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Withers vertical movement symmetry is useful for locating the primary lame limb in naturally occurring lameness

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Abstract

Background: During orthopaedic assessment of lame horses, a head nod is commonly present in both primary forelimb and hindlimb lame horses. Additional motion metrics that could assist clinicians in correctly differentiating between these two scenarios would be of great clinical value.

Objectives: The primary objective of this study was to examine whether withers movement asymmetry can be used in a clinical setting to distinguish primary forelimb lameness from compensatory head movement asymmetry due to primary hindlimb lameness.

Study design: Retrospective, multicentre study.

Methods: Movement asymmetry of head, withers and pelvis was measured using multi-camera optical motion capture, as part of routine lameness investigations at four European equine hospitals. Vertical movement asymmetry parameters from 317 horses trotting in a straight line were compared before and after successful diagnostic analgesia of a single limb. Descriptive statistics, *t*-tests and linear models were used to analyse the data.

Results: In forelimb lame horses, 80%–81% showed head and withers asymmetry both indicating lameness in the same forelimb. In hindlimb lame horses, 69%–72% showed head asymmetry ipsilateral to the lame hindlimb and withers asymmetry diagonal to the lame hindlimb, thus, head and withers asymmetry indicated lameness in different forelimbs. A large (>15 mm) compensatory head nod was seen in 28%–31% of the hindlimb lame horses. In 89%–92% of these, head and withers asymmetry indicated lameness in different forelimbs. Withers asymmetry decreased linearly with reduced head or pelvic asymmetry for both forelimb and hindlimb lame horses.

Main limitations: Compensatory strategies were evaluated on group level to identify common patterns, potentially ignoring uncommon individual strategies.

Conclusions: Withers vertical movement asymmetry metrics can be useful in helping to locate the primary lame limb during quantitative lameness assessment. Head and withers movement asymmetry parameters generally indicate the same forelimb in forelimb lame horses, but different forelimbs in hindlimb lame horses.

KEYWORDS
compensatory lameness, gait analysis, horse, kinematics, optical motion capture, withers asymmetry

1 | INTRODUCTION

Lameness in one limb disrupts movement symmetry throughout the horse's body, which complicates the localisation of pain during lameness evaluations. Compensatory head movement asymmetries in hindlimb lame horses, and pelvic movement asymmetries in horses with forelimb lameness, have been demonstrated in straight line trot[1–5] and on the lunge.[6] In primary hindlimb lameness, compensatory head movement asymmetry mimicking ipsilateral forelimb lameness is evident as a lower minimum position of the head during the lame hind diagonal stance.[1,2,4–6] Horses with primary forelimb lameness demonstrate a more complex pattern. Compensatory pelvic asymmetry mimicking diagonal hindlimb lameness dominates in both induced[1,2] and naturally occurring forelimb lameness.[3,5] This compensatory asymmetry consists of a reduced maximum height (decreased push-off) after diagonal hindlimb stance.[2,3,5,6] In addition, compensatory asymmetry mimicking ipsilateral impact lameness may be found, measured as a difference in mid-stance minimum position of the pelvis[2,5,6] or as reduced peak vertical force.[7,8]

The compensatory head nod in horses with a primary hindlimb lameness, particularly the difference in head minimum position, can be large enough in relation to the pelvic asymmetry to be mistaken for a primary forelimb lameness.[2,6] Such misinterpretation may delay correct diagnosis and can be a contributing factor to the low inter-observer agreement for lameness assessment between veterinarians.[9,10]

However, lameness results in vertical movement asymmetry not only of the head and pelvis, but also of the horse's trunk, for example, at the withers.[1,11,12] Some commercially available systems for clinical lameness detection offer the possibility to measure withers asymmetry. In horses with induced forelimb lameness,[11,12] withers asymmetry usually indicates lameness in the same forelimb, that is, head and withers asymmetries agree. In contrast, in horses with induced hindlimb lameness that show a compensatory head nod, the head asymmetry commonly indicates the ipsilateral forelimb (e.g., right fore if right hind is lame), while the withers asymmetry indicates the diagonal forelimb (e.g., left fore if right hind is lame Figure 1).[12] If this applies also in horses with naturally occurring lameness, measuring withers

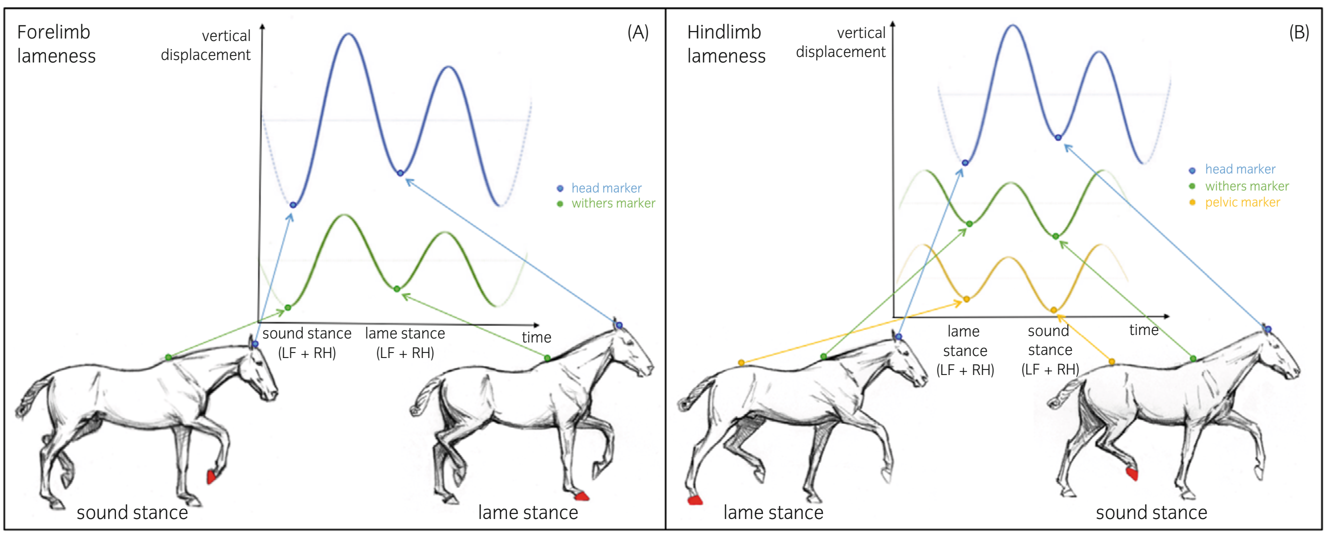

FIGURE 1 (A) *Primary right forelimb lameness*. During the sound diagonal stance (left forelimb [LF]—right hindlimb [RH]), the horse reaches a lower vertical position for both head and withers compared with the lame diagonal stance. Head and withers asymmetry parameters agree and both indicate lameness in the right forelimb. Arrows indicate the minimum points reached by the upper body landmarks during each diagonal stance. (B) *Primary right hindlimb lameness*. During the stance phase of the sound diagonal (left hindlimb [LH]—right forelimb [RF]), the withers and pelvic markers exhibit a lower vertical position but the head exhibits a higher vertical position compared with the lame diagonal. Head and withers asymmetry parameters disagree and head asymmetry indicates lameness in the right forelimb, whereas the withers asymmetry parameter indicates the left fore. Arrows indicate the minimum points reached by the upper body landmarks during each diagonal stance. Diagram reproduced with permission of the Editor of *Equine Veterinary Journal*.[12]

asymmetry could assist veterinarians in identifying whether the primary lameness is in a forelimb or a hindlimb.

