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For Research by Colorado State University into Validating a Hoof-based Sensor System for Detection of Subtle Lameness in the Horse

Validation of a Hoof-based Sensor System for Detection of Subtle Lameness in the Horse

Lameness is documented as one of the leading causes of wastage in all types of performance horses and accounts for up to $1 billion dollars in losses to the equine industry every year. Mild and subclinical lameness has been shown to lead to decreased and suboptimal performance. As early lameness is not always appreciable at all gaits and during every stride, they are more difficult to identify. Additionally, subtle gait abnormalities can be identified prior to catastrophic injuries, and as these injuries give the equine industry a poor public perception, early detection and prevention is critical.

The mainstay of equine lameness diagnosis is the subjective lameness examination, which often encompasses a baseline examination as well as flexion tests and nerve blocks. It has been demonstrated that the lameness examination is not reliable between examiners and bias is introduced by the examiner when he is aware that a nerve block was performed. Thus, there is a need to have objective tools to supplement the subjective lameness examination. There is also a need to develop horse-mounted motion analysis systems that can be used while horses are being ridden. Traditionally, these sensors have been used on the head and body of horses to measure changes in motion, or kinematics. The development of small, lightweight sensors, such as the inertial measurement unit (IMU), can allow the evaluation of equine distal limb motion in all three planes: forward, side-to-side, and vertical. Our goal is to develop a hoof-mounted system that can collect meaningful kinematic data, which can be used to supplement the subjective lameness examination and eliminate the bias of evaluating nerve blocks.

In this investigation, we first examined the specific kinematic changes that occur at the level of the hoof in both the lame and non-lame forelimb using a rapidly reversible, experimental model of weight-bearing forelimb lameness. We induced mild to moderate degrees of lameness, which were not visible at the walk, but could be visually detected at the trot. After induction of the most severe lameness, a nerve block was used to eliminate the lameness. Kinematic data were collected using both 3-D optical methods (both fore-hooves) and an inertial measurement unit (IMU) (lame hoof). As the IMU has not been previously used on the hoof for lameness diagnosis, the goal was to validate it to the current gold standard of kinematic analysis, i.e., the 3-D optical system.

Using 3-D optical kinematic data, we determined that with induction of very mild lameness, we could detect differences in both stance and swing phases of stride. In particular, we found differences in hoof orientation between the lame and non-lame forelimbs during both the beginning of stance, hoof contact, and at the end of stance, break-over. At both the walk and trot, the non-lame hoof had a more heel-first landing compared to the lame hoof. The lame hoof also went through a smaller forward rotation during break-over compared to the non-lame forelimb at the trot. The lame hoof showed a greater forward acceleration during break-over compared to the non-lame limb and to the lame limb before lameness induction. We found that after eliminating the lameness with a commonly used nerve block, the hoof orientation at landing were no longer different between the forelimbs at both the walk and trot. However, not all kinematics returned to baseline following the nerve block.

We found that there were kinematic differences at the level of the hoof when very mild lameness was induced. We also determined that even though there was no visible lameness at the walk, there were still significant changes to the hoof kinematics. Therefore, changes to optical kinematics of the hoof could be a method for lameness detection at both the walk and trot. We are currently analyzing the IMU kinematic data to determine if it can detect similar kinematic changes, as it could be more easily utilized in a clinical setting.

Effect of forelimb lameness on hoof kinematics of horses at a trot

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Objective—To determine kinematic changes to the hoof of horses at a trot after induction of unilateral, weight-bearing forelimb lameness and to determine whether hoof kinematics return to prelameness values after perineural anesthesia.

Animals—6 clinically normal Quarter Horses.

Procedures—For each horse, a sole-pressure model was used to induce 3 grades (grades 1, 2, and 3) of lameness in the right forelimb, after which perineural anesthesia was administered to alleviate lameness. Optical kinematics were obtained for both forelimbs with the horse trotting before (baseline) and after induction of each grade of lameness and after perineural anesthesia. Hoof events were identified with linear acceleration profiles, and each stride was divided into hoof-contact, break-over, initial-swing, terminal-swing, and total-swing segments. For each segment, kinematic variables were compared within and between limbs by use of mixed repeated-measures ANOVA.

Results—During hoof-contact, the left (nonlame) forelimb hoof had greater heel-down orientation than did the right (lame) forelimb hoof, and during break-over, the nonlame hoof went through a larger range of motion than did the lame hoof. Maximum cranial acceleration during break-over for the lame hoof was greater, compared with that at baseline or for the nonlame hoof. Following perineural anesthesia, the sagittal plane orientation of the hoof during hoof-contact did not vary between the lame and nonlame limbs; however, interlimb differences in maximum cranial acceleration and angular range of motion during break-over remained.

Conclusions and Clinical Relevance—Results suggested that hoof kinematics may be useful for detection of unilateral, weight-bearing forelimb lameness in horses that are trotting. (*Am J Vet Res* 2013;74:1183–1191)

Lameness is one of the most important medical issues of horses[1] and accounts for annual losses up to $1 billion for the US equine industry.[2] Horses with subclinical or mild lameness often have suboptimal performance.[3,4] Early detection of mild lameness is important for horses, particularly competition horses, in which suboptimal performance can be career limiting, so that appropriate measures can be taken to alleviate the lameness and improve the performance and quality of life of affected horses.

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Abbreviation

IMU	Inertial measurement unit

Lameness in horses is generally detected and monitored by means of a subjective lameness examination.[5] The most commonly used lameness scoring systems have grades, or scores, that are defined by specific criteria; however, there can be substantial variability within a grade such that use of that system can be challenging for longitudinal monitoring of lameness in an individual horse, especially when the severity of lameness changes only minimally between examinations.[6] Results of multiple studies[6–9] suggest that subjective lameness scoring systems are not reliable for clinical use, particularly for horses with mild lameness. Additionally, in 1 study,[6] observer bias was detected in the subjective lameness scores assigned to horses following administration of perineural anesthesia. Therefore, an accurate, objective method is needed to supplement the subjective lameness examination for the detection and monitoring of horses with mild lameness as well as to assess the response of those horses to perineural anesthesia.

Several studies[5,10–15] have been conducted to investigate the efficacy of kinetics and kinematics for the evaluation of horses with mild lameness. In a study[10] in which stationary force platform analysis was used as a kinetic method to detect horses with lameness, peak vertical force and impulse parameters were significantly decreased in horses with mild lameness (ie, grade, < 1.5/5), compared with those for nonlame horses. Unfortunately, the use of stationary force platform analysis for evaluation of lameness in horses is limited because of the lack of availability of equipment and experienced personnel to run the equipment, the increased time required for data collection and analysis, and expense, compared with the time and expense for a subjective lameness examination. In horses, optical methods can be used to detect alterations in distal limb kinematics such as stride length, step length, hoof height, and sagittal-plane joint angles after induction of lameness.[11–13] Although alterations in those variables have been detected at both a walk and a trot, the alterations are more pronounced at a trot.[11] Because optical kinematics suffer from many of the limitations of stationary force platform analyses, other kinematic analysis systems are currently being investigated to objectively characterize lameness in horses. These kinematic analysis systems use multiple microelectromechanical components, such as accelerometers, gyroscopes, and GPS tracking devices, which have wireless or telemetric components for data transmission.[14–16] Results of a study[5] indicate that the use of an inertial sensor system that monitors movement of the horse's head or pelvis during a trot detected unilateral forelimb or hind limb lameness earlier (ie, when lameness was less severe) than did 3 experienced equine veterinarians who used a subjective lameness scoring system. However, the use of an inertial sensor system to detect lameness in horses at a walk or for longitudinal assessment of lameness in an individual horse has not been evaluated.[17] Because inertial sensors are becoming increasingly small and lightweight, it should be possible to attach them to the distal aspect of a limb of a horse without causing substantial alteration to the movement of that limb. In fact, the rigid attachment of an inertial sensor to the hoof is ideal because motion artifact is eliminated. In horses, the kinematics of the limbs change when 1 limb becomes lame[11–13]; therefore, measurement of hoof kinematics might be another method to diagnose and monitor lameness. Although hoof displacement or position has been investigated in lame horses,[11–13] to our knowledge, no studies have been conducted to evaluate other linear and angular changes in the forelimb hooves of horses following induction of unilateral lameness. Optical methods remain the gold standard for collection of kinematic data, and intra- and interlimb comparisons of kinematic changes might be useful for the identification of horses with mild lameness. Linear and angular limb movement can also be measured by means of an IMU, which could be used in a horse-mounted method to evaluate lameness.

The objective of the study reported here was to use optical methods to characterize kinematic variables of the hoof for horses at a trot before and after induction of unilateral, weight-bearing forelimb lameness and following administration of perineural anesthesia to alleviate that lameness. Following lameness induction, we hypothesized that sagittal-plane kinematic variables for the lame limb would differ significantly from those of that limb prior to lameness induction (baseline) and those of the contralateral nonlame limb, and these differences would be detectable even at the mildest grade of lameness induced. We also hypothesized that following perineural anesthesia of the medial and lateral palmar nerves of the lame limb, the sagittal-plane kinematics of that limb would not differ from those at baseline.

