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Lungeing on hard and soft surfaces: movement symmetry of trotting horses considered sound by their owners

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Summary

Reasons for performing study: Lungeing is often part of the clinical lameness examination. The difference in movement symmetry (MS) – a commonly employed lameness measure – has not been quantified between surfaces.

Objectives: To compare head and pelvic MS between surfaces and reins during lungeing.

Study design: Quantitative gait analysis in 23 horses considered sound by their owners.

Methods: Twenty-three horses were assessed in-hand and on the lunge on both reins on hard and soft surface with inertial sensors. Seven MS parameters were quantified and used to establish two groups: symmetrical (N=9) and forelimb lame (N=14) horses based on values from straight-line assessment. MS values for left rein measurements were side-corrected to allow comparison of the amount of MS between reins. A mixed model (P<0.05) was used to study effects on MS of surface (hard/soft) and rein (inside/outside with respect to MS on straight).

Results: In forelimb lame horses, surface and rein were identified as significantly affecting all head MS measures (rein: all P<0.0001, surface: all P<0.042). In the symmetrical group no significant influence of surface or rein was identified for head MS (rein: all P>0.245, surface: all P>0.073). No significant influence of surface or rein was identified for any of the pelvic MS measures in either group.

Conclusions: We confirm that while more symmetrical horses show consistent amount of MS across surfaces/reins, horses objectively quantified as lame on the straight show decreased MS during lungeing, in particular with the lame limb on the inside of a hard circle. MS variation within group questions straight line MS as a sole measure of lameness without quantification of MS on the lunge, ideally on hard and soft surface to evaluate differences between reins and surfaces. In future, thresholds for lungeing need to be determined using simultaneous visual and objective assessment.

Keywords: Horse; Lameness; Lunge; Surface; Movement Symmetry

Introduction

Lameness is one of the most important performance limiting manifestations of a medical problem in horses with important financial consequences [1,2,3]. Lungeing on different surfaces is often part of a lameness examination, aiding decision making [4]. When visually assessing lameness even experienced observers often disagree [5]. Inertial measurement units (IMUs) can now accurately quantify movement symmetry (MS) parameters [6,7] and are practical for use during the clinical lameness examination [8,9,10,] quantifying important lameness parameters such as head nod [11] and hip hike [12].

Adaptations in sound horses and links to the lameness examination

On the lunge, the centripetal force produced by both inside and outside limbs [13] renders movement of sagittal plane landmarks asymmetrical [14,15] with body lean angle towards the inside of the circle [16] increasing with increasing speed and decreasing circle radius [14]. Clinically, lungeing on different surfaces helps discriminating between different causes of lameness [4]. The systematic adaptation of a horse's MS on the lunge –increased head downward movement during outside forelimb stance and increased movement amplitude of the inside tuber coxae during outside hind limb stance [14,15] – may contribute to the clinical usefulness of lungeing by exacerbating asymmetries over the perception threshold [17]. However, quantitative evidence with respect to differences between hard and soft surfaces – clinically used to discriminate between different causes of lameness – is to date not available.

Adaptations in horses with induced lameness

When inducing lameness in horses on the lunge [18] with a screw-shoe model [19], forelimb lame horses show the most pronounced effects when the lame limb is on the outside of the circle, the limb with which sound horses produce the highest peak forces [13]. For induced hind limb lameness the most pronounced change in MS is observed with the lame limb on the inside, resulting in a summation of circle-dependent effects [14,15] and the effects of induced lameness. Compensatory head movement as a reaction to inducing hind limb lameness mimics ipsilateral forelimb lameness (similar to what is observed on the straight), [20] while compensatory pelvic movement as a reaction to induced forelimb lameness mimics mixed ipsilateral and contralateral hind limb lameness [18].