The aim of this study was therefore to describe associations between changes in movement asymmetry of the head, withers and pelvis in horses with naturally occurring lameness responsive to diagnostic analgesia. Our first hypothesis was that head and withers movement asymmetry parameters agree (with both indicating the lame forelimb) in horses with a positive response to forelimb diagnostic analgesia. Our second hypothesis was that head and withers movement asymmetry disagree (indicate lameness in different forelimbs) in hindlimb lame horses with a positive response to diagnostic analgesia.

2 | MATERIALS AND METHODS

2.1 | Study design

This retrospective multicentre study involved horses presenting for lameness examination between 2015 and 2020 at the University Equine Clinic at the Swedish University of Agricultural Sciences in Uppsala, Sweden; the University Equine Clinic at Utrecht University, The Netherlands; the Equine Clinic in Lüsche, Germany; and the Evidensia Specialist Equine Hospital in Helsingborg, Sweden. Objective movement symmetry data, collected as part of routine lameness examinations, were reviewed and horses were included if they had successful objective measurements (criteria specified below) of a clear and consistent lameness (head or pelvic asymmetry above thresholds outlined below) which was reduced by at least 70% after diagnostic analgesia in a single limb.

2.2 | Data collection

Objective lameness assessments were performed in straight line trot using an optical motion capture system (Qualisys AB), where the three-dimensional (3D) position of skin-mounted spherical reflective markers was measured within a calibrated volume. The markers (diameter 25 mm) were attached with double-sided adhesive tape to predefined anatomical landmarks. Movement asymmetry parameters were calculated based on vertical movements of reflective markers: one attached over the highest point of the withers (withers), one in the midline between the tubera sacrale (pelvis), one on each tuber coxae (tuber coxae) and one between the ears (poll) or in the midline of the forehead. The head marker location (poll or forehead) was always consistent for all measurements within each horse. Marker position data were collected at 100–200 Hz while the horses were trotting in a straight line on a hard or soft surface (for surface and camera set-up details see Table S1). A baseline trial was conducted before diagnostic analgesia, and then one or more trials after each diagnostic analgesia.

2.3 | Data processing

The 3D coordinates and locations of the markers were extracted from the motion capture software Qualisys Track Manager[13] and the data included were checked manually to ensure correct identification. Marker coordinates were exported to Matlab[14] for further analysis using custom-written scripts.

Stride segmentation was carried out based on peaks in the vertical movement of the tubera sacrale, while left/right step differentiation was performed using a classification algorithm based on expected characteristics of pelvic roll and yaw calculated from the coordinate data for the tuber coxae markers.[15] The vertical movement signals of head, withers and pelvis were high-pass filtered using a 4th-order zero-phase Butterworth filter, with the cut-off frequency adjusted to 70% of the stride frequency of the horse in each trial.[16] Speed was calculated as the distance that the pelvis marker moved in the horizontal (x–y) plane in each frame divided by sampling frequency, following band-pass filtering (0.01–16 Hz) of the coordinate data to remove noise. The values obtained were then averaged first for each stride and then for each trial.

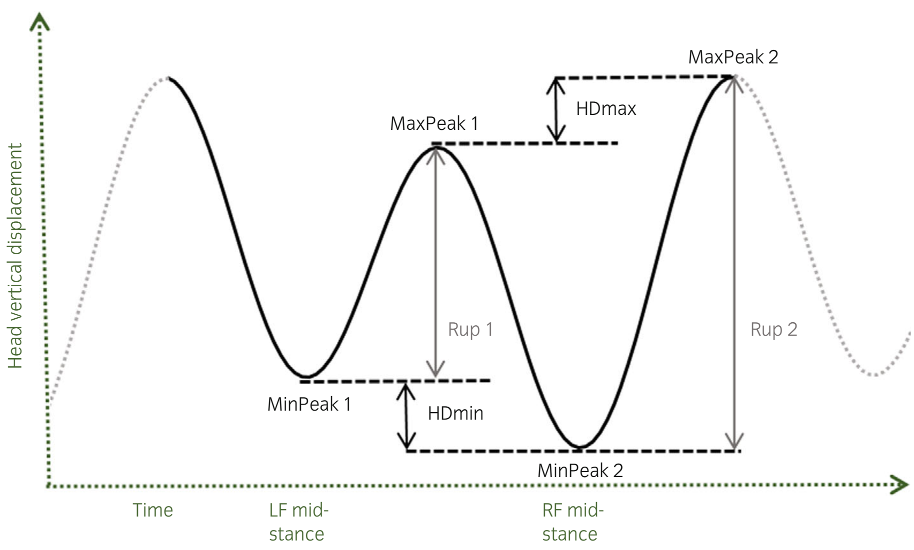

FIGURE 2 Vertical asymmetry parameters used in the study. Vertical displacement of the head plotted against time during a full stride in trot. Example of negative head displacement (HDmin, HDmax and HDRup (Rup 1–Rup 2)) for a horse with left forelimb lameness. Withers and pelvis vertical displacement show a similar pattern in trot and asymmetry parameters were calculated in the same way, but from withers/pelvis vertical displacement. Asymmetry parameters were calculated as mean across strides for each trial.

2.3.1 | Vertical movement symmetry

From the vertical movement of the head (H), withers (W) and pelvis (P) markers, three asymmetry parameters were calculated for each location on a stride-by-stride basis (Figure 2). Comparing the first and the second half of the stride, differences between the local vertical displacement minima (HDmin/WDmin/PDmin), maxima (HDmax/WDmax/PDmax) and upward range between minima and subsequent maxima (HDRup/WDRup/PDRup) were determined and mean values were calculated for each trial. Following the common convention, these variables were determined such that a positive value indicated right-sided lameness and a negative value left-sided lameness.

2.3.2 | Timing

Differences in timing of minima (min, MinPeak in Figure 2) and maxima (max, MaxPeak in Figure 2) occurring during the same half-stride were calculated between head and withers (H–W) and between head and pelvis (H–P). Differences were labelled ipsilateral (I) for the half stride where the forelimb on the lame side was in stance (right forelimb if the horse was lame on the right forelimb or hindlimb) and contralateral (C) otherwise. Overall, there were eight timing differences: H–W C min, H–W C max, H–W I min, H–W I max, H–P C min, H–P C max, H–P I min and H–P I max. These timing differences were calculated by first expressing minima and maxima occurrences as a percentage of stride duration and then subtracting the percentage value for the withers or pelvis from the corresponding percentage value for the head. A positive timing difference then indicates that the corresponding extreme value occurred later for the head than for the withers (H–W variables) or pelvis (H–P variables), that is the head movement was delayed relative to withers or pelvic movement.

2.3.3 | Outlier removal

Strides with head vertical range of motion outside ±40% of the trial mean vertical head range of motion, with pelvic vertical range of motion outside ±20% of the trial mean vertical pelvis range of motion, and/or with strides with a stride duration outside ±20% of the trial mean stride duration were automatically removed, in order to exclude strides where the horse was not in steady-state locomotion. Data for the remaining strides were averaged over each trial and the trial mean values for each parameter were used for further analysis.

