were 122 geldings, 77 mares (3 spayed), and 15 sexually intact males. Age was not recorded in 31 horses, and sex was not recorded in 22 horses. There were 99 American Quarter Horses or Quarter Horse types (American Paint Horse or Appaloosa), 31 warmbloods, 23 Thoroughbreds, 19 Arabians, 12 American Saddlebreds, 11 Missouri Fox Trotters, 9 mixed-breed horses, 4 draft-breed horses, 2 Tennessee Walking Horses, 2 donkeys, 2 ponies, 1 mule, and 1 Morgan. Breed was not recorded in 20 horses. All horses were required to trot naturally to be instrumented and to be included in the study. Some horses (n = 136) were evaluated at the University of Missouri Veterinary Teaching Hospital for lameness, poor performance, or prepurchase evaluation. Additionally, horses that belonged to the University of Missouri Teaching Herd (n = 21) and to 2 college riding stables (56 and 23) were evaluated. The horses evaluated in this study represented a heterogeneous sampling of clinically normal horses and horses with mild to moderate forelimb and hind limb lameness. Although some of the horses at the 2 college riding stables had mild lameness, all were in regular training and use. No horses with lameness considered by any veterinary evaluator to have an AAEP grade > 3 were used in this study. Use of horses owned by the University of Missouri was performed in accordance with institutional animal care and use policies. Permission for instrumentation of horses and collection and use of data was obtained from the owners or assigned agents for all privately owned horses.

**Data collection—**After horses were instrumented, data collection was initiated as the horse was trotted in a straight line on a flat surface and restrained on a lead shank. For 2 horses that would not lead easily, data were collected as the horse was ridden in a straight line. For each horse, data were collected for 2 consecutive trials ≤ 5 minutes apart in the same area. No attempt was made to control speed of movement, and in many instances, the person leading the horse was not the same for both trials. Data were collected over the course of the investigation in various locations and surface conditions (asphalt, hard-packed dirt, or raked dirt). The number of consecutive strides for which data were collected depended on the length of available flat area on which to trot the horse in a straight line, but data were collected for at least 6 strides for each trial (mean, 48 strides/trial; range, 6 to 118 strides/trial). All trials were completed before any nerve or joint blocks or flexion tests were performed on the horses.

**Instrumentation—**Each horse was instrumented with 2 single-axis acceleration sensors and 1 single-axis piezoelectric, gyroscopic sensor. One acceleration sensor was attached to the dorsum of the head with tape on the most dorsal aspect of the crown piece of the head halter or to a felt head bumper with a preplaced piece of industrial strength hook-and-loop patch.[a] The other accelerometer was attached to the midline dorsum of the croup region as a marker for the pelvis, between the tubera sacrale, with a strip of industrial-strength hook-and-loop patch[a] secured with either glue or tape. In some horses with long hair, the site between the tubera sacrale was clipped of hair (but not shaved) before placing the strip of hook-and-loop patch[a] or the sensor was secured additionally with strips of duct tape applied to provide downward pressure on the pelvic sensor. The gyroscopic sensor was attached to the dorsal surface of either the pastern (proximal phalangeal area) or hoof with tape or was placed in a specially designed neoprene pastern wrap. Total instrumentation time was < 3 minutes.

Each sensor consisted of a surface-mounted, microelectrical-mechanical device (accelerometer[b] or gyroscope[c]), radio transceiver (open wireless technology standard) and antenna,[d] 4.2-V lithium-polymer battery,[e] microcontroller,[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 3 slave nodes wirelessly connected to a master node (a universal serial bus receiver) on a portable personal computer. Sensor data were digitally sampled (8-bits) at 200 Hz in real time as the horse was moving. The 3 channels were synchronized by use of an onboard 40-MHz crystal with an accuracy of 10 ppm, giving a timing accuracy of 5 ns/sample. Maximum transmission distance depended on the location but was always > 100 m. Data acquisition and analysis software were custom written for the application.[g,h]