Materials and Methods

Animals—Six Quarter Horses were used for the study reported here as well as a companion study,[18] and the data for both studies were obtained concurrently. Each horse was determined to be clinically normal on the basis of results of a physical examination and was not perceptibly lame at a walk or trot (ie, had a subjective lameness score of 0/5 as determined with the lameness scale developed by the American Association of Equine Practitioners[19]). The age of the horses ranged from 2 to 9 years, and the mean ± SD body weight and wither height of the horses were 364 ± 19 kg and 1.46 ± 0.03 m, respectively. Prior to initiation of the study, all horses were acclimated to the laboratory where the gait analysis data were collected. The hooves of each horse were trimmed and balanced, and the forelimb hooves were shod. A steel keg shoe (weight, 324.8 ± 23.5 g) was applied to the hoof of the left forelimb, and a similar steel keg shoe (weight, 333.7 ± 25.6 g; **Figure 1**) with a nut welded to the inner edge of both the medial and lateral branches of the shoe between the third and fourth nail holes was applied to the hoof of the right forelimb. The nuts were welded to the shoe in a manner similar to that described in another study[20] such that they were flush with the solar aspect of the shoe and did not contact the horse's sole during weight bearing. All study procedures were approved by the Colorado State University Institutional Animal Care and Use Committee.

Study design—For each horse, kinematic data for both forelimbs were obtained before (baseline) and after induction of each of 3 grades (grades 1, 2, and 3) of increasing lameness in the right forelimb as well as after the administration of perineural anesthesia to the right forelimb to alleviate the lameness. The lameness grades induced were subjectively defined and were modified slightly from the lameness scale developed by the American Association of Equine Practitioners.[19] Briefly, grade 1 was defined as an intermittent lameness at a trot; grade 2 was defined as a consistent, mild lameness at a trot; and grade 3 was defined as a consistent, moderate lameness at a trot. None of the grades resulted in lameness at a walk. Horses were allowed to rest for several minutes between data collection periods to minimize the effect of fatigue.

Instrumentation of horses—An aluminum base plate (8.8 × 1.9 × 0.3 cm; weight, 14.2 g) was adhered to the hoof of each forelimb with hoof acrylic.[a] To this base plate, screws were used to attach another piece of aluminum (7 to 9 × 1.5 × 0.1 cm; weight, 3.4 g) that was conformed to the dorsal aspect of the hoof to provide additional support and surface area, to which a strain gauge was attached with adhesive. A cable connected each strain gauge to a data collection source that was mounted on the horse's back with a surcingle that encircled the thorax at approximately the level of the sixth and seventh ribs.

Two 4-mm screws were used to attach a marker triad to the lateral aspect of the base plate (**Figure 2**). The marker triad (15 × 13 cm; weight, 37.6 g) was composed of an aluminum frame stiffened with a uniaxial carbon sandwich structure with a balsa wood core (4.6 × 2.8 × 0.6 cm) and moved rigidly with the hoof. Three spherical retroreflective markers (diameter, 2.0 cm) were attached at the distal aspect of each arm of the triad with machine screws such that the markers were 10 to 11 cm apart. An IMU[b] (5.1 × 3.8 × 1.6 cm; weight, 58.6 g) was attached to the marker triad of the right forelimb, and a custom-machined piece of metal (3.6 × 3.1 × 1.2 cm; weight, 75.7 g) was attached to the marker triad of the left forelimb. A cable connected the IMU to a handheld computer that was mounted on the horse's back adjacent to the data collection source for the strain gauges with the same surcingle (combined weight of the surcingle, data collection source for strain gauges, and handheld computer, 9.5 kg). The cables for the IMU and strain gauges were loosely secured to each forelimb at the distal aspect of the metacarpus and distal aspect of the antebrachium with an elastic bandage.[c] The total weight of the marker triad attached to the right forelimb was 113.8 g, and the total weight of the marker triad attached to the left forelimb was 130.9 g; the weight of the marker triad attached to left forelimb was greater than that of the marker triad attached to the right forelimb because of the larger mass of the ma-

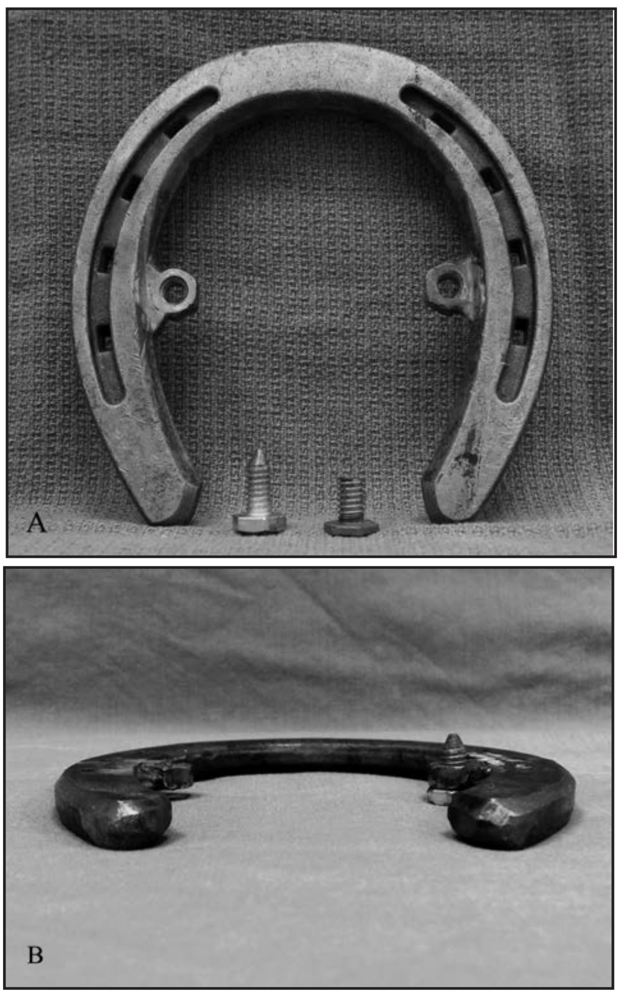

Figure 1—Photographs of a modified steel keg shoe that was applied to the hoof of the right forelimb of each of 6 clinically normal Quarter Horses for induction of lameness by means of a sole-pressure model. A—A nut was welded to the inner edges of the medial and lateral branches of the shoe between the third and fourth nail holes such that it was flush with the solar aspect of the shoe. B—Lameness was induced by threading a 6-mm-diameter screw with a blunt or tapered end into each nut such that the head of the screw was flush with the ground when the horse was bearing weight on the limb. The length of the screws used to induce lameness varied and was positively associated with the grade, or severity, of lameness that was induced. Three grades of lameness were induced in the right forelimb in a sequential manner (ie, induction of grade 1 lameness, followed by grade 2, and then grade 3). Grade of lameness was subjectively determined at a trot. Grade 1 was defined as intermittent lameness; grade 2 was defined as consistent, mild lameness; and grade 3 was defined as consistent, moderate lameness, and none of the grades resulted in lameness at a walk.

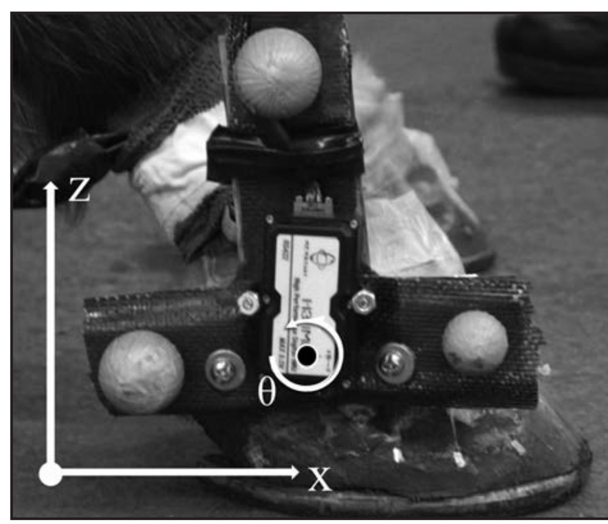

Figure 2—Photograph of the marker triad that was attached to the lateral aspect of the hoof of the right forelimb of each of 6 clinically normal Quarter Horses to obtain optical kinematic data. The marker triad (15 X 13 cm; weight, 37.6 g) was positioned on the hoof such that it moved rigidly with the hoof and did not touch the metacarpophalangeal joint. It was composed of an aluminum frame stiffened with a uniaxial carbon sandwich structure with a balsa wood core (4.6 X 2.8 X 0.6 cm). Three spherical retroreflective markers (diameter, 2.0 cm) were attached at the distal aspect of each arm of the triad with machine screws such that the markers were 10 to 11 cm apart. An IMU (5.1 X 3.8 X 1.6 cm; weight, 58.6 g) was attached to the marker where the 3 arms intersected. A similar marker triad was attached to the lateral aspect of the hoof of the left forelimb of each horse, except the IMU was replaced with a custom-machined piece of metal (3.6 X 3.1 X 1.2 cm; weight, 75.7 g). Superimposed on the photograph are the virtual hoof marker (black circle), which served as the reference point for monitoring the motion of the hoof, and vectors (white arrows) to indicate the directions of the kinematic measurements that were obtained in the sagittal plane. The cranial-to-caudal (X) axis was positive cranially, the vertical (Z) axis was positive proximally, and the sagittal-plane rotation (θ) was positive in a counterclockwise rotation (ie, heel-down was positive).

chined metal on the left marker triad; this difference was balanced by the additional weight of the cable that was attached to the IMU unit on the right forelimb.

