

# Evaluation of a sensor-based system of motion analysis for detection and quantification of forelimb and hind limb lameness in horses

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**Objective**—To compare a sensor-based accelerometer-gyroscopic (A-G) system with a video-based motion analysis system (VMAS) technique for detection and quantification of lameness in horses.

**Animals**—8 adult horses.

**Procedure**—2 horses were evaluated once, 2 had navicular disease and were evaluated before and after nerve blocks, and 4 had 2 levels of shoe-induced lameness, alternatively, in each of 4 limbs. Horses were instrumented with an accelerometer transducer on the head and pelvis, a gyroscopic transducer on the right forelimb and hind feet, and a receiver-transmitter. Signals from the A-G system were collected simultaneously with those from the VMAS for collection of head, pelvis, and right feet positions with horses trotting on a treadmill. Lameness was detected with an algorithm that quantified lameness as asymmetry of head and pelvic movements. Comparisons between the A-G and VMAS systems were made by use of correlation and agreement ( $\kappa$  value) analyses.

**Results**—Correlation between the A-G and VMAS systems for quantification of lameness was linear and high ( $r^2 = 0.9544$  and  $0.8235$  for forelimb and hind limb, respectively). Quantification of hind limb lameness with the A-G system was higher than measured via VMAS. Agreement between the 2 methods for detection of lameness was excellent ( $\kappa = 0.76$ ) for the forelimb and good ( $\kappa = 0.56$ ) for the hind limb.

**Conclusions and Clinical Relevance**—The A-G system detected and quantified forelimb and hind limb lameness in horses trotting on the treadmill. Because the data are collected wirelessly, this system might be used to objectively evaluate lameness in the field. (*Am J Vet Res* 2004;65:665–670)

Lameness is the most common medical condition affecting horses, resulting in an estimated \$600 million to \$1 billion annual loss to the horse-owning public.<sup>1</sup> Many treatment regimens for lameness in horses have gained acceptance after clinical trials that used

only subjective evaluation of lameness. However, agreement for designation and quantification of mild to moderate lameness, even among experienced equine clinicians, is poor.<sup>2</sup> Therefore, an objective, accurate, and user-friendly method of lameness detection would be an important investigative and clinical tool.

Objective methods of detecting and quantifying lameness help prevent inadvertent evaluation bias in clinical trials. Objective methods of measurement of lameness in horses, because they quantify lameness on a continuous scale, are also inherently more precise than subjective lameness scales that categorize lameness into discrete grades. Therefore, detection of partial improvement in lameness after treatment is more likely with an objective method of lameness evaluation. For these reasons, the search for and validation of objective methods of lameness evaluation in horses are warranted.

Several objective methods of lameness evaluation in horses have been described. Stationary force plate analysis, which is a very accurate and precise kinetic technique that quantifies ground reaction forces, correlates well with severity of lameness on a stride-by-stride basis.<sup>3–5</sup> However, the limited surface area of commercially available force plate platforms restricts data collection in horses to 1 stride/trial. Data on additional strides require additional trials, and the horse must return repeatedly over the force plate. Because continuous data cannot be collected, stride-by-stride variation in lameness over short periods will not be detected. Continuous collection of ground reaction forces by use of instrumented shoes or force-measuring equine treadmills has been described but is yet to be perfected for routine use.<sup>6,7</sup> Force-measuring horse-shoes are technically difficult to construct, and because of added size and weight, they may artificially affect the horse's movement. An elegant description of a force-measuring equine treadmill has recently been published,<sup>7</sup> but in our opinion, it is rather complex and unwieldy and would be difficult to apply except in a laboratory situation.

By contrast, computerized motion analysis techniques utilize the latest video-based animation technology to facilitate the study of lameness in horses.<sup>8–10</sup> This technology provides an objective method for evaluation of lameness in horses moving on a high-speed treadmill. With this technology, analysis of the symmetry of vertical head movement and correlation with forelimb foot vertical movement is used to detect (right vs left) and quantify forelimb lameness.<sup>11</sup> However, because it is costly and difficult to use and constrains the horse to a treadmill, video-based kinematic analy-

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sis is not suitable for routine diagnostic use. The purpose of the study reported here was to evaluate a sensor-based system of motion analysis for the detection and quantification of forelimb and hind limb lameness in horses.