Study aims

Mobile gait analysis systems now allow quantitative assessment of movement patterns under a variety of conditions. Clinically, quantifying locomotor adaptations to circular motion in horses with defined diagnoses will help establish evidence-based decision strategies. Here we address a question with relevance for both scientific studies and clinical lameness examinations: do horses that are perceived to be symmetrical (moving symmetrically on the straight with asymmetry around/below the limits of human perception; <25%: [17]) adapt differently to lungeing on hard and soft surfaces than horses falling just outside the normal range? The aim of this study was to quantify the effect of lungeing on vertical head and pelvic MS when trotting on a hard compared to a soft surface. We hypothesized that, compared to horses whose motion is quantifiably symmetrical on the straight, mildly forelimb lame horses will show characteristic differences in MS between surface/rein combinations with decreasing MS on the hard surface.

Materials and Methods

Horses

Twenty seven general riding horses of different breeds (body height: 1.28-1.73 m, median: 1.6 m; body mass: 363-603 kg, median: 500 kg) were enrolled in this study. All horses were in regular exercise and were deemed sound by their owners/riders at the time of data collection. The two data collection locations each had a riding arena with a rubber and a sand surface respectively (‘soft surface’) and a flat concrete surface (‘hard surface’). Ethical approval was obtained from the Royal Veterinary College Ethics and Welfare Committee.

Gait analysis setup

Four MTx[a] IMUs were attached to each horse: poll, os sacrum and left (LTC) and right tuber coxae (RTC). An Xbus[a] was attached to a surcingle transmitting raw IMU data via Bluetooth at 100 Hz per individual sensor channel to a laptop computer running MTManager[a] software and custom written MATLAB[b] scripts for data analysis.

Data collection protocol

All horses were trotted in-hand in a straight line and lunged on a circle of 10 m diameter (marker placed on the lunge line), on both reins. Horses were trotted at their preferred speed on both hard and soft surfaces, subjectively aiming (counting steady-state strides – the horse trotting at constant speed and circle radius – during data collection) to collect a minimum of 15 continuous strides for each rein. The order of which each data set was recorded (in-hand, left/right, hard/soft) was randomized.

Quantification of movement symmetry

Based on vertical movement for each horse and condition three published MS measures were calculated for head and pelvis: symmetry index (SI for upward displacement: [11]), difference between displacement minima and maxima (MinDiff, MaxDiff: [21]) as well as one additional measure for the pelvis: difference in upward movement amplitude between left and right tuber coxae (HHD: [15]). Further details about these MS measures are summarized in Table S1.

Table 1 summarizes the SI values for all 27 horses on the straight for the horses from the two data collection locations. Horses were categorized into different asymmetry groups based on thresholds for head and pelvic movement symmetry during straight-line trot (SI_{poll} and SI_{pelvis}) derived from data of clinically sound horses previously [11]. The resulting normal ranges for symmetrical horses were defined as $0.82 \leq SI_{poll} \leq 1.18$ and $0.83 \leq SI_{pelvis} \leq 1.17$ [15]. Four horses, objectively classified as outside normal limits in both forelimbs and hind limbs (quantitatively forelimb and hind limb lame), were excluded from further analysis to minimize the possibility of multiple compensatory effects acting simultaneously. Consequently, data of 23 horses were used and subdivided into two asymmetry groups: nine horses moving symmetrically on the straight were found with SI_{poll} and SI_{pelvis} values within normal limits. Fourteen horses objectively categorized as forelimb lame (equivalent to approximately a lameness of grade 1 based on [11]) were identified.

Statistical Analysis

Statistics were carried out in SPSS[c]. Effects were considered significant for $P<0.05$. For each horse and each condition median MS values across strides were calculated. All median MS measures ($SI_{head/pelvis}$, $MinDiff_{head/pelvis}$, $MaxDiff_{head/pelvis}$, HHD) for trot on the straight and on left/right circle were found to be normally distributed based on Kolmogorov-Smirnov tests ($P>0.19$ for all seven MS measures). In order to assess the size of the introduced movement asymmetries as a function of surface and rein, MS measures from left rein lungeing were 'side-corrected', effectively making the horses trot on the right rein: MinDiff, MaxDiff and HHD were multiplied by -1 and SI was mirrored with respective to '1'. This is equivalent to observing a horse's movement through a mirror when being lunged on the left rein while

observing the actual horse and not its mirror image when being lunged on the right rein. This procedure – together with categorizing exercise conditions into inside and outside rein (inside rein: e.g. a horse with LF asymmetry or lameness on the left rein or a horse with RF asymmetry or lameness on the right rein) – effectively allows combining LF and RF lame horses into one group of forelimb lame horses when studying amounts of asymmetry.
Mixed models with surface (hard/soft), rein (inside/outside with respect to the identified direction of MS on the straight) and data collection location as factors were tried on data sets from the symmetrical and the lame horses. Data collection location was not found to alter the model outcome nor identified as significantly influencing any of the seven MS measures and was hence excluded from the final model implemented.

