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Head, withers and pelvic movement asymmetry and their relative timing in trot in racing Thoroughbreds in training

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Summary

Background: Horses show compensatory head movement in hindlimb lameness and compensatory pelvis movement in forelimb lameness but little is known about the relationship of withers movement symmetry with head and pelvic asymmetry in horses with naturally occurring gait asymmetries.
Objectives: To document head, withers and pelvic movement asymmetry and timing differences in horses with naturally occurring gait asymmetries.
Study design: Retrospective analysis of gait data.
Methods: Head, withers and pelvic movement asymmetry and timing of displacement minima and maxima were quantified from inertial sensors in 163 Thoroughbreds during trot-ups on hard ground. Horses were divided into 4 subgroups using the direction of head and withers movement asymmetry. Scatter plots of head vs. pelvic movement asymmetry illustrated how the head–withers relationship distinguishes between contralateral and ipsilateral head–pelvic movement asymmetry. Independent *t* test or Mann–Whitney *U* test ($P<0.05$) compared pelvic movement asymmetry and timing differences between groups.
Results: The relationship between head and withers asymmetry (i.e. same sided or opposite sided asymmetry) predicts the relationship between head and pelvic asymmetry in 69–77% of horses. Pelvic movement symmetry was significantly different between horses with same sign vs. opposite sign of head–withers asymmetry ($P<0.0001$). Timing of the maximum head height reached after contralateral ('sound') stance was delayed compared to withers ($P = 0.02$) and pelvis ($P = 0.04$) in horses with contralateral head–withers asymmetry.
Main limitations: The clinical lameness status of the horses was not investigated.
Conclusion: In the Thoroughbreds with natural gait asymmetries investigated here, the direction of head vs. withers movement asymmetry identifies the majority of horses with ipsilateral and contralateral head and pelvic movement asymmetries. Withers movement should be further investigated for differentiating between forelimb and hindlimb lame horses. Horses with opposite sided head and withers asymmetry significantly delay the upward movement of the head after 'sound' forelimb stance.

Keywords: horse; movement asymmetry; trot; relative timing

Introduction

Lame horses employ compensatory force and impulse distributions between the lame limb and one or more of the other limbs [1,2]. Visually and kinematically this results in a compensatory head nod indicating a 'false' (compensatory) ipsilateral forelimb lameness in horses with primary hindlimb lameness and a 'false' (compensatory) contralateral hindlimb lameness in horses with a primary forelimb lameness [3–5]. Horses with induced hindlimb lameness show a compensatory ipsilateral forelimb lameness while horses with induced forelimb lameness, show a more complex kinematic pattern, indicating a compensatory reduction in pelvic downward movement ipsilaterally and a compensatory reduction in contralateral hindlimb push-off [6,7].

The relationship between head and withers movement asymmetry is different between horses with induced forelimb lameness and horses with induced hindlimb lameness [8]. In the first group, head and withers movement agree in the direction of asymmetry, i.e. both show reduced downward movement during the stance phase of the affected limb resulting in movement asymmetry measures with the same sign (are either both negative or both positive). In the second group, there is disagreement between the direction of head and withers movement asymmetry. Horses with induced left hindlimb lameness show an increased head height during mid stance of the left fore (LF) and an increased withers height during mid stance of the right fore (RF) resulting in one measure being positive and the other being negative (i.e. showing opposite sign).

The aim of this study was to investigate the frequency of occurrence of ipsilateral and contralateral head–withers asymmetries and to quantify their relationship with ipsilateral and contralateral head–pelvic movement asymmetries. Ultimately, this is related to the question whether the assessment of withers movement asymmetry (in addition to head and pelvic movement asymmetry) may allow differentiation between horses with primary forelimb lameness (showing a contralateral compensatory hindlimb lameness) and horses with primary hindlimb lameness (showing an ipsilateral compensatory forelimb lameness). We hence hypothesised that horses with opposite signs of head and withers movement asymmetry will more frequently show ipsilateral head and pelvic movement asymmetries (i.e. consistent with observations in horses with primary hindlimb lameness), while horses showing the same sign of head and withers movement asymmetry will more commonly show contralateral head and pelvic movement asymmetries (i.e. consistent with observations in horses with primary forelimb lameness). Investigating a potential means for achieving same sided vs. opposite sided head–withers asymmetry, we hypothesised that there will be differences in timing of head movement relative to withers and pelvis movement between horses showing opposite signs of head–withers asymmetry and horses showing same sided head–withers movement asymmetry.

Materials and methods

Animals and procedures

Data for this retrospective study had been collected as part of routine gait analysis conducted at approximately 4-weekly intervals in racing Thoroughbreds in training at Singapore Turf Club. The horses presented a subsample of the horses in training as part of a longitudinal study.

In total, 1015 gait analysis entries recorded from 281 horses between 17 November 2014 and 31 August 2015 were screened according to the following criteria:

- For horses with multiple gait analysis events, only the entry with the highest head asymmetry value was retained; this ensured that a good range of asymmetries was represented in the database. Depending on the time of recruitment of each horse to the overarching study, between one (horses recruited in August 2015) and 10 (horses recruited in November 2014) assessments were available per horse. In order not to bias the results of the current study towards horses with multiple entries, only one entry was selected per horse. Since the ultimate aim is to investigate the use of withers movement for the detection of lameness, the specific entry was chosen as the one with the highest amount of head asymmetry, i.e. the entry in which the amount of measured head movement asymmetry was most consistent with movement asymmetry in horses showing a head nod.
- Entries were excluded if the horse had received any treatments (e.g. sedation, shockwave therapy or local analgesic injection; nonsteroidal anti-inflammatory drugs within 1 week of data collection; or intra-articular medication within 1 month of data collection); this procedure aimed at inclusion of 'naturally occurring' gait asymmetries in horses without any veterinary interventions.