Induction of lameness and perineural anesthesia—For each horse, 3 grades of lameness were induced in the right forelimb in a sequential manner (ie, induction of grade 1 lameness, followed by grade 2, and then grade 3). A 6-mm-diameter screw with either a blunt or 2-mm-diameter tapered end was threaded completely into both the medial and lateral nuts welded to the steel shoe such that the head of the screw was in contact with the ground when the horse was bearing weight on the right forelimb (Figure 1). The horse was then trotted briefly to subjectively determine the severity of lameness. This process was repeated with longer or shorter screws as necessary until each desired severity of lameness was achieved, at which time lameness trials were performed for data collection purposes. The screw length required to induce each grade of lameness was recorded for each horse. The weight (median, 7.8 g; range, 6.8 to 10.6 g) added to the shoe of the right forelimb by the 2 screws used for lameness induction varied with the screw length required to achieve the desired severity of lameness.

Following data collection for grade 3 lameness, perineural anesthesia was administered to the right forelimb of each horse. Briefly, 3 mL of a 2% mepivacaine solution was injected SC in the regions surrounding the medial and lateral palmar nerves. If the lameness in the right forelimb had not resolved by > 80% at 10 minutes after mepivacaine administration, an additional 1.5 mL of a 2% mepivacaine solution was injected SC in the regions surrounding the medial and lateral palmar nerves, and the horse was reassessed 5 minutes later.

Lameness trial facilities and protocol—Horses were walked or trotted on a runway (length, 24.8 m; width, 1.2 m) that consisted of an asphalt surface covered with a 9.3-mm-thick rubberized mat. The optical capture volume (ie, portion of the runway where kinematic data for the horse were obtained) had a length of 3.7 m, width of 1.3 m, and height of 2.4 m and was located near the midway point of the runway such that the horse could maintain a constant velocity when passing through it. Three-dimensional optical kinematic data were obtained with 8 infrared cameras[d] that were suspended from overhead beams; 4 cameras were suspended on each side of the optical capture volume. The cameras operated at 200 Hz and were connected to an optical kinematic system[e] that was calibrated to yield coordinates to within 1.2 mm.

The velocity of each horse during each trial (ie, trip over the runway) was calculated by the use of 5 infrared timing gates[f] that were spaced 1.5 m apart along the central portion of the runway, which included the entire optical capture volume. The timing gates were triggered to send a signal to the optical kinematic system by the horse as it traveled on the runway, and the time stamps of those signals were used to calculate the horse's mean velocity.

During collection of baseline data, the mean velocity at a walk and a trot was determined for each horse. Subsequently, for each horse during each data collection period, 4 to 5 acceptable trials were recorded for the right and left forelimbs at both a walk and trot. An acceptable trial was defined as a trial during which the horse traveled straight through the optical capture volume at a consistent velocity that was within ± 10% of its mean baseline velocity for the gait being evaluated. Because not all trials through the optical capture volume contained a full stance and swing for both forelimbs, a horse might have to perform up to 8 trials during each data collection period to ensure that 4 acceptable trials were obtained for each forelimb.

Data collection—Optical coordinate data were low-pass filtered at 15 Hz with a recursive fourth-order Butterworth filter. A virtual marker was created between the cranial and caudal retroreflective markers of the marker triad, and this served as a local origin to track the motion of the hoof. The linear movement of the hoof was tracked in the sagittal plane (cranial-to-caudal [X] and proximal-to-distal [Z] acceleration; Figure 2). Hoof events were determined by evaluation of the X and Z acceleration profiles of the stride. Briefly, hoof contact was defined as the last peak in the Z acceleration curve before a period of smaller accelerations. Heel-off was defined as the first peak in the Z acceleration curve after the period of smaller accelerations. Toe-off was defined as the second peak in the Z acceleration curve, which also corresponded to an inflection point in the X acceleration curve. These hoof events were used to divide the stride into total-stance (hoof-contact to toe-off), break-over (heel-off to toe-off), total-swing (toe-off to hoof-contact), initial-swing (toe-off to initial 25% of swing), and terminal-swing (75% of swing to hoof-contact) segments.

Toe-off was set as the global origin for the coordinate system; thus, translations of the hoof at all other events were relative to the location of the virtual marker at toe-off. To ensure that the coordinate system was in line with the direction of travel by the horse, the global x-axis was aligned with the virtual marker at the second hoof contact. Subsequently, the global x- and z-axes were positive cranially and proximally, respectively. Within the sagittal plane about the y-axis (medial to lateral) through the virtual marker, heel-down hoof orientation (ie, counterclockwise rotation from the lateral aspect; Figure 2) was positive. Hoof orientation was determined with the markers on the triad. Because the marker triad was not perfectly parallel to the ground, the orientation of the hoof during the middle of total stance (when the metacarpal bone was perpendicular to the ground as determined by visual assessment of the optical data) was used to adjust the sagittal orientation of the hoof such that 0° was level with the ground.

For each forelimb during each lameness trial, data collected included the instantaneous position, velocity, acceleration, and sagittal-plane orientation of the hoof at hoof-contact, heel-off, and toe-off. Additionally, the total range of motion for the hoof was determined for the total-swing, initial-swing, and terminal-swing segments of the stride.

Statistical analysis—For each forelimb hoof during each segment of the stride (hoof-contact, break-over, initial-swing, terminal-swing, and total swing), descriptive statistics were generated for variables such as duration and hoof orientation, acceleration, velocity, and range of motion in the sagittal plane. The data for each variable were plotted and visually examined for normality. When necessary, a logarithmic transformation was applied to the data to achieve a normal distribution prior to the performance of statistical comparisons. Each data collection period was considered a treatment, which was categorized as baseline (prior to lameness induction), grade 1, grade 2, grade 3, and after block (after administration of perineural anesthesia). For each variable (ie, outcome of interest), comparisons within and between forelimbs were made by use of mixed ANOVA for repeated measures, in which treatment and forelimb (lame or nonlame) were included as fixed effects, horse identification was included as a random effect, and horse velocity during the trial was included as a confounding variable. For within-limb comparisons, each respective treatment (grade 1, grade 2, grade 3, or after block) was compared with the baseline treatment. All analyses were performed with a commercially available statistical software program,[g] and values of $P < 0.05$ were considered significant.

Results

Animals—Lameness was successfully induced in all horses. For the first 2 horses evaluated, blunt-ended screws were used to induce lameness; however, in 1 of those horses, only grade 1 and grade 2 lameness could be induced because the horse developed decreased sensitivity to the sole pressure model, even with the use of the longest screws that were available at that time. Additionally, the longest blunt-ended screws tended to push the shoe away from the hoof instead of threading into the sole. Therefore, for the subsequent 4 horses that were evaluated, longer screws with tapered ends were used, which more readily induced the desired severity of lameness. Consequently, analyses for baseline, grade 1, and grade 2 treatments included data from all 6 horses, whereas analyses for grade 3 and after-block treatments included data from only 5 horses. Within 24 hours after lameness induction, none of the horses had perceptible lameness when trotting.

Intralimb kinematic changes—Select kinematic variables for the right (lame) and left (nonlame) forelimbs during total stance (**Table 1**) and swing (**Table 2**) at a trot were summarized. For the lame limb, significant kinematic changes from baseline were detected for grades 1, 2, and 3 and after-block treatments and were most frequently detected during the total stance (hoof-contact and break-over) phase of the stride. For the nonlame limb, significant kinematic changes from

Table 1—Mean (SD) kinematic variables for the lame (right) and nonlame (left) forelimbs during the total stance (hoof contact to toe-off) phase of the stride at a trot for 6 clinically normal Quarter Horses before (baseline) and after induction of 3 grades (grades 1, 2, 3) of increasingly severe lameness in the right forelimb and following perineural anesthesia in the right forelimb to alleviate the lameness (after block).

		Treatment				
Stance segment	Variable	Baseline	Grade 1	Grade 2	Grade 3	After block
Hoof-contact	X acceleration (m/s²)					
	Lame	–40.348 (10.071)	–45.114 (15.102)*†	–45.814 (12.104)*†	–46.679 (9.758)*†	–42.930 (10.966)*†
	Nonlame	–38.214 (10.219)	–41.073 (13.913)	–41.831 (12.231)†	–38.573 (13.385)	–38.872 (11.858)†
	Orientation (°)					
	Lame	–1.35 (2.35)	–1.28 (2.60)*	–1.19 (2.75)*	–0.36 (2.38)*	–0.47 (2.60)
	Nonlame	–0.78 (2.95)	0.16 (2.22)†	0.09 (2.59)†	0.17 (2.69)†	–0.89 (2.31)
Break-over	Duration (s)					
	Lame	0.055 (0.011)	0.054 (0.009)	0.053 (0.009)†	0.053 (0.009)	0.052 (0.006)†
	Nonlame	0.054 (0.009)	0.054 (0.009)	0.054 (0.009)	0.052 (0.008)	0.054 (0.009)
	X acceleration (m/s²)					
	Maximum					
	Lame	45.784 (12.707)	48.726 (12.910)*†	49.108 (16.059)*†	51.771 (13.988)*	48.776 (11.327)*
	Nonlame	44.481 (14.262)	47.835 (15.087)	44.797 (13.593)	42.909 (11.633)	44.395 (13.451)
	Mean					
	Lame	27.682 (6.512)*	28.823 (6.021)*	28.408 (7.468)*†	28.598 (6.190)*†	27.551 (4.423)*
	Nonlame	24.836 (6.650)	26.199 (6.549)	25.262 (6.554)†	25.139 (5.384)†	23.467 (4.444)†
	Orientation (°)					
	Minimum					
	Lame	–45.73 (5.96)	–44.82 (5.24)*	–44.04 (3.72)*	–43.27 (3.84)*	–43.63 (5.46)*
	Nonlame	–46.98 (7.63)	–48.57 (6.89)†	–47.87 (5.82)	–47.12 (5.02)	–49.29 (5.40)
	Range of motion (°)					
	Lame	42.09 (5.48)	41.37 (5.11)*	40.05 (3.49)*†	39.75 (3.77)*†	39.56 (5.42)*†
	Nonlame	43.05 (7.44)	44.66 (6.82)†	43.97 (5.80)	42.96 (4.92)	44.79 (5.08)

