Comparison of results for body-mounted inertial sensor assessment with final lameness determination in 1,224 equids

Shannon K. Reed DVM, MS

Joanne Kramer DVM, MS

Lori Thombs PhD

Jael B. Pitts DVM, MS

David A. Wilson DVM, MS

Kevin G. Keegan DVM, MS

From the E. Paige Laurie Endowed Program in Equine Lameness, Veterinary Medical Health Center, College of Veterinary Medicine (Reed, Kramer, Pitts, Wilson, Keegan), and the Social Sciences Statistics Center, Department of Statistics, College of Arts and Sciences (Thombs), University of Missouri, Columbia, MO 65211. Dr. Reed's present address is Galbreath Equine Center, Department of Clinical Sciences, College of Veterinary Medicine, The Ohio State University, Columbus, OH 43210. Dr. Pitts' present address is Waller Equine Hospital, Waller, TX 77484.

Address correspondence to Dr. Keegan (keegank@missouri.edu).

OBJECTIVE
To compare results for initial body-mounted inertial sensor (BMIS) measurement of lameness in equids trotting in a straight line with definitive findings after full lameness evaluation.

ANIMALS
1,224 equids.

PROCEDURES
Lameness measured with BMIS equipment while trotting in a straight line was classified into categories of none, forelimb only, hind limb only, and 8 patterns of combined forelimb and hind limb lameness (CFHL). Definitive findings after full lameness evaluation were established in most horses and classified into types (no lameness, forelimb- or hind limb–only lameness, CFHL, or lameness not localized to the limbs). Observed proportions of lameness type in equids with definitive findings for each initial BMIS-assessed category were compared with hypothetical expected proportions through χ^2 goodness-of-fit analysis.

RESULTS
The most common initial BMIS-assessed lameness category was CFHL (693/1,224 [56.6%]), but this was the least common definitive finding (94/862 [10.9%]). The observed frequency of no lameness after full lameness evaluation was greater than expected only when initial BMIS measurements indicated no lameness. The observed frequency of forelimb-only lameness was greater than expected when initially measured as forelimb-only lameness and for CFHL categories consistent with the diagonal movement principle of compensatory lameness. Observed frequency of hind limb–only lameness was greater than expected when initially measured as hind limb–only lameness and for CFHL categories consistent with the sagittal movement principle of compensatory lameness. Equids initially assessed as having no lameness had the highest (103/112 [92%]) and those assessed as CFHL pattern 7 (forelimb with contralateral hind limb impact-only lameness) had the lowest (36/66 [55%]) rates of definitive findings.

CONCLUSIONS AND CLINICAL RELEVANCE
In equids, results of initial straight-line trotting evaluations with a BMIS system did not necessarily match definitive findings but may be useful in planning the remaining lameness evaluation. (*J Am Vet Med Assoc* 2020;256:590–599)

Body-mounted inertial sensors are now being used to objectively evaluate for lameness in equids.[1–13] Head and pelvic acceleration signals, after removing components attributable to noise and random movement, are converted into position trajectories.[14,15] Differences in relative maximum and minimum vertical positions (ie, heights) of the head and pelvis between left and right portions of the stride are calculated for trotting strides selected by the user for analysis.[3,12] The mean and SD of these differences from multiple contiguous strides are calculated and reported as several measurements, including overall amplitude of lameness, strength of evidence for lameness (the lower the stride-by-stride variation, the stronger the evidence), identification of the limb or limbs involved, and timing of lameness (ie, occurring mainly within the first or second parts of stance duration; termed impact and pushoff lameness, respectively).[11,16] The information can be used to evaluate the effect of anesthetic nerve blocks[7–9] and other treatments,[10,13] flexion tests,[17] lunging,[18,19] and evaluation of patients under saddle[19] during lameness assessment. Because this method is easy and practical to use for clinical examinations, large databases of objective data obtained from horses and other equids evaluated by vet-

ABBREVIATIONS

BMIS	Body-mounted inertial sensor
CFHL	Combined forelimb and hind limb lameness
HDmax	Difference in head maximum heights between right and left portions of the stride
HDmin	Difference in head minimum heights between right and left portions of the stride
PDmax	Difference in pelvis maximum heights between right and left portions of the stride
PDmin	Difference in pelvis minimum heights between right and left portions of the stride

erinarians because of lameness or poor performance have been acquired. Identification of patterns in these objective data that may be related to the location of the cause of lameness might provide predictive information useful to practicing veterinarians. This information may also be used to generate specific testable hypotheses for investigators researching lameness.

In quadrupeds, lameness can be found to originate with an abnormality in a single limb, it can be bilateral but confined to either end of the body (ie, forelimbs or hind limbs exclusively), or it can involve a combination of (1 or more) forelimbs and hind limbs. Simultaneous lameness in a forelimb and hind limb has been further subdivided into compensatory lameness, or an apparent lameness without pain that results from weight shifting off of or away from a primarily affected limb, and secondary lameness, which arises from overload damage owing to weight shifting off a primarily affected limb. Compensatory lameness develops at the opposite end of the body from the primary lameness (ie, in hind limbs of equids with forelimb lameness and in forelimbs of equids with hind limb lameness); it is nonpathological, presumably appears simultaneously with primary lameness, and is expected to disappear with the resolution of primary lameness. Conversely, secondary lameness is probably associated with pain. It may not be detected until after primary lameness is found and will continue following the resolution of primary lameness, and both forelimbs or both hind limbs can be involved at the same time. Compensatory lameness in horses has been well studied with kinematics,[20,21] force-measuring treadmills,[22,23] and BMIS systems,[24,25] whereas secondary lameness is a logically suspected but less studied concept supported by clinical opinion.[26]

It should be noted that some sources argue that compensatory lameness should not be called lameness[27–30] or should instead be called false lameness because the limb with signs of lameness is normal. Also, some textbooks do not differentiate between compensatory and secondary lameness, implying instead that they are the same entity.[26] However, this viewpoint suggests that lameness is a disease or syndrome, rather than a clinical sign. We use the terms compensatory and secondary to qualify the lameness as a clinical sign and not as a disease.[31] A consistent intent to use the term lameness to describe a clinical sign is well documented.[32–37]

Compensatory lameness patterns generally follow what has been referred to as the sagittal and diagonal compensatory movement principles,[20] also described as the law of sides.[37] The sagittal compensatory movement principle states that ipsilateral CFHL usually indicates primary hind limb lameness. The diagonal compensatory movement principle states that contralateral CFHL usually indicates primary forelimb lameness. In contrast, secondary lameness patterns attributable to overloading are generally considered to be contralateral only and to occur at the same end or opposite ends of the body.