**Data analysis—**Vertical head and pelvic acceleration and right forelimb (pastern or dorsal hoof areas) angular velocity data were collected, processed, and analyzed as described.[12–15] Briefly, lameness was detected and quantified by analyzing the patterns of vertical head and pelvic movement (**Figure 1**). Angular velocity of the distal portion of the right forelimb was used to determine stride rate and timing of right forelimb stance and swing phases. Vertical head and pelvis acceleration were doubly 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 use of a moving-window, curve-fitting approach. Input variables for processing included doubly integrated head and pelvic acceleration, error between the deconvoluted processed and collected raw signals < 1%, stride rate, window width (time) equivalent to a mean of 2 full strides, and a point-weight function based on distance from the center of the moving window. Temporal association of the harmonic head and pelvic components with the stride cycle was determined by overlaying acceleration signals on the angular velocity signal of the right forelimb. When attached to the dorsal surface of the distal portion of the right forelimb, the gyroscope gave flat (hoof) or positive (pastern) signal deflection when the right forelimb was in stance and negative signal deflection when in swing. From the position of the right forelimb, the position of all other limbs during movement could be estimated as long as the horse was moving with known gait.

Asymmetries of vertical movement of the head and pelvis between the right and left strides were determined by use of 2 general approaches: determining the ratio of the root-mean–squared amplitudes of the first to the second head and pelvic harmonics by use of the entire processed signal from the trial and summing the harmonics to determine corrected head and pelvic height signals and then calculating minimum and maximum head and pelvic height differences (in millimeters) between the right and left sides for every stride in the trial. The first approach generates an overall measure of HMA and PMA over the entire trial, with 0 as a minimum value signifying perfect symmetry and increasing values signifying increasing asymmetry with increasing lameness. The second approach calculates stride-by-stride asymmetry and distributes asymmetry to the right and left sides depending on the sign (+ or –) of maximum and minimum head and pelvic height differences (HDmax, HDmin, PDmax, and PDmin). Stride-by-stride difference in head maximum positions