2.4 | Data analysis

Horses were initially separated into forelimb lame and hindlimb lame, based on whether they responded to diagnostic analgesia in a forelimb or a hindlimb. The horses in each of these categories were then further divided into three groups, based on their vertical movement asymmetry at baseline and following diagnostic analgesia. The three forelimb lameness groups were Group 1: HDmin, Group 2: HDmax, Group 3: HDRup. The three hindlimb lameness groups were Group 4: PDmin, Group 5: PDmax, Group 6: PDRup. Horses were included in these groups based on fulfilling all of the following criteria: (a) baseline value for the asymmetry parameter in question (for each group) exceeding a specified threshold (HDmin/HDmax: >|15| mm, HDRup: >|20| mm, PDmin/PDmax: >|7| mm, PDRup: >|10| mm) and with standard deviation lower than the mean value; (b) >70% decrease in the same parameter after diagnostic analgesia; and (c) asymmetry data from both baseline and diagnostic analgesia trials for at least eight strides after outlier removal. Each horse was included in multiple groups if it met the above criteria for more than one parameter. However, horses with response to diagnostic analgesia in a forelimb were not eligible for PD subgroups, and vice versa. If a horse had data from several visits (dates of presentation to the clinic) that met all criteria for a group, the visit with the largest proportional decrease following diagnostic analgesia for the parameter in question was selected. Similarly, if diagnostic analgesia was performed multiple times on the same limb, the trial with the highest proportional decrease relative to baseline was chosen. If diagnostic analgesia was performed in multiple limbs before a positive response was recorded, or if the initial asymmetry indicated the opposite limb compared with where diagnostic analgesia was performed (i.e., a HDmin value indicating right fore, but diagnostic analgesia performed on the left fore), that visit was excluded.

The asymmetry variables used (Figure 2) are by convention positive for right-sided lameness and negative for left-sided lameness. To enable pooling of data in descriptive and analytical statistics, all values for asymmetry parameters were multiplied by -1 for horses with baseline left-sided lameness (diagnostic analgesia performed on the left forelimb or hindlimb). This effectively rendered all horses initially right forelimb or hindlimb lame. To specifically study horses with hindlimb lameness and large compensatory head movement asymmetry, subsets of Groups 4 and 5 with absolute HDmin asymmetry >15 mm ipsilateral to the lame hindlimb at initial measurement were created.

2.5 | Statistical analysis

Statistical analysis was performed using R[17] open software. To evaluate associations between changes in the different asymmetry parameters between baseline and post-analgesia trials, linear models were created using the lm function in the *stats* package (version 4.0.5). A separate model was made for each asymmetry parameter group. Change (in mm) between baseline and post-analgesia in the parameter on which group selection had been based was used as independent variable and changes in the other parameters were used as outcome, resulting in 2–4 univariable models per group. Addition of change in speed as a fixed factor and data collection location as a random factor was evaluated. Scatter plots were used to confirm that a linear relationship was a reasonable assumption. Normality of residuals was verified using quantile–quantile plots and homoscedasticity by plotting the residuals against the fitted values. Leverage plots were scrutinised to identify influential outliers. The overall level of significance was set to $p < 0.05$.

Paired *t*-tests were used to evaluate changes in each group between baseline and post-analgesia in timing difference between minima and maxima of the head, withers and pelvis. Welch two-sample t-tests were used to test the difference in timing between the combined forelimb and the hindlimb lameness groups at the initial measurement before diagnostic analgesia. The assumption of normal distribution of each set of differences was verified using quantile–quantile plots. Level of significance was set to $p < 0.05$ and to adjust for multiple comparisons (48 paired t-tests and eight Welch two-sample t-tests, respectively) Bonferroni post hoc correction was applied.

3 | RESULTS

3.1 | Descriptive findings

In total, data from 1208 horses on which measurements were performed during lameness investigations involving diagnostic analgesia were evaluated for inclusion in the study, of which data from a total of 317 horses were included in the final analysis (Figure 3).

The 317 horses represented in the data comprised 153 eldings, 149 mares, 7 stallions and 8 horses of unknown gender, with a mean age of 11 years (range 2–32 years, age not recorded in 9 horses). They comprised 204 Warmblood type horses, 24 ponies, 13 Quarter horses, 10 Icelandic horses, 9 PRE horses and 57 of other, mixed or unknown breed. Mean (±SD) number of strides per trial was 25 (±7) before and 21 (±7) after outlier removal. Descriptive statistics for the vertical movement symmetry measurements made before and after diagnostic analgesia for the six selected groups can be found in Table S2. Changes in each asymmetry parameter between the initial measurement and the measurement after diagnostic analgesia per group are shown in Figure 4.

A contingency table (Table 1) of the forelimb HDmin and WDmin indicated as lame before diagnostic analgesia for each lameness group