The purposes of the retrospective study reported here were to estimate the prevalence of forelimb-only lameness, hind limb–only lameness, and CFHL in equids as measured by a BMIS system when trotting in a straight line during the initial lameness evaluation at a veterinary teaching hospital, to determine the proportions of equids with various CFHL patterns during this evaluation, and to investigate associations between the pattern of lameness detected by BMIS assessment and the location of the cause of lameness after full lameness evaluation.

Materials and Methods

Case selection criteria

All equids that were routinely evaluated for lameness or poor performance by clinicians at the University of Missouri Veterinary Health Center's Equine Hospital who used a BMIS system were eligible for study inclusion. Equids that underwent evaluation as part of academic lameness investigations (screening for lameness instruction laboratories and conferences) were also included in the study. A few animals in which lameness was initially detected as part of a prepurchase examination and that subsequently underwent full lameness evaluation were also included.

Medical records review

Electronic medical records of equids that underwent the described lameness examinations between May 1, 2011, and January 9, 2017, were collected and reviewed by 1 author (KGK). Information in the medical record that was collected and reviewed included signalment (age, breed, and sex), reason for evaluation, history, results of physical examination, results of lameness evaluation (including results of nerve blocks), imaging reports, surgery reports (if applicable), case summary and recommendations, letters to referring veterinarians (if applicable), and final diagnosis given by the attending veterinarian. After review of the medical record, a determination was made of whether a definitive diagnosis was achieved or not. If a definitive diagnosis was achieved, the location of the cause of lameness was determined to be in the forelimbs only, hind limbs only, ≥ 1 forelimb and ≥ 1 hind limb (ie, CFHL), or a location not in the limbs. Determination that a definitive diagnosis was achieved also included establishing that no lameness-causing abnormality was present (ie, that an equid was normal).

Lameness assessment

Diagnosis and localization of lameness were attempted with a variety of techniques that included physical examinations, palpation and manipulation of the limbs and torso, application of nerve blocks, and diagnostic imaging (eg, radiography, ultrasonography, scintigraphy, CT, or MRI). The extent of investigation to confirm the location of lameness varied among animals. Definitive diagnosis was not possible in some equids for reasons that included an inability to safely continue nerve blocking attempts owing to the temperament of the animal, owner financial limitations, no desire by the owner to pursue in-depth or continued workup, and exhaustion of all available diagnostic techniques.

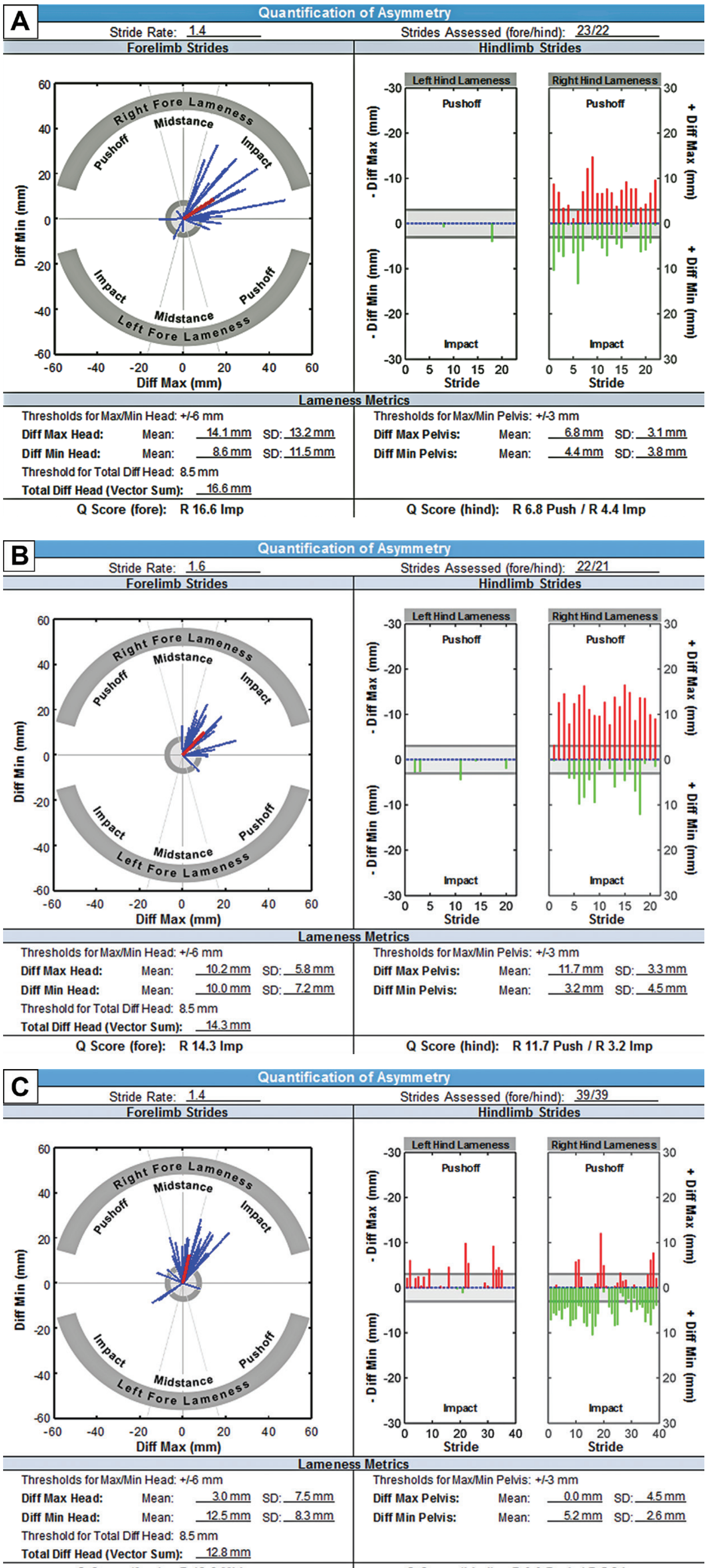
A positive response to a diagnostic nerve block, which we defined as a ≥ 50% decrease in lameness amplitude, was required before it was determined that the location for a cause of lameness in a limb was identified. In a few equids, the location was established to the limb only without blocking on the basis of signs such as development of acute cellulitis with lameness in the same limb. Identification of the location of the cause of lameness in the contralateral half or opposite end of the body when that lameness became apparent after the initial lameness was reduced or eliminated after a positive response to a nerve block was investigated if possible and approved by the owner. Some equids had a definitive abnormality that caused lameness, but the abnormality was not located in the limbs. This determination required performance of diagnostic nerve blocks or full neurologic evaluation with radiography and myelography, scintigraphic imaging with a strong response to treatment, consistent and confirmatory clinicopathologic results for blood and spinal fluid analysis, or positive results for other medical tests, depending on the specific final diagnosis.