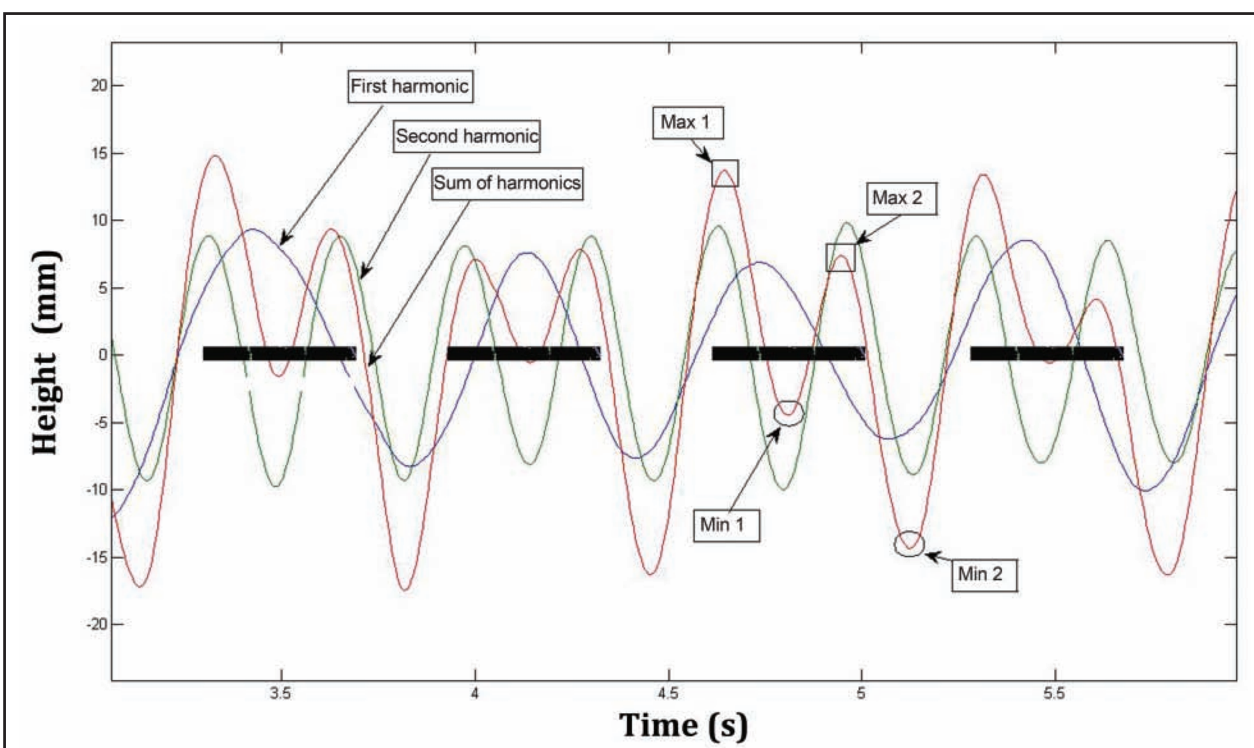


Figure 1—Illustration of a plot of the first harmonic, second harmonic, and sum of harmonics of the height of vertical movement of the head or pelvis of a trotting horse. Max 1 = Maximum head and pelvis height at the beginning of right fore- and hind limb stance phase. Max 2 = Maximum head and pelvis height after the end of right fore- and hind limb stance phase. Min 1 = Minimum head and pelvis height during right fore- and hind limb stance phase. Min 2 = Minimum head and pelvis height during right fore- and hind limb swing (left fore- and hind limb stance phase). Black bars are estimates of the timing of right forelimb stance phase.

and PDmax are measures of the symmetry of head and pelvic thrust upward after the end of the forelimb and hind limb stance, respectively. Stride-by-stride difference in head minimum positions and PDmin are measures of the symmetry of head and pelvic fall during the first half of stance of the forelimbs and hind limbs, respectively. An expected value of maximum or minimum height difference of a horse with perfect right to left symmetry is 0, with increasingly negative or positive values depending on the magnitude of right or left asymmetry.

Thus, for each trial, 6 measures of asymmetry were generated: HMA, mean HDmax, mean HDmin, PMA, mean PDmax, and mean PDmin. Test-retest repeatability for each measure was determined by calculation of the change in mean between trials, typical error (within-subjects SD), intraclass correlation coefficient between the 2 trials, 95% CI for a single measure (1.96 × typical error), and 95% CI for a difference between 2 measures (2.77 × typical error). Nonuniform error (heteroscedasticity) was determined visually for each measure by plotting the first trial versus the second trial. Data were $\log_{10}$ transformed when there was apparent dependence of trial difference on trial mean (ie, heteroscedasticity). Stride rate was determined in each trial by use of a custom-developed peak detection algorithm applied to the right forelimb gyroscopic signal.

To estimate the minimum number of strides needed for lowest variance between trials and between strides in a trial, the trial difference for all variables and stride-to-stride SD in HDmax, HDmin, PDmax, and PDmin were also determined separately for 8 equally sized groups of horses defined by the number of strides for which data were collected per trial (< 27, 28 to 31, 32 to 35, 36 to 40, 41 to 51, 52 to 62, 63 to 77, and > 77 strides). The difference between groups with different numbers of strides for which data were collected for all lameness variables was determined by use of 1-way ANOVA, with values of $P < 0.05$ considered significant. Multiple comparisons were made by use of a Dunnett test with a control of < 27 strides for which data were collected in a single trial.

## Results

The overall measures of head and pelvic signal asymmetries, HMA and PMA, had substantial heteroscedasticity (ie, trial difference varied with trial mean) and were therefore $\log_{10}$ transformed. After $\log_{10}$ transformation, heteroscedasticity was not apparent (ie, trial difference did not vary with trial mean; **Figures 2 and 3**). All repeatability measures for HMA and PMA are therefore reported as percentages. By contrast, none of the measures of head and pelvic height differences that distribute lameness to the left or right side (HDmin, HDmax, PDmin, and PDmax) had heteroscedasticity (**Figures 4 and 5**). All repeatability measures for HDmin, HDmax, PDmin, and PDmax are therefore reported in raw units of height (mm). The 95% CI for stride rate between trials was ± 0.10 strides/s, with a mean stride rate for all horses of 1.5 strides/s. Stride rate variation was independent of mean stride rate.