Grade of lameness was subjectively determined at a trot. Grade 1 was defined as intermittent lameness; grade 2 was defined as consistent, mild lameness; and grade 3 was defined as consistent, moderate lameness, and none of the grades resulted in lameness at a walk. Each stride taken by a horse was divided into segments on the basis of 3 hoof events that were defined by the kinematic data curves. The hoof events included hoof contact, which was defined as the last peak in the Z acceleration curve before a period of smaller accelerations; heel-off, which was defined as the first peak in the Z acceleration curve after the period of smaller accelerations; and toe-off, which was defined as the second peak in the Z acceleration curve and corresponded to an inflection point in the X acceleration curve. The segments of the stride were total stance, which consisted of hoof contact and break-over (heel-off to toe-off); initial swing (toe-off to initial 25% of swing); terminal swing (75% of swing to hoof contact); and total swing (toe-off to hoof contact). The orientation of the hoof during the middle of total stance (when the metacarpal bone was perpendicular to the ground) was used to adjust the sagittal orientation of the hoof such that 0° was level with the ground. The cranial-to-caudal (X) variables were positive cranially, the vertical (Z) variables were positive proximally, and the sagittal-plane orientation was positive in a counterclockwise rotation (ie, heel-down was positive). Range of motion was calculated from the difference in the maximum and minimum orientations for each stride segment. Grade 3 lameness could not be induced in 1 horse; therefore, for grade 3 and after-block treatments, the mean (SD) represents data from only 5 horses, whereas the mean (SD) for the other treatments represents data from all 6 horses.

*Within a treatment and variable, the value for the lame forelimb differs significantly ($P < 0.05$) from that for the nonlame forelimb. †Within a forelimb, value differs significantly ($P < 0.05$) from that at baseline.

Table 2—Mean (SD) kinematic variables for the lame and nonlame forelimbs during the swing (toe-off to hoof-contact) phase of the stride at a trot for the horses of Table 1.

		Treatment				
Swing segment	**Variable**	**Baseline**	**Grade 1**	**Grade 2**	**Grade 3**	**After block**
Initial-swing	Orientation (°)					
	Maximum					
	Lame	–45.03 (6.35)	–44.75 (5.27)*	–44.24 (3.82)*	–44.30 (5.93)*	–43.83 (4.48)*
	Nonlame	–47.18 (7.30)	–49.17 (6.90)	–46.82 (5.84)	–47.16 (4.75)	–48.59 (5.35)
	Minimum					
	Lame	–108.61 (5.71)	–109.95 (4.49)*	–109.96 (5.05)	–109.90 (5.19)*	–109.97 (4.11)*
	Nonlame	–109.44 (4.89)	–111.19 (4.83)†	–110.59 (5.93)†	–111.44 (3.80)	–112.05 (5.24)†
	Mean					
	Lame	–92.60 (5.21)	–93.35 (3.51)*	–93.10 (3.85)*	–93.28 (4.65)*	–93.09 (3.45)*
	Nonlame	–93.76 (4.94)	–95.71 (4.26)†	–94.48 (4.56)	–95.17 (3.36)	–95.79 (3.89)
	Range of motion (°)					
	Lame	63.58 (8.40)	65.20 (7.97)*	65.71 (7.27)*	65.60 (7.51)	66.14 (6.18)*
	Nonlame	62.26 (7.83)	62.02 (8.35)	63.77 (8.38)	64.28 (5.79)	3.45 (7.51)
Terminal-swing	X velocity (m/s)					
	Maximum					
	Lame	6.441 (0.447)	6.570 (0.543)*	6.549 (0.311)*	6.506 (0.301)*	6.408 (0.375)
	Nonlame	6.541 (0.461)	6.798 (0.631)†	6.776 (0.350)†	6.630 (0.283)†	6.554 (0.569)
	X acceleration (m/s²)					
	Minimum					
	Lame	–112.149 (19.935)	–111.768 (18.594)*	–111.204 (18.745)*	–108.434 (21.057)*†	–107.882 (18.833)*†
	Nonlame	–115.652 (21.334)	–117.054 (21.282)	–117.807 (18.521)	–115.521 (17.555)	–120.979 (21.790)
	Z position (m)					
	Maximum					
	Lame	0.051 (0.011)	0.048 (0.011)	0.050 (0.010)*	0.052 (0.011)	0.049 (0.010)*
	Nonlame	0.049 (0.007)	0.048 (0.009)	0.045 (0.007)†	0.049 (0.011)	0.043 (0.008)†
	Z velocity (m/s)					
	Maximum					
	Lame	0.361 (0.422)	0.349 (0.328)*	0.393 (0.378)	0.322 (0.333)*	0.475 (0.349)*
	Nonlame	0.411 (0.336)	0.452 (0.346)	0.481 (0.343)	0.461 (0.339)	0.540 (0.271)
Total-swing	Duration (s)					
	Lame	0.384 (0.020)	0.384 (0.015)*	0.390 (0.018)*	0.387 (0.024)	0.385 (0.016)
	Nonlame	0.382 (0.022)	0.380 (0.017)	0.379 (0.017)	0.373 (0.015)	0.385 (0.021)
	X position (m)					
	Mean					
	Lame	0.968 (0.084)	0.977 (0.073)	0.997 (0.104)*	0.989 (0.098)	0.972 (0.073)
	Nonlame	0.973 (0.097)	0.995 (0.092)	0.966 (0.080)	0.958 (0.081)	0.960 (0.073)
	Z position (m)					
	Maximum					
	Lame	0.105 (0.022)	0.105 (0.021)	0.105 (0.021)	0.112 (0.023)*	0.110 (0.018)*
	Nonlame	0.105 (0.021)	0.102 (0.014)	0.100 (0.016)	0.104 (0.022)	0.089 (0.017)
	Z acceleration (m/s²)					
	Minimum					
	Lame	–64.874 (20.016)	–64.342 (22.429)	–62.268 (19.104)*	–59.883 (17.749)*	–72.141 (28.065)
	Nonlame	–68.435 (19.209)	–68.599 (27.219)	–76.094 (26.389)	–70.488 (16.100)	–64.823 (15.505)

See Table 1 for key.

baseline were detected for grades 1, 2, and 3 and after-block treatments, and these changes were detected during both the total stance and swing phases of the stride.

Interlimb kinematic changes—Among the treatments, 34 of 94 (36.2%) kinematic variables varied significantly between the lame and nonlame forelimbs. Of those variables, significant interlimb differences were detected for 14 of 36 cranial-to-caudal (X) variables, 17 of 35 vertical (Z) variables, 2 of 17 sagittal-plane orientation variables, and 1 of 6 temporal variables. Significant interlimb differences were detected during all segments of the stride and for all treatments.

Discussion

Results of the present study indicated that multiple sagittal-plane hoof kinematic variables were significantly altered at a trot following induction of unilateral, weight-bearing forelimb lameness in clinically normal horses. These kinematic alterations were identified during both the stance and swing phases of the stride at even the most mild (grade 1) severity of lameness induced. Because the characterization of kinematic alterations among the different grades of lameness was beyond the scope of this study, multiple comparisons were not performed to determine whether alterations in kinematics were associated with severity of lameness; however, as expected, the number of kinematic variables that varied significantly from baseline (prior to induction of lameness) and between the lame and nonlame limbs increased as the severity of lameness that was induced increased.

During the total stance phase of the stride for horses at a trot, multiple kinematic variables were significantly altered, even at grade 1 lameness. Following induction of grades 1, 2, and 3 lameness, the right (lame) forelimb had a significantly greater caudal (X) acceleration at hoof-contact (ie, beginning of total stance), compared with that at baseline or for the left (nonlame) forelimb, and after administration of the perineural anesthesia, caudal acceleration of the lame limb at hoof contact appeared to return to that at baseline. This change in the cranial-to-caudal acceleration of the lame limb suggested that horses slow the advance of the lame limb to a greater extent than that of the nonlame limb before maximum weight bearing, which occurs during the middle of stance.

Following induction of each grade of lameness in the present study, the hoof orientation at hoof-contact for the nonlame limb had a more positive angle, compared with that at baseline or for the lame limb, which indicated that the hoof of the nonlame limb was landing in a heel-first manner. During the break-over segment, the lame limb was more rapidly unloaded than was the nonlame limb, as evidenced by the increased maximum and mean cranial (X) acceleration and decreased minimum orientation angle and range of motion for the lame limb, compared with those for the nonlame limb. The minimum orientation during break-over represents the hoof orientation at toe-off; the fact that the minimum orientation for the lame limb was less than that for the nonlame limb after induction of each grade of lameness likely contributed to the decreased range of motion for the lame limb, compared with that for the nonlame limb. Because significant interlimb differences were detected for maximum cranial acceleration, minimum orientation, and range of motion during break-over at the mildest (grade 1) lameness induced in the present study, those variables might be sensitive indicators for the diagnosis of subclinical forelimb lameness in horses.

