Title: Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge and the relationship with hind limb symmetry or asymmetry

Author: L. Greve, T. Pfau, S. Dyson

PII: S1090-0233(17)30008-4
DOI: http://dx.doi.org/doi: 10.1016/j.tvjl.2017.01.003
Reference: YTVJL 4938

To appear in: *The Veterinary Journal*

Accepted date: 3-1-2017

Original Article

Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge and the relationship with hind limb symmetry or asymmetry

L. Greve [a, b, *], T. Pfau [b], S. Dyson [a]

[a] *Centre for Equine Studies, Animal Health Trust, Lanwades Park, Kentford, Newmarket, Suffolk CB8 7UU, UK*
[b] *Department of Clinical Science and Services, The Royal Veterinary College, University of London, Hawkshead Lane, North Mymms, Hatfield AL9 7TA, UK*

* Corresponding author. Tel.: +44 163 8751908
E-mail address: line.greve@aht.org.uk (L. Greve).

Highlights

- Objective: to determine thoracolumbar movement parameters in sound trotting horses
- Circles induce changes in thoracolumbar movement compared with straight lines
- Changes in thoracolumbar movement are associated with alterations in hindlimb gait

Abstract

Equine movement symmetry is changed when turning, which may induce alterations in thoracolumbosacral kinematics; however, this has not previously been investigated. Our objectives were to document thoracolumbar movement in subjectively sound horses comparing straight lines with circles on both reins and to relate these observations to the objectively determined symmetry/asymmetry of hindlimb gait. Fourteen non-lame horses were assessed prospectively in a non-random, cross-sectional survey. The horses were trotted in straight lines and lunged on both reins and inertial sensor data collected at landmarks: withers, T13 and T18, L3, tubera sacrale, and left and right tubera coxae. Data were processed using published methods; angular motion range of motion (ROM; flexion-extension, axial rotation, lateral bending) and translational ROM (dorsoventral and lateral) and symmetry within each stride were assessed.

The dorsoventral movement of the back exhibited a sinusoidal pattern with two oscillations per stride. Circles induced greater asymmetry in dorsoventral movement within each stride (mean ± standard deviation, up to 9 ± 6%) compared with straight lines (up to 6 ± 6%). The greatest amplitude of dorsoventral movement (119 ± 14mm in straight lines vs. 126 ± 20mm in circles) occurred at T13. Circles induced greater flexion-extension ROM (> 1.3°; $P = 0.002$), lateral bending (> 16°; $P < 0.001$), and lateral motion (> 16mm; $P = 0.002$) compared with straight lines. Circles induced a movement pattern similar to an inside hindlimb lameness, which was significantly associated with the circle-induced greater asymmetry of dorsoventral movement of the thoracolumbar region (P = 0.03). Moving in a circle induces measurable changes in thoracolumbar movement compared with moving in straight lines, associated with alterations in the hindlimb gait.

Keywords: Biomechanics; Back pain; Equine; Inertial measurement units; Lameness

Introduction

Equine spinal motion has been assessed in great detail in vitro (Jeffcott and Dalin, 1980; Townsend et al., 1983) and to some extent in vivo (Faber et al., 2000, 2001a, b; Licka et al., 2001a, b). Movement symmetry is changed when turning (Pfau et al. 2012), which may induce alterations in thoracolumbosacral kinematics, however this has not been investigated.

Optical motion capture is the current reference standard to capture thoracolumbar kinematics with high repeatability (Faber et al., 2001a, b, 2002) and has previously been used in asymptomatic riding horses (Johnson and Moore-Colyer, 2009) and in sports horses with epaxial muscle pain (Wennerstrand et al., 2004). However, the constriction of camera calibration makes it difficult and the high cost of multiple specialist cameras required to cover large areas (e.g. a whole riding arena) makes it economically unviable to be used outside gait laboratories. Preliminary work using inertial measurement units (IMUs) in non-ridden horses compared with optical motion capture concluded that IMUs are a reliable and accurate tool to measure thoracolumbar movement (Warner et al., 2010). More recently IMUs have been used to establish reference values for thoracolumbar movement in Franches-Montagnes horses in-hand and under saddle (Heim et al., 2015). Various methods have been developed to enable left/right asymmetry to be quantified numerically based on vertical displacement of upper body landmarks (Buchner et al., 1996; Peham et al., 1996; Uhlir et al., 1997; Keegan et al., 2001; Kramer et al., 2004). Symmetry indices can be calculated to quantify movement symmetry between the movement amplitudes of the two halves within each stride, while MinDiff and MaxDiff are used to quantify the differences in minimum and maximum displacement of the body landmark to which the sensor is attached, respectively, reached during and after the two stance phases.