## Materials and Methods

**Horses**—Eight adult horses were used in this study. Six horses belonged to the University of Missouri teaching herd, 4 of which were shod with adjustable heart-bar shoes on all 4 feet that were capable of inducing temporary lameness. Two of the horses were client-owned horses with navicular disease and were used in the study after obtaining signed consent from the owners. All horses were trained to trot on a treadmill.<sup>a</sup> This experimental protocol was reviewed and approved by the University of Missouri Animal Care and Use Committee.

**Instrumentation**—For each horse, a single-axis accelerometer<sup>b</sup> in a noninverting amplifier, low-pass filter design (resolution, 20 mV/G [G (acceleration due to gravity) = 9.8 m/s<sup>2</sup>]; gain, 43.5X; cutoff frequency, 50 Hz) was attached to the head halter near the horse's poll with tape and to the dorsum of the midline in the pelvic region by a hook-and-loop patch glued to a clipped area on the skin between the sacral tuberosities (Fig 1). The accelerometer

transducers measure the combination of gravitational and unidirectional inertial acceleration. In addition, a piezoelectric vibrating gyroscopic transducer<sup>c</sup> in a noninverting amplifier, low-pass filter design (resolution, 0.67 mV/degree/s; gain, 2X; cutoff frequency, 53 Hz) was attached to the dorsal surfaces of the right forelimb and right hind limb hoof walls with sticky cloth tape. The gyroscopic transducers measure right forelimb and right hind limb hoof wall angular velocity through the phenomenon of Coriolis force, which is generated when a rotational angular velocity is applied to a vibrating element. The gyroscopic transducers are used to determine the onset and end of right forelimb and hind limb stance phases. Total time for instrumentation was approximately 20 minutes.

A 4-channel A/D (analog/digital) converter and low-power transmitter (transmission frequency, 1.9 GHz),<sup>d</sup> powered by 3 AA-size batteries and weighing 231.5 g, was attached to the dorsum of the horse at the thoracolumbar junction with a hook-and-loop patch glued to the skin or to a girth strap worn by the horse (Fig 1). Lead wires from the transducers were threaded through the mane and taped to the limbs before being connected to the transmitter. The accelerometer (21 × 21 × 9 mm) and gyroscopic (27 × 27 × 12 mm) transducers weighed 29 and 33 g, respectively. The digital signal was then transmitted at 200 Hz to another receiver attached through a universal serial bus port to a laptop computer.<sup>e</sup> Data collection was performed with a custom-written graphical user interface.<sup>f</sup> Vertical head and pelvic acceleration and right forelimb and hind limb foot angular velocity were collected as a 4-column comma-separated value file. Inspection of the signals for fidelity was performed with the graphing options in a software program (Fig 2).<sup>g</sup>