Results

Number of strides and stride duration

For each horse and condition a mean ± standard deviation (SD) of 38±8 strides with a minimum of 15 strides per condition was recorded. Stride duration on the soft surface was 716±43 ms on the straight, 737±46 ms on the left circle and 730±37 ms on the right circle. Stride duration for the hard surface was 702±35 ms on the straight, 711±39 ms on the left circle and 705±36 ms on the right circle. Overall horses showed stride durations of 734±41 ms on the soft circle and 708±37 ms on the hard circle.

Movement symmetry for lungeing on soft and hard surface in sound horses

Table 2 summarizes median values for head and pelvic MS for the nine horses of the symmetrical group on left and right rein. On the right rein, SI is generally <1 for poll and >1 for pelvic measurement. This indicates increased movement amplitude during the outside limb stance phase (LF, LH). On this rein, MinDiff is >0 for the poll and <0 for the pelvis relating to increased downward movement during outside stance; MaxDiff is <0 for both poll and pelvis, with interquartile ranges often including 0 (symmetrical movement). HHD on the right rein is generally <0 indicating increased upward movement of the inside (right) tuber coxae measured during outside hind limb pushoff. On the left rein, the opposite pattern is observable.

Table 3 gives median (and interquartile range) values obtained for all seven head and pelvic MS measures for the nine horses of the symmetrical group for inside and outside rein. Inside and outside rein in this group of symmetrical horses was determined with respect to the direction of asymmetry – with values tending towards those of either RF or LF lameness, but within current normal limits (i.e. non-lame). (see table 1). Generally, median side-corrected MS values are similar between inside and outside rein for the same surface (inside soft versus outside soft or inside hard versus outside hard) with a maximum difference between reins of 2 mm (MinDiff), 3 mm (MaxDiff and HHD) and 0.07 (SI).

Differences between rein/surface combinations for different groups of horses

Figures 1 and 2 show the side-corrected head and pelvic MS values measured for the two groups for the four different rein/surface combinations. Generally there was considerable spread of MS values within each category within each group of horses as illustrated by the width of the boxes (25th and 75th percentile). Head and pelvic MS across surface/rein conditions show comparatively small and consistent median values in the symmetrical horses. In the forelimb lame horses, in particular head MS median values vary considerably across conditions deviating most clearly from perfect symmetry ('1' for SI, '0' for MinDiff and MaxDiff) when the lame limb is on the inside of the circle. This effect appears exacerbated on the hard surface. With the lame limb on the outside of the circle the forelimb lame horses show more symmetrical head movement (median values closer to '0' or '1', Figure 1).

In the symmetrical horses, mixed model analysis did not reveal any significant influence of surface or rein on any of the three head or any of the four pelvic MS measures. In the forelimb lame horses, rein was identified to significantly influence SI_{poll}, $MinDiff_{Poll}$ and $MaxDiff_{poll}$ (all $P<0.0001$). Surface was also found to significantly influence all three head MS measures (SI_{poll}: $P=0.002$, $MinDiff_{poll}$: $P=0.002$, $MaxDiff_{poll}$: $P=0.042$). None of the pelvic symmetry measures was significantly influenced by either rein or surface (rein: all $P>0.200$; surface: all $P>0.076$).

Discussion

We investigated head and pelvic MS in two groups of horses trotting on the lunge on hard and soft surfaces. In the absence of a gold standard for defining soundness when the horse is on the lunge, the horses were categorized into symmetrical and forelimb lame based on quantitative MS measured during straight-line trot based on thresholds established from published data from clinically sound horses [11]. The measure used here for this purpose (SI) normalizes the quantified differences between the two halves of the stride to the overall range of motion observed for each landmark. As a consequence, this measure appears to be less affected by horse size – which was different in this study and the cited study from which the threshold was derived [11] – however, further studies should investigate the effect of horse size on different movement symmetry measures.