At a minimum, all equids were evaluated with BMIS equipment[a,b] while trotting in a straight line. The equids were instrumented with head, right forelimb pastern region, and pelvis sensor devices placed and secured according to manufacturer recommendations and as previously described elsewhere.[1,3–6,17,24,25,37] Most were led by a handler with a lead shank during evaluation; in some situations (most commonly for evaluation of Missouri Fox Trotters), trotting in a straight line was analyzed under saddle. Equids that were capable of lunging were also evaluated while lunging in both directions on ≥ 1 surface, which was usually soft. Many animals were also evaluated after flexion tests and while lunging on a second, harder surface. Some equids were additionally evaluated under saddle with a rider in an arena. For study purposes, only the straight-line evaluation at the trot was considered for the initial BMIS results, but final localization of the cause of lameness relied on BMIS measurement and evaluation of results for all activities (lunging, flexion tests, and under-saddle evaluation as applicable) in addition to the results of nerve blocking and imaging procedures deemed necessary by the clinician and allowed by the owner.

Forelimb lameness was considered present in the initial BMIS-assessed straight-line trotting evaluation when the mean vector sum (calculated as the square root of $[HDmax^2 + HDmin^2]$) for all strides in a trial was > 8.5 mm and the SD of HDmin was < 120% of the mean for all strides analyzed in that trial.[3–6] Hind limb lameness was considered present in the initial straight-line evaluation when the absolute value of mean PDmax, mean PDmin, or both was > 3 mm and the SD of that measurement was less than the mean of all strides analyzed.[3–6] These restrictions allowed a small concession for consistency (strength of evidence) of vertical head movement for forelimb lameness determination, compared with vertical pelvic movement for hind limb lameness determination, because of a naturally higher stride-by-stride variation in vertical head (vs vertical pelvic) movement. In some equids, straight-line trotting data that satisfied these requirements were not collected at the beginning of the lameness evaluation but were obtained after stabilization of the lameness by collecting data from additional trials or while exercising the animal lightly with lunging on a soft surface. If data for multiple straight-line trials were collected before evaluating an equid in other activities (eg, lunge, flexion tests, or under saddle), the last straight-line trial before these activities that satisfied these requirements was used for analysis. If multiple straight-line trials were collected after, but not before, these activities, the first straight-line trial after these activities that satisfied the requirements was used for analysis.

Forelimb and hind limb lameness were further assessed as pushoff or impact types. Forelimb impact lameness was identified when HDmin and HDmax were of the same sign (positive or negative), and forelimb pushoff lameness was identified when HDmin and HDmax were of opposite signs, with positive and negative values (if exceeding the threshold and consistent) for HDmin indicating right and left forelimb lameness, respectively. Hind limb pushoff lameness was identified on the basis of PDmax values, and hind limb impact lameness was identified on the basis of PDmin values, with positive values (if exceeding the threshold and consistent) indicating right hind limb lameness and negative values indicating left hind limb lameness. The described method,[14–17,19,21,38–41] measurements,[1,5,10,12] and thresholds[3–5,11] for assessment of forelimb and hind limb lameness in horses have been previously described.

All BMIS assessments of CFHL when trotting in a straight line were further classified into 8 distinct patterns on the basis of lameness in a forelimb and ≥ 1 hind limb and the timing of hind limb lameness (ie, impact [occurring in the first half of the hind limb stance phase, with PDmin exceeding the threshold], pushoff [occurring in the second half of the hind limb stance phase, with PDmax exceeding the threshold], or both). To limit the different patterns of CFHL to a reasonable number for analysis and because forelimb pushoff lameness prevalence was low, differentiation of forelimb impact or pushoff lameness was not considered in the definition of CFHL patterns. The 8 patterns represented all possible CFHL patterns with the consideration that forelimb lameness cannot be measured bilaterally from a single straight-line trial, but hind limb lameness can be assessed as bilateral if it is a pushoff type on one side and an impact type on the other. The CFHL patterns were defined as lameness in a forelimb with concurrent hind limb lameness as follows **(Figure 1)**: ipsilateral hind limb