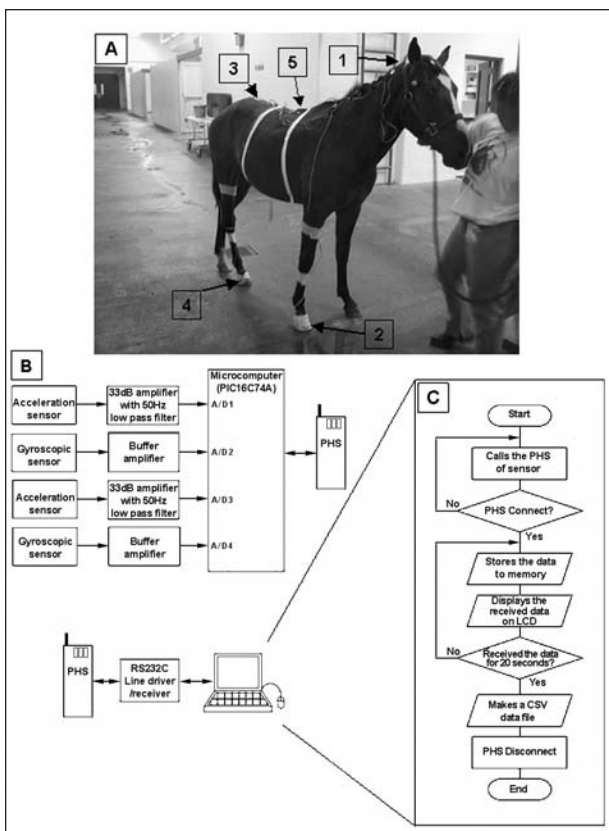


Figure 1—An accelerometer-gyroscopic system used for detection and quantification of lameness in horses. A—Photograph of an instrumented horse. 1 = Uniaxial accelerometer attached to the top of the head halter. 2 = Gyroscopic transducer taped to the right forefoot. 3 = Uniaxial accelerometer attached to an adhesive patch glued to the skin between the tubera sacrale. 4 = Gyroscopic transducer taped to the right hind foot. 5 = Transmitter-receiver attached to an adhesive patch glued to the skin along the dorsum of the back. B—Block diagram of the accelerometer-gyroscopic system. PHS = Personal “handy-phone” system. C—Flow chart of software control of accelerometer-gyroscopic system.

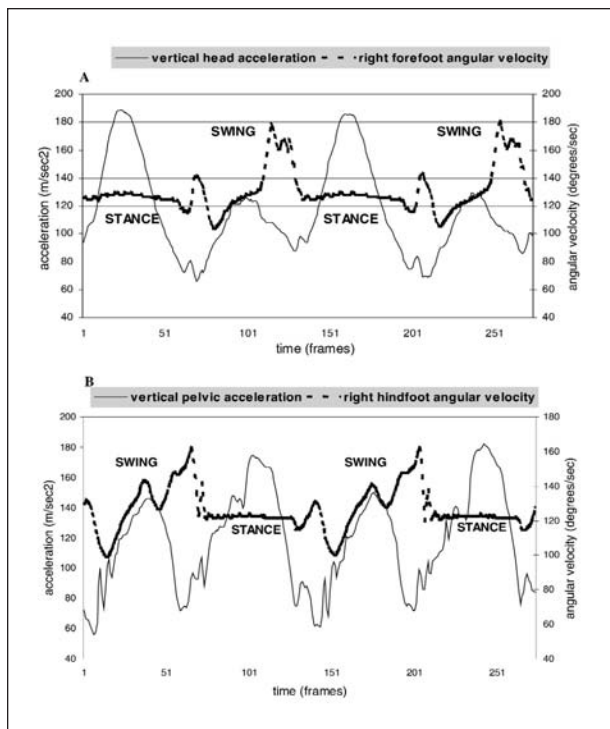


Figure 2—Illustration of raw data from an accelerometer-gyroscopic system used for detection and quantification of lameness in horses. A—Head accelerometer and right forefoot angular velocity signals for 2 strides (1.23 seconds). Notice the asymmetric head accelerometer signal versus time, indicating forelimb lameness. B—Pelvic accelerometer and right hind foot angular velocity signals for 2 strides (1.23 seconds). Notice the asymmetric pelvic accelerometer signal versus time, indicating hind limb lameness.

The data were used as input for a custom-written program<sup>h</sup> that computes the second integral of the vertical head and pelvic acceleration and yields the vertical positions of the head and pelvis versus time. After vertical head and pelvic positions were obtained, the severity of lameness was determined by use of a curve-fitting technique.<sup>11</sup> Briefly, it is assumed that vertical head and pelvic motion is described by 3 components: a harmonic component with frequency  $2\omega$  ( $\omega$  = strides per second), describing normal, biphasic, vertical movement; a harmonic component with frequency  $\omega$ , describing the contribution of unilateral lameness to vertical movement; and a low-frequency, transient component, describing extraneous vertical movement.