Change in mean, typical error, intraclass correlation coefficient, and 95% CIs for all measures of all horses (n = 236) were tabulated **(Table 1)**. Variability for measures of vertical HMA was greater than for those of vertical PMA. Mean HMA for all 236 horses was 1.02 and ranged from 0.32 (least asymmetric vertical head movement) to 5.32 (most asymmetric vertical head movement). Mean PMA for all 236 horses was 0.41 and ranged from 0.10 (least asymmetric vertical pelvis movement) to 4.91 (most asymmetric vertical pelvic movement). Means of the absolute values (because values ranged from negative to positive values) of HDmin, HDmax, PDmin, and PDmax for all 236 horses were 8.50, 6.86, 3.64, and 4.75 mm, respectively. Mean HDmin and HDmax for each horse trial ranged from –62.26 to +65.72 mm (total range, 127.98 mm) and –42.10 to +44.86 mm (total range, 86.96 mm), respectively. Mean PDmin and PDmax for each

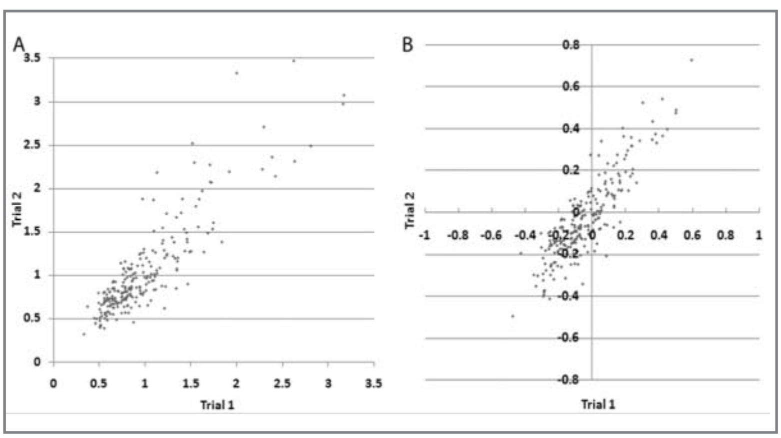


Figure 2—Graph of heteroscedasticity of HMA of trotting horses. A—Intertrial correlation (raw data); notice increasing variance with increasing HMA. B—Intertrial correlation after $\log_{10}$transformation of raw data; notice stable variation with increasing HMA.

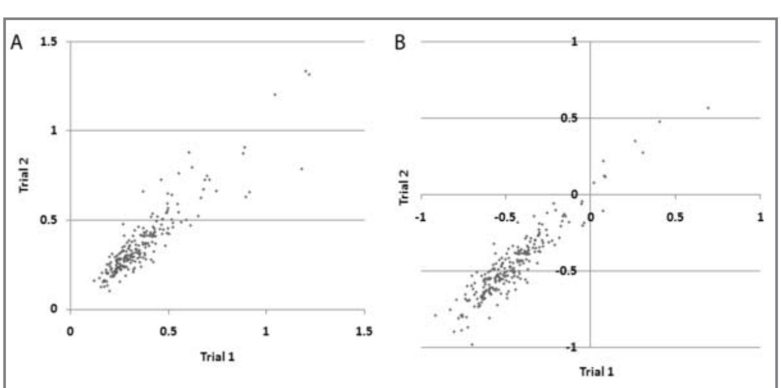


Figure 3—Graph of heteroscedasticity of PMA of trotting horses. A—Intertrial correlation (raw data); notice increasing variance with increasing PMA. B—Intertrial correlation after $\log_{10}$transformation of raw data; notice stable variation with increasing PMA.

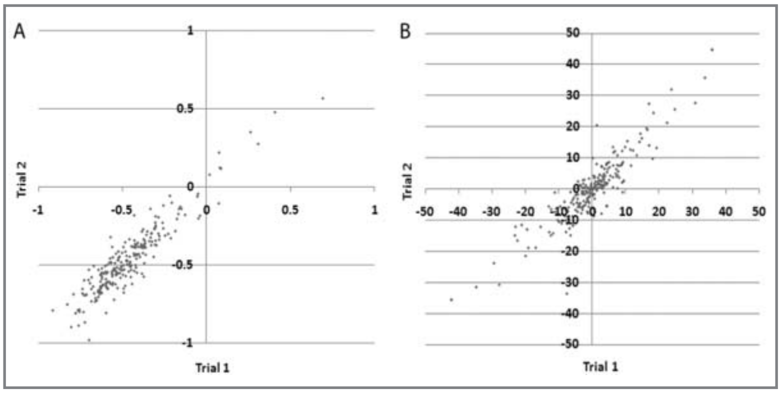


Figure 4—Graph of nonheteroscedasticity of HDmin and HDmax of trotting horses. A—Intertrial correlation of HDmin (raw data); notice equivalent variance with increasing HDmin. B—Intertrial correlation of HDmax (raw data); notice equivalent variance with increasing HDmax.