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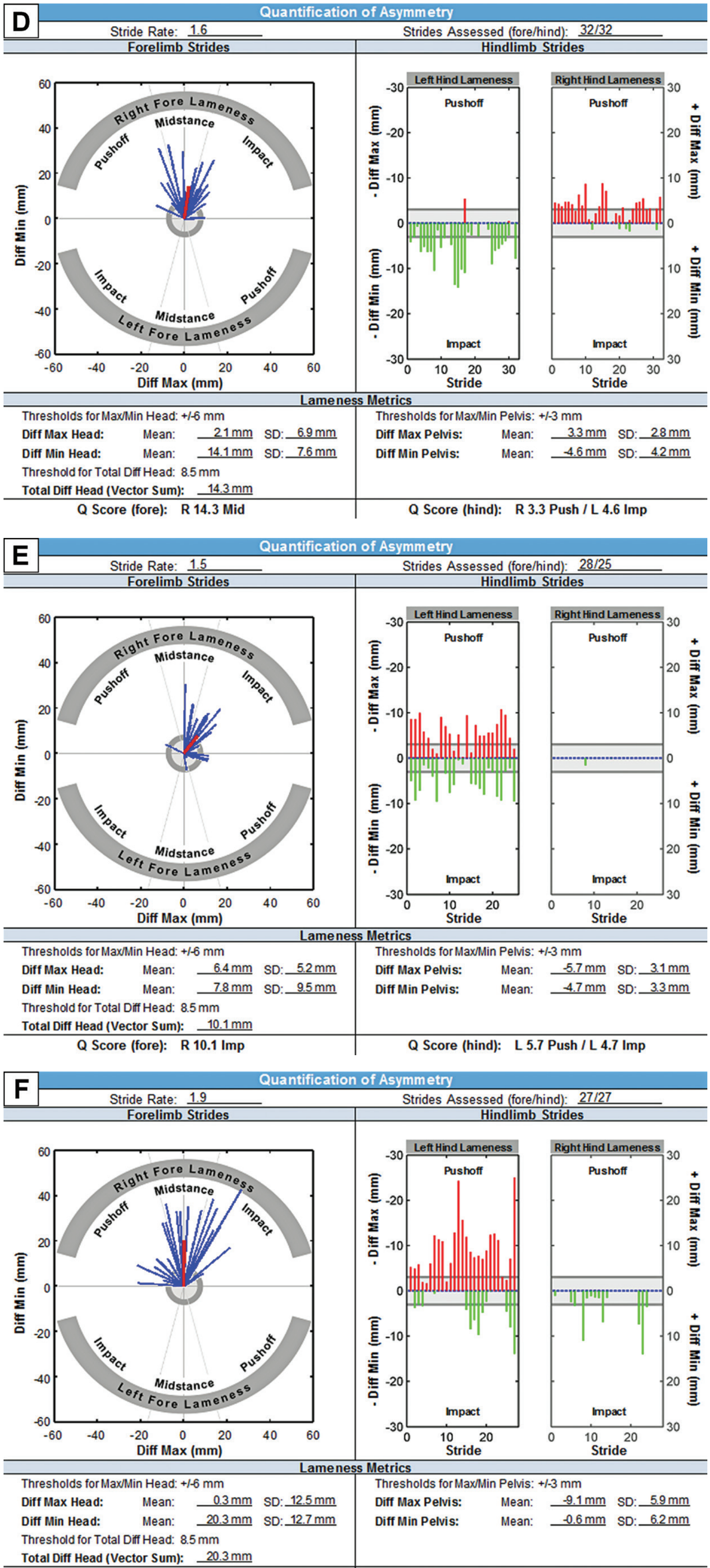
pushoff and impact lameness (pattern 1), ipsilateral hind limb pushoff lameness only (pattern 2), ipsilateral hind limb impact lameness only (pattern 3), ipsilateral hind limb pushoff lameness and contralateral hind limb impact lameness (pattern 4), contralateral hind limb pushoff and impact lameness (pattern 5), contralateral hind limb pushoff lameness only (pattern 6), contralateral hind limb impact lameness only (pattern 7), or contralateral hind limb pushoff lameness and ipsilateral hind limb impact lameness (pattern 8). Patterns 1, 2, and 3 agreed best with the first (sagittal compensatory movement) principle of the law of sides, and patterns 5, 6, and 7 agreed best with the second (diagonal compensatory movement) principle of the law of sides. Patterns 4 and 8 indicated a pushoff lameness in one hind limb and impact lameness in the other.

Statistical analysis

For all equids and for equids with a definitive diagnosis, the observed frequency of initial BMIS assessment of no lameness (or lameness not in the limbs), forelimb-only lameness, hind limb–only lameness, and CFHL (all patterns combined) was compared with expected frequency. Additionally, for equids in each BMIS-assessed initial lameness category (no lameness or lameness not in the limbs, forelimb-only lameness, hind limb–only lameness, and each of the 8 different types of CFHL) with definitive lameness findings after full lameness evaluation, the observed frequency of final lameness localization was compared with the expected frequency. Observed versus expected frequencies were assessed for significance with χ^2 goodness-of-fit analysis. Expected frequency of lameness localization falling into the 4 aforementioned categories was calculated on the basis of 2 a priori assumptions: first, that there was a 1:1 chance of having or not having lameness in a particular limb (ie, lameness was either present or absent in that limb), and second, that the chance of lameness in one limb was independent of the chance of lameness in another limb. This produced 16 different potential combinations of limb lameness ranging from no limbs involved to 4 limbs involved, with expected frequencies of 1 of 16 (6.25%; ie, only 1 combination was



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possible) for no limbs affected, 3 of 16 (18.75%; left limb, right limb, or both) for forelimb-only and hind limb–only lameness, and 9 of 16 (56.25%; various possible combinations of left and right forelimbs and hind limbs) for CFHL. Values of $P < 0.05$ were considered significant. Post hoc pairwise comparisons of observed versus expected frequency were performed with Bonferroni-adjusted P values (0.05/44 pairwise comparisons = 0.0011). All comparisons were performed with statistical software.[c]