The amplitudes of the 2 harmonics were not constant over the data collection periods; therefore, after eliminating the transient component, we estimated the effective amplitude of each harmonic by computing the root-mean-square. The effective amplitudes were designated  $A_1$  and  $A_2$ , respectively, and the severity of lameness was described by the ratios  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  for the forelimb and hind limb, respectively. Side of lameness (right vs left) was determined by correlating a graphical display of vertical head position (minus the transient component) with angular velocity of the corresponding right foot (Fig 3).

#### Video-based kinematic gait analysis—

Horses were marked with 22-mm-diameter retroreflective spheres at 4 locations on the body, including the zygomatic protuberance on the right side of the head, the lateral surface of the right forelimb foot, the dorsal midline of the pelvis between the tubera sacrale on top of the pelvic accelerometer, and the lateral surface of the right hind limb foot. Kinematic gait analysis was performed by use of a video-based motion analysis system (VMAS)<sup>i</sup> with 5 visible-red-light-detecting cameras at 120 frames/s. The data output of the VMAS was a large spreadsheet file of the 3-dimensional positions of the 4 markers on each horse. From this large spreadsheet file, we took the vertical position of the 4 markers, which served as input into the lameness detection algorithm, and generated the ratios  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$ . The vertical positions of the right forelimb and hind limb feet served to designate stance and swing phases of the right limbs. Side of lameness (right vs left) was determined by correlating a graphical display of vertical pelvic position (minus the transient component) with vertical position of the corresponding right foot.

For the purposes of this study, we defined the cutoff or threshold values between soundness and lameness for  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  as  $0.52 \pm 0.21$  and  $0.17 \pm 0.05$ , respectively. These values were determined in another study.<sup>12</sup> Thus, the threshold value of  $A_{1poll}/A_{2poll}$  and between soundness and apparent forelimb lameness was 0.73, and the threshold value of  $A_{1pelvis}/A_{2pelvis}$  between soundness and apparent hind limb lameness was 0.22.

**Data collection—**Data were collected from the accelerometer-gyroscopic system and the VMAS while the horses were trot-

ting at a comfortable speed (approx 4 m/s) on an equine treadmill. Collection of data from both systems was simultaneous but not synchronized. In most instances, data were collected for 3 trials at 30 s/trial. This resulted in collection of data from 80 to 100 strides/horse at each condition tested. Data were collected from the university-owned horses shod with the adjustable heart-bar shoes before and after the application of 2 levels (mild and moderate) of temporary lameness to each limb, yielding 36 (4 × 9) instances collected. Order of limb selection for lameness induction was randomized. The 2 university horses that were not shod with the heart-bar shoes had data collection only once, giving 2 additional instances. The 2 client-owned horses with navicular disease were part of an ongoing clinical trial that was not associated with this project and had data collection before palmar digital nerve block, after palmar digital nerve block of the most affected limb, and after bilateral palmar digital nerve block,