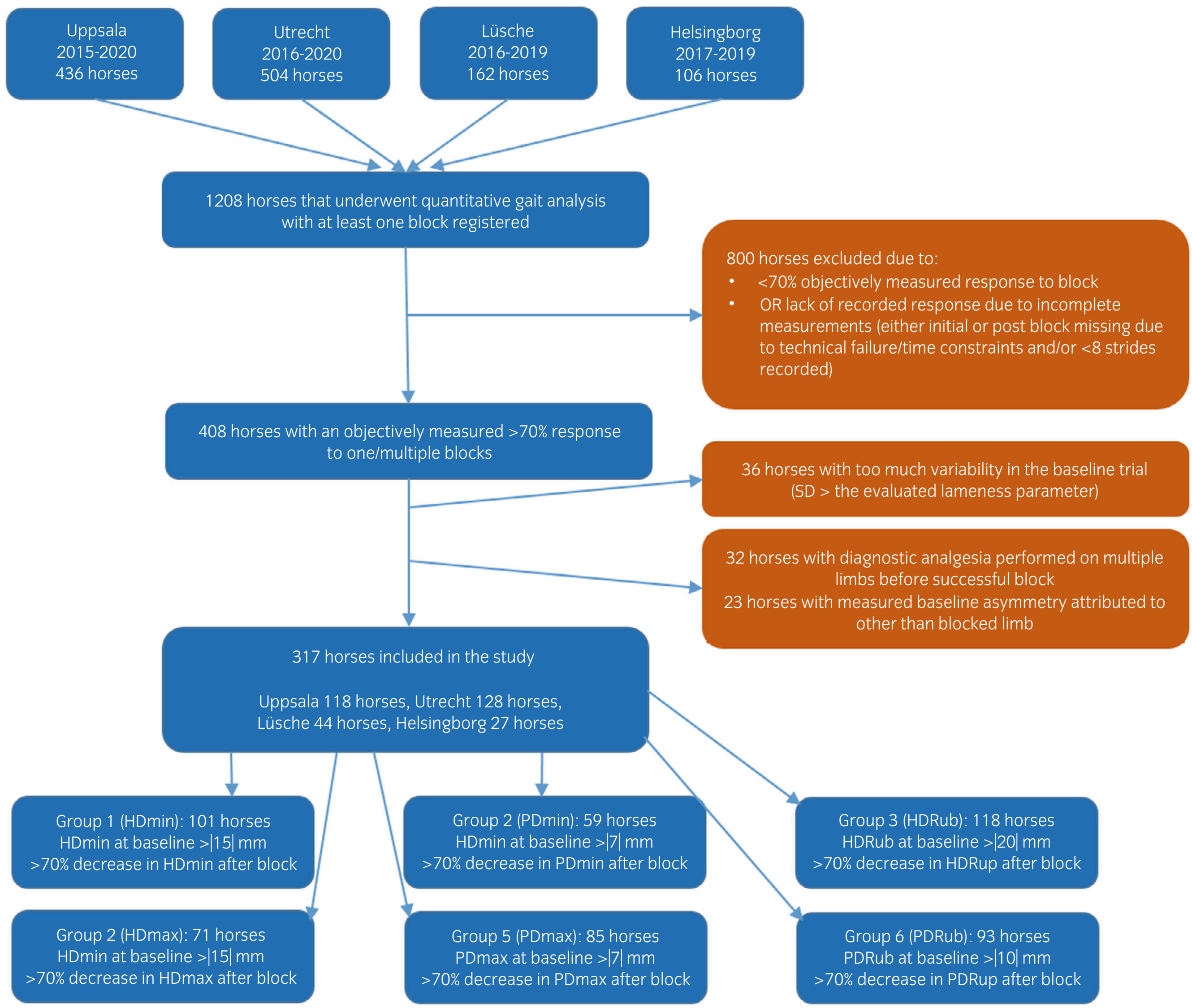

FIGURE 3 Flow chart showing the selection process for horses included in the study. Horses could be included in multiple groups if they met the inclusion criteria (e.g., a horse with initial pelvis displacement PDmin and PDmax asymmetry >|7|mm where both asymmetries decreased by >70% was included in both Groups 4 and 5).

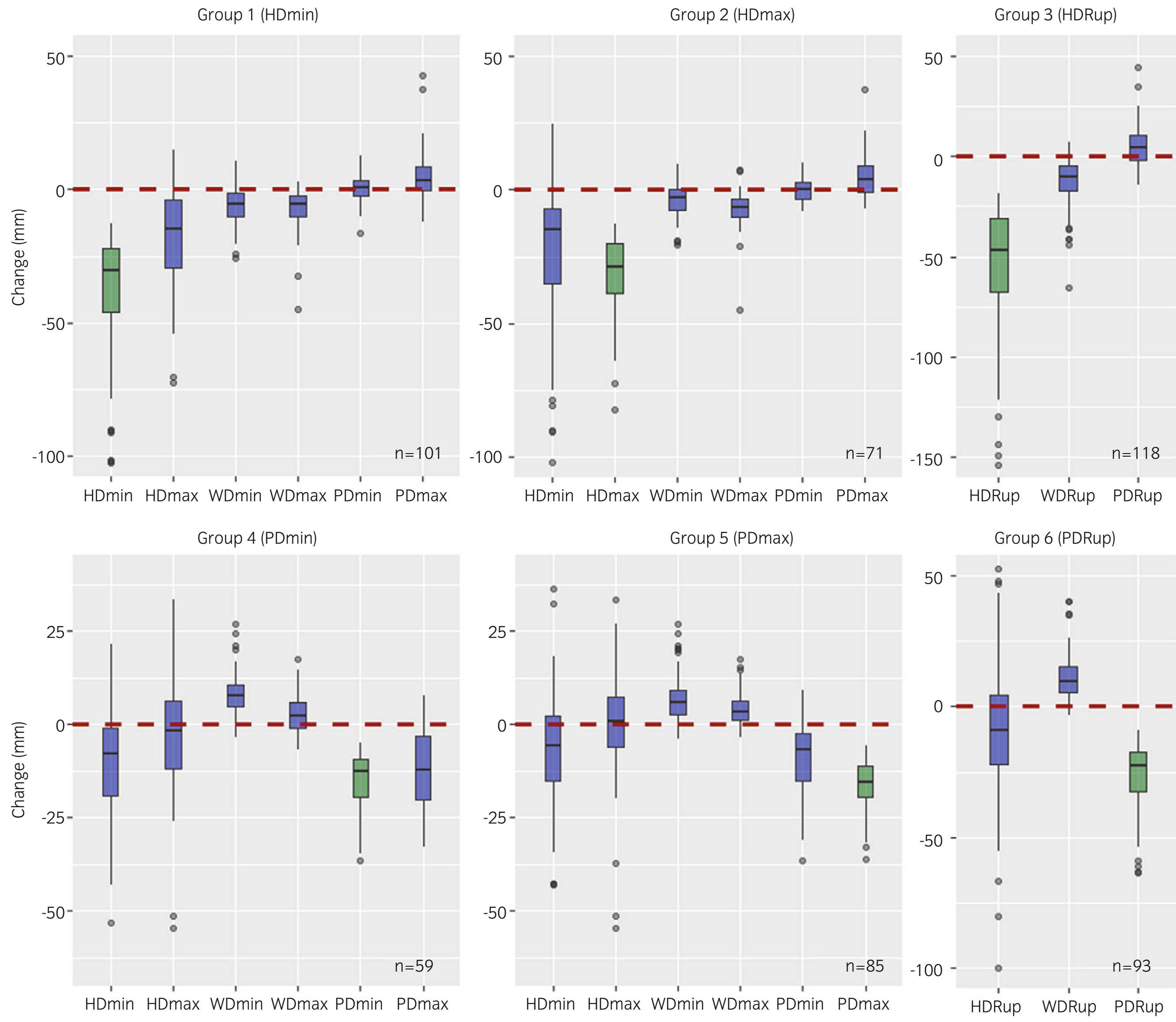

FIGURE 4 Change (mm) in head (HD), withers (WD) and pelvis displacement (PD) asymmetry parameters per lameness group between baseline measurement and measurement after diagnostic analgesia. The green box indicates the parameter that needed to decrease in response to diagnostic analgesia for the horse to be included in that lameness group. Before calculating the change in asymmetry, asymmetry parameter values for horses with lameness in the left limb were multiplied by -1, effectively rendering all horses initially right limb lame (HDmin/HDmax/HDRup are right forelimb lame, PDmin/PDmax/PDRup are right hindlimb lame). Boxplots show median values (horizontal bold line), 25th and 75th percentile (interquartile range [IQR], box limits), whiskers (thin lines) extending to median ±1.5*IQR and dots representing outliers.

showed that among horses with forelimb lameness, 80%–81% showed ipsilateral head and withers movement asymmetry (both indicating right forelimb lameness). Among hindlimb lameness cases, 69%–72% presented with ipsilateral head asymmetry (indicating right forelimb lameness) and diagonal withers asymmetry (indicating left forelimb lameness). In hindlimb lame horses with large ipsilateral head asymmetry (HDmin >15 mm), 89%–92% showed diagonal withers asymmetry.

3.2 | Statistical models

After inspection of the residuals, the linear model fits were considered adequate. Addition of speed as a fixed factor had no or only minimal effects on the associations between asymmetry variables (Table S3), and was hence omitted. Addition of data collection location as a random factor rendered a singular fit in almost half of the models and minimally affected the associations in the rest (Table S3), and was hence omitted. Linear model output is presented in Table 2 and correlations to the change in WDmin in Figure 5.

3.2.1 | Associations between head and withers asymmetry and between pelvis and withers asymmetry

In the lameness groups selected for response to forelimb diagnostic analgesia (Groups 1–3, HDmin/HDmax/HDRup, see Table 2), the model-estimated change (slope) in the withers asymmetry parameters

TABLE 1 Pattern of head and withers asymmetry in the different lameness groups at baseline.