The nine symmetrical horses showed asymmetry patterns that are consistent with previously published data collected with full six degree of freedom IMUs for vertical movement [14, 15]. In these horses, none of the MS measures showed significant differences between surfaces or reins. However considerable spread of MS values within this group (as well as within the forelimb lame group, see figure 1) indicates that individual horses cope differently with the constraints of circular movement [22]. We simply do not know how the spread of MS values is related to biological variation (except for speed and circle radius, which systematically affect movement symmetry [14]), due to handedness of the horse or to asymmetrical handling/riding, or to different orthopaedic deficits (mainly the lame group) as well as subclinical or bilateral lameness within the symmetrical group (i.e. below the current threshold and below 25% asymmetry suggested as the limit of human perception [17]). The variation observed on the lunge within both groups clearly emphasizes the need to quantitatively assess horses on the straight as well as on the lunge whenever possible to minimize the likelihood of classifying sub-clinically or bilaterally lame horses in biomechanical investigations as ‘sound’. However, specific thresholds need to be established based on horses clinically diagnosed and confirmed by gold standard kinetic analysis to be free of lameness but this is difficult on the lunge. In a first approximation, this could be achieved based on horses judged as being sound through visual assessment by the majority of a number of experienced clinicians but the agreement is rather low when assessing lameness on the lunge (see e.g. [23]) and speed dependency of objective parameters [24] further complicates this.

In the forelimb lame horses, all three head MS measures were significantly altered between surfaces and reins. In general, the highest amount of asymmetry was found for lungeing on a hard surface with the lame limb on the inside of the circle. Circular movement has been shown to cause increased extra-sagittal joint torques in particular on hard surfaces where the hoof cannot sink into the surface [13]. We hypothesize that these torques exacerbate pain in lame horses. Here, in the majority of horses the highest amount of asymmetry was detected with the lame limb on the inside of the circle and this limb has been observed to be at an increased inclination angle with the surface [25] and circle and lameness dependent effects add up.

Differences between symmetrical and mildly lame horses

In the symmetrical group, changes in for example side-corrected $MaxDiff_{poll}$ and $MinDiff_{poll}$ are of similar magnitude between surface/rein combinations (Table 3, Figure 1) and are generally small (median values of around 10 mm). Hence, the values observed here for the majority of horses in this group are consistent with values measured for horses considered 'sound' by the majority of veterinarians in a recent study with simultaneous visual and objective IMU based assessment of horses on the lunge [23]. However, some horses in the symmetrical group exceed these values (some clearly) and it seems possible that these horses are in fact lame; alternatively it is equally possible, that even completely sound horses do not show equal amounts of movement symmetry on both reins, for example related to speed and circle diameter [14], which should hence be kept comparable between reins. The fact that MS values for these horses were found within normal limits when quantified on the straight, questions the grouping of horses into lameness categories just based on straight line assessment.

Mildly lame horses on the other hand generally show more prominent changes with median values across all horses of up to 35 mm. Assuming an overall movement amplitude of the head of 70 to 100 mm [11] this translates into percentage asymmetry values of 35 to 50 %, even in these horses which on the straight only showed mild asymmetries. This further emphasizes the benefit of lungeing to exacerbate small movement asymmetries above the proposed threshold for human detection of 25 % [17]. Although we cannot exclude that some of the horses in the symmetrical group showed sub-clinical or bilateral lameness, the differences identified here between the more symmetrical and forelimb lame group suggests that the majority of horses in the symmetrical group are sound and differences in the amount of asymmetry between reins are very small in these horses. Further studies should concentrate on quantifying surface and rein related changes in horses with clinically diagnosed lesions to establish appropriate threshold values (based on sensitivity and specificity for detecting lameness) on the lunge.