After application of above criteria, a total of 163 data entries from 163 Thoroughbreds in race training were included in the analysis.

Data collection

Each horse had been equipped with a validated inertial sensor based gait analysis system [9,10], here consisting of 5 sensors (4× Xsens MTx: triaxial accelerometer ±10 gravitational acceleration, triaxial gyroscope: ±1200°/s, triaxial magnetometer: ±750 mGauss and 1× Xsens MTi-G: as MTx plus additional 4 Hz GPS). The MTx sensors were attached with double sided tape to the head piece over the poll, and to the skin over the withers, the left and the right *tubera coxae*. The MTi-G sensor was attached between the 2 *tubera sacrale* with the GPS antenna approximately 5 cm left of the sensor. Data were transmitted wirelessly via Bluetooth with a sample rate of 100 Hz per sensor channel to a nearby laptop computer running proprietary software (Xsens, MTManager). According to the manufacturer's specifications, time synchronisation between multiple sensors is <200 μs.

Horses were trotted in a straight line over a flat, concrete surface at the training stable where they were housed multiple times until a sufficient number of strides (≥25, [11]; counted 'by eye' during data collection, exact number assessed during data analysis) had been collected. Trials with aberrant behaviour such as tripping, excessive pulling or changing gait were marked as 'unsuitable for data analysis' and thus excluded from data analysis; data collection was then repeated until consistent trotting was achieved (judged subjectively).

Data analysis

Kinematic data: Data analysis was performed with custom written MATLAB[a] scripts implementing published protocols [9]. In brief, calibrated acceleration data were rotated into a horse-gravity based right handed Cartesian coordinate reference frame and then highpass filtered (fourth order Butterworth filter, cut off frequency 1 Hz) and numerically double integrated to displacement data. Continuous displacement data streams were segmented into strides based on vertical velocity and roll of the *tuber sacrale* sensor [12].

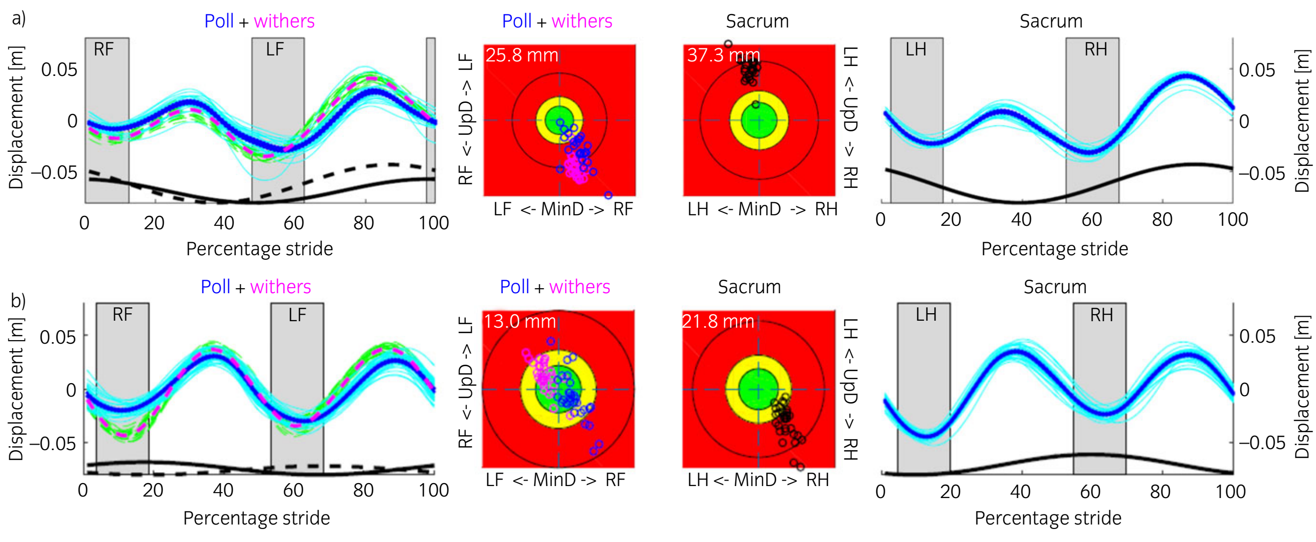

Fig 1: Examples of horses showing a) ipsilateral head (blue, left panel) and withers (green/magenta, left panel) asymmetry in vertical movement or b) contralateral head and withers asymmetry. Also shown is pelvic vertical movement (right panel) and scatter plots of difference in vertical head ($MinD_{head}$) displacement minima vs. upward head movement difference (UpD_{head}; blue circles, left middle panel) and $MinD_{withers}$ vs. $UpD_{withers}$ (magenta circles, right middle panel) as well as $MinD_{pelvis}$ vs. UpD_{pelvis} (black circles, right middle panel). The sign convention for calculating asymmetry values used here and previously [13] subtracts the value of the second minimum (or maximum or upward movement amplitude), i.e. corresponding to left fore (LF) or right hind (RH) stance from the value of the first minimum (or maximum or upward movement amplitude), i.e. corresponding to right fore (RF) or left hind (LH) stance. Black lines (head: solid; withers: dashed) represent the first harmonic fitted to the data via Fourier analysis illustrating amount (amplitude of the lines) and phasing (timing of minima and maxima) of the asymmetry between stride halves. a) This horse shows positive $MinD_{head}$ and positive $MinD_{withers}$ indicative of a higher head and withers position at mid stance of the RF limb resulting in the blue circles (head) and magenta circles (withers) both indicating a RF movement asymmetry occupying the right half of the scatter plot. This horse also shows a positive $MinD_{pelvis}$ indicative of a higher pelvic position at mid stance of the LH limb indicating a LH movement asymmetry with the black circles occupying the left half of the scatter plot. Head and pelvis show signs of contralateral movement asymmetry. b) This horse shows positive $MinD_{head}$ and negative $MinD_{withers}$ indicative of a higher head position at mid stance of the RF limb and higher withers position at mid stance of the LF limb. This results in the blue circles (head) indicating a RF movement asymmetry occupying the right half of the scatter plot and the magenta circles (withers) indicating a LF movement asymmetry occupying the left half of the scatter plot. This horse also shows a negative $MinD_{pelvis}$ indicative of a higher pelvic position at mid stance of the RH limb indicating a RH movement asymmetry with the black circles occupying the right half of the scatter plot. Head and pelvis show signs of ipsilateral movement asymmetry.