		Selected group[a]					
HDmin[b]	WDmin[b]	Group 1 (HDmin)	Group 2 (HDmax)	Group 4 (PDmin)	Group 5 (PDmax)	Group 4 (PDmin) with ipsilateral HDmin[c]	Group 5 (PDmax) with ipsilateral HDmin[c]
RF	RF	81%	80%	5%	6%	11%	8%
LF	RF	-	4%	2%	2%	-	-
LF	LF	-	2%	24%	20%	-	-
RF	LF	19%	14%	69%	72%	89%	92%
No. of horses in group		101	71	59	85	18	24

Note: Contingency table showing the forelimb in which HDmin and WDmin indicated lameness before diagnostic analgesia. To combine data from horses with left- and right-sided lameness, values for horses with initial lameness in the left limb were multiplied by −1, effectively rendering all horses initially right limb lame (RF in the HDmin/HDmax group, RH in the PDmin/PDmax group).

Abbreviations: HD, head displacement; RF/LF, right/left forelimb; PD, pelvis displacement; RH, right hindlimb; WD, withers displacement.

[a]Groups of horses selected based on initial lameness exceeding a specified threshold (HDmin/HDmax: >|15|mm, PDmin/PDmax: >|7|mm) and a >70% objectively measured reduction in diagnostic analgesia for the specific variable.

[b]The forelimb in which this asymmetry parameter indicated lameness.

[c]Ipsilateral (RF) HDmin >15 mm before diagnostic analgesia.

TABLE 2 Linear model output for the six groups of horses.

Selected group[a]	Outcome variable	Independent variable	Estimate (mm)	95% CI	R	p-Value
Group 1 (HDmin)	Change in WDmin[b]	Change in HDmin[b]	0.18	0.12, 0.24	0.54	**<0.001**
	Change in WDmax[b]		0.17	0.12, 0.22	0.58	**<0.001**
	Change in PDmin[b]		−0.04	−0.08, 0.01	−0.16	0.1
	Change in PDmax[b]		−0.19	−0.25, −0.13	−0.55	**<0.001**
Group 2 (HDmax)	Change in WDmin[b]	Change in HDmax[b]	0.14	0.05, 0.22	0.37	**0.001**
	Change in WDmax[b]		0.18	0.11, 0.25	0.53	**<0.001**
	Change in PDmin[b]		−0.05	−0.11, 0.01	−0.20	0.1
	Change in PDmax[b]		−0.15	−0.26, −0.05	−0.34	**0.004**
Group 3 (HDRup)	Change in WDRup[b]	Change in HDRup[b]	0.20	0.15, 0.25	0.62	**<0.001**
	Change in PDRup[b]		−0.12	−0.16, −0.07	−0.41	**<0.001**
Group 4 (PDmin)	Change in HDmin[b]	Change in PDmin[b]	0.72	0.12, 1.32	0.31	**0.02**
	Change in HDmax[b]		−0.26	−0.78, 0.25	0.13	0.3
	Change in WDmin[b]		−0.49	−0.64, −0.34	−0.65	**<0.001**
	Change in WDmax[b]		−0.29	−0.46, −0.12	−0.42	**0.001**
Group 5 (PDmax)	Change in HDmin[b]	Change in PDmax[b]	0.76	0.30, 1.22	0.34	**0.001**
	Change in HDmax[b]		−0.01	−0.48, 0.47	0.00	0.9
	Change in WDmin[b]		−0.51	−0.66, −0.35	−0.58	**<0.001**
	Change in WDmax[b]		−0.35	−0.47, −0.23	−0.54	**<0.001**
Group 6 (PDRup)	Change in HDRup[b]	Change in PDRup[b]	0.65	0.27, 1.02	0.34	**0.001**
	Change in WDRup[b]		−0.48	−0.58, −0.38	−0.71	**<0.001**

Note: Estimated change (mm) in each outcome variable for each mm change in the independent variable that occurred in response to diagnostic analgesia. p-Values in bold indicate that the estimated slope is significantly different from zero.

Abbreviations: HD, head displacement; PD, pelvis displacement; R, correlation coefficient; WD, withers displacement; 95% CI, 95% confidence interval.

[a]Groups of horses selected based on initial lameness exceeding a specified threshold (HDmin/HDmax: >|15|mm, HDRup: >|20|mm, PDmin/PDmax: >|7|mm, PDRup: >|10|mm) and >70% objectively measured reduction in response to diagnostic analgesia for the specific variable. HDmin/HDmax/HDRup are right forelimb lame. PDmin/PDmax/PDRup are right hindlimb lame.

[b]Change in asymmetry parameters in mm between baseline trial and trial after diagnostic analgesia.