Results of other studies[21,22] indicate that the duration of total stance increases in both lame and nonlame limbs as severity of lameness increases. Investigators of another study[12] reported that for horses at a trot, the duration of the stance phase was increased for the lame diagonal pair of limbs, compared with that for the nonlame diagonal pair of limbs. Conversely, in the present study, following lameness induction, the duration of the stance phase did not increase from baseline for either the lame or nonlame limb and did not vary significantly between the lame and nonlame limbs, and those findings were consistent with results of a study conducted by Ishihara et al.[10]

Investigators of another study[22] suggest that weight-bearing lameness has only a minimal effect on kinematics during the swing phases of the stride. In the present study, we identified several kinematic variables that were altered between the lame and nonlame limbs during the swing segments. For example, following induction of grade 1 and grade 2 lameness, the duration of total-swing was significantly longer for the lame limb, compared with that for the nonlame limb. Results of other studies[12,22] indicate that the duration of swing for a lame limb decreased from baseline only after induction of moderate lameness (ie, mild lameness was detectable at a walk). For the horses of the present study, the most severe lameness induced (grade 3) did not result in perceptible lameness at a walk, which suggested that the lameness induced in this study was not as severe as that induced in those other studies[12,22] and may explain why the duration of the swing for the lame limb was not shortened.

Even after the mildest grade of lameness was induced in the present study, several kinematic variables during the swing phase of the stride differed significantly between the lame and nonlame limbs. During the initial-swing segment, the range of motion for the lame limb was significantly greater, compared with that for the nonlame limb. Because the lame limb went through a smaller range of motion during break-over than did the nonlame limb, it is possible that this extra rotation during the swing phase was a compensatory change. During the terminal-swing segment, the nonlame limb had greater maximum cranial (X) and vertical (Z) velocity and decreased minimum cranial acceleration, compared with those for the lame limb. The cranial variable differences between the 2 limbs indicated that the nonlame limb began the terminal-swing segment sooner than did the lame limb; thus, more caudal acceleration was required to slow the hoof for impact for the nonlame limb than for the lame limb. As expected, the total-swing segment was longer for the lame limb, compared with that for the nonlame limb; therefore, the lame limb moved slower and had smaller accelerations through the swing phase than did the nonlame limb. For the forelimb of a horse, maximum vertical velocity typically occurs as the hoof is undergoing a final rotation to prepare for landing.[16] For the horses of the present study, the hoof of the nonlame limb generally landed in a flat or heel-first manner and the vertical velocity of the hoof likely attributed to its rotation; however, the hoof of the lame limb generally landed with a toe-down orientation such that less proximal velocity was required to rotate the hoof into its final position for landing.

In the present study, the lame limb had a higher maximum vertical position during the swing phase, compared with that of the nonlame limb, as evidenced by the significant difference between the 2 limbs for this variable at grade 2 lameness during the terminal-swing segment and at grade 3 lameness during the total-swing segment. In another study,[11] the vertical position of the nonlame limb during the swing phase was greater than that of the lame limb. The reason the findings of the present study appear to conflict with those of that other study[11] was most likely associated with differences in how the position of the hoof was determined between the 2 studies. In the present study, the position of the hoof was determined by multiple markers and increased rotation of the hoof exaggerated the extent of vertical movement. Because the hoof of the lame limb had a more toe-down orientation than did the hoof of the nonlame limb, the lame limb would appear to have a greater maximum vertical position, compared with that of the nonlame limb.

Following administration of perineural anesthesia in the lame limb, only some of the kinematic variables returned to baseline values, whereas other kinematic variables remained significantly altered from baseline. For both the lame and nonlame limbs, the orientation of the hoof at hoof-contact and maximum cranial velocity during the terminal-swing segment did not vary significantly from baseline after perineural anesthesia. However, for the lame limb, cranial acceleration at hoof-contact, range of motion during the break-over segment, and cranial acceleration during the terminal-swing segment varied significantly from baseline after perineural anesthesia; for the nonlame limb, cranial acceleration at hoof-contact, mean cranial acceleration during the break-over segment, minimum orientation during the initial-swing segment, and vertical position during the terminal-swing segment varied significantly from baseline after perineural anesthesia. Perineural anesthesia alters the neural pathways in the limb; therefore, it was not totally unexpected that some of the kinematic variables for the lame and nonlame limbs did not return to values similar to those at baseline.

Some kinematic variables evaluated in the present study varied significantly between the forelimbs before induction of lameness, and because of this inherent asymmetry between the limbs, interlimb comparisons were not performed for those variables after the other treatments (grade 1, grade 2, grade 3, and after block). Interlimb asymmetry at baseline might have been caused by lameness that could not be detected by the subjective method used in this study. Results of other studies indicate that the use of a stationary force platform[10] or an inertial sensor system[5] had greater sensitivity than did subjective lameness examination for identification of horses with mild lameness. It is possible that the optical kinematics system used in the present study may similarly be more sensitive than subjective lameness examination for the detection of subclinically lame horses; however, evaluation of a larger number of horses is necessary to verify this. Another possible explanation for the forelimb asymmetry observed at baseline for some of the kinematic variables was the laterality, or handedness, of the horses evaluated. Many horses preferably use one forelimb more than the other during both grazing and ambulation, and this laterality begins at a young age.[23,24] Additionally, investigators of another study[25] reported that forelimb asymmetries exist in clinically normal horses during various phases of the stride and are likely associated with differences in hoof conformation between the 2 limbs. Within a horse, conformational asymmetry between the hooves of the forelimbs could contribute to significant interlimb differences in the kinematics of the distal portion of the limb. Measurement of hoof conformation during the various phases of the stride was beyond the scope of the present study, and we chose to make interlimb comparisons after lameness induction and perineural anesthesia only for those kinematic variables that did not differ significantly at baseline. Nevertheless, the fact that forelimb asymmetry was identified at baseline for some of the kinematic variables evaluated in the present study suggested that both intra- and interlimb kinematic comparisons should be performed for detection of lameness in horses.

The sole-pressure model used in the present study induced lameness consistently, and that lameness was rapidly reversible. Although most horses that are clinically lame do not have lameness caused by pressure to the sole, the kinematic changes associated with lameness induced by the sole-pressure model are believed to be similar to those associated with lameness induced by other causes.[11] Consequently, the sole-pressure model has been accepted and used in many studies[5,12–14,20] that assessed both kinetic and kinematic methods for the detection of lameness in horses. In 1 of the first 2 horses evaluated in the present study, we were unable to induce grade 3 lameness with blunt-ended screws; thus, we modified the sole-pressure model slightly and used screws with tapered ends instead of blunt ends so that all 3 grades of lameness could be consistently induced in the remaining 4 study horses. Because the primary objective of this study was to identify kinematic variables that were useful for the diagnosis of mild lameness in horses, we do not feel that the use of data from only 5 instead of 6 horses for the analyses for the grade 3 and after-block treatments was a major limitation.

The horizontal velocity of a horse affects the kinematics of the distal aspect of the limbs[26]; therefore, in the present study, we ensured that each horse traveled over the runway with a consistent velocity during each trial. During the collection of baseline data, each horse was allowed to trot at a comfortable velocity, the mean velocity was calculated for the baseline trials, and then a range of ± 10% of that mean velocity was calculated and used to delimit the range within which that horse's velocity had to be for all subsequent trials to be considered acceptable. This process mimics that of subjective clinical lameness examinations in which a horse is routinely examined at a speed dictated by that individual horse. Results of another study[27] indicate that the most reproducible kinematic measurements are obtained when a horse is allowed to move at its own individual optimum speed because at that speed, the variation in motion is minimized. In a study[28] in which the vertical head excursion of lame horses was evaluated, horses with mild lameness had no increase in the asymmetry of head motion when horizontal speed was increased. Thus, lameness in a horse can be adequately detected when it is moving at its own individual optimum speed, rather than at a predetermined speed that is used for the evaluation of all horses.

Investigators of other studies[12,13] that evaluated the kinematics of the stride of horses divided the stride into only 2 phases, stance and swing. In the present study, we further subdivided the stance and swing phases on the basis of specific hoof events that could be identified on the X and Z acceleration curves. To our knowledge, this is the first study in which the stance phase of the stride was divided into hoof-contact and break-over segments and the swing phase was divided into initial-swing, terminal-swing, and total-swing segments. As expected, subtle kinematic alterations occurred during each segment of the stance and swing phases (eg, increase in maximum vertical velocity of the nonlame limb during terminal-swing and changes in hoof orientation during hoof-contact, break-over, and initial-swing) that would have been missed had those 2 phases not been subdivided into their respective segments.

In addition to the various segments of the stride, linear and angular kinematic data were also evaluated for hoof events (hoof-contact, heel-off, and toe-off). The kinematic variables determined at heel-off and toe-off were reflected in the data for the break-over and initial-swing segments; however, the kinematic variables determined at hoof-contact were not reflected well in the data for the terminal-swing segment. This was especially true for sagittal plane orientation of the hoof because the maximum sagittal plane orientation during the terminal-swing segment occurred immediately before hoof-contact when the hoof underwent a final counterclockwise rotation. Consequently, we decided to report the instantaneous kinetic data at hoof-contact in addition to the kinematic data for each segment of the stride.

Results of the present study indicated that even mild, weight-bearing lameness in a forelimb of a horse can result in altered kinematics for the distal portion of both the lame and nonlame limbs when the horse is trotting. Further study is necessary to determine whether these kinematic changes also occur in horses that are walking. For several kinematic variables following induction of lameness, a significant difference between the 2 forelimbs was often identified, whereas within the lame limb, a significant difference from baseline was not detected; therefore, data should be obtained from both forelimbs during kinematic analyses. Following perineural anesthesia, kinematic values for hoof orientation at hoof-contact and maximum cranial acceleration during the break-over segment did not differ from those at baseline; therefore, those values could be useful for the objective assessment of the effect of the perineural anesthesia. Additional studies with a larger number of horses with clinical lameness are necessary to determine whether the use of a hoof-mounted kinematic monitoring system is clinically useful for lameness diagnosis and monitoring in horses.