Results

The study criteria were met for 1,224 equids. These included 659 American Quarter Horses or Quarter Horse types (including Paint and Appaloosa breeds), 153 Thoroughbreds, 127 warmblood-type horses, 52 Arabians, 39 Missouri Fox Trotters, 28 American Saddlebreds, 25 Tennessee Walking Horses, 18 draft-type horses, 11 Morgans, and 8 donkeys or mules. Fifty-six animals had breed recorded as other or had records annotated with horse or equine without breed specification; 27 were classified as mixed-breed horses, and 21 were listed as different pony breeds or miniature horses. There were 682 geldings, 497 mares, and 45 stallions. Mean ± SD age was 12 ± 5 years (range, 1 to 37 years). The total numbers of horses and observed numbers of horses with a definitive diagnosis in each initial BMIS-assessed category are summarized **(Table 1)**.

Of the 1,224 equids evaluated initially with a BMIS system when trotting in a straight line, 112 (9.2%) measured as having no lameness, 161 (13.2%) measured as having forelimb-only lameness, 258 (21.1%) measured as having hind limb–only lameness, and 693 (56.6%) measured as having CFHL. For the entire study sample, the observed frequency of CFHL was not significantly different from the expected frequency, but the observed frequency of forelimb-only lameness was less than ($P < 0.0001$) the expected frequency and observed frequency of no lameness ($P < 0.0001$) and hind limb–only lameness ($P = 0.001$) was greater than the expected frequency. Of the 1,224 equids, 862 (70.4%) had a definitive diagnosis (ie, finding of no lameness or a definitive localization of the cause of lameness). Of these 862 equids,

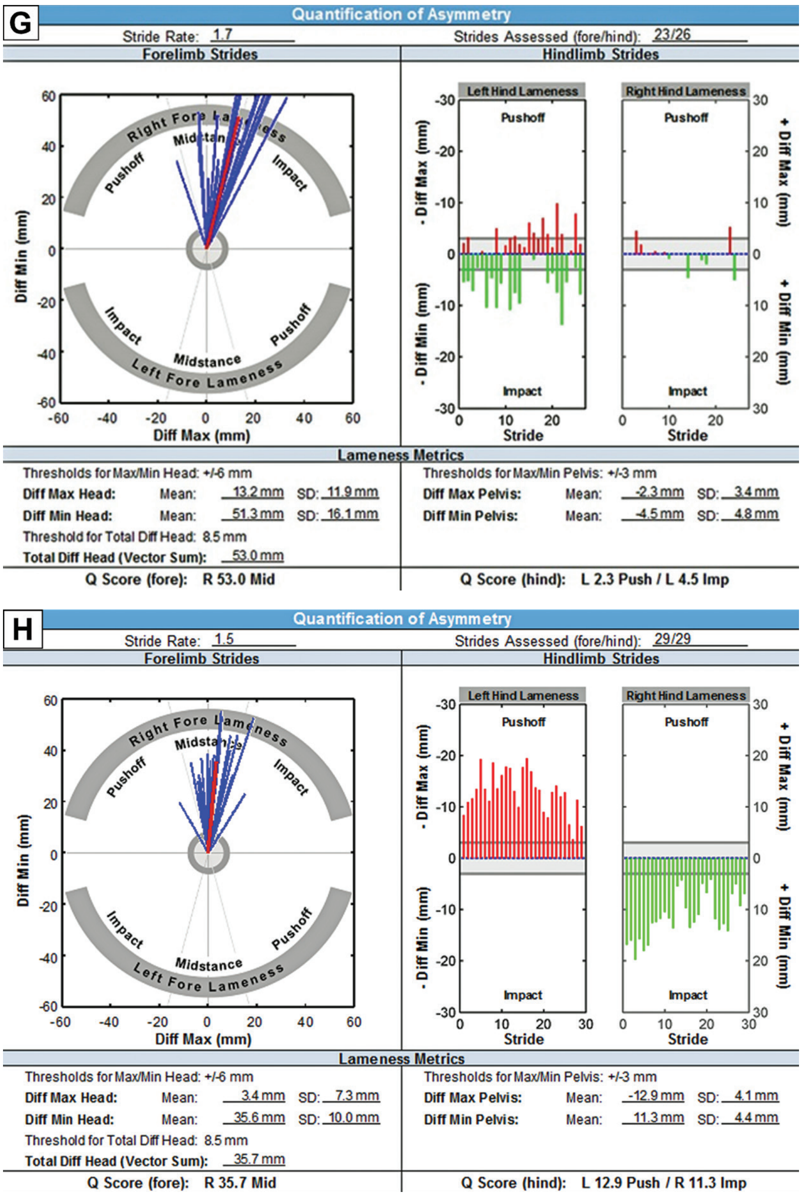

Figure 1—Representative examples (system output) of the 8 categories of CFHL measured by BMIS straight-line trotting evaluation. A—Pattern 1: forelimb lameness with ipsilateral hind limb impact and pushoff lameness. B—Pattern 2: forelimb lameness with ipsilateral hind limb pushoff lameness only. C—Pattern 3: forelimb lameness with ipsilateral hind limb impact lameness only. D—Pattern 4: forelimb lameness with ipsilateral hind limb pushoff and contralateral hind limb impact lameness. E—Pattern 5: forelimb lameness with contralateral hind limb impact and pushoff lameness. F—Pattern 6: forelimb lameness with contralateral hind limb pushoff lameness only. G—Pattern 7: forelimb lameness with contralateral hind limb impact lameness only. H—Pattern 8: forelimb lameness with contralateral hind limb pushoff and ipsilateral hind limb impact lameness. The left side of each panel indicates status of forelimb lameness, and the right side indicates status of hind limb lameness; left and right subpanels on the right side depict status of left and right hind limb lameness. Each example indicates a right forelimb lameness with blue lines (each indicating a stride) projecting upward. Length of blue lines depicts the vector sum of HDmax and HDmin. Vertical red lines projecting upward indicate hind limb pushoff lameness. Length of red lines depicts PDmax. Green lines projecting downward indicate hind limb impact lameness. Length of green lines depicts PDmin. Diff Max Head = HDmax. Diff Max Pelvis = PDmax. Diff Min Head = HDmin. Diff Min Pelvis = PDmin. The Q score for the forelimb represents the vector sum with a label of L (left) if HDmin is negative and R (right) if HDmin is positive. The Q scores for impact (Imp) and pushoff (Push) components of hind limb lameness represent the absolute values of PDmin and PDmax, respectively.