Compensatory effects

When inducing lameness on the lunge, specific patterns of referred asymmetry can be observed [18]. Here, for the forelimb lame horses no significant pelvic MS differences between surface/rein combinations were found. This may be related to the small effect of 0.2 mm compensatory asymmetry for each 1 mm of primary asymmetry [18]. Hence the compensatory changes may only be detectable for more clearly asymmetrical horses. Alternatively the compensatory mechanisms observed in induced lameness may differ from the ones in mild clinical lameness [26] and indeed the spread of MS values indicates that individual horses cope differently and different anatomical structures may be causing the lameness.

Classification of horses based on straight line movement based on threshold values

Twenty-seven horses in regular exercise and judged sound by their owners/riders were recruited into the study. Objective MS assessment during trot in-hand revealed that only nine horses were within ‘normal limits’ based on previously published research [11]: we used 18% ($0.82<SI_{poll}<1.18$) and 17% ($0.83<SI_{pelvis}<1.17$) as cutoff values. These thresholds are also consistently below the suggested threshold of 25% for human perception of movement asymmetry [17].

The low number of horses found within normal limits poses the question whether the current thresholds need refining and whether in principle a quantitative assessment just based on straight line measurement is suitable as an inclusion/exclusion criterion in scientific studies. Similar to what is done in a clinical lameness examination, horses should hence be – whenever feasible – also assessed on the lunge when objective gait data is used as an inclusion/exclusion criterion. Regardless of whether in-hand or on the lunge, theoretically, thresholds should be based on minimal important differences (MIDs) [27] derivable from long-term studies investigating changes in diagnosed conditions. In a first step – since MIDs are not yet available – and despite known limitations [27] reference values [28] derived from a larger number of 'normal' subjects, should be used. Interestingly, a recent study with IMUs [29] presents more stringent thresholds for in-hand assessments: 6 mm for head movement and 3 mm for pelvic movement, i.e. 6 to 9% or 3 to 5% again based on an assumed movement amplitude of 70 to 100 mm [11]; as a result more horses would have been categorized as lame in this study.

Lameness or handedness?

Ultimately – independent of whether in-hand or on the lunge – it needs to be investigated how much asymmetry is related to pain and hence constitutes a lameness and how much asymmetry is related to handedness of the horse or asymmetrical handling or riding [30-33]. Here, we assume that horses showing MS of similar magnitude to horses with mild induced lameness [11] are lame, however no diagnostic analgesia was performed in the privately owned horses recruited as 'being perceived sound by their owner'. Hence, we do not have a clinical diagnosis. Individual horses may suffer from a variety of orthopaedic conditions. The spread of symmetry values within each surface/rein category suggests that this was the case for at least part of the horses. This calls for a larger scale study with horses with clinically diagnosed lesions and quantitative gait assessment in-hand and on the lunge.

Confounding variables: speed, circle radius, stride time

Ideally – to identify purely surface related changes – each horse should be lunged with identical circle radius and speed for all surface/rein combinations since speed and circle radius affect body lean [16] and hence MS [14]. However, in practice in particular with lame horses, this may be difficult. If tight control of these parameters is not possible then regression equations should be used to correct for the differences. These are to date only available for lungeing on a soft surface [14] and speed and circle radius need measuring for usage of these equations (e.g. global positioning system). This was not possible for all horses due to the use of an indoor arena in one location.

The reduced stride times observed on the hard surface suggest that the horses adapt differently. In general, reduced stride time (increasing stride frequency) is related to increased speed [34] however on the lunge, reduced stride time may simply indicate that the horses trot with shorter and quicker strides similar to previous findings [13].

Conclusions

In this study, head and pelvic movement asymmetry was found to be generally small and not significantly different between surfaces and reins on the lunge in horses quantitatively assessed as within normal limits during trot in-hand. This may indicate that – independent of surface – these horses distribute weight almost evenly between inside and outside limbs. Mildly forelimb lame horses showed an increase in asymmetry with the lame limb on the inside of the circle with a more pronounced effect on the hard surface. Larger scale studies with horses with clinically diagnosed lesions now need to be conducted to objectively quantify lesion specific changes on hard and soft lunge in order to implement truly evidence based thresholds for this exercise condition which is part of many lameness and pre-purchase examinations.

Conflict of interest statement

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

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Manufacturer Details

[a]Xsens, Enschede, the Netherlands.