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a. Equi-Thane SuperFast, Vettec Inc, Oxnard, Calif.
b. H3-IMU, MemSense LLC, Rapid City, SD.
c. Vetrap, 3M Co, Saint Paul, Minn.
d. Volant, Peak Performance Technologies Inc, Centennial, Colo.
e. Vicon-Motus, version 9.2, Vicon Motion Systems Inc, Centennial, Colo.
f. MEK 92-PAD photoelectric control, Mekontrol Inc, Northboro, Mass.
g. STATA, version 11, Stata Corp LP, College Station, Tex.

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Effect of forelimb lameness on hoof kinematics of horses at a walk

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Objective—To determine kinematic changes to the hoof of horses at a walk after induction of unilateral, weight-bearing forelimb lameness and to determine whether hoof kinematics return to prelameness (baseline) values after perineural anesthesia.

Animals—6 clinically normal Quarter Horses.

Procedures—For each horse, a sole-pressure model was used to induce 3 grades of lameness in the right forelimb, after which perineural anesthesia was administered to eliminate lameness. Optical kinematics were obtained for both forelimbs with the horse walking before (baseline) and after induction of each grade of lameness and after perineural anesthesia. Linear acceleration profiles were used to identify hoof events, and each stride was divided into hoof-contact, break-over, initial-swing, terminal-swing, and total-swing segments. Kinematic variables were compared within and between limbs for each segment by use of mixed repeated-measures ANOVA.

Results—During the hoof-contact and terminal-swing segments, the hoof of the left (nonlame) forelimb had greater sagittal-plane orientation than did the hoof of the right (lame) forelimb. For the lame limb following lameness induction, the break-over duration and maximum cranial acceleration were increased from baseline. After perineural anesthesia, break-over duration for the lame limb returned to a value similar to that at baseline, and orientation of the hoof during the terminal-swing segment did not differ between the lame and nonlame limbs.

Conclusions and Clinical Relevance—Subclinical unilateral forelimb lameness resulted in significant alterations to hoof kinematics in horses that are walking, and the use of hoof kinematics may be beneficial for the detection of subclinical lameness in horses. (*Am J Vet Res* 2013;74:1192–1197)

Lameness is an important and prevalent medical condition in horses[1] and accounts for up to $1 billion in losses for the US equine industry annually.[2] Horses with subclinical or mild lameness have suboptimal performance,[3,4] and mild lameness is often a precursor to severe or catastrophic musculoskeletal injury. Therefore, detection of horses with subclinical or mild lameness is important so that measures can be taken to correct or alleviate the lameness and thereby improve the welfare of affected horses. Additionally, sensitive methods are needed for assessment of lame horses following treatment to determine when an individual horse can safely return to prelameness activity or exercise without risking reinjury.

In horses, lameness is typically detected and monitored by means of a subjective lameness examination, in which horses are visually assessed at both a walk and a trot before a lameness grade, or score, is assigned.[5] Unfortunately, results of multiple studies[6–9] suggest that the use of subjective lameness scoring systems is not clinically reliable for identification of lame horses, especially when the lameness is mild. Furthermore, in 1 study,[6] investigators identified inherent bias in subjective lameness scores following administration of perineural anesthesia. Thus, adjunct methods that are more sensitive and objective than the subjective lameness examination are necessary for detection and monitoring of horses with mild lameness and assessment of lame horses after administration of perineural anesthesia. Because horses with mild or moderate lameness are frequently not perceptibly lame at a walk,[5] they are often not extensively examined at that gait during a subjective lameness examination. However, effective evaluation of lameness in horses at a walk would be beneficial, particularly for those in which observation at a gait faster than a walk might be detrimental.

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Multiple studies[10–14] have been conducted to evaluate the efficacy of objective methods, such as kinetics and kinematics, for the detection of lameness in horses at both a walk and a trot. Results of studies[10–12] suggest that the use of stationary force platform kinetic and optical kinematic systems is just as sensitive as or more sensitive than subjective lameness examination performed by experienced equine veterinarians for diagnosing mild lameness in horses that are trotting. Few studies have been conducted to evaluate the efficacy of kinetic or kinematic methods for detecting subclinical or mild lameness in horses at a walk. In 1 study,[13] horses in which mild lameness at a trot but no detectable lameness at a walk was induced had significant changes in hoof kinetics, compared with hoof kinetics obtained prior to lameness induction. Investigators of another study[14] reported that optical kinematic values of the hoof were altered from prelameness values for horses in which mild to moderate lameness at a walk was induced. In clinically normal horses with unilateral, weight-bearing forelimb lameness, alterations in hoof kinematics occur in both the lame and nonlame limbs at a trot[12]; therefore, alterations in hoof kinematics may also occur at a walk, and characterization of those changes might be beneficial for the diagnosis of lameness in horses.

The objectives of the study reported here were to determine kinematic changes to the hoof of horses at a walk after induction of unilateral, weight-bearing forelimb lameness that was perceptible only at a trot and to determine whether hoof kinematics return to prelameness (baseline) values after perineural anesthesia. We hypothesized that after lameness induction, kinematic variables would vary from baseline values and between the lame and nonlame forelimbs for various segments of the stride when horses were walking, and that kinematic variables would return to values similar to those at baseline after perineural anesthesia. Our goal was to identify specific kinematic variables that were substantially altered at a walk by lameness during predefined segments of the stride.

Materials and Methods

Animals—Six Quarter Horses were used for the study reported here as well as a companion study,[12] and data for the 2 studies were obtained concurrently. Each horse was determined to be clinically normal and was not perceptibly lame at a walk or a trot. The horses ranged in age from 2 to 9 years and had a mean ± SD weight and wither height of 364 ± 19 kg and 1.46 ± 0.03 m, respectively. Prior to study initiation, horses were acclimated to the laboratory where the gait analysis data were collected. The hooves of each horse were trimmed and balanced, and the hooves of the forelimbs were shod as described.[12] Each horse was instrumented with retroreflective markers and an inertial measurement unit[a] for collection of kinematic data as described.[12] All study procedures were approved by the Colorado State University Institutional Animal Care and Use Committee.

Study design—For each horse, kinematic data for both forelimbs were obtained before (baseline) and after induction of each of 3 grades (grades 1, 2, and 3) of lameness in the right forelimb as well as after administration of perineural anesthesia to the right forelimb to alleviate the lameness. A 5-point lameness scale, modified from the one developed by the American Association of Equine practitioners,[5] was used to define the grades of lameness induced. Grade of lameness was subjectively assessed at a trot. Briefly, grade 1 was defined as intermittent mild lameness, grade 2 was defined as consistent mild lameness, and grade 3 was defined as consistent, moderate lameness; none of the grades resulted in perceptible lameness at a walk. Between data collection periods, horses were allowed to rest for several minutes to minimize the effect of fatigue.

Induction of lameness and perineural anesthesia—For each horse, 3 grades of lameness were induced in the right forelimb in a sequential manner by means of a sole-pressure model as described.[12] Briefly, a 6-mm-diameter screw with either a blunt or tapered end was threaded into both the medial and lateral nuts welded to the steel shoe on the hoof of the right forelimb such that the head of the screw was in contact with the ground when the horse was bearing weight on that limb. The horse was trotted briefly to subjectively determine the severity of lameness, and the process was repeated with longer or shorter screws as necessary until the desired severity of lameness was achieved. The screw length (range, 11 to 17 mm) required to induce each grade of lameness was recorded. After induction of each grade of lameness, lameness trials were performed for data collection purposes. Following data collection for grade 3 lameness, perineural anesthesia was administered with a 2% mepivacaine solution to the regions surrounding the medial and lateral palmar nerves of the right forelimb of each horse as described.[12]

Lameness trial facilities and protocol—All lameness trials were performed in a gait analysis laboratory as described.[12] Briefly, each horse was walked or trotted on an asphalt runway (length, 24.8 m; width, 1.2 m) that was covered with a 9.3-mm-thick rubberized mat. The optical capture volume (ie, portion of the runway where kinematic data for the horse were obtained; length, 3.7 m; width, 1.3 m; height, 2.4 m) was located in the central portion of the runway such that the horse could maintain a constant velocity when passing through it. Eight infrared cameras[b] were used to obtain 3-D optical kinematic data; 4 cameras were suspended from overhead beams on each side of the optical capture volume. The cameras operated at 200 Hz and were connected to an optical kinematic system[c] that was calibrated to provide coordinates to within 1.2 mm. Five infrared timing gates[d] were spaced 1.5 m apart along the central portion of the runway, which included the entire optical capture volume. During each trial (ie, trip over the runway), the timing gates were triggered by the passing of the horse to send a signal to the optical kinematic system, and the time stamps of those signals were used to calculate the horse's mean velocity.

The mean velocity at a walk and a trot was determined for each horse during collection of baseline data. Subsequently, for each horse after induction of each grade of lameness and perineural anesthesia, 4 to 5 acceptable trials were recorded for the right and left forelimbs at both a walk and trot. An acceptable trial was defined as a trial during which the horse traveled straight through the optical capture volume with a velocity that was ± 10% of its mean baseline velocity for the gait being evaluated.