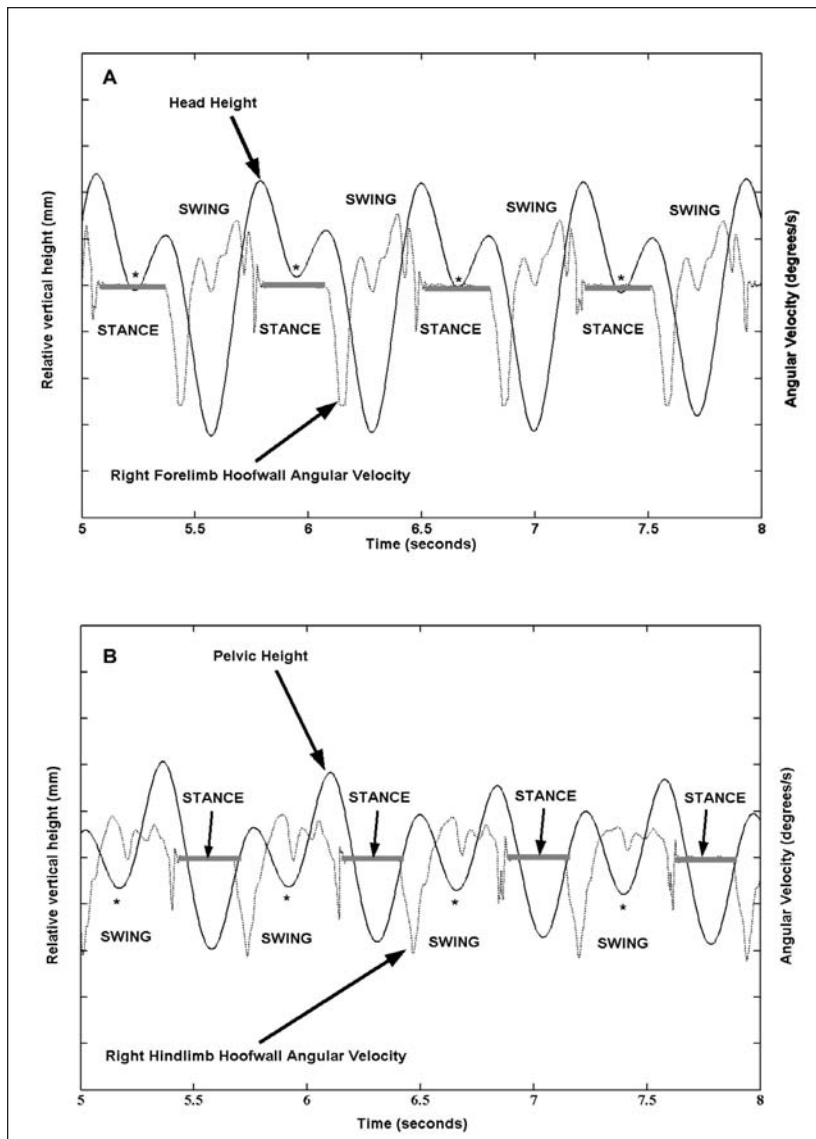


Figure 3—Illustration of transformed data used for detection and quantification of lameness in horses. A—Transformed head accelerometer signal (solid line) correlated with right forefoot gyroscopic signal (dotted line). \*Notice less downward movement of the head during the stance phase of the right forelimb, indicating right forelimb lameness. B—Transformed pelvic accelerometer signal (solid line) correlated with right hind foot gyroscopic signal (dotted line). \*Notice less downward movement of the pelvis during the swing phase of the right hind limb (stance phase of the left hind limb), indicating left hind limb lameness.

yielding an additional 6 (2 × 3) instances. Altogether, 44 instances were collected (36 + 2 + 6).

Data from 2 of the instances of mild induced forelimb lameness could not be retrieved because of computer file corruption, leaving 42 instances. By use of the VMAS as the gold standard or reference method and previously determined threshold values of  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  between lameness and soundness, there were 10 instances of soundness, 9 of right forelimb lameness, 9 of left forelimb lameness, 7 of right hind limb lameness, and 7 of left hind limb lameness. In 4 instances, data from the pelvis and right hind limb foot could not be collected with the accelerometer-gyroscopic system, resulting in the collection of pelvic and right hind limb foot data from both systems in 38 instances, representing 9 instances of soundness, 8 of right forelimb lameness, 7 of left forelimb lameness, 7 of right hind limb lameness, and 7 of left hind limb lameness.