For further analysis, movement symmetry was calculated from vertical displacement data [13,14]. In brief, differences between the 2 displacement minima reached at approximately mid stance (MinD), differences between the 2 displacement maxima reached at approximately mid aerial phase (MaxD), differences between the 2 upward movement amplitudes from mid stance to mid aerial phase (UpD, i.e. non-normalised upward symmetry index) were calculated for the 3 sensors attached over the sagittal midline of the horse (poll, withers, *tuber sacrale*). In addition, the difference between left and right *tuber coxae* upward movement amplitude during contralateral stance was calculated as the hip hike difference (HHD). Mean values (across strides) for 10 movement asymmetry parameters were calculated: 3 each from poll, withers and *tuber sacrale* and HHD calculated from the *tubera coxae*.

Relative timing of head and withers and head and pelvic movement was quantified by determining the timing of the 2 local vertical displacement minima and maxima as percentage of the stride cycle and subtracting the value for withers or pelvis movement from the corresponding head movement value. Positive differences indicate a delay and negative values an early rise or fall of the head compared to withers (or pelvis). In order to combine the 4 subgroups of horses (LF, RF, left hind [LH] and right hind [RH], see below) into 2 subgroups (fore and hind), timing values for LF stance for the LF subgroup were combined with timing values for RF stance for the RF subgroup and timing values for LH stance for the LH subgroup with timing values for RH stance for the RH subgroup. Eight timing differences HWCmn, HWCmx, HWImn, HWImx, HPCmn, HPCmx, HPImn, HPImx were calculated: differences between head and withers (HW), between head and pelvis (HP) for the ipsilateral (I) or contralateral (C) stance phase (with respect to the subgroup labelling) and for timings of the minimum (mn) and the maximum (mx).

Assessment of distribution assumptions and descriptive statistics

Movement asymmetry parameters were assessed for normality using the Shapiro–Wilk test. All parameters (except $MaxD_{head}$ and UpD_{head}) were found to be normally distributed (all P>0.07). $MaxD_{head}$ was normally distributed (P = 0.73) after removal of 4 outliers; even after attempted outlier removal UpD_{head} differed from a normal distribution (P = 0.03). Mean, standard deviation, minimum and maximum values were calculated in Microsoft Excel illustrating the range of movement asymmetries shown. All timing differences, except HWCmx were found not to follow a normal distribution (all other P<0.007).

Division of data set into subgroups

Four subgroups were created representing possible combinations of the direction of head and withers movement asymmetry based on $MinD_{head}$ and $MinD_{withers}$. $MinD_{head}$ was chosen for this task since it is closely linked to the difference in force production between contralateral limbs at mid stance [15]. Based on the observation, that horses with induced forelimb lameness show same sided head and withers asymmetry and horses with induced hindlimb lameness show opposite sided head and withers asymmetry [8] and based on the observation, that hindlimb lame horses show an ipsilateral compensatory forelimb lameness [3,5], the subgroups of horses representing different types of movement asymmetries were labelled as follows based on the sign of $MinD_{head}$ and $MinD_{withers}$:

- LF: horses with negative head and withers MinD, i.e. increased head and withers height during LF mid stance.
- RF: horses with positive head and withers MinD, i.e. increased head and withers height during RF mid stance.
- LH: horses with negative head and positive withers MinD, i.e. increased head height during LF mid stance and increased withers height during RF mid stance.
- RH: horses with positive head and negative withers MinD, i.e. increased head height during RF mid stance and increased withers height during LF mid stance.

Sign conventions for calculating movement symmetry parameters are consistent with a previous study [13]. Two examples are given in Fig 1 showing vertical movement of head (poll), withers and mid pelvis (sacrum) as well as scatter plots of MinD vs. UpD visualising the directionality of 2 of the extracted movement asymmetry parameters for head, withers and mid pelvis movement asymmetry.

TABLE 1: Mean, standard deviation (s.d.), minimum (min) and maximum (max) for all n = 163 horses (ALL) and for horses with positive values (n = 67 to n = 103) and for the horses with negative (neg) values (n = 60 to n = 96)