Data collection—Optical coordinate data were low-pass filtered at 15 Hz with a recursive fourth-order Butterworth filter. Between the cranial and caudal retroreflective markers on the marker triad, a virtual marker was created to serve as a local origin, or reference point, to track the motion of the hoof. Linear movement of the hoof was tracked in the sagittal plane (cranial to caudal [X] and proximal to distal [Z]) as described.[12] The X and Z acceleration profiles of the stride were used to identify hoof events. Briefly, hoof-contact was defined as the last peak in the Z acceleration curve before a period of smaller accelerations, and heel-off was defined as the last peak in the Z acceleration curve after the smaller accelerations. Toe-off was defined as the second peak in the Z acceleration curve, which corresponded to an inflection point in the X acceleration curve. These hoof events were used to divide the stride into total-stance (hoof-contact to toe-off), break-over (heel-off to toe-off), total-swing (toe-off to hoof-contact), initial-swing (toe-off to initial 25% of swing), and terminal-swing (75% of swing to hoof-contact) segments.

The global origin for the coordinate system was toe-off, and translations of the hoof at all other events were relative to the location of the virtual marker at toe-off. For each trial, the x-axis was aligned with the virtual marker at the second hoof-contact to ensure that the coordinate system was aligned with the direction of travel for the horse. The x-axis was positive cranially, and the z-axis was positive proximally. Within the sagittal plane about the y-axis (medial to lateral) through the virtual marker, heel-down hoof orientation was positive and toe-down hoof orientation was negative. Because the marker triad was not perfectly parallel to the ground, the hoof orientation during the middle of the total-stance segment (when the metacarpal bone was perpendicular to the ground) was used to adjust the sagittal orientation of the hoof such that 0° was level with the ground.

Data collected for each forelimb during each lameness trial included the instantaneous position, velocity, acceleration and sagittal-plane orientation of the hoof at hoof-contact, heel-off, and toe-off. Also, the total range of motion for the hoof was determined for the initial-swing, terminal-swing, and total-swing segments of the stride.

Table 1—Mean (SD) kinematic variables for the lame (right) and nonlame (left) forelimbs during the total stance (hoof-contact to toe-off) phase of the stride at a walk for 6 clinically normal Quarter Horses before (baseline) and after induction of 3 grades (grades 1, 2, and 3) of increasingly severe lameness in the right forelimb and following perineural anesthesia in the right forelimb to alleviate the lameness (after block).

		Treatment				
Stance segment	**Variable**	**Baseline**	**Grade 1**	**Grade 2**	**Grade 3**	**After block**
Hoof-contact	Orientation (°)					
	Lame	0.70 (3.16)	0.61 (2.90)	0.58 (2.50)*	0.37 (1.96)*	1.54 (2.83)†
	Nonlame	1.20 (2.72)	0.81 (2.73)	1.41 (2.42)	1.84 (2.72)†	1.19 (2.96)
Break-over	Duration (s)					
	Lame	0.092 (0.013)*	0.094 (0.015)†	0.095 (0.013)†	0.093 (0.012)†	0.092 (0.010)
	Nonlame	0.096 (0.012)	0.091 (0.015)	0.094 (0.015)	0.094 (0.015)	0.091 (0.014)
	X position (m)					
	Minimum					
	Lame	–0.046 (0.008)	–0.046 (0.008)*	–0.046 (0.007)*	–0.044 (0.007)*	–0.043 (0.007)*
	Nonlame	–0.043 (0.007)	–0.042 (0.008)	–0.042 (0.007)	–0.041 (0.007)†	–0.039 (0.008)†
	Mean					
	Lame	–0.031 (0.006)	–0.031 (0.006)*	–0.031 (0.005)*	–0.030 (0.005)*	–0.029 (0.005)*†
	Nonlame	–0.029 (0.005)	–0.028 (0.005)	–0.029 (0.005)	–0.027 (0.005)	–0.027 (0.006)†
	X acceleration (m/s²)					
	Maximum					
	Lame	39.162 (5.242)*	41.083 (6.257)*	42.564 (7.094)*†	41.630 (6.408)*	44.046 (7.109)*†
	Nonlame	37.290 (8.409)	37.885 (7.821)	38.876 (7.446)	38.055 (6.447)	38.111 (6.890)
	Z velocity (m/s)					
	Maximum					
	Lame	0.697 (0.140)*	0.714 (0.173)*	0.729 (0.174)*	0.774 (0.102)*	0.801 (0.101)*†
	Nonlame	0.625 (0.157)	0.615 (0.168)	0.659 (0.143)	0.620 (0.145)	0.645 (0.135)
Total-stance	Duration (s)					
	Lame	0.804 (0.051)	0.786 (0.068)	0.799 (0.067)	0.831 (0.069)†	0.840 (0.047)†
	Nonlame	0.819 (0.046)	0.792 (0.065)	0.805 (0.064)	0.840 (0.065)	0.838 (0.050)

Grade of lameness was subjectively determined at a trot. Grade 1 was defined as intermittent lameness; grade 2 was defined as consistent, mild lameness; and grade 3 was defined as consistent, moderate lameness; none of the grades resulted in lameness at a walk. Each stride taken by a horse was divided into segments on the basis of 3 hoof events that were defined by the kinematic data curves. The hoof events included hoof contact, which was defined as the last peak in the Z acceleration curve before a period of smaller accelerations; heel-off, which was defined as the first peak in the Z acceleration curve after the period of smaller accelerations; and toe-off, which was defined as the second peak in the Z acceleration curve and corresponded to an inflection point in the X acceleration curve. The segments of the stride were total-stance, which consisted of hoof-contact and break-over (heel-off to toe-off); initial-swing (toe-off to initial 25% of swing); terminal-swing (75% of swing to hoof contact); and total-swing (toe-off to hoof-contact). The orientation of the hoof during the middle of total-stance (when the metacarpal bone was perpendicular to the ground) was used to adjust the sagittal orientation of the hoof such that 0° was level with the ground. Cranial-to-caudal (X) variables were positive cranially, vertical (Z) variables were positive proximally, and the sagittal-plane orientation was positive in a counterclockwise rotation (ie, heel-down was positive). Range of motion was calculated from the difference in the maximum and minimum orientations for each stride segment. Grade 3 lameness could not be induced in 1 horse; therefore, for grade 3 and after-block treatments, the mean (SD) represents data from only 5 horses, whereas the mean (SD) for the other treatments represents data from all 6 horses.

*Within a treatment and variable, the value for the lame forelimb differs significantly ($P < 0.05$) from that for the nonlame forelimb. †Within a forelimb, value differs significantly ($P < 0.05$) from that at baseline.

Statistical analysis—Data were analyzed in a manner similar to that described.[12] Briefly, each data collection period was considered a treatment, which was categorized as baseline (prior to induction of lameness), grade 1, grade 2, grade 3, and after block (after administration of perineural anesthesia). For each treatment and forelimb hoof during each segment of the stride (hoof-contact, break-over, initial-swing, terminal-swing, and total-swing segments), descriptive statistics were generated for each kinematic variable or outcome. Mixed ANOVA for repeated measures was used to make comparisons between and within forelimbs for each outcome. For each respective model, treatment and forelimb (lame or nonlame) were included as fixed effects, horse identification was included as a random effect, and horse velocity during the trial was included as a confounding factor. For within-limb comparisons, each respective treatment (grade 1, grade 2, grade 3, or after block) was compared with the baseline treatment. All analyses were performed with a commercially available statistical software program,[e] and values of $P < 0.05$ were considered significant.

Results

Animals—Lameness that was subjectively apparent only at a trot was successfully induced in all horses; however, as discussed,[12] grade 3 lameness could not be induced in 1 horse. Therefore, analyses for grade 3 and after-block treatments included data from only 5 horses, whereas analyses for baseline, grade 1, and grade 2 treatments included data from all 6 study horses. None of the horses had perceptible lameness when trotting 24 hours after lameness induction.

Intralimb kinematic changes—Select kinematic variables for the right (lame) and left (nonlame) forelimbs during total stance (**Table 1**) and swing (**Table 2**) at a walk were summarized. For the lame limb, significant kinematic changes from baseline were detected during both the stance and swing phases of the stride. Maximum and mean X position were increased for grade 1 and grade 2 treatments, duration of break-over was increased after induction of all grades of lameness, maximum X acceleration during break-over and mean hoof orientation during total-swing were increased for grade 2 and after-block treatments, duration of total-stance was increased for grade 3 and after-block treatments, hoof orientation at hoof contact and maximum Z velocity during initial-swing and total-swing were increased, and mean X position during break-over was decreased for the after-block treatment. For the nonlame limb, significant kinematic changes were detected only during the stance phase of the stride. Hoof orientation during hoof-contact was increased for the grade 3 treatment, minimum X position during break-over was

Table 2—Mean (SD) kinematic variables for the lame and nonlame forelimbs during the swing (toe-off to hoof-contact) phase of the stride at a walk for the horses of Table 1.