HipHike difference (HHD) quantifies the difference in upward movement of each tuber coxae during contralateral hindlimb stance and this measure reflects one of the visual observations in horses with hindlimb lameness (May and Wyn-Jones, 1987). When measuring pelvic movement symmetry parameters (MinDiff, MaxDiff, HHD) quantifying the response to diagnostic analgesia in horses with hindlimb lameness, the most consistent changes were observed in MinDiff and HHD (Pfau et al. 2014).

There is evidence that saddle slip consistently to one side occurs in approximately 50% of horses with hindlimb lameness (Greve and Dyson, 2013, 2014) suggesting that the movement of the thoracolumbar region is altered by hindlimb lameness. However, we need to understand better the relationship between pelvic and thoracolumbar symmetry in sound horses and those with hindlimb lameness, and in particular to establish the interrelationship between the symmetry and amplitude of thoracolumbar movement and the hindlimb gait under a variety of movement conditions. Horses adapt to experimentally induced lameness by extending the thoracolumbar region and decreasing the range of motion (ROM) of the lumbosacral segment (Gómez Álvarez et al., 2008); induced epaxial muscle pain results in reduced movement of the thoracolumbar region (Wennerstrand et al., 2004, 2009). When measuring changes in thoracolumbar dimensions with a flexible curve ruler every two months over one year, it was demonstrated that the presence of pre-existing lameness had a negative influence on the development of the epaxial musculature (Greve and Dyson, 2015), presumably related to reduced use of the thoracolumbar epaxial muscles.

With sensitive measurement techniques one might expect to be able to measure asymmetry in pelvic and thoracolumbar movement in circles in sound horses, because in circles the inside and outside hindlimbs are each describing a path with a different radius. This alters the symmetry in loading and push off from each hindlimb during a stride compared with moving in straight lines and has been quantified in horses on the lunge (Pfau et al., 2012).

Our objectives were to document movement of the thoracolumbar region in subjectively sound horses in straight lines in hand and on the lunge, comparing left and right reins, and relate these observations to the objectively determined symmetry or asymmetry of hindlimb gait. We hypothesised that trotting in circles will induce asymmetry in the thoracolumbar movement which is symmetrical between the left and right reins and that these changes will be associated with alterations in the hindlimb gait.

Materials and methods

A prospective study was performed comprising sports horses, in regular work, presumed by the riders to be sound. This was a convenience sample, selected based on proximity to the authors. All horses were ridden by the normal rider in usual tack and had no recent history of lameness or epaxial muscle pain. Age, breed, gender, height (copied from the passport), work discipline and level of training or competition were recorded. The current study was approved by the Ethical Review Committee of the Animal Health Trust (AHT 14.2014; 28 February 2014) and there was informed owner consent.

Horse inclusion criteria

Fourteen selected horses were sound in hand, no more than grade 1/8 lame (Dyson, 2011) after flexion of a single limb, and sound on the lunge on soft and firm surfaces and ridden (Dyson and Greve, 2016).

Inertial measurement units (IMUs)

Objective gait assessment was performed 4 -14 days after the initial gait assessment. Each horse was instrumented with seven MTx (18 × *g*, 1200 degree/s) miniaturised IMUs (Xsens Technologies) and one MTi-G IMU with integrated global positioning system receiver. The IMUs were attached to the head (the poll, using a custom-made velcro attachment to the head piece of the bridle) and to the left and right tubera coxae, over the midline of the horse at the level of the tubera sacrale (MTi-G), the withers, T13, T18 and L3; the sensors were in custom-made pouches and attached with double-sided tape (F ball Impact Tape, F. Ball). An elasticated surcingle was used to fix the wireless transmitter unit (Xbus, Xsens Technologies) to the horse's body. Sensors were attached in three strings (1, head; 2, left and right tubera coxae, tubera sacrale, L3; 3, withers, T13, T18) to the Xbus transmitting IMU data at a sampling rate of 100Hz per individual sensor channel.