	ALL				Positive values				Negative values				Absolute difference
	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max	Mean
$MinD_{pelvis}$	−0.7	9.2	−25.2	31.0	6.5	6.2	0.3	31.0	−7.3	5.9	−25.2	0.0	0.8
$MaxD_{pelvis}$	−2.1	10.3	−36.6	23.1	6.9	5.7	0.2	23.1	−9.1	7.2	−36.6	0.0	2.2
UpD_{pelvis}	−1.4	16.3	−48.3	37.2	12.3	10.2	0.1	37.2	−12.6	10.8	−48.3	−0.3	0.3
HHD	4.6	21.4	−48.3	72.8	17.0	14.5	0.2	72.8	−16.7	12.6	−48.3	0.0	0.3
$MinD_{head}$	0.9	19.4	−58.5	51.0	15.7	9.6	0.6	51.0	−16.5	12.1	−58.5	−0.5	0.8
$MaxD_{head}$	−1.0	12.9	−37.2	47.2	9.7	9.3	0.1	47.2	−9.5	8.0	−37.2	−0.4	0.2
UpD_{head}	−2.0	27.2	−73.3	104.7	20.2	16.5	0.1	104.7	−20.6	12.8	−73.3	−0.4	0.4
$MinD_{withers}$	0.5	9.0	−25.8	24.4	7.0	5.4	0.2	24.4	−7.2	5.6	−25.8	−0.1	0.2
$MaxD_{withers}$	−2.0	9.2	−27.9	21.0	6.6	5.4	0.1	21.0	−7.9	6.2	−27.9	0.0	1.3
$UpD_{withers}$	−2.4	14.4	−47.1	46.5	10.4	8.9	0.1	46.5	−11.8	9.7	−47.1	−0.2	1.4

HHD, hip hike difference; MinD, minimum difference; MaxD, maximum difference; UpD, upward movement difference. Absolute difference: difference in absolute mean values between horses with negative and horses with positive values.

TABLE 2: Mean, median and 25th and 75th percentile for timing differences for displacement minima and maxima between head and withers and between head and pelvic movement. Positive values indicate a delay of head movement relative to withers or pelvic movement. Values are given as percentage of stride time

	HWCmn	HWCmx	HWImn	HWImx	HPCmn	HPCmx	HPImn	HPImx
Mean	1.82	3.23	2.23	0.85	−0.90	1.39	−0.42	−1.63
Median [25th, 75th]	2 [0,3]	3 [2,5]	2 [0,4]	1 [0,2]	−1 [−2.5,1]	1 [0,3]	0 [−2,1]	−1 [−3,1]

H, head; W, withers; P, pelvis; C, contralateral, i.e. the stance phase of the limb on the opposite side to the 'lame' limb; I: ipsilateral, i.e. the stance phase of the limb on the same side as the 'lame' limb; mn: timing difference between minima; mx: timing difference between maxima.

For the investigation of timing differences between head, withers and pelvic movement subgroups LF and RF and subgroups LH and RH were combined as follows:

- F: combined subgroups LF and RF, i.e. horses with same sided head–withers asymmetry.
- H: combined subgroups LH and RH, i.e. horses with opposite sided head–withers asymmetry.

Prediction of contralateral or ipsilateral head and pelvic asymmetries from the relationship between the direction of head and withers movement asymmetry

In order to test whether the relationship between the direction of head and withers movement asymmetry is a good predictor for the presence of ipsilateral head and pelvic movement asymmetry – typically seen in horses with primary hindlimb lameness – or contralateral head and pelvic movement asymmetries – typically seen in horses with primary forelimb lameness, the following procedures were implemented:

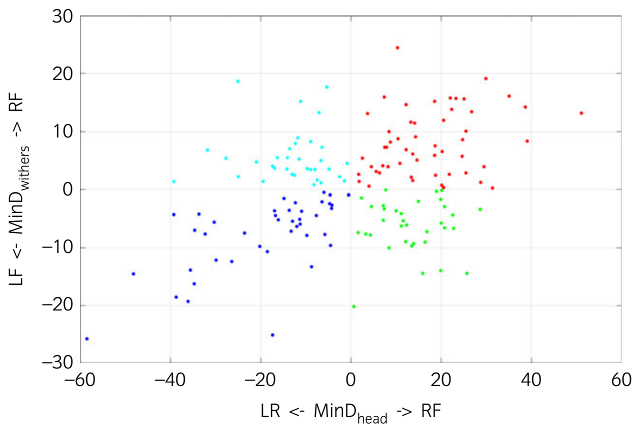

Fig 2: Difference in vertical head ($MinD_{head}$) and withers ($MinD_{withers}$) displacement minima between contralateral stance phases in 163 Thoroughbred racehorses. Colours indicate the 4 different combinations of the direction (sign) of head and withers movement asymmetry. Red, subgroup RF, (n = 54): positive $MinD_{head}$ and $MinD_{withers}$. Dark blue, subgroup LF, (n = 41): negative $MinD_{head}$ and $MinD_{withers}$. Green, subgroup RH, (n = 34): positive $MinD_{head}$, negative $MinD_{withers}$; Cyan, subgroup LH, (n = 34): negative $MinD_{head}$, positive $MinD_{withers}$.

- Scatter plots were created of head MinD vs. all 4 pelvic asymmetry values. Subgroup mean and s.d. values illustrated how well the subgrouping procedure ‘predicts’ the observed pelvic asymmetries.
- The percentage of horses showing pelvic asymmetry values consistent with the types of asymmetry indicated by the subgroup label were calculated for all 4 pelvic asymmetry values (MinD, MaxD, UpD, HHD). In particular, the percentage of horses in the LF (RF) group showing pelvic asymmetry direction consistent with RH (LH) asymmetry were determined and the percentage of horses in the LH (RH) group showing pelvic asymmetry direction consistent with LH (RH) asymmetry.
- Independent *t* tests ($P<0.05$, Microsoft Excel) compared the pelvic movement asymmetry parameters between subgroups LF and LH as well as between subgroups RF and RH. This addresses the question of whether the applied grouping based on head–withers movement asymmetry results in differences in pelvic movement asymmetry consistent in direction with the compensatory movements seen in forelimb or hindlimb lame horses. In other words: is withers movement potentially useful to differentiate between horses with primary forelimb lameness and horses with primary hindlimb lameness showing compensatory head movement asymmetry?