[b]MATLAB; The Mathswork Inc, Natick, Massachusetts, USA.

[c]SPSS Inc, Chicago, Illinois, USA.

Table 1:

Body height, body mass, and head and pelvic MS quantified with body mounted IMUs during trot on the straight. Also given are direction of asymmetry for thoracic (LF/RF) and pelvic (LH/RH) limbs identified by objective symmetry index analysis and asymmetry group of each horse for data analysis purposes. All horses – independent of whether attributed to the 'symmetrical' or lame group – are attributed an 'asymmetry direction' in order to be able to assess differences between inside and outside rein. Median values and ranges for each data collection location (1 and 2) are also given. Horses outside normal range for both forelimbs and hind limbs were excluded from the study.

Horse	Location	withers height (m)	body mass (kg)	SI_{Poll} hard surface straight line	SI_{Pelvis} hard surface straight line	assym. direction	Group
1	1	1.6	524	0.61	1.10	RF	lame
2	1	1.68	596	0.61	1.17	RF	lame
3	1	1.5	490	0.72	1.02	RF	lame
4	1	1.55	538	0.87	1.15	RF	sound
5	1	1.63	603	0.79	1.01	RF	lame
6	1	1.63	524	0.93	1.08	RF	sound
7	1	1.48	478	1.19	1.53	LF/RH	**excluded**
8	1	1.65	500	1.19	1.00	LF	lame
9	1	1.5	478	0.9	0.9	RF	sound
10	1	1.55	530	1.36	0.88	LF	lame
11	1	1.58	480	1.31	0.83	LF	lame
12	1	1.65	560	1.47	1.00	LF	lame
13	1	1.65	590	1.11	1.09	LF	sound
median (range)		**1.6 (1.48-1.68)**	**524 (478-603)**	**0.93 (0.61-1.47)**	**1.02 (0.83-1.53)**		
14	2	1.48	390	0.85	1.01	RF	sound
15	2	1.6	550	0.96	1.06	RF	sound
16	2	1.45	490	1.4	1.08	LF	lame
17	2	1.48	408	0.56	1.02	RF	lame
18	2	1.5	464	0.82	0.99	RF	sound
19	2	1.65	603	0.98	0.88	RF	sound
20	2	1.65	504	0.72	0.96	RF	lame
21	2	1.6	458	0.6	1.00	RF	lame
22	2	1.28	303	1.26	1.25	LF/RH	**excluded**
23	2	1.7	560	0.7	1.23	RF/RH	**excluded**
24	2	1.55	600	0.77	0.82	RF/LH	**excluded**
25	2	1.43	363	0.97	0.88	RF	sound

26	2	1.5	414	0.59	0.89	RF	lame
27	2	1.73	511	0.64	1.03	RF	lame
median (range)		**1.53 (1.28-1.73)**	**477 (303-603)**	**0.795 (0.56-1.4)**	**1.005 (0.82-1.25)**		

Table 2: Values for MS measures (before side-correction) for the symmetrical horses (N=9) on left (L) and right (R) rein on hard (H) and soft (S) surface illustrating the circle-dependent adaptations. For poll, SI is >1 for left rein and <1 for right rein, MinDiff is <0 for left rein and >0 for right rein and MaxDiff is >0 for left rein and <0 for right rein. With the exception of MaxDiff pelvic MS values show the opposite pattern of poll values. MaxDiff and HHD values are >0 for left rein and <0 for right rein. Interquartile ranges exclude the value for symmetry in 10 out of 12 conditions for the poll and in 5 cases for pelvic measurements. Given are median values for each condition and interquartile ranges (bracketed values). MinDiff, MaxDiff and HHD values in mm.