103 (11.9%) initially measured (with the BMIS system) as having no lameness, 109 (12.6%) measured as having forelimb-only lameness, 158 (18.3%) measured as having hind limb–only lameness, and 492 (57.1%) measured as having CFHL. Among these horses, the observed frequency of hind limb–only lameness or CFHL was not significantly different than the expected frequency, but the observed frequency of no lameness was greater than ($P < 0.0001$) and the observed frequency of forelimb-only lameness was less than ($P < 0.0001$) the expected frequency.

Of 161 equids with forelimb-only lameness assessed on initial BMIS evaluation, 79 (49.1%) had predominantly or exclusively right forelimb lameness and 82 (50.9%) had predominantly or exclusively left forelimb lameness (an equid with bilateral forelimb lameness not predominant on 1 side would have registered results indicating no lameness). Of the 258 equids with hind limb–only lameness assessed on initial BMIS evaluation, 125 (48.4%) had predominantly or exclusively right hind limb lameness, 122 (47.3%) had predominantly or exclusively left hind limb lameness, and 11 (4.3%) had bilateral hind limb lameness.

Of 161 equids identified as having forelimb-only lameness on initial BMIS evaluation, 119 (73.9%) had lameness in the first half of the stance (impact lameness) and 42 (26.1%) had lameness in the second half of the stance (pushoff lameness). Of 258 equids that had hind limb–only lameness identified during the initial evaluation, 92 (35.7%) had only impact lameness, 102 (39.5%) had only pushoff lameness, 53 (20.5%) had pushoff and impact lameness in the same hind limb, and 11 (4.3%) had pushoff lameness in one hind limb and impact lameness in the other.

The observed frequency of no lameness after full lameness evaluation was greater than expected only for the initial BMIS-assessed category of no lameness ($P < 0.0001$; Table 1). The observed frequency of forelimb-only lameness after full lameness evaluation was greater than expected for the initial BMIS-assessed category of forelimb-only lameness and for CFHL patterns 3, 5, 6, 7, and 8 ($P < 0.0001$ for all comparisons). The observed

Table 1—Definitive diagnosis rates and results of χ^2 goodness-of-fit analysis for differences between observed and expected frequencies of definitive findings after full lameness evaluation in 1,224 equids examined for lameness or poor performance between May 1, 2011, and January 9, 2017, and categorized by initial BMIS-assessed lameness category.

			Definitive findings after full lameness evaluation			
Initial BMIS-assessed lameness category	No. of equids	No. (%) of equids with a definitive diagnosis	None (no lameness, lameness not localized to limbs)	Forelimb only (unilateral, bilateral)	Hind limb only (unilateral, bilateral)	CFHL
None	112	103 (92.0)	61* (57, 4)	19 (12, 7)	20 (16, 4)	3†
Forelimb only	161	109 (67.7)	13 (6, 7)	64* (52, 12)	17 (14, 3)	15†
Hind limb only	258	158 (61.2)	16 (3, 13)	29 (22, 7)	102* (71, 31)	11†
CFHL pattern	693	492 (71.0)	26 (0, 26)	234* (171, 63)	167* (128, 39)	65†
1	132	109 (82.6)	3 (0, 3)	11 (7, 4)	80* (65, 15)	15†
2	71	44 (62.0)	1 (0, 1)	5 (3, 2)	29* (18, 11)	9‡
3	68	53 (77.9)	5 (0, 5)	24* (18, 6)	18§ (11, 7)	6†
4	28	20 (71.4)	4 (0, 4)	4 (1, 3)	7 (4, 3)	5
5	119	84 (70.6)	2 (0, 2)	55* (40, 15)	16 (15, 1)	11†
6	158	110 (69.6)	5 (0, 5)	86* (67, 19)	5† (4, 1)	14†
7	66	36 (54.5)	3 (0, 3)	27* (19, 8)	2 (2, 0)	4†
8	51	36 (70.6)	3 (0, 3)	22* (16, 6)	10 (9, 1)	1†
All	**1,224**	**862 (70.4)**	**116 (66, 50)**	**346 (257, 89)**	**306 (229, 77)**	**94**

Values for definitive findings represent number of equids. Values of $P < 0.0011$ were considered significant (with Bonferroni adjustment).
*Frequency is greater than expected ($P < 0.0001$). †Frequency is less than expected ($P < 0.0001$). ‡Frequency is less than expected ($P = 0.001$). §Frequency is greater than expected ($P = 0.001$)
Expected frequency for CFHL = Total number with definitive diagnosis X 9/16. Expected frequency for forelimb-only or hind limb–only lameness = Total number with definitive diagnosis X 3/16. Expected frequency for no lameness = Total number with definitive diagnosis X 1/16.
For study purposes, only the straight-line evaluation at the trot was considered for initial BMIS results, but final localization or identification of the cause of lameness relied on use of all available diagnostic information. Only data for equids with definitive findings were included in the goodness-of-fit analysis. The category of none included equids identified as having no lameness and those for which the cause of lameness was not localized to the limbs. The CFHL patterns were designated as lameness in a forelimb with one of the following: ipsilateral hind limb push off and impact lameness (pattern 1), ipsilateral hind limb push off lameness only (pattern 2), ipsilateral hind limb impact lameness only (pattern 3), ipsilateral hind limb push off and contralateral hind limb impact lameness (pattern 4), contralateral hind limb push off and impact lameness (pattern 5), contralateral hind limb push off lameness only (pattern 6), contralateral hind limb impact lameness only (pattern 7), or contralateral hind limb push off and ipsilateral hind limb impact lameness (pattern 8).