Relative timing of head movement with respect to withers and pelvis movement

Here we test the hypothesis that horses achieve opposing signs of head–withers movement asymmetry by delaying or advancing head movement in relation to the withers or pelvic movement. Mann–Whitney *U* tests ($P<0.05$, all variables except difference in timing of head and withers maximum height after contralateral ‘sound’ stance) or independent *t* tests ($P<0.05$) compared the relative head–withers and the relative head–pelvis timing between horses with ipsilateral head–withers asymmetry (group F) and horses with contralateral head–withers asymmetry (group H).

Results

Descriptive statistics

A total of 5317 strides (per horse: 33 ± 9 strides, minimum 12 strides, maximum 70 strides) were assessed. Median values for head, withers and pelvic movement asymmetry varied considerably across the 163 Thoroughbred race horses with mean values close to zero and standard deviations generally larger than the respective means (see Table 1). Means, medians and values of 25th and 75th percentile for the timing differences between head and withers and head and pelvis are presented in Table 2.

TABLE 3: Mean, standard deviation (s.d.), minimum (Min) and maximum (Max) for the 4 subgroups of horses grouped by the type of head-withers asymmetry relationship

	LF (n = 41)				RF (n = 54)				LH (n = 34)				RH(n = 34)				|LF|–|RF|	|LH|–|RH|
	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max	Mean	Mean
$MinD_{pelvis}$	−3.5 RH	6.7	−20.9	6.2	2.7 LH	7.7	−15.9	24.4	4.8 LH	9.1	−11.9	31.0	−8.1 RH	7.9	−25.2	7.4	0.8	3.3
$MaxD_{pelvis}$	3.1 RH	8.1	−22.0	16.3	−7.3 LH	10.3	−36.6	22.9	−5.9 LH	7.7	−17.7	8.9	3.7 RH	9.1	−16.1	23.1	4.2	2.2
UpD_{pelvis}	6.6 RH	11.1	−14.9	37.2	−10.0 LH	14.2	−43.0	33.0	−10.7 LH	13.6	−48.3	9.3	11.8 RH	13.2	−10.8	34.5	3.4	1.1
HHD	−6.1 RH	16.0	−48.3	26.7	15.6 LH	19.1	−41.9	55.1	17.2 LH	17.3	−20.3	72.8	−12.5 RH	15.2	−47.7	11.3	9.5	5.3
$MinD_{head}$	−19.2 LF	13.8	−58.5	−0.5	17.3 RF	10.6	1.7	51.0	−13.1 LF	8.7	−39.3	−0.8	13.4 RF	7.3	0.6	28.6	1.9	0.3
$MaxD_{head}$	2.2 LF	12.5	−17.3	46.2	−5.5 RF	11.4	−37.2	15.6	5.0 LF	15.6	−27.1	47.2	−3.9 RF	9.1	−24.1	14.9	3.3	1.1
UpD_{head}	20.4 LF	22.6	−4.4	105	−21.9 RF	17.9	−73.3	10.2	17.1 LF	18.4	−20.0	60.8	−16.3 RF	11.5	−37.3	6.4	1.5	0.8
$MinD_{withers}$	−7.9 LF	6.3	−25.8	−0.5	7.9 RF	5.7	0.2	24.4	5.5 RF	4.5	0.8	18.6	−6.3 LF	4.6	−20.2	−0.1	0	0.8
$MaxD_{withers}$	0.0 S	8.9	−15.7	20.8	−3.1 RF	10.2	−27.9	21.0	−3.8 RF	8.6	−22.1	10.4	−0.7 RF	8.2	−15.4	18.4	3.1	3.1
$UpD_{withers}$	7.6 LF	12.0	−9.4	46.5	−10.6 RF	12.4	−47.1	16.1	−8.8 RF	10.8	−34.3	7.0	5.3 LF	9.8	−13.0	32.9	3.0	3.5

Subgroup LF: reduced downward movement of poll and withers during left forelimb stance. Subgroup RF: reduced poll and withers downward movement during right forelimb stance. Subgroup LH: reduced poll downward movement during left forelimb stance and reduced withers downward movement during right forelimb stance. Subgroup RH: reduced head downward movement during right forelimb stance and reduced withers downward movement during left forelimb stance. Differences in absolute asymmetry values between subgroups LF and RF and between subgroups LH and RH. HHD, hip hike difference; MinD, minimum difference; MaxD, maximum difference; UpD, upward movement difference.

Timing differences are generally small, ranging from −1.6% to +3.2%. Four (out of 4) mean and median values of head–withers timing difference are positive indicating a delay of head movement compared to withers movement. One (out of 4) mean and median values of head–pelvis timing difference is positive indicating a general advance timing of the head compared to the pelvis.

Head and withers movement asymmetry

Figure 2 illustrates movement asymmetry values for the 4 subgroups of horses representing the 4 different combinations of the direction of head and withers movement asymmetry (based on the differences between head ($MinD_{head}$) and withers ($MinD_{withers}$) minimum height achieved during the 2 forelimb stance phases). In total, 95 horses showed head and withers asymmetry with the same sign; 54 of these horses showed increased head height during RF stance (group RF, red) and 41 horses showed increased head height during LF stance (group LF, blue). Sixty-eight horses showed head and withers movement asymmetry with opposite sign; 34 of these horses showed increased head height during RF stance and increased withers height during LF stance (group RH, green) and 34 horses showed increased head height during LF stance and increased withers height during RF stance (group LH, cyan).

Mean values for groups LF and RF (as well as for groups LH and RH) show asymmetry values of opposite sign (see Table 3). Absolute differences for absolute mean values between groups LF and RF (Table 3, column LF-RF) and between groups LH and RH (Table 3, column LH-RH) are generally close to zero with the largest differences found for pelvic movement asymmetry in particular for $MaxD_{pelvis}$, UpD_{pelvis} and for HHD.