Dynamic assessment with IMUs

Fourteen horses selected as sound were trotted in hand on a soft surface (an indoor arena approximately 25 m × 60 m, with sand and fibre on a very firm base, n = 2; or with a very soft base, n = 10; or an outdoor arena approximately 30 m × 70 m with sand and fibre on a firm base, n = 2) and then lunged on the left rein followed by the right rein using a consistent lunging technique, with a lunge line attached to the inside bit ring. The handlers (selected according to their familiarity with the horses) were asked to use the same lunge line with a fixed length of 5 m resulting in a circle diameter of approximately 10 m. The handlers were asked to allow the horses to trot in hand and on the lunge at each horse's preferred speed. IMU data were collected for at least 40 strides. Notes and video recordings acquired during data collection described deviations from the expected movement condition, e.g., changes in gait, speed or gait quality. If a horse deviated from the required movement condition (e.g., broke into a different gait) data collection was repeated. One trot trial at the horse's preferred speed on the lunge on both left and right reins in trot was recorded for each circumstance. Two trials were performed in four horses trotting in straight lines and up to ± 5 mm difference of the median of any outcome variable between trials was achieved. The video recordings of the horses were acquired from outside of the circle. Video recordings of the horses were acquired during objective data acquisition for subsequent assessment by SJD. Intra-assessor repeatability of the 20 horses videoed was performed three times at intervals of 2 months and 100% agreement was achieved with regard to the presence of lameness (yes/no). Previous intra-assessor repeatability has been documented in 50 horses that were randomly selected and assessed twice in a random order at an interval of 1-4 months; 98% correlation was achieved for lameness group (Greve and Dyson, 2014).

Data processing

Vertical displacement of the tubera sacrale and the left and right tubera coxae was determined. Processing of IMU data followed published methods (Pfau et al., 2005) with custom-written software in MATLAB (The Mathworks).

Quantification of kinematic symmetry measures

The following kinematic symmetry measurements were determined: symmetry index, MinDiff and MaxDiff for pelvis and HHD. A horse moving perfectly symmetrically would have a symmetry index of 1 and MinDiff, MaxDiff and HHD values of 0. Detailed description of the calculations can be found elsewhere (Pfau et al., 2012). MinDiff > 0 mm means greater downward movement during right hindlimb (RH) stance compared with left hindlimb (LH) stance, whereas MinDiff < 0 mm means greater downward movement during the LH stance compared with RH stance. MaxDiff < 0 mm means greater upward movement after RH stance compared with LH stance, whereas MaxDiff > 0 mm means greater upward movement after LH stance compared with RH stance.

Three-dimensional kinematics of the vertebral column

A standard right-handed orthogonal Cartesian coordinate system was used (craniocaudal or x positive axis directed along the line of progression; dorsoventral or z axis vertical [aligned with gravitational field] and positive in the upward direction; lateral-lateral or y, axis perpendicular to the first two axes positive to the left of the line of progression). The craniocaudal (x), lateral-lateral (y) and dorsoventral (z) displacement data in the horse based reference system were calculated following published methods (Pfau et al. 2005, Warner et al., 2010) with modified highpass filter frequencies chosen as 1.5 Hz for dorsoventral and 0.75 Hz for lateral-lateral movement.

Outcome variables

Angular movement (a change in orientation) of the withers, T13, T18 and L3 was assessed in three planes measured in degrees as ROM: flexion-extension ROM, which is the body rotation about the transverse (lateral-lateral); axial rotation ROM, which is the body rotation about the longitudinal (craniocaudal) axis; and lateral bending, which is the body rotation about the vertical (dorsoventral) axis. Translational movement in two directions was measured in mm. Displacement in the vertical direction (up and down movement of the whole horse) and lateral-lateral direction (side to the side movement of the whole horse) at the withers, T13, T18 and L3 and the asymmetry of the two oscillations of the thoracolumbar movement during a stride (asymmetry) based on the symmetry index (SI) were considered. SI is always calculated as the movement amplitude of the first half of the stride (LH right forelimb, RF; diagonal stance phase) minus the movement amplitude of the second half of the stride (RH and left forelimb, LF; diagonal stance phase) and then normalised by dividing by the range of motion and 1 is added.

SI = ([Amplitude up1–Amplitude up2]/maximum[amplitude up1; up2]+1,

where maximum [amplitude up1; up2] is the maximum of the two (Starke et al. 2012). Guidelines are SI < 0.83 is left hindlimb lameness and SI > 1.17 is right hindlimb lameness (Starke et al. 2012), however, this has not been verified scientifically. Asymmetry was defined as the absolute value of (1-SI) x 100%. In addition, the differences between the two peaks (maxima) [MaxDiff] and two troughs (minima) [MinDiff] of the vertical movement signal were measured. SI<1, MinDiff<0 and MaxDiff>0 indicates left-sided asymmetry. SI>1, MinDiff>0 and MaxDiff<0 indicates right-sided asymmetry. Non-directional asymmetry measures were determined by taking the absolute value of the directional asymmetry measures.

Sample size calculation

Based on our hypothesis that the thoracolumbar movement symmetry will show a linear association with the hindlimb symmetry, we planned a study in which regression analysis would be performed for the non-directional T13 asymmetry against hindlimb asymmetry (measured as HHD) for pooled data acquired in straight lines in hand and lunging. Pilot data from three horses indicate that the standard deviation (SD) of HHD for all conditions pooled together was 14.1 mm and the SD of the regression errors was 0.93 and the slope was -0.4. Based on this pilot data, a sample size of three horses is enough to be able to reject the null hypothesis that this slope equals zero with probability (power) 0.8. The Type I error probability associated with this test of this null hypothesis is 0.05.