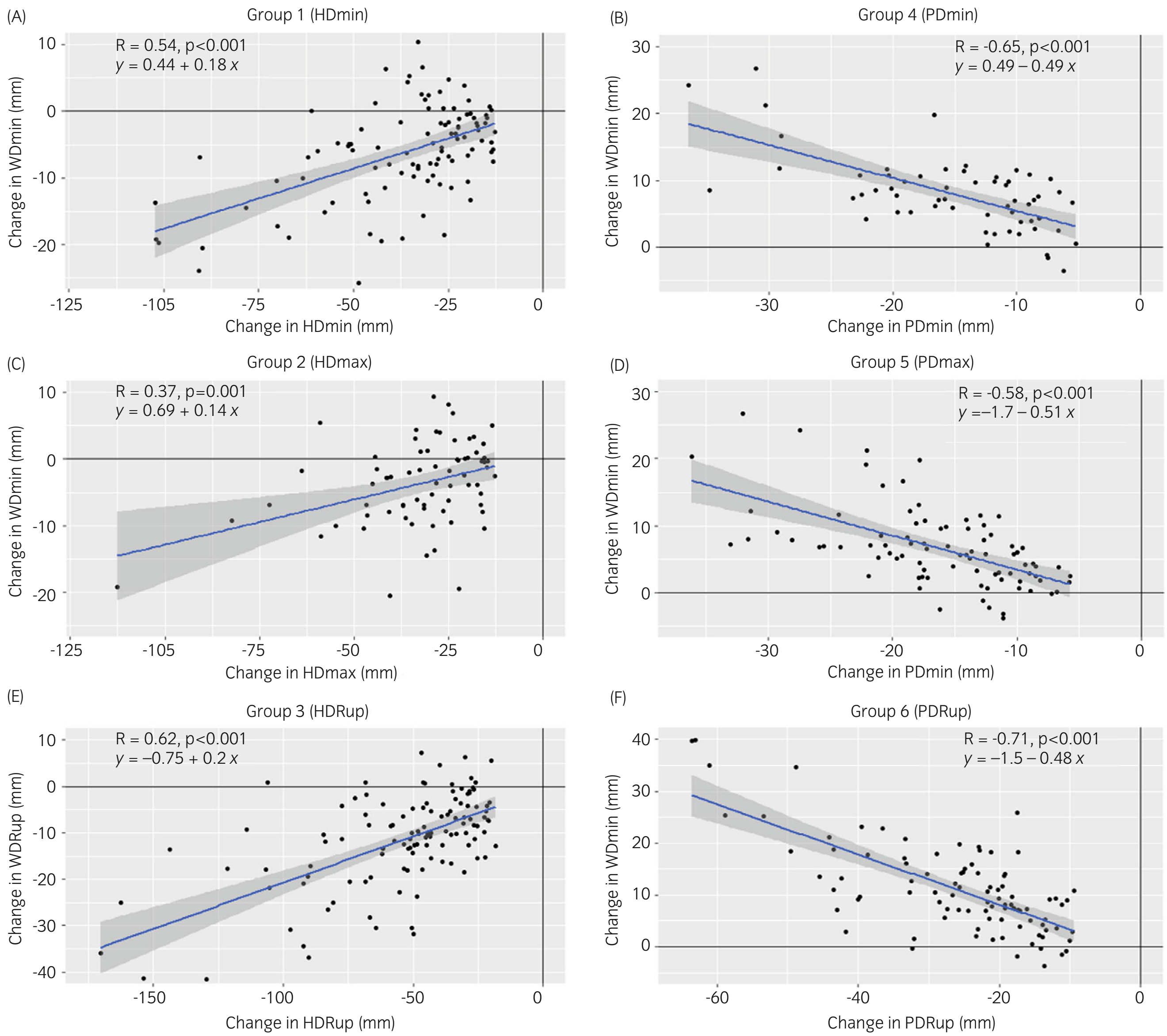

FIGURE 5 Linear correlation of the change in response to diagnostic analgesia in the initial lameness parameter of each lameness group with the change in withers (WD) asymmetry. A moderate positive correlation was seen for horses with forelimb lameness and a moderate negative correlation for horses with hindlimb lameness. Before calculating the change in asymmetry, asymmetry parameter values for horses with lameness in the left limb were multiplied by −1, effectively rendering all horses initially right limb lame (HDmin/HDmax/HDRup are right forelimb lame, PDmin/PDmax/PDRup are right hindlimb lame). Thus in horses with right forelimb lameness the withers measurements generally indicate the right forelimb, while in horses with right hindlimb lameness the withers measurements generally indicate the left forelimb.

(WDmin/WDmax/WDRup) was 0.14–0.20 mm for each mm change in the respective head parameter (Table 2). The change in head and withers asymmetry showed a moderate positive correlation. In the groups selected for response to hindlimb diagnostic analgesia (Groups 4–6, PDmin/PDmax/PDRup, see Table 2), the model-estimated change (slope) in the withers asymmetry parameters (WDmin/WDmax/WDRup) was −0.51 to −0.29 mm for each mm change in the respective pelvis parameter (Table 2). Pelvic asymmetry and withers asymmetry thus showed a moderate negative correlation. These results are illustrated in Figure 5, which shows that for the forelimb lame groups, reduced head movement asymmetry was associated with a decrease in withers asymmetry. The withers asymmetry initially indicated lameness in the lame forelimb. For the hindlimb lame groups, a decrease in pelvic movement asymmetry was correlated with reduced withers asymmetry. The withers asymmetry initially indicated lameness in the forelimb diagonal to the lame hindlimb.

3.2.2 | Associations between head and pelvis asymmetry

Analysis of associations between head and pelvic asymmetry for the forelimb lame groups (Groups 1–3, HDmin/HDmax/HDRup) showed that the model-estimated change (slope) in PDmax/PDRup was −0.19

to −0.12 mm for each mm change in head asymmetry (Table 2). In the hindlimb lame groups (Groups 4–6, PDmin/PDmax/PDRup), the model-estimated change (slope) in HDmin/HDRup was 0.65–0.72 mm for each mm change in pelvis asymmetry (Table 2).

3.2.3 | Timing differences

The differences in timing of minima and maxima between head and withers and between head and pelvis met the normality assumption. The timing between head and withers (H–W) changed significantly in response to diagnostic analgesia in all three forelimb lame groups except for the timing in reaching the max peak during the lame forelimb stance (H–W I max) in Group 2 (Table 3, for a graphical example, see Figure 6). The timing between head and pelvis (H–P) changed significantly in response to diagnostic analgesia in all forelimb and hindlimb lameness groups, except for the timing in reaching the min peak during the lame hindlimb stance (H–P C min) in Group 6 (Table 3). For some of the relative timing variables (H–W C min, H–W I max, H–P I max), there was also a significant difference between the combined forelimb and hindlimb lame groups at the baseline measurement (before diagnostic analgesia).

4 | DISCUSSION

The results obtained in this study support the two hypotheses we tested, that is, that head and withers vertical movement asymmetry metrics indicate lameness in the same forelimb in horses with forelimb lameness, but different forelimbs in horses with hindlimb lameness.

TABLE 3 Differences in timing of minimum and maximum displacement between the head, withers and pelvis at baseline (Pre) and after diagnostic analgesia (Post).

	H–W C min			H–W C max			H–W I min			H–W I max		
Selection	Pre	Post	*p*-Value	Pre	Post	*p*-Value	Pre	Post	*p*-Value	Pre	Post	*p*-Value
Group 1 (HDmin)[a]	1.9	2.8	**<0.001**	6.0	3.1	**<0.001**	4.1	2.4	**<0.001**	0.1	2.9	**<0.001**
Group 2 (HDmax)[a]	1.9	3.2	**<0.001**	6.7	4.8	**<0.001**	6.0	2.8	**<0.001**	1.5	2.2	0.05
Group 3 (HDRup)[a]	1.9	3.2	**<0.001**	6.2	3.8	**<0.001**	4.7	2.4	**<0.001**	0.6	3.0	**<0.001**
Group 4 (PDmin)[a]	2.5	2.9	0.2	5.0	3.1	**<0.001**	4.2	3.1	**<0.001**	2.1	3.3	**<0.001**
Group 5 (PDmax)[a]	3.2	3.0	0.4	5.4	4.0	**<0.001**	4.4	3.6	0.002	2.8	3.4	0.003
Group 6 (PDRup)[a]	2.9	2.8	0.5	5.2	3.4	**<0.001**	4.0	3.3	**0.001**	2.5	3.5	**<0.001**
Forelimb[b]	2.0			5.9			4.4			0.7		
Hindlimb[b]	3.0			5.1			4.1			2.7		
p-Value[c]	**0.002**			0.02			0.4			**<0.001**		

	H–P C min			H–P C max			H–P I min			H–P I max		
	Pre	Post	*p*-Value	Pre	Post	*p*-Value	Pre	Post	*p*-Value	Pre	Post	*p*-Value
Group 1 (HDmin)[a]	0.2	1.6	**<0.001**	5.0	1.9	**<0.001**	2.3	0.7	**<0.001**	−1.5	1.9	**<0.001**
Group 2 (HDmax)[a]	0.0	1.6	**<0.001**	5.8	3.7	**<0.001**	4.2	1.1	**<0.001**	−0.2	1.0	**0.001**
Group 3 (HDRup)[a]	0.3	2.0	**<0.001**	5.2	2.6	**<0.001**	2.8	0.5	**<0.001**	−1.0	1.8	**<0.001**
Group 4 (PDmin)[a]	0.2	1.3	**0.001**	4.8	2.2	**<0.001**	3.5	1.7	**<0.001**	0.5	2.3	**<0.001**
Group 5 (PDmax)[a]	0.9	1.7	**<0.001**	5.3	3.2	**<0.001**	3.5	2.0	**<0.001**	1.2	2.2	**<0.001**
Group 6 (PDRup)[a]	0.5	1.2	0.002	4.9	2.4	**<0.001**	3.2	1.8	**<0.001**	0.8	2.4	**<0.001**
Forelimb[b]	0.2			5.0			2.7			−0.9		
Hindlimb[b]	0.8			4.8			3.3			1.2		
p-Value[c]	0.1			0.7			0.2			**<0.001**		

Note: For a graphical example, see Figure 6. Mean values are given as percentage of stride duration (for SD, mean difference and 95% confidence intervals, see Table S4). Timing differences were labelled ipsilateral (I) for the half-stride where the forelimb on the lame side was in stance (right forelimb if the horse was lame on the right forelimb or hindlimb) and contralateral (C) otherwise; min/max: timing difference in reaching the minima (min, MinPeak in Figure 2) and maxima (max, MaxPeak in Figure 2) occurring during the same half-stride. Positive values indicate a relative delay of head movement compared with withers/pelvic movement. *p*-Values in bold indicate a significant difference in the paired *t*-test with Bonferroni post hoc correction (uncorrected *p*-Values shown).