Prediction of contralateral or ipsilateral head and pelvic asymmetries from the relationship between the direction of head and withers movement asymmetry

The 4 movement asymmetry subgroups (Table 3, LF, RF, LH, RH) present with mean asymmetry values representing a contralateral head–pelvic asymmetry pattern for subgroups LF and RF and an ipsilateral head–pelvic asymmetry pattern for subgroups LH and RH. Average $MinD_{pelvis}$ for LF horses is −3.5 mm (i.e. RH asymmetry), for RF horses +2.7 mm (i.e. LH asymmetry), for LH horses +4.8 mm and for RH horses −8.1 mm.

Figure 3 illustrates the relationship between head and pelvic movement asymmetry for the 4 subgroups for each of the 4 pelvic movement asymmetry parameters. Independent of the specific pelvic parameter, the majority of horses with same sided head and withers asymmetry (red: RF; blue: LF) showed contralateral head–pelvic asymmetry while the majority of horses with opposite sided head–withers asymmetry (green: head RF, withers LF; cyan: head LF, withers RF) showed ipsilateral head–pelvic asymmetry (see Fig 3 A–D). On average across all movement asymmetry subgroups, between 69 and 77% of horses showed the above pattern (see Table 4 for individual percentages subdivided by subgroup and pelvic asymmetry measure). Independent *t* tests (equal variance between groups assessed with

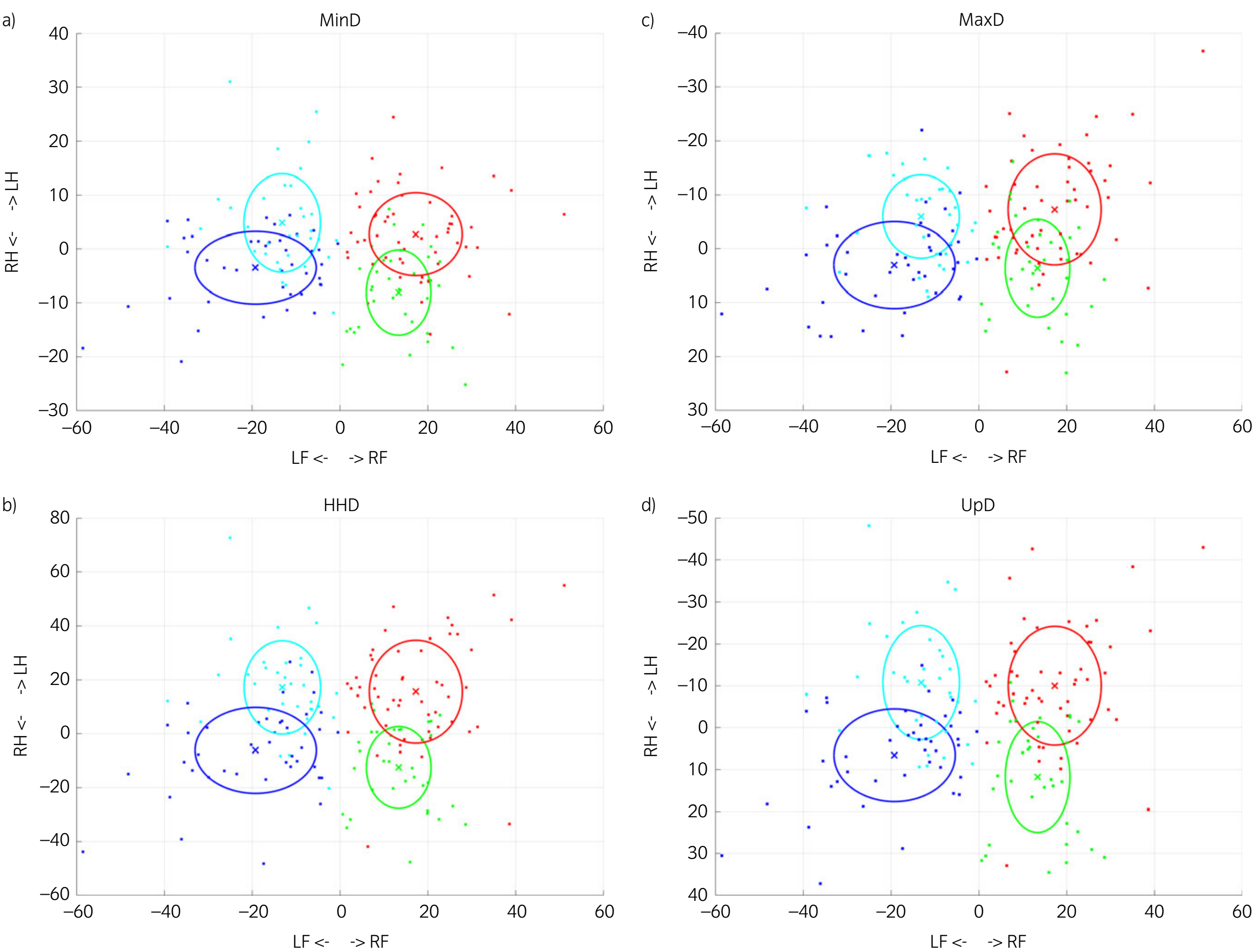

Fig 3: Scatter plots of $MinD_{head}$ against different pelvis movement symmetry measures a) $MinD_{pelvis}$, b) HHD, c) $MaxD_{pelvis}$, d) UpD_{pelvis}) showing values for individual horses (small squares), mean values for each subgroup (crosses) and area covering ±1 s.d. for each subgroup (ellipses). For colour coding see Fig 2.