frequency of hind limb–only lameness after full lameness evaluation was greater than expected for the initial BMIS-assessed category of hind limb–only lameness ($P < 0.0001$) and for CFHL patterns 1, ($P < 0.0001$), 2 ($P < 0.0001$), and 3 ($P = 0.001$) and less than expected for initial BMIS-assessed CFHL pattern 6 ($P < 0.0001$). The observed frequency of CFHL after full lameness evaluation was less than expected for all initial BMIS-assessed lameness categories except for pattern 4. No horses were determined to have no lameness after full lameness evaluation if measurements indicated CFHL on initial BMIS assessment while trotting in a straight line.

Equids initially assessed as having no lameness with the BMIS system when trotting in a straight line had the highest (103/112 [92%]) definitive diagnostic rate after full lameness evaluation. Equids initially assessed as having CFHL pattern 7 (forelimb lameness with ipsilateral hind limb impact lameness only) with the BMIS system when trotting in straight line had the lowest (36/66 [54.5%]) definitive diagnostic rate.

Discussion

In the present study, the assessment of CFHL during initial BMIS evaluation of equids trotting in a straight line was more common than identification of forelimb-only or hind limb–only lameness, accounting for 693 of 1,224 (56.6%) cases in which animals were evaluated because of lameness or poor performance. However, ultimate localization of a lameness-causing abnormality in both a forelimb and hind limb was identified in only 94 of 862 (10.9%) equids that had definitive findings. In a small proportion of cases (112/1,224 [9.2%]), no lameness was detected during the initial BMIS-assessed straight-line trotting. However, in almost half of these cases in which a definitive diagnosis was achieved (46/103 [44.7%]), a cause of lameness was ultimately identified during or after other components of the evaluation, including flexion tests, lunging, and, in some cases, evaluation under saddle, and later localized by use of diagnostic nerve blocks.

When forelimb-only or hind limb–only lameness was detected during the initial BMIS straight-line trotting evaluation, the most common outcome was eventual localization of the primary cause of lameness to that same limb. However, 17 of 109 (15.6%) animals with definitive findings that were initially identified as having forelimb-only lameness ultimately had the primary abnormality localized to a hind limb, and 15 (13.8%) were found to have CFHL. Similarly, 29 of 158 (18.4%) equids identified with the BMIS system as having hind limb–only lameness when initially trotting in a straight line had a final determination of primary abnormality in a forelimb, with another 11 (7%) found to have CFHL. These findings might have been attributable to compensatory or secondary lameness, with a primary lameness below the detection threshold, so that it was not until other parts of the lameness evaluation, including nerve blocking, were completed that the primary lameness became apparent.

The most commonly detected CFHL patterns on initial evaluation were forelimb lameness with contralateral hind limb pushoff, ipsilateral hind limb pushoff and impact, contralateral hind limb pushoff and impact, and ipsilateral hind limb pushoff lameness (patterns 6, 1, 5, and 2, respectively, in descending order of frequency). These patterns were identified for 480 of the 693 (69.3%) equids that were assessed as having CFHL with the BMIS system when trotting in a straight line. Patterns 1 and 2 can be attributed to the first principle of the law of sides. Patterns 5 and 6 can be attributed to the second principle of the law of sides. Indeed, the most common location of a definitive cause of lameness was in the forelimbs for equids identified as having initial BMIS-assessed CFHL patterns 6 (86 forelimb-only lameness and 14 CFHL; 100/110 [90.9%]) and 5 (55 forelimb-only lameness and 11 CFHL; 66/84 [78.6%]) and in the hind limbs for those identified as having BMIS-assessed CFHL patterns 1 (80 hind limb–only lameness and 15 CFHL; 95/109 [87.2%]) and 2 (29 hind limb–only lameness and 9 CFHL; 38/44 [86.4%]). These results suggested that compensatory lameness is a major reason for CFHL.

Forelimb lameness with only ipsilateral (CFHL pattern 3) or only contralateral (CFHL pattern 7) hind limb impact lameness was less common. Pattern 3 can be equally explained by primary forelimb or primary hind limb lameness, assuming that weight will be shifted away from a painful limb to its contralateral counterpart in the opposite half of the body in a trotting quadruped. Landing with more force on the contralateral limb in the opposite end of the body will make the ipsilateral limb in the opposite end of the body appear to land with less force and thus will appear as lameness in that (ipsilateral) limb. Our results supported this, with fairly similar frequencies for localization of the definitive cause of lameness in a forelimb (24/53 [45%]) or in a hind limb (18 [34%]) and a low frequency (6 [11%]) in both a forelimb and a hind limb for pattern 3. An ipsilateral lameness pattern signifying primary hind limb lameness and a contralateral pattern signifying primary forelimb lameness are generally expected in accordance with the law of sides, but results of the present study suggested that when the CFHL pattern detected at the beginning of the lameness examination is ipsilateral and the hind limb lameness is impact only, the first principle of the law of sides breaks down. The primary lameness can be in the forelimb, hind limb, or both. Similarly, pattern 7 cannot be explained by any known compensatory lameness pattern but can be equally explained as primary forelimb with secondary hind limb lameness or primary hind limb with secondary forelimb lameness. However, in our study sample, definitive localization for a cause of lameness in these equids was usually in the forelimbs only (27/36 [75%]) and less commonly in the hind limbs only (2 [6%]) or in both a forelimb and hind limb (4 [11%]). More importantly, equids with this pattern of CFHL had the lowest rate of definitive findings (36/66 [55%]) among the initially assigned lameness categories. These findings suggested that a CFHL with hind limb impact lameness alone will be more of a diagnostic challenge for definitive localization of primary lameness on the basis of initial BMIS assessment for equids trotting in a straight line.