Abbreviations: C, contralateral; H, head; HD, head displacement; I, ipsilateral; P, pelvis; PD, pelvis displacement; W, withers; WD, withers displacement.

[a]Groups selected based on initial lameness exceeding a specified threshold (HDmin/HDmax: >|15|mm, HDRup: >|20|mm, PDmin/PDmax: >|7|mm, PDRup: >|10|mm) and a >70% reduction in response to diagnostic analgesia. HDmin/HDmax/HDRup are right forelimb lame. PDmin/PDmax/PDRup are right hindlimb lame.

[b]Forelimb is the combination of Groups 1–3 and hindlimb of Groups 4–6, with each horse represented once.

[c]*p*-Value for a Welch two-sample *t*-test between the forelimb and the hindlimb group at the initial measurement before diagnostic analgesia (Pre).

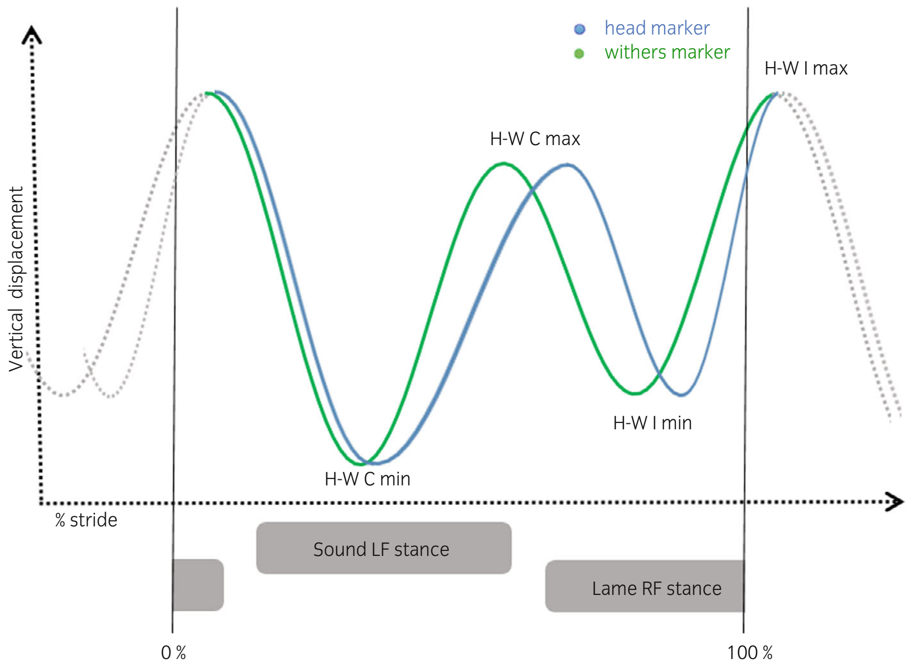

FIGURE 6 Graphical example of the timing differences found between head and withers (H–W) vertical displacement minimum (min) and maximum (max) for Group 1 horses (HDmin) before diagnostic analgesia (Pre-columns for Group 1 in the top part of Table 3). Timing differences are exaggerated for illustrative purposes and are not true to scale. I, ipsilateral: the half-stride where the forelimb on the lame side was in stance (right forelimb if the horse was lame on the right forelimb or hindlimb) and contralateral (C) otherwise. In Group 1 horses (with initial right forelimb lameness as measured by HDmin), there was a delay in the rise of the head compared with the withers at the maximum before (H–W C max), and fall of the head at the minimum during (H–W I min), the lame right forelimb stance (Table 3, Group 1 (HDmin) Pre columns). After diagnostic analgesia (which decreased HDmin by >70%), head and withers were more in sync at the same points of the stride cycle (Table 3, Group 1 (HDmin) Post columns).

We show, for the first time, clear associations between changes in these withers asymmetry metrics and the decrease in the primary lameness in response to diagnostic analgesia. This was demonstrated in a large sample of horses with naturally occurring lameness and a clear, objectively measured reduction in response to diagnostic analgesia.

At presentation, 80%–81% of horses with forelimb lameness showed head and withers movement asymmetry, with both indicating lameness in the lame forelimb (later confirmed). Head movement asymmetry has previously been linked to relatively lower peak vertical force production by the lame forelimb.[18] Furthermore, there was a positive correlation between the change in withers asymmetry and the decrease in head asymmetry in response to diagnostic analgesia. This means that both head and withers asymmetry decreased in the lame limb when the lameness was successfully blocked. Similar results have been reported for horses with a subjectively evaluated positive response to diagnostic analgesia.[19] From a clinical perspective, if a horse shows head movement asymmetry indicative of right forelimb lameness, withers asymmetry also indicating the right forelimb supports the presence of a primary forelimb lameness.

In horses with hindlimb lameness responding to diagnostic analgesia, 69%–72% initially presented with head and withers asymmetry indicating lameness in different forelimbs. Furthermore, while the withers asymmetry was reduced in response to the block, the direction of change was opposite to that of the corresponding pelvic asymmetry parameter. Similar findings have been made in a study of horses with a subjectively judged positive response to diagnostic analgesia.[19]

We believe these differences observed in head and withers asymmetry pattern could be useful in a clinical setting for distinguishing between true forelimb lameness and compensatory head movement asymmetry originating from a primary hindlimb lameness.[1,2,4–6] To investigate this further, hindlimb lame horses with an absolute value for HDmin >15 mm were selected. This magnitude of ipsilateral head movement asymmetry, which was seen in 28%–31% of the hindlimb lame horses included in the study (Groups 4–5), was deemed sufficiently large to be easily mistaken for a primary forelimb lameness. This proportion of hindlimb lame horses with large ipsilateral head asymmetry is similar to that found in other studies.[4,12] In the present study, 89%–92% of these hindlimb lame horses showed head and withers asymmetry indicating lameness in different forelimbs. This suggests that head and withers asymmetry indicating lameness in different forelimbs is a relatively strong signal to the clinician that the horse's primary problem is hindlimb lameness, while when both indicate the same forelimb this suggests true forelimb lameness (Figure 1). Withers asymmetry is difficult to assess visually, but it can easily be measured using an objective gait analysis system, which is an added incentive for using such a system.