TABLE 4: Percentage of horses within the 4 subgroups showing the 'expected' head-pelvic movement asymmetry pattern (contralateral for subgroups LF and RF, ipsilateral for subgroups LH and RH) choosing the sign of each of the pelvic movement asymmetry parameters as a criterion (MinD, MaxD, UpD, HHD)

Subgroup	$MinD_{pelvis}$	$MaxD_{pelvis}$	UpD_{pelvis}	HHD
LF (n = 41)	63.4	68.3	70.7	56.1
RF (n = 54)	64.8	74.1	81.5	83.3
LH (n = 34)	67.6	73.5	76.5	88.2
RH (n = 34)	85.3	58.8	76.5	70.6
Average	69.3	69.3	76.7	74.8

HHD, hip hike difference; MinD, minimum difference; MaxD, maximum difference; UpD, upward movement difference.

Levene's test of equal variance) between the subgroups LF and LH and between the subgroups RF and RH for all 4 pelvic movement asymmetry measures showed significant differences (all P<0.0001 for *t* tests, all P>0.083 for Levene's test of equal variance, see Table 3 for descriptive statistics).

The timing difference between head and withers movement and between head and pelvic movement (see Table 5) was, with the exception of HWCmax (P = 0.016) and HPCmax (P = 0.047), not significantly different between horses of group F (head–withers asymmetry consistent with the asymmetry direction seen in forelimb lameness) and horses of group H (head–withers asymmetry consistent with the asymmetry direction seen in hindlimb lameness). HWCmax quantifies the timing difference between the maximum head and withers height reached after contralateral stance, i.e. after RF stance for a horse of group LF, indicating a timing difference after the stance phase of the 'sound' forelimb. HPCmax quantifies the timing difference between the maximum head and pelvis height reached after contralateral forelimb stance, i.e. after RF stance for a horse of group LH.

Discussion

Here we have shown that, in line with our hypothesis, in the majority of Thoroughbred racehorses with natural gait asymmetries, the relationship between the direction of head and withers movement asymmetry distinguishes between horses with ipsilateral and contralateral head and pelvic movement asymmetry.

It was also shown that horses with contralateral head–withers asymmetry show a difference in head movement timing compared to horses with ipsilateral head–withers asymmetry. Maximum head height – compared to withers and pelvic maximum height – is delayed in horses with contralateral head–withers asymmetry after the forelimb stance phase of the 'unaffected' forelimb. This means that head movement peaks later after LF stance in horses with head–withers movement indicative of RH lameness compared to horses with head–withers movement indicative of RF lameness. Studies with simultaneous measurement of force and movement should be conducted to investigate the underlying mechanism.

Compensatory mechanisms

The majority of racehorses used in this study (95 of 163) showed same sided head–withers movement asymmetry. Based on the observation, that horses with induced forelimb lameness show same sided head–withers movement asymmetry [8], we speculate that the primary source of gait asymmetry in these horses originates from within one of the thoracic limbs. The greater number of these may – at least in part – be related to the selection criterion used here favouring database entries with higher amounts of head movement asymmetry. The majority of these horses (between 56 and 83%) show contralateral head–pelvic movement asymmetry, which would be consistent with studies demonstrating contralateral head–pelvic movement asymmetries in clinically forelimb lame horses [3,4]. The situation is, however, slightly different in studies with induced forelimb lameness on a treadmill [7] and on the lunge [6], showing ipsilateral pelvic weight bearing asymmetry and contralateral pelvic push-off asymmetry. In our study both weightbearing ($MinD_{pelvis}$) and push-off ($MaxD_{pelvis}$, UpD_{pelvis}) related pelvic parameters are in the majority consistent with contralateral pelvic movement asymmetry. This discrepancy may be related to the generally larger contralateral compensatory $MaxD_{pelvis}$ agreeing with the visual clinical observation of a contralateral compensatory hindlimb lameness in forelimb lame horses. This is, however, not consistent with the 63–65% of horses in our study showing contralateral $MinD_{pelvis}$. Further studies should elucidate the possible role of lameness grade and diagnosis in the occurrence of ipsilateral and contralateral compensatory weightbearing asymmetry ($MinD_{pelvis}$) and compare this to the reported transfer of weight backward along the lame diagonal [2]. Finally, the horses here did not undergo a comprehensive lameness examination and as a consequence the percentage of horses with asymmetries originating from multiple limbs is unknown.

The remainder of the racehorses used in this study (68 of 163) showed opposite sided head–withers movement asymmetry. This leads to speculation that the gait asymmetry in these horses primarily originates from one of the pelvic limbs [8]. The majority of these horses (between 68 and 88%) show ipsilateral head–pelvic movement asymmetry consistent with previous observations in clinically hindlimb lame horses [3,5].

Based on observations in horses with induced lameness [8], plotting vertical movement of head, withers and pelvis would allow assessing whether movement patterns are consistent with the typically observed patterns. If a horse shows a same-sided head–withers asymmetry and a contralateral head–pelvic asymmetry, then this horse behaves in accordance to horses with induced forelimb lameness. Hence, when working up a clinical case with an obvious head nod, the presence of same or opposite sided head–withers asymmetry may help in deciding whether to start the diagnostic process in the forelimb or in the hindlimb. Further studies in horses with clinically diagnosed causes of lameness are required to confirm whether this will indeed be possible.