		Treatment				
Swing segment	Variable	Baseline	Grade 1	Grade 2	Grade 3	After block
Initial-swing	Z velocity (m/s)					
	Maximum					
	Lame	0.817 (0.125)	0.823 (0.183)	0.858 (0.175)*	0.879 (0.124)*	0.934 (0.110)*†
	Nonlame	0.752 (0.174)	0.779 (0.135)	0.762 (0.119)	0.764 (0.154)	0.765 (0.137)
Terminal-swing	X position (m)					
	Maximum					
	Lame	1.542 (0.091)	1.575 (0.079)	1.578 (0.082)†	1.549 (0.079)	1.540 (0.106)
	Nonlame	1.559 (0.099)	1.578 (0.089)	1.581 (0.090)	1.565 (0.093)	1.561 (0.120)
	Mean					
	Lame	1.455 (0.085)	1.487 (0.076)†	1.485 (0.069)	1.457 (0.061)	1.443 (0.089)
	Nonlame	1.475 (0.094)	1.496 (0.072)	1.494 (0.077)	1.478 (0.081)	1.475 (0.104)
	Orientation (°)					
	Maximum					
	Lame	1.81 (3.44)	1.28 (3.44)	1.39 (3.11)*	0.91 (2.17)*	2.49 (2.89)
	Nonlame	2.65 (4.44)	2.57 (4.62)	2.85 (3.71)	2.79 (3.79)	2.08 (4.00)
	Mean					
	Lame	−14.78 (3.56)	−15.31 (4.14)	−16.01 (3.97)*	−15.40 (3.71)	−16.10 (4.06)
	Nonlame	−13.08 (3.88)	−13.13 (4.60)	−13.56 (3.89)	−14.15 (5.26)	−15.49 (4.99)
Total-swing	X position (m)					
	Maximum					
	Lame	1.542 (0.091)	1.575 (0.079)†	1.578 (0.082)†	1.549 (0.079)	1.540 (0.106)
	Nonlame	1.551 (0.095)	1.571 (0.088)	1.568 (0.089)	1.551 (0.092)	1.534 (0.108)
	Mean					
	Lame	0.802 (0.046)	0.824 (0.045)†	0.820 (0.038)†	0.803 (0.031)	0.795 (0.047)
	Nonlame	0.812 (0.055)	0.821 (0.040)	0.821 (0.040)	0.806 (0.044)	0.798 (0.054)
	Z velocity (m/s)					
	Maximum					
	Lame	0.823 (0.128)	0.844 (0.165)	0.858 (0.175)*	0.900 (0.171)*	0.958 (0.152)*†
	Nonlame	0.791 (0.190)	0.776 (0.133)	0.759 (0.120)	0.768 (0.152)	0.770 (0.133)
	Orientation (°)					
	Maximum					
	Lame	2.02 (3.56)	1.39 (3.54)	1.39 (3.11)	0.91 (2.17)*	2.49 (2.89)
	Nonlame	2.02 (3.89)	1.81 (4.59)	2.09 (3.64)	2.83 (3.50)	1.63 (3.92)
	Mean					
	Lame	−64.70 (3.36)	−64.78 (3.24)	−66.53 (3.29)*†	−64.9 (2.42)	−66.07 (3.27)†
	Nonlame	−64.57 (3.98)	−64.98 (3.93)	−64.57 (2.60)	−63.99 (3.29)	−65.40 (2.80)

See Table 1 for key.

decreased for grade 3 and after-block treatments, and mean X position during break-over was decreased for the after-block treatment.

Interlimb kinematic changes—Among the treatments, 38 of 94 (40.4%) kinematic variables varied significantly between the lame and nonlame forelimbs. Of those variables, significant differences were detected for 12 of 36 cranial-to-caudal (X) variables, 20 of 35 vertical (Z) variables, 5 of 17 sagittal-plane orientation variables, and 1 of 6 temporal variables. For all treatments, significant interlimb differences were detected during all segments of the stride.

Discussion

Results of the present study indicated that several sagittal-plane hoof kinematic variables were significantly altered at a walk following induction of mild, unilateral, weight-bearing forelimb lameness (ie, lameness was visually perceptible only at a trot) in clinically normal horses. These kinematic alterations were detected during both the stance and swing phases of the stride, even at the most mild (grade 1) severity of lameness induced. For example, in the lame limb, duration of break-over and mean and maximum cranial (X) position during total-swing (ie, swing length) were significantly increased from baseline following induction of grade 1 lameness. Investigators of other studies[15,16] reported that the duration of the stance phase (hoof-contact to toe-off) during a trot increases following induction of unilateral, weight-bearing forelimb lameness, compared with that before lameness induction for both the lame and nonlame limbs, and suggested that this is a compensatory mechanism by the horse to maintain the vertical impulse of the limbs in response to a decrease in peak vertical force. Results of the present study were similar to those of studies[15,16] that evaluated forelimb kinematics at a trot and indicated that mild lameness alters the duration of stance at a walk as well. To our knowledge, the present study was the first to evaluate forelimb kinematics during break-over in horses at a walk. In the companion study[12] to the one reported here, in which data were obtained concurrently from the same horses, the duration of break-over for the lame limb at a trot was significantly shorter than that at baseline, whereas in the present study, the duration of break-over for the lame limb at a walk was significantly longer than that at baseline. These findings suggested that the mechanism responsible for break-over duration varies and is dependent on the gait of the horse.

In the present study and its companion study,[12] maximum cranial acceleration of the lame limb during break-over was significantly increased at both a walk (grade 2 lameness only) and trot (grade 1 and grade 2 lameness). After perineural anesthesia, the maximum cranial acceleration of the lame limb during break-over returned to a value similar to that at baseline when horses were trotted,[12] but remained significantly increased from baseline when horses were walked.

For the horses of the present study, the swing length for the lame limb increased significantly from baseline after induction of grade 1 and grade 2 lameness, but returned to a value similar to that at baseline after induction of grade 3 lameness and after perineural anesthesia. Conversely, in another study,[17] swing length of the lame forelimb was significantly decreased from its prelameness swing length when horses were trotted; however, the lameness induced in the horses of that study[17] was perceptible at a walk and was more severe than the lameness induced in the horses of the present study. The difference in the severity of lameness induced between the present and that other study[17] might be responsible for the apparently contradicting findings regarding swing length. Thus, swing length is likely dependent on and will vary with severity of lameness and the gait at which the horse is evaluated.

For the nonlame limb after induction of grade 3 lameness, the hoof orientation at hoof-contact during a walk was significantly increased from that at baseline, which suggested that the hoof of the nonlame limb landed with a more heel-down orientation when the contralateral limb was moderately lame than it did prior to lameness induction. In the companion study,[12] the hoof orientation at hoof-contact for the nonlame limb during a trot was significantly increased from baseline following induction of all grades of lameness. Conversely, for the lame limb, the hoof orientation at hoof-contact did not vary significantly from that at baseline following induction of lameness at either a walk or a trot; however, hoof orientation of the lame limb at hoof-contact was increased from baseline after perineural anesthesia when horses were walked. Additionally, at a walk, hoof orientation at hoof-contact varied significantly between the lame and nonlame limbs following induction of grade 2 and grade 3 lameness, whereas at a trot, hoof orientation at hoof-contact varied significantly between the lame and nonlame limbs after all 3 grades of lameness were induced.[12] Thus, although hoof orientation at hoof-contact was significantly altered for both forelimbs at a walk and a trot, this alteration was only evident at a walk after induction of more severe (grade 2 or grade 3) lameness.

Following administration of perineural anesthesia in the present study, break-over duration and mean and maximum swing length during terminal- and total-swing segments for the lame limb returned to values that did not differ significantly from those at baseline, and values for mean and maximum hoof orientation during the terminal-swing segment no longer varied significantly between the lame and nonlame limbs. However, following perineural anesthesia, the hoof orientation at hoof-contact for the lame limb was increased significantly from baseline, whereas it did not differ from baseline following induction of all 3 grades of lameness. This finding suggested that hoof orientation of the lame limb at hoof-contact during a walk might be a clinically useful kinematic to assess to determine whether lameness was successfully alleviated by perineural anesthesia.

The sole-pressure model consistently induced lameness that was rapidly reversible in the horses of the present study. Although sole pressure is not a common cause of lameness in clinically lame horses, the kinematic changes that occur with this model are believed to be similar to those associated with lameness induced by other causes.[14] Consequently, the sole-pressure model has been used by investigators of multiple studies[11–13,17–19] to induce lameness in horses to evaluate objective methods of lameness detection at both a walk and trot. However, most of those studies[12,13,17–19] did not investigate kinematic alterations in horses at a walk.

To our knowledge, significant lameness-induced alterations in forelimb kinematics of horses at a walk have been reported by investigators of only 1 other study.[14] The lameness induced in the horses of that study[14] was perceptible at a walk and was more severe than the lameness induced in the horses of the present study. Nevertheless, results of the present study indicated that horses with unilateral forelimb lameness that was perceptible only at a trot had several kinematic changes in both the lame and nonlame limbs when walking. On the basis of results of the present study and its companion study,[12] sagittal-plane orientation of the hoof at hoof-contact and maximum cranial acceleration during break-over were increased from baseline for the lame limb after lameness induction when horses were walked and trotted. Therefore, those variables should be assessed further in a larger number of horses with lameness of varying severity to determine whether they could be clinically useful for identifying and monitoring lame horses. Additionally, because the values for several hoof kinematic variables (eg, mean and maximum X position during terminal- and total-swing segments and break-over duration for the lame limb and hoof orientation at hoof-contact for the nonlame limb) returned to values similar to those at baseline following perineural anesthesia, further research should be conducted to determine whether monitoring those variables can be used to assess whether perineural anesthesia was successful in alleviating lameness at a walk in horses that are subjectively lame only at a trot. Identification of such variables would be clinically valuable, particularly for horses for which a subjective lameness examination conducted at a trot is contraindicated. Horse-mounted kinematic systems are becoming more readily available; thus, use of a hoof-based sensor system may be useful clinically as an objective method for evaluation of lameness in horses. Further research is necessary to determine changes in the hoof kinematics of lame horses in the frontal and transverse planes.

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b. Volant, Peak Performance Technologies Inc, Centennial, Colo.
c. Vicon-Motus, version 9.2, Vicon Motion Systems Inc, Centennial, Colo.
d. MEK 92-PAD photoelectric control, Mekontrol Inc, Northboro, Mass.
e. STATA, version 11, StataCorp LP, College Station, Tex.

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