In clinical practice, a compensatory head nod measured as an HDmin asymmetry should be regarded as an expected finding in predominantly hindlimb lame horses. All three groups with hindlimb lameness in this study (Groups 4–6) showed a decrease in a head movement asymmetry (HDmin or HDRup) attributed to the ipsilateral forelimb following successful diagnostic analgesia, agreeing with earlier findings.[1,2,4–6] This confirms the presence of a causal relationship between head and pelvic movement asymmetry in these cases. However, in terms of magnitude this is not a 1:1 relationship, and the variation between horses is considerable. The estimated decrease in HDmin presented here is notable, but the correlation between the reductions in head and pelvic movement asymmetry was weak ($R = 0.0$–0.34). Similar findings have been reported previously for hindlimb lame horses. A correlated change was seen in two previous studies,[2,6] whereas others found a correlation only in some groups[5] or not at all.[4] Intuitively, hindlimb lame horses with a large pelvic movement asymmetry should show a large head nod and vice versa, but both the present and previous studies suggest that the magnitude of compensatory head movement asymmetry does not strictly follow the degree of pelvic movement asymmetry in hindlimb lame horses. This variation in compensatory strategy between horses could be linked to, for example, anatomical conformation, movement pattern, neck and back pathology and/or additional lame limbs.

On examining the timing of head movement in relation to withers and pelvis difference values, it was found that the rise and the fall of the head was generally delayed in relation to the rise and fall of the withers and pelvis, which is in agreement with observations in presumed sound Warmblood horses in a previous study.[20] However, there were still differences both between sound and lame diagonals, and before versus after successful diagnostic analgesia. In measurements before diagnostic analgesia, the pattern of the results suggested that the head and withers/pelvis were generally more in sync before (timing difference between maximum values) and during (timing difference between minimum values) the diagonal stance, when the lame horses likely transferred the load forward within the diagonal pair of limbs[7] (e.g., H–W C min and H–W I max, see Figure 6). For example, in forelimb lame horses the head and withers rose closer together in time before, and were lowered almost simultaneously during, the sound forelimb stance (see Figure 6). After diagnostic analgesia, the delay between head and withers movement increased for these instances. In contrast, when the horses likely transferred the load backwards within the diagonal[7] (e.g., H–W C max and H–W I min, see Figure 6), the head movement was further delayed relative to the withers, that is, a larger positive value. For example, before and during the lame forelimb stance, the head movement was more delayed relative to withers movement (Figure 6). A similar pattern was seen for the timing between head and pelvis in the hindlimb lame groups. These changes in relative timing between head/withers/pelvis that occur in lame horses could be a further clue to the more detailed mechanisms of lameness compensation and merit further investigation. In addition, on comparing all forelimb lame horses to all hindlimb lame horses before diagnostic analgesia, significant effects of location (fore versus hind) were observed. These observed differences between fore- and hindlimb lame horses could have potential value in helping the clinician locate the primary lameness, meriting more detailed investigation.

In the groups of horses with forelimb lameness (Groups 1–3), the change in pelvic asymmetry showed a compensation mimicking diagonal hindlimb lameness, in agreement with previous findings.[1–3,5,6] The compensatory effect was a reduced maximum vertical height reached by the pelvis after diagonal hindlimb push-off (PDmax), which is consistent with previous observations.[2,3,5,6] In some earlier studies a small ipsilateral compensatory weight-bearing asymmetry (PDmin) was also seen,[2,5,6] in agreement with reduced loading of the ipsilateral hindlimb.[7,8] However, a diagonal hindlimb attributed PDmin has also been reported.[5] The present study found no PDmin compensation, which is consistent with findings in another study on naturally occurring forelimb lameness.[3] This discrepancy might be due to PDmin compensation only being present in some horses, differing with the degree of lameness and/or between different causes of lameness, breeds and/or surfaces. In clinical practice, a small pelvic asymmetry mimicking pushoff lameness in the diagonal hindlimb should be expected in forelimb lame horses.

The approach used to investigate possible compensatory strategies differed somewhat between the present and recently published similar studies.[5,21] We selected horses with a clear initial lameness and a marked reduction in lameness after diagnostic analgesia. We then regressed the change in corresponding asymmetry parameters between the confirmed primary location (head/forelimb or pelvis/hindlimb) and the other measured locations, where compensatory movements might occur. If significant, such correlations confirm that concurrent asymmetries are compensatory, as they change in parallel to the decrease in main lameness. However, while this method is good for detecting common patterns, unusual compensatory strategies found only in a minority of subjects will be missed. Division into groups based on initial asymmetry pattern[5] might reveal unusual compensatory patterns. However, if a horse suffers from primary lameness in multiple limbs, this could confound the initial asymmetry combinations measured, thereby allocating some horses to the wrong groups. This misallocation to groups might increase variation in response to diagnostic analgesia such that true compensatory movements are missed. A previous study evaluated only the initial lameness pattern, and not the concurrent change after diagnostic analgesia in the presumed compensatory asymmetries, leaving their compensatory nature somewhat uncertain.[21] However, the most commonly reported initial head and pelvic compensatory patterns for forelimb and hindlimb lameness in these two studies[5,21] agree with those presented here.

The thresholds for initial lameness used for inclusion in this study were chosen based on the authors' clinical experience of when lameness is visible and measurement variability using the current objective system.[22] The requirement for a 70% reduction in lameness might exceed what is clinically deemed a positive response, depending on the diagnostic analgesic procedure performed. In interleukin-1β induced stifle joint lameness, a mean decrease of 64% in PDmin and 82% in PDmax post-diagnostic analgesia has been reported.[23] A large reduction was used as an inclusion criterion in the present study to reduce the risk of including false-positive responders to diagnostic analgesia due to large inter-run variability in degree of lameness. These stringent inclusion criteria enabled reliable evaluation of true compensatory strategies adopted by clinically lame horses, but extrapolating the results to horses with smaller initial lameness or a less clear response to diagnostic analgesia requires caution, since these horses were not represented in the dataset analysed.

5 | CONCLUSIONS

In horses with forelimb lameness confirmed by diagnostic analgesia, head and withers movement asymmetry parameters agreed and indicated, in the majority of cases, the same forelimb. In contrast to this, head and withers movement asymmetry generally disagreed and indicated lameness in different forelimbs in horses with confirmed hindlimb lameness. Quantification of withers asymmetry is therefore a useful complement in objective clinical lameness assessment to help locate the primary lameness.

There was a clear compensatory ipsilateral head asymmetry in some, but not all, horses with hindlimb lameness. In horses with forelimb lameness, a compensatory diagonal decrease in hindlimb push-off was evident, mimicking a diagonal hindlimb lameness. The timing of head movement in relation to withers and pelvic movement was found to change when the horse compensated for lameness, and should be further investigated.

AUTHOR CONTRIBUTIONS

The study concept was developed by Marie Rhodin, Pia Haubro Andersen and Thilo Pfau. The data used were originally collected by clinicians at the participating equine clinics (including Emma Persson-Sjodin, Elin Hernlund, Karin Holm Forsström, Filipe M. Serra Bragança, Aagje Hardeman, Line Greve and Marie Rhodin). The data were first organised by Emma Persson-Sjodin. Anna Byström and Filipe M. Serra Bragança contributed to the development of the data analysis MATLAB scripts. Data analysis and statistical analysis were performed by Emma Persson-Sjodin, Anna Byström, Elin Hernlund and Agneta Egenvall. The paper was written by Emma Persson-Sjodin, Marie Rhodin and Elin Hernlund with the support of the co-authors, who all gave their final approval of the manuscript. Emma Persson-Sjodin had full access to all data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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CONFLICT OF INTEREST STATEMENT

No competing interests have been declared.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/evj.13947.

DATA AVAILABILITY STATEMENT

The underlying data for the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL ANIMAL RESEARCH

Research ethics committee oversight not required by this journal: retrospective analysis of clinical data.

INFORMED CONSENT

Explicit owner informed consent for inclusion of animals in this study was not stated.

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