We also investigated the timing of head movement in relation to withers and pelvic movement. It was shown that in particular the maximum position of the head reached after the stance phase of the 'unaffected' limb (the LF limb in horses with symmetry patterns consistent with RF or RH lameness) is delayed in horses showing asymmetry patterns consistent with hindlimb lameness compared to horses showing asymmetry patterns

TABLE 5: Difference in head and withers and head and pelvic timing for horses showing patterns of head, withers and pelvic movement asymmetry consistent with forelimb lameness (F) and horses showing patterns of head, withers and pelvic movement asymmetry consistent with hindlimb lameness (H)

	HWCmn	HWCmx	HWImn	HWImx	HPCmn	HPCmx	HPImin	HPImx
Median H	2	3.5	3	1	−1	2	0	−1
Median F	2	2	2	1	0	1	−1	−2
H–F	0	**1.5**	1	0	−1	**1**	1	1
P value	0.57	**0.016**	0.22	0.31	0.500	**0.047***	0.076	0.60

*P-value for comparison between group F and H for parameter HPCmax based on independent *t* test (Shapiro–Wilk test for HPCmax P = 0.061), all other comparisons based on Mann–Whitney *U* test (Shapiro–Wilk test for all other timing parameters P<0.007). Differences significant at *P*<0.05 in bold. H, head, W, withers, P, pelvis; C, contralateral, i.e. the stance phase of the limb on the opposite side to the 'lame' limb; I: ipsilateral, i.e. the stance phase of the limb on the same side as the 'lame' limb; mn: timing difference between minima; mx: timing difference between maxima.

consistent with forelimb lameness. No other timing differences were found to be significantly different between the 2 groups of horses. It is possible that other timing differences exists, that are smaller than can be detected with the inertial sensors used here with a sample rate of 100 Hz (temporal resolution of 10 ms).

The exciting aspect of the differences in movement asymmetry and their timing now lies in investigating the head–withers relationship in horses with diagnosed lameness issues comparing asymmetry and timing before and after positive (and negative) joint or nerve blocks. Whenever possible it would seem advisable to use force platform measurements as an adjunct, establishing how the measured kinematic changes are related to the causes of these changes, i.e. forces and moments under the limbs [16].

Movement asymmetry and lameness

The lack of full clinical assessment of lameness in these horses is the main limitation of this study. In the presence of a full lameness examination including diagnostic analgesia, further conclusions could have been drawn from the data presented here. It is not possible to answer questions such as: Are the horses that conform with the previously measured asymmetry patterns of head, withers and pelvis truly lame in the predicted limb? Are horses that are not consistent with these patterns lame in more than one limb? Which of the horses are truly lame and which show normal deviations from perfectly symmetrical movement?

The latter point is of fundamental importance, since recent studies both with expert veterinary assessment of horses [17,18] and based on measurement of gait asymmetries [19–21] have identified up to 75% of horses as lame or 'outside normal thresholds'. On an individual horse basis in the clinical lameness examination, the decision whether or not a horse presents with a lameness is guided by assessments/measurements of the horse under a variety of conditions, e.g. after diagnostic analgesia [22–24], on the lunge on different surfaces [25] or after flexion tests [26,27]. This allows the veterinarian to draw conclusions based on changes within a given subject rather than making use of a general threshold to classify the horses as sound or lame. The use of a threshold to distinguish between sound and lame horses is more suitable for increasing the repeatability of subject selection in scientific studies by using an objective, quantitative measurement rather than a subjective opinion about the lameness status.

In the current study, we are not applying any movement asymmetry thresholds to the gait analysis results for 2 reasons. First, we are interested in the presence of a more general 'mechanism' linking the direction of head, withers and pelvic movement asymmetry independent of whether the movement asymmetry values for head and pelvis are above or below a predefined lameness threshold, hence a dichotomy between lame and nonlame horses is not required. Second, in horses for which multiple instances of gait analysis results were available over the study period, our selection method was biased towards higher asymmetry values. This was implemented intentionally, since in trot, as a symmetrical gait, the expectation would be for horses to show near symmetrical movement (low asymmetry values) and we were interested in evaluating the existence of a 'mechanism' over a larger range of asymmetry values. Random sampling over a larger cohort of horses would be advantageous to avoid this selection bias; however, it has to be emphasised, that neither pelvic nor withers movement asymmetry were evaluated in the selection process, removing the possibility of subconsciously including horses showing the hypothesised head–withers–pelvis asymmetry patterns.

Conclusions

Thoroughbred racehorses in training show a range of head, withers and pelvic movement asymmetries in terms of direction and magnitude. We have shown that: 1) the majority of horses with contralateral head–withers asymmetry show ipsilateral head–pelvic asymmetry; and 2) the majority of horses with ipsilateral head–withers asymmetry show contralateral head–pelvic asymmetry. The relationship between head and withers asymmetry predicts the pattern of head and pelvic asymmetry, which has previously been shown to be consistent with the origin of a lameness from either one of the thoracic limbs or one of the pelvic limbs; this is known as the 'law of sides'. However, the source of the gait asymmetries in the horses that are not in line with the above head, withers and pelvic asymmetry patterns needs further investigation as well as to what extent the measured asymmetries in the racing Thoroughbreds studied here are normal biological variation (for horses training and exercising at high speed) or are related to some underlying pathological process. This requires horses with a clinical diagnosis.

The relationship between head and withers asymmetry appears to be related to the timing of the head compared to withers and pelvic movement. The head timing differs between horses with asymmetry patterns consistent in direction with hindlimb lameness and horses with asymmetry patterns consistent in direction with forelimb lameness.

Authors' declaration of interests

No competing interests have been declared.

Ethical animal research

This study was authorised by the Royal Veterinary College Ethics and Welfare Committee (URN 2013 1238) and Singapore Turf Club had approved the collection of gait data.

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Authorship

The study was designed by T. Pfau and M. Sepulveda Caviedes and executed by K. Noordwijk, M. Sepulveda Caviedes, A. Barstow and B. Forbes. All authors contributed to data analysis and interpretation. T. Pfau and K. Noordwijk prepared the initial manuscript draft. All authors contributed to manuscript revision and approved the final version of the manuscript.

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