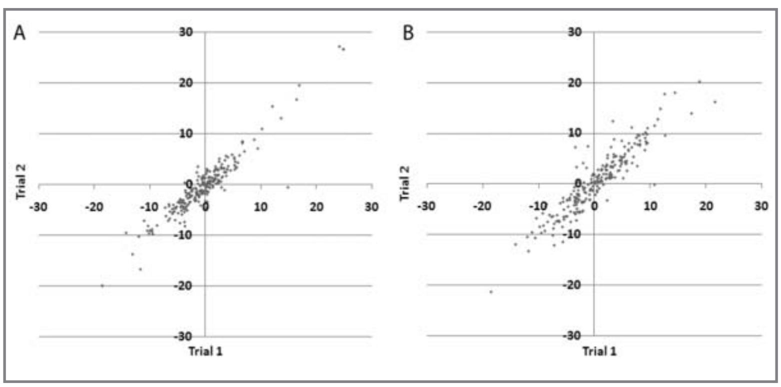


Figure 5—Graph of nonheteroscedasticity of PDmin and PDmax of trotting horses. A—Intertrial correlation of PDmin (raw data); notice equivalent variance with increasing PDmin. B—Intertrial correlation of PDmax (raw data); notice equivalent variance with increasing PDmax.

horse trial ranged from –19.88 to +27.25 mm (total range, 47.13 mm) and –21.29 to +26.82 mm (total range, 48.11 mm), respectively. Considering that HDmax, HDmin, PDmax, and PDmin variation did not depend on mean asymmetry (ie, did not vary with severity of lameness) and their trial-by-trial within-subject SD was smaller relative to total range measured in all 236 horses (2.5%, 3.5%, 2.9%, and 3.5% for HDmin, HDmax, PDmin, and PDmax, respectively), these measures were considered more appropriate than were HMA and PMA to quantify severity of lameness.

Change in mean between trials for all measures and stride-by-stride SD for HDmin, HDmax, PDmin, and PDmax for 6 to 27, 28 to 31, 32 to 35, 36 to 40, 41 to 51, 52 to 62, 63 to 77, and > 77 strides were tabulated (**Tables 2 and 3**). Trial difference was not affected by the number of strides for which data were collected. However, stride-by-stride SD of HDmax, PDmax, and PDmin significantly increased as the number of strides for which data were collected increased. Standard deviation of HDmax was significantly increased, compared with a control of < 27 strides for which data were collected, when data were collected for > 63 strides. Both hind limb lameness measures, PDmax and PDmin, had significantly greater stride-by-stride variability, compared with a control of < 27 strides, when data were collected for > 41 strides.

Table 1—Test-retest repeatability of a wireless inertial sensor system for detecting HMA and PMA in trotting horses.

| Measure | Change in mean from trial 1 to trial 2 | Typical error | ICC | 95% CI* | 95% CI† |
|---|---|---|---|---|---|
| HMA (%) | 3.1 | 16.8 | 0.885 | 30.7 | 44.1 |
| HDmin (mm) | 0.22 | 3.15 | 0.936 | 6.50 | 9.18 |
| HDmax (mm) | 0.09 | 3.17 | 0.900 | 6.28 | 8.87 |
| PMA (%) | 2.5 | 14.1 | 0.952 | 26.0 | 37.1 |
| PDmin (mm) | –0.01 | 1.36 | 0.935 | 3.00 | 4.25 |
| PDmax (mm) | 0.23 | 1.69 | 0.925 | 3.47 | 4.90 |

*Confidence interval for a single measure (1.96 X typical error). †Confidence interval for a difference between 2 consecutive measures (2.77 X typical error).