Surface		**Poll**			**Pelvis**			
	Rein	**SI**	**MinDiff**	**MaxDiff**	**SI**	**MinDiff**	**MaxDiff**	**HHD**
Soft	L	1.16 (1.1, 1.23)	-5 (-15, -4)	7 (-1, 8)	0.99 (0.92, 1.08)	6 (0, 7)	5 (-1,6)	6 (1, 15)
	R	0.72 (0.66, 0.88)	8 (3,16)	-9 (-11, -4)	1.07 (0.92, 1.11)	-8 (-12, 2)	-3 (-7, -2)	-7 (-13,11)
Hard	L	1.25 (1.11, 1.48)	-8 (-16, -2)	4 (2, 5)	0.9 (0.84, 0.99)	7 (-3, 13)	2 (-8, 5)	10 (0, 12)
	R	0.67 (0.55, 0.79)	11 (8,19)	-7 (-18, 5)	1.08 (0.94, 1.14)	-8 (-12, -3)	-4 (-7, -1)	-6 (-10, 6)

Table 3: Values for side-corrected MS measures for the group of symmetrical horses (N=9) on inside (I) and outside (O) rein on hard (H) and soft (S) surface. Inside and outside limb was determined with respect to the direction of asymmetry during the baseline straight-line assessment, see table 2, e.g. inside rein is right rein for RF asymmetrical horses and left rein for LF asymmetrical horses. Given are median values for and interquartile ranges (bracketed values). MinDiff, MaxDiff and HHD values in mm.

Surface	**Rein**	**Poll**			**Pelvis**			
		SI	**MinDiff**	**MaxDiff**	**SI**	**MinDiff**	**MaxDiff**	**HHD**
S	**I**	0.86 (0.68; 0.91)	5 (2; 15.5)	-8 (-11; -1.5)	1.04 (0.91; 1.12)	-7 (-10.5; 3)	-3 (-7.5; 1.5)	-6 (-11; 12.5)
	O	0.84 (0.71; 0.91)	6 (3; 17)	-8 (-10; 3.5)	1.01 (0.91; 1.11)	-6 (-12.5; 3.5)	-5 (-7.5; 3.5)	-8 (-16.5; 5.5)
H	**I**	0.74 (0.56; 0.87)	11 (5; 18.5)	-7 (-17; -2.5)	1.1 (0.94; 1.15)	-8 (-15.5; -1)	-4 (-7.5; 1)	-6 (-11.5; 6.5)
	O	0.68 (0.41; 0.86)	13 (2; 32.5)	-4 (-16; 0.5)	1.08 (0.94; 1.17)	-7 (-12.5; 3)	-2 (-5.5; 9)	-9 (-19.5; 6)

Table S1: Summary of Inertial measurement unit (IMU) derived movement symmetry (MS) measures derived from vertical head and pelvic movement.

MS measure	Landmark(s)	Quantifies what? Relevant how?	Refs
SI	Head: poll, midline Pelvis: tuber sacrale, midline	Difference in movement amplitude during left/right half of stride normalized to overall movement amplitude. Directional measure of the amount of asymmetry regardless of whether related to weight bearing (minimum position at mid stance) or pushing off (maximum position during aerial phase)	[11]
MinDiff	Head: poll, midline Pelvis: tuber sacrale, midline	Difference between lowest point reached at left and right mid stance. Directional measure quantifying the difference in weight bearing by comparing the vertical height achieved at mid stance.	[21]
MaxDiff	Head: poll, midline Pelvis: tuber sacrale, midline	Difference between highest point reached after left and right stance. Directional measure quantifying the difference in propulsive effort by comparing the vertical height reached in mid aerial phase.	[21]
HHD	Pelvis: Left and right tuber coxae (LTC, RTC)	Difference in upward movement amplitude during contralateral stance, i.e. during right hind stance for LTC and during left hind stance for RTC. Directional measure quanitfying the 'hip hike', i.e. the difference in movement amplitude between the left and right hip.	[15] based on [12]

Figure Legends

Fig. 1. Side corrected head MS measures for the four different surface (H: hard, S: soft) and rein (I: inside, O: outside) combinations for the two groups of horses (symmetrical, N=9, left column; forelimb lame, N=14, right column). The line of perfect symmetry during straight line trotting is given as a dashed line to allow for easier judgment about the condition(s) which cause(s) the most prominent change in MS.
Boxes: line: median; box: 25th and 75th percentile; whiskers: maxima and minima not considered outliers.