**Statistical analyses**—For both systems, severity of forelimb and hind limb lameness was calculated as the  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$ , respectively. The pooled intertrial SD was calculated as an estimate of the precision for each system. Differences between the calculation of lameness between the 2 systems were investigated by use of a paired *t* test with  $\alpha = 0.05$ . Pearson product moment correlations were calculated between the data collected simultaneously from both systems. Also, by use of the threshold values for  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  as designators of lameness, agreement analyses (calculation of the  $\kappa$  value) between the accelerometer-gyroscopic system and the VMAS were performed. The  $\kappa$  value represents total agreement beyond chance.<sup>13</sup> For clinical purposes,  $\kappa$  values from 0.3 to 0.5 were considered acceptable, values from > 0.5 to 0.7 were considered good, and values > 0.7 were considered excellent.<sup>13</sup>

## Results

For the accelerometer-gyroscopic system, the pooled intertrial SDs of  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  were 0.24 and 0.06, respectively. For the VMAS, the pooled intertrial SDs of  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  were 0.18 and 0.05, respectively.

Correlation between the accelerometer-gyroscopic system and the VMAS for apparent forelimb lameness calculation was linear and high ( $r^2 = 0.954$ ; Fig 4). No significant difference was found between forelimb lameness calculated by the accelerometer-gyroscopic system and the VMAS ( $P = 0.669$ ).

By use of the mean  $A_{1poll}/A_{2poll}$  ratio plus 1 SD in a group of 17 horses with no previous history of lameness in a previous kinematic study<sup>12</sup> as the threshold between soundness and forelimb lameness, there were 3 of 42 instances in which the accelerometer-gyroscopic system indicated forelimb lameness, but VMAS did not, and 2 in which the VMAS indicated lameness, but the accelerometer-gyroscopic system did not. The 3 instances of measured forelimb lameness by the accelerometer-gyroscopic system for which the VMAS did not indicate lameness occurred only after induced hind limb lameness. The apparent forelimb lameness in these instances was considered as evidence of false, compensatory lameness detectable by the accelerometer-gyroscopic system but not by the VMAS. In 1 instance in which the VMAS detected lameness but the accelerometer-gyroscopic system did not, the horse was thought to be sound. In the other instance, the horse was believed to have mild forelimb lameness.

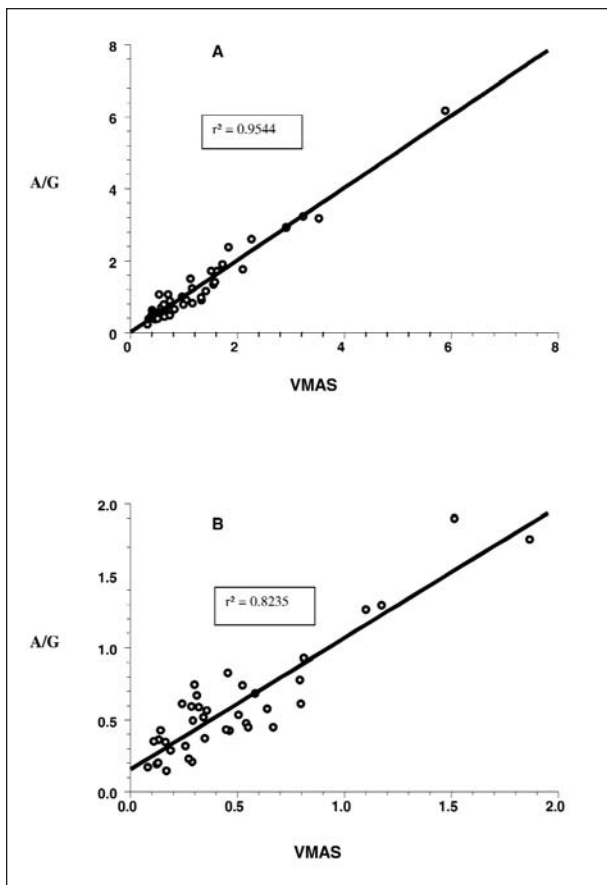


Figure 4—Correlation of lameness severity between video-based kinematic system (VMAS) and accelerometer-gyroscopic system (A/G). A—Correlation of forelimb lameness severity. B—Correlation of hind limb lameness severity.