Typical error = Within-subjects SD. ICC = Intraclass correlation coefficient between trial 1 and trial 2. Because HMA and PMA variability is proportional to sample mean, variability is reported as percentage of mean.

Table 2—Mean trial difference for inertial sensor measures of lameness for various numbers of strides for which data were collected in trotting horses.

| Measure | No. of strides | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 27 (n = 33) | 28–31 (n = 34) | 32–35 (n = 24) | 36–40 (n = 27) | 41–51 (n = 31) | 52–62 (n = 28) | 63–77 (n = 29) | > 77 (n = 30) |
| HMA | 0.15 | 0.23 | 0.19 | 0.18 | 0.16 | 0.11 | 0.25 | 0.18 |
| HDmin (mm) | 3.23 | 3.65 | 2.41 | 2.79 | 3.09 | 2.45 | 4.10 | 3.58 |
| HDmax (mm) | 3.39 | 2.43 | 3.56 | 4.47 | 2.42 | 2.75 | 3.85 | 3.24 |
| PMA | 0.08 | 0.06 | 0.08 | 0.05 | 0.06 | 0.05 | 0.06 | 0.05 |
| PDmin (mm) | 1.74 | 1.07 | 1.29 | 0.99 | 1.47 | 1.40 | 1.31 | 1.42 |
| PDmax (mm) | 1.87 | 1.72 | 1.93 | 1.56 | 1.87 | 1.56 | 1.80 | 1.58 |

Table 3—Stride-to-stride SD for inertial sensor measures of lameness for various numbers of strides for which data were collected in trotting horses.

| Measure | No. of strides | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 27 (n = 33) | 28–31 (n = 34) | 32–35 (n = 24) | 36–40 (n = 27) | 41–51 (n = 31) | 52–62 (n = 28) | 63–77 (n = 29) | > 77 (n = 30) |
| HDmin (mm) | 7.88 | 8.53 | 8.75 | 8.70 | 8.85 | 8.81 | 9.16 | 9.09 |
| HDmax (mm) | 8.33 | 7.30 | 8.83 | 9.87 | 9.46 | 9.74 | 10.21* | 10.54* |
| PDmin (mm) | 2.98 | 2.79 | 3.28 | 3.41 | 3.97* | 3.81* | 3.80* | 4.07* |
| PDmax (mm) | 3.57 | 2.96 | 3.79 | 3.80 | 4.50* | 4.48* | 4.56* | 4.57* |

*Significantly ($P < 0.05$) different than value for < 27 strides.

## Discussion

In this study, the authors provide the methodology and estimate the repeatability of a potential objective lameness detection and evaluation aid for regular use by equine veterinarians conducting clinical case studies in field-type, overground settings. The method is noninvasive, and instrumentation is simple and rapidly accomplished. Data are collected in real time. Data analysis is quick and uses asymmetry-detection algorithms that are accurate for detection of lameness in horses. Trials are repeatable, with insignificant changes in mean values and high correlation between successive trials.

To detect fine gradations of abnormality that may be clinically relevant, a diagnostic test must be repeatable. It is important to determine how repeatable a lameness diagnostic test is before it can be evaluated as clinically useful to equine practitioners. Comparing repeatability of this sensor-based system with intra-evaluator repeatability of subjective evaluation of lameness by use of the AAEP or another lameness scale was not possible because repeat evaluations on the same subject a few minutes apart by the same examiner cannot be effectively separated or masked from the results of the first evaluation. Masking subjective evaluations of the same evaluator on the same horse under these conditions can only be accomplished by archiving the horse's movement, such as on digital media, and then evaluating in a masked fashion in random order at a later date. This adds additional variables and restrictions that would likely decrease precision of subjective evaluation and reflect poorly on its usefulness as a diagnostic test. Real-time, overground evaluation of lameness is more repeatable among observers, compared with evaluating videotapes of lame horses.[16] It is possible to compare repeatability with reproducibility or agreement among evaluators (masked to each other's evaluation) by subjectively grading the same horse at the same time. Repeatability can also be compared with that of other objective diagnostic tests that have been accepted as precise measures of lameness in horses (eg, use of a stationary force plate and camera-based kinematic analysis of gait on a treadmill).