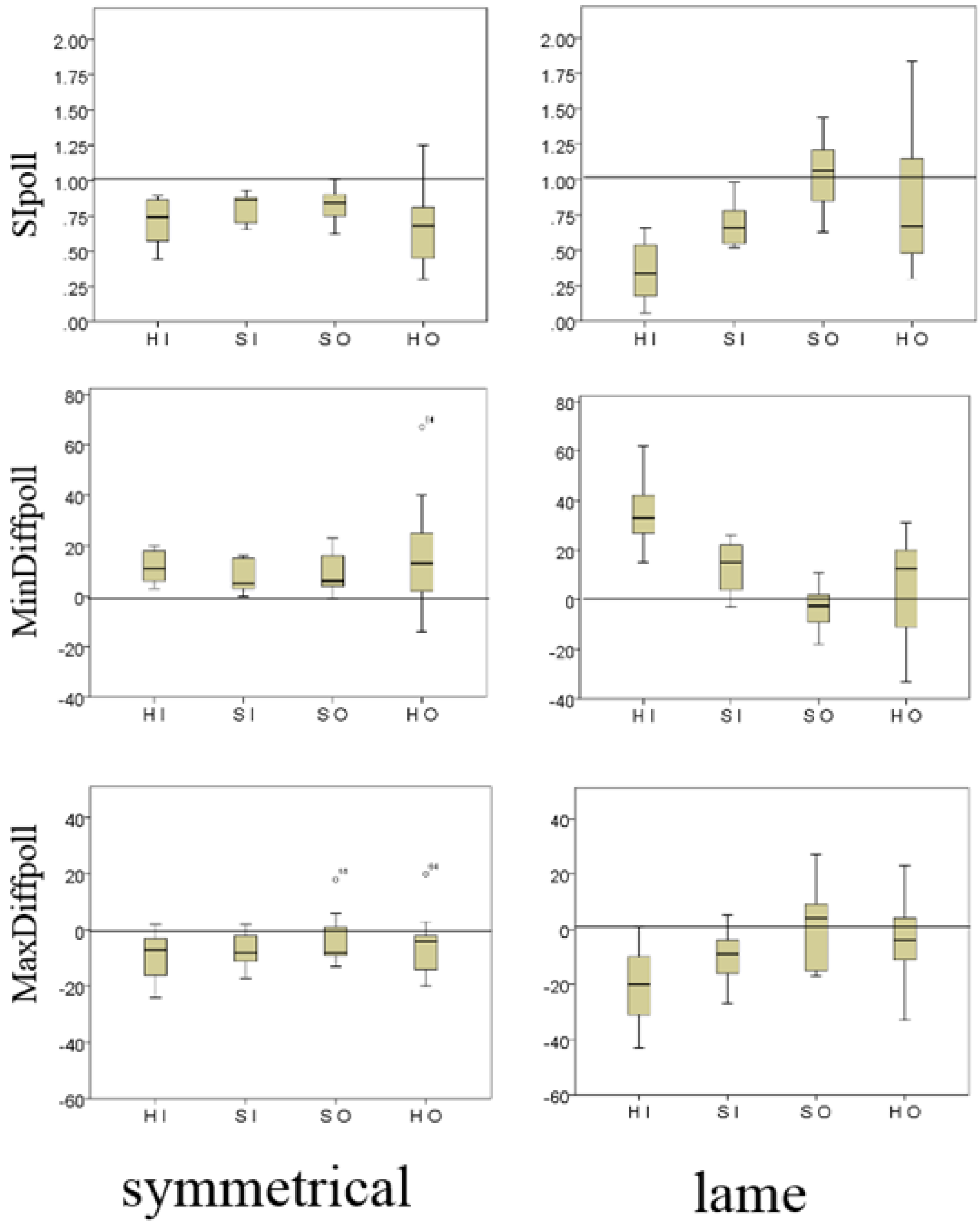

Fig. 2. Side corrected pelvic MS measures for the four different surfaces (H: hard, S: soft) and rein (I: inside, O: outside; defined with respect to direction of asymmetry on straight line) combinations for the two groups of horses (symmetrical, N=9, left column; forelimb lame, N=14, right column). The line of perfect symmetry during straight line trotting given as a line to allow for easier jbudgment about the condition(s) which cause(s) the most prominent change in MS.