The  $A_{1poll}/A_{2poll}$  measurement for the accelerometer-gyroscopic system in this case was 0.65, slightly below both the threshold between soundness and forelimb lameness (0.72) and the measurement found with VMAS (0.82). Agreement for the determination of forelimb lameness between the 2 systems was excellent ( $\kappa = 0.76$ ).

Correlation between the accelerometer-gyroscopic system and the VMAS for apparent hind limb lameness was linear and high ( $r^2 = 0.824$ ). Calculation of apparent hind limb lameness from the accelerometer-gyroscopic system was consistently higher than that calculated from the VMAS ( $P < 0.001$ ). The mean  $A_{1pelvis}/A_{2pelvis}$  ratio for the accelerometer-gyroscopic system was 0.11 higher than for the VMAS.

By use of the mean  $A_{1pelvis}/A_{2pelvis}$  ratio plus 1 SD in a group of 17 horses with no previous history of lameness in a previous kinematic study<sup>12</sup> as the threshold between soundness and lameness, there were 5 of 38 instances with hind limb lameness indicated by the accelerometer-gyroscopic system but not by the VMAS. In 4 of these instances, a false, compensatory hind limb lameness was detected along with the primary induced forelimb lameness. The remaining instance was detected after an induced right hind limb lameness in which the accelerometer-gyroscopic system indicated mild right hind limb lameness but the VMAS did not. By use

of this same threshold for the detection of hind limb lameness, there was only 1 instance in which the accelerometer-gyroscopic system did not detect lameness when lameness was indicated by the VMAS. In this 1 instance, the horse was believed to be sound. Agreement for the determination of hind limb lameness between the 2 systems was good ( $\kappa = 0.56$ ).

## Discussion

This report describes a method of continuous lameness quantification that could be implemented in the field without a treadmill. The method measured poll and whole-pelvis vertical acceleration and angular velocity of the right forelimb and hind limb feet with body sensors and transformed these signals into information that was analyzed by published algorithms.<sup>11</sup> The time required for instrumentation was reasonable (approx 20 minutes), and the wires from the transducers to the transmitter on the girth did not seem to affect the movement of the horses. Data collection was continuous for 30 seconds but could have been extended to several minutes.

The high correlation between the output of the accelerometer-gyroscopic system and the VMAS indicated that either can be used to measure the same parameter. Because the video-based technique has been proven in previous studies to be a reliable indicator of lameness, the new accelerometer-gyroscopic system can be used for the same purpose. High correlation was maintained despite the fact that data collection was not synchronized between the 2 systems.

This accelerometer-gyroscopic system is not without potential problems. Signals from the accelerometer contain components of inertial and gravitational acceleration. Imperfect placement of the accelerometer such that the active axis is not exactly vertical will cause slight depression in the measurement of true vertical acceleration. Also, backward and forward movement of the transducer will contribute to the vertical acceleration signal. Because perfect placement of the accelerometer transducers on the head and pelvis such that the active axis is always oriented exactly perpendicular to the ground surface throughout the entire stride cycle is not possible, there will be some systematic and random error in the measurement of true vertical acceleration. However, despite these expected errors, our measurements of forelimb and hind limb lameness approximated those obtained from the VMAS. It remains to be determined whether the system will perform adequately in a field setting in which changes in surface elevation may affect the vertical acceleration signal. Evaluating lameness while the horse is trotting overground on a flat surface should minimize this error.

Severity of hind limb lameness measured by the accelerometer-gyroscopic system was systematically greater than that measured by the VMAS. The mean  $A_{1pelvis}/A_{2pelvis}$  ratio was 0.11 higher for the accelerometer-gyroscopic system than for the video-based system. The greater response of the accelerometer-gyroscopic system was probably attributable to dynamic pelvic rotation. Rotation of the pelvis changes the orientation of the accelerometer transducer attached to the dorsum

of the pelvis. This rotational movement will contribute to the vertical pelvic acceleration signal. Because it is known that the pelvis rotates toward the side of hind limb lameness, the asymmetric nature of the vertical pelvic acceleration signal will be amplified with unilateral hind limb lameness and potentially increase the sensitivity of the accelerometer-gyroscopic system. The threshold level between soundness and hind limb lameness using this lameness detection algorithm will have to be separately established for the accelerometer-gyroscopic system.