In the only study[16] that estimated reproducibility of subjective, simultaneous evaluation of real-time, overground equine lameness by multiple examiners, the 95% CI for the difference in 2 AAEP scores was 2.0 grades for the forelimb and 2.3 grades for the hind limb. In that study,[16] no horses had a lameness grade of > 4; thus, the 95% CIs represented 50% and 57.5% of the total possible range of forelimb and hind limb lameness scores, respectively. In addition, in that study,[16] the variance of scores was highly dependent on mean score, with the highest variability between mean AAEP scores of 1 and 2 approaching a coefficient of variation (typical error/mean) of 150% for forelimb and hind limb evaluations. In the present study, no horses had an AAEP lameness grade > 3 and variance was proportional to the mean for HMA and PMA, and the 95% CIs for a difference in the 2 evaluations were 44.1% and 37.1% of the mean, respectively. The coefficients of variations for these measures of the inertial sensor system were 16.8% for HMA and 14.1% for PMA. The 95% CIs for a difference between 2 trials for the measures of lameness specific to limb (HDmin = 9.18 mm, HDmax = 8.87 mm, PDmin = 4.25 mm, and PDmax = 4.90 mm) were 7.1%, 10.2%, 9.0%, and 10.2%, respectively, of the total range in the 236 horses in the present study. These comparisons suggest that a single wireless, inertial sensor evaluation is more repeatable than a single subjective lameness evaluation score obtained by use of the AAEP lameness scale.

It is difficult to make a direct comparison of repeatability between the results of the present study and previous studies that used a stationary force plate to evaluate lameness in horses. The measures evaluated by use of the 2 systems are inherently different. The force plate records a ratio-scaled measure on a single limb (eg, peak vertical force on the right forelimb) for a single stride. Quantification of the opposite limb requires collection of additional data. The inertial sensor system described here records the difference between limbs, including both an overall, ratio-scaled measure of the right to left asymmetry (HMA and PMA) over many strides and a single, interval-scaled measure of the right to left asymmetry of a single stride (HDmin, HDmax, PDmin, and PDmax). The force plate acquires an absolute measurement on 1 limb, and the inertial-sensor system acquires a relative measurement of the difference between right and left limbs. Stationary force plate data are expressed in units of force or as a standardized ratio of peak vertical force to body weight with a nonarbitrary, absolute zero at non–weight bearing lameness (0 kg of vertical force or 0 kg of vertical force/kg of body weight). A value expected in a clinically normal horse is near 100% of body weight. In samples of horses, even those with mild lameness, the expected mean values will be > 80% to 90%. Conversely, the inertial sensor data are expressed either as a ratio with a value expected in a clinically normal horse of 0 (HMA and PMA) or as positive and negative values near 0 (HDmin, HDmax, PDmin, and PDmax). In samples of horses with mild lameness, the expected mean values for HMA and PMA will be between 0 and 1 except in severe cases of lameness, and the expected mean values for HDmin, HDmax, PDmin, and PDmax will be either > or < 0 depending on the side of lameness. Coefficients of variation (error/mean) are not comparable between the 2 methods for determination of precision. Instead, intertrial variance can be compared with ranges of measures in the respective samples.

There have been 2 studies[7,8] on the use of a stationary force plate to detect and evaluate lameness in horses, with within-subject coefficient of variation of peak vertical force < 10%. In an in-depth study[8] on the use of a force plate to detect forelimb lameness in horses, the within-subject coefficient of variation for peak vertical force ranged from 4.0% for horses thought to be subclinically lame to 8.0% for horses with grade 4 lameness. In that study,[8] the best-case scenario for the determination of the ratio of estimated mean within-subject SD to the range of vertical peak force in the group of horses (ranging from nonlame to grade 4 lameness) is calculated at 5.7%. These results and those of other studies indicate that use of a stationary force plate is a repeatable, or precise, measure of lameness in horses. It is reasonable to conclude that the stationary force plate should be considered a gold standard for detection and evaluation of the severity of equine lameness.

In the present study, the coefficient of variation of HMA, or the overall measure of forelimb lameness, was 16.8%, higher than that reported for forelimb lameness by use of the stationary force plate. Our coefficient of variation for a general measure to evaluate hind limb lameness (PMA) was lower at 14.1%. However, in the present study, the ratios of within-subject SD to the range of values of the interval-scaled measures were of lesser amplitude (HDmin = 2.5%, HDmax = 3.6%, PDmin = 2.9%, and PDmax = 3.5%) than force measures in previous stationary force plate studies.