The least commonly observed CFHL patterns during the initial evaluation in our study involved pushoff lameness in one hind limb and impact lameness in the other, making up only 79 of 693 (11.4%) initial BMIS-assessed CFHLs (51 of pattern 8 and 28 of pattern 4). Forelimb lameness with contralateral hind limb pushoff and ipsilateral hind limb impact lameness (pattern 8) can be explained with a slight modification of the second principle of the law of sides adding compensatory ipsilateral hind limb impact lameness as a consequence of weight shifting from a primarily affected forelimb. Observation of this effect is supported in some studies[21,23,42] that used BMIS systems, kinematics, and force-measuring treadmills, but not in others.[7,14,18] Nevertheless, equids with this pattern of CFHL had a high rate of definitive findings (36/51 [71%]), and a definitive abnormality was found in the forelimbs of 23 of 36 (64%) affected animals (22 forelimb-only lameness and 1 CFHL). Forelimb lameness with ipsilateral hind limb pushoff and contralateral hind limb impact lameness (pattern 4), which cannot be explained solely by compensatory lameness mechanisms, was detected least often (28/1,224 [2.3%] equids of the study sample and 28/693 [4%] equids with CFHL) and had the most evenly spread distribution for the definitive location of the cause of lameness (4/20 [20%] in forelimbs only, 7 [35%] in hind limbs only, 5 [25%] in both forelimbs and hind limbs, and 4 [20%; the highest rate of such findings in the study] not localized to the limbs). The most common diagnosis for animals with lameness not localized to the limbs was cervical vertebral osteoarthritis; others included equine protozoal myelitis, cervical vertebral instability or narrowing, polysaccharide storage myopathy and tying up, impinging vertebral spinous processes, thoracolumbar facet joint (synovial intervertebral articulation) osteoarthritis, equine degenerative myelopathy, and tail injury. The small number of animals with each of these causes of lameness precluded investigation of associations between initial BMIS-assessed lameness patterns and specific diagnoses.

A definitive diagnosis of no lameness-causing abnormality, or findings that an equid was clinically normal, was not evident for any animals in the study that were identified as having CFHL on initial BMIS evaluation when trotting in a straight line. The milder a primary lameness is, the less likely it is to cause compensatory or secondary lameness in another limb. Investigation of CFHL is understandably more complex than assessment of lameness in a single limb, and clinicians may have had less confidence in determining that there was no orthopedic or neurologic abnormality in such animals. It might be that identification of CFHL in equids trotting in a straight line is a stronger sign that abnormality exists than if forelimb-only or hind limb–only lameness is initially detected, and this is a potential consideration when BMIS evaluations are used to assess for lameness during prepurchase examinations.

Most of the equids in the present study (659/1,224 [53.8%]) were Quarter Horses or Quarter Horse types used in a variety of disciplines including barrel racing, reining, cutting, roping, mounted shooting, and western pleasure. The prevalences of forelimb-only lameness, hind limb–only lameness, and CFHL from populations with different breed and use distributions may differ from those found in the present study.

Observation for and measurement of asymmetric whole-pelvis fall and rise between right and left hind limb stance phases (PDmin and PDmax) to detect and characterize hind limb lameness should not be confused with observing for and measuring asymmetric tuber coxae vertical movement between the right and left sides of the pelvis. Both are measurements of asymmetry, but the former determines the asymmetric shape of whole-pelvis trajectory, whereas the latter assesses either greater elevation or greater depression of vertical tuber coxae movement on the side of the lame hind limb as a proxy for asymmetric pelvic rotation. Because absolute asymmetry measurements are greater for the pelvic rotation method than for the vertical pelvic movement method at equivalent lameness amplitudes,[12,40] differences are probably easier to detect subjectively with the rotation method, and asymmetric vertical tuber coxae excursion is strongly correlated with pain-induced lameness.[2,12,40] However, observation for asymmetry in total vertical movement of the tuber coxae between the left and right sides (instead of asymmetric trajectory of a midline location) requires assessment of the animal from behind and placing sensors to the left and right of the midline if measurements are to be obtained. This makes assessment of asymmetric pelvic rotation less practical than asymmetric whole-pelvis vertical trajectory for detection of hind limb lameness in equids. Also, in a few instances, we have evaluated equids assumed to be clinically normal on the basis of history and physical examination results and found observable asymmetric pelvic rotation but symmetric vertical whole-pelvis trajectory. Likewise, in a few instances, we have evaluated equids with definitive hind limb abnormalities and lameness on the opposite side of presumed lameness according to assessment of asymmetric pelvic rotation. We have not seen or measured this discrepancy in animals with asymmetric vertical whole-pelvis rise and fall. Vertical movement of the whole pelvis is the variable most likely to be closely correlated with vertical ground reaction force and impulse, which have been shown to be the kinetic variables most closely associated with pain during weight bearing.[43,44]

In most equids of the present study for which a cause of lameness was found or lack of lameness was confirmed, results of the initial straight-line trotting evaluation were identical to definitive results found after consideration of all lameness evaluation results. However, this was not always the case. Our results suggested that most CFHL patterns seen during the initial straight-line trotting evaluation that can be easily explained by compensatory movement principles may be useful for localization of primary limb lameness in many cases, but that some CFHL patterns, specifically those in which hind limb lameness is only of the impact type, suggest that the diagnostic process will be more difficult. Results of initial straight-line trotting evaluations with a BMIS system may be helpful in planning how to proceed with the remaining lameness evaluation.

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Footnotes

a. Lameness Locator, Equinosis LLC, Columbia, Mo.
b. The Q with Lameness Locator, Equinosis LLC, Columbia, Mo.
c. SAS, version 9.4, SAS Institute Inc, Cary, NC.

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