There have been other reports<sup>14,15</sup> of the use of accelerometer and gyroscopic body sensors for gait and lameness evaluation in humans and horses and a few that have compared body-sensor to video-based motion analysis.<sup>16,17</sup> To our knowledge, this is the first description of this comparison in horses.

An accelerometric device used for detection of lameness in horses has been described.<sup>18</sup> It consisted of 2 uniaxial (dorsoventral and lateromedial) accelerometers attached at the sternum to a leather belt around the girth of the horse. Symmetry and regularity of dorsoventral trunk acceleration were used to quantify lameness, and symmetry of the mediolateral trunk acceleration was used to determine lameness side. Although overall the device was able to indicate the correct side of lameness in 13 of 17 horses, there were substantial errors in side detection for horses with mild hind limb lameness.<sup>19</sup>

The system described in this report has some disadvantages and advantages, compared with the accelerometric system described by Barrey et al.<sup>19</sup> The major disadvantage is that our system uses 4 transducers instead of 2. The wires from the gyroscopic transducers on the horse's right forelimb and hind limb feet must cross over articulating limb segments; therefore, the wires must be securely taped to the limbs and anchored well near their connection to the receiver-transmitter. This takes time and is slightly irritating to the horse. Another disadvantage is that the pelvic accelerometer must be attached to the dorsum of the pelvis. We have accomplished this by clipping the hair over the dorsal aspect of the pelvis and gluing an adhesive patch to the skin, which may be displeasing to some clients.

The advantages of our system include higher sampling rate (200 Hz vs 50 Hz) and specific determination of lameness to the lame limb. The high sampling rate in our system permitted timed events such as the onset of foot impact and liftoff, which are used to determine stance and swing phases of the stride, to be determined precisely. Thus, localization of the lameness component ( $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$ ) within the stride can be done more precisely. Determination of when  $A_{1poll}/A_{2poll}$  and  $A_{1pelvis}/A_{2pelvis}$  occur within the stride may be helpful for further differentiation of clinical lameness (eg, determining whether it is occurring at impact, midstance, or the beginning or end of breakover). More importantly, our system was designed to partition the lameness into lameness of the forelimb and hind limb and then to determine side of lameness. This specific determination of lameness may allow the user to determine the side and severity of the prima-

ry lameness as well as any compensatory lameness that occurs secondarily.<sup>20,21</sup>

We believe this system can be eventually used as a clinical tool in difficult lameness cases and as an objective method of lameness evaluation for clinical trials. The system must be further tested in clinical, field-type settings. Higher intertrial variability might be expected in clinical, field-type settings because the speed of movement will be more difficult to precisely control. The transmission range of the system must also be determined. Additional development that would make this system more clinically applicable would be to design the transducers to transmit wirelessly to a receiver attached to the horses' girth. This would greatly reduce setup time and remove the irritation of the wires taped to the horse's limbs.

<sup>1</sup>Sato I, Equine Dynamics, Raymore, Mo.

<sup>2</sup>EFFA08TD01X, Matsushita Electronic Components Ltd, Osaka, Japan.

<sup>3</sup>Gyrostar, muRata North America Inc, Smyrna, Ga.

<sup>4</sup>Personal Handyphone System, Adapter Mode TPA1005, Toshiba Corp Inc, Japan.

<sup>5</sup>Dell Inspiron 8100, Dell Computer Corp, Round Rock, Tex.

<sup>6</sup>Visual Basic 2003, Microsoft Corp, Redmond, Wash.

<sup>7</sup>Microsoft Excel 2003, Microsoft Corp, Redmond, Wash.

<sup>8</sup>Matlab, version 6.1, The MathWorks Inc, Natick, Mass.

<sup>9</sup>Vicon 250, Vicon Motion Systems, Lake Forest, Calif.

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