It should be noted that this inertial sensor system does not measure true head and pelvic position in 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 (perpendicular) 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 and in the frontal plane for the pelvic-mounted sensor. However, the data-processing approach used in this method quantifies movement asymmetry by estimating the shape of the head and pelvic movement signals. It is therefore less dependent upon true head and pelvic movement amplitudes and more dependent on relative head and pelvic height between right and left half strides. If the head and pelvic rotation is equal in amplitude but opposite in direction in each half stride (right vs left), the effect of sensor rotation will be minimized. However, the effect of head and pelvic rotation on the calculation of the variables used to measure asymmetry and lameness in this study is best studied by use of a head-to-head comparison with traditional line-of-sight kinematic analysis. Collection of true head and pelvic trajectory data with inertial sensors would require incorporation of additional sensors and integration of additional data channels, both of which would adversely influence the final size and weight of the sensors, range and speed of data transmission, and final cost of development and manufacture.

There was no relationship between trial difference and the number of strides for which data were collected for any inertial sensor-derived measure of lameness. Therefore, test-retest repeatability of the inertial sensor system was not dependent on the number of strides for which data were collected. However, stride-by-stride variability was significantly increased in 1 forelimb lameness measure (HDmax) if data were collected for > 63 contiguous strides and in 2 hind limb lameness measures (PDmax and PDmin) if data were collected for > 41 strides. These were unexpected results. The horses used in this study were a heterogeneous sample of nonlame horses and horses with lameness from AAEP grades 1 to 3. It is possible that lameness in some of the horses was exacerbated between the trials, with increased numbers of strides during the evaluation. It is also possible that in some horses, gait improved with mild exercise (ie, horses warmed out of lameness) during the course of collecting data. Any change in lameness, either an improvement or worsening during the course of collecting data, that would result in unequal amounts of pain among steps will increase stride-by-stride variability. Although it was not recorded, it is possible that there was a higher incidence of changing handlers between trials when data were collected for a large number of strides. With high numbers of strides, it was also more likely to have data collected for all strides in broken segments, with intervals of returning to a starting position (ie, turning around) between collected segments, or to have had the horse misbehave and move erratically during data collection. Although these strides are automatically removed before data analysis, such that only strides in which the horse is trotting are saved for analysis, such factors undoubtedly introduce variation into measurements. The increase in variation for the head (approx 2 mm) and pelvic difference measurements (1 mm) with increased number of strides is less than the within-subjects SD for each measure.

Results of this study suggest that an inertial sensor system to measure asymmetry of head and pelvic movement as an aid in the detection and evaluation of lameness in horses trotting in a straight line is repeatable enough to investigate for clinical use. Because of its ease of use and acceptable results without strictly controlling the environment to collect data (velocity of gait or surface characteristics), acceptance for conduction of field studies and for use in clinical cases by practicing veterinarians would be more widespread than use of a stationary force plate or camera-based kinematic evaluation. Studies determining this system's accuracy for detection of lameness should be conducted with experimental models of induced lameness and by comparison with reasonable gold standards, including use of a stationary force plate and camera-based kinematic gait analysis. A recent increase in numbers of studies[17–20] in the veterinary literature on the use of inertial sensors to evaluate lameness in horses suggests there is increased interest by the veterinary community in these systems, and further work should be encouraged and supported.

a. 3M Dual Lock Tape, ULine, Waukegan, Ill.
b. MMA7260QT, ± 1.5 to 6 g, Freescale Semiconductor, Austin Tex.
c. Gyrostar ENC-03M, Murata Electronics North America, Smyrna, Ga.
d. EYSF1SAJJ, Taiyo Yuden Co Ltd, Tokyo, Japan.
e. Hyper Power Co Ltd, Shenzhen, China.
f. PIC18LF452/PQ(44), Microchip Technology Inc, Chandler, Ariz.
g. Delphi, Borland Software Corp, Austin, Tex.
h. MATLAB, The Mathworks Inc, Natick, Mass.

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