Statistical analysis

Descriptive analysis was carried out for outcome variables for straight lines in hand and lunging. Mixed effect models were used to assess the relationship between symmetry of the thoracolumbar movement amplitude between the first and second halves of the stride, surface and the hindlimb gait measured as HHD, MinDiff, MaxDiff. All analyses were adjusted for the clustering effect of horse. Those variables that were statistically significant at $P < 0.20$ were put forward for inclusion in a multivariable, mixed-effects linear model. Biologically meaningful interaction terms for all variables retained in the final model were assessed. Final model results were reported as parameter estimates and *P*-values. All statistical analyses were performed using SPSS Statistics 20 (SPSS), with significance set at $P < 0.05$.

Results

The animals ranged in age from 3 to 13 years (mean, 7 years; median, 6.5 years) and comprised 10 geldings, one stallion and three mares. Horses were used for dressage (*n* = 12) and show jumping (*n* = 2). Breeds represented were Warmbloods (*n* = 12) and ponies (*n* = 2). Bodyweights ranged from 400 to 630 kg (mean, 564 kg; median, 590 kg) and in height from 1.48 to 1.74 m (mean, 1.66 m; median, 1.69 m).

Quantification of thoracolumbar movement

The means ± standard errors for the outcome variables are shown in Table 1.

Straight lines

The dorsoventral (z) displacement had two peaks per stride and exhibited a sinusoidal pattern with two almost symmetrical oscillations in straight lines. The amplitude of movement in straight lines was greatest at T13, with less movement amplitude cranially (withers) and caudally (L3; Fig. 1a). The dorsoventral ROM of movement ranged from 75-125 mm for the withers, 94-138 mm at T13, 92-134 mm at T18 and 76-122 mm at L3. In contrast displacement in a lateral (y) direction had only one peak and one trough per stride. The ranges of displacement were 18-88 mm for the withers, 14-53 mm at T13, 17-50 mm at T18 and 19-81 mm at L3. Flexion-extension ROM was smaller than axial rotation ROM for all the sensor locations (Fig. 1c-d). Flexion-extension ROM and axial rotation ROM were greatest towards the withers. The axial rotation ROM ranged from 13-28° for the withers, 5-14° at T13, 5-16° at T18 and 7-19° at L3 (Fig. 1c). The flexion-extension ROM ranged from 4-11° for the withers, 3-5° at T13, 2-7° at T18 and 4-7° at L3 (Fig. 1d). The lateral bending ranged from 6-11° for the withers, 3-6° at T13, 3-8° at T18 and 3-8° at L3. In straight lines, there were small asymmetries in the dorsoventral movement between the two halves of the stride (at T13 the symmetry was [mean ± SD] 95 ± 4%)

and slightly less symmetry cranially and caudally (withers, T18 and L3 up to 94 ± 6%; Fig. 2a). The mean ± SD (range) in straight lines of the absolute pelvis MinDiff was 4.9 ± 5.3 mm (0 mm, 18 mm), pelvis MaxDiff was 3.5 ± 3.5 mm (0 mm, 14 mm) and HHD was 6.1 ± 5.9 mm (0 mm, 17 mm; Fig. 2b).

Differences between straight lines and circles

Circles induced significantly greater flexion-extension ROM (mean 5.3°) compared with straight lines (mean 4.0°) for T13 ($P < 0.001$), for T18 (mean circles 5.1° vs. straight lines 4.0°; $P = 0.002$) and for L3 (mean circles 7.1° vs. straight lines 5.3°; $P = 0.001$; Fig. 1d). Circles also induced significantly greater lateral bending (mean 29°) compared with straight lines (mean 8°) for withers ($P < 0.001$), for T13 (mean circles 29° vs. straight lines 5°; $P < 0.001$), for T18 (mean circles 28° vs. straight lines 5°; $P < 0.001$) and for L3 (mean circles 29° vs. straight lines 5°; $P < 0.001$). There were no differences in axial rotation ROM for any sensor location between circles and straight lines (Fig. 1c). The displacements in a lateral (y) direction were significantly greater on the lunge for T13 (mean 46 mm) compared with straight lines (mean 30 mm; $P < 0.001$) and for T18 on the lunge (mean 48 mm) compared with straight lines (mean 36 mm; $P = 0.002$; Fig. 1b). Circles did not induce any significantly different amplitude of dorsoventral displacement compared with straight lines when considering the mean of the two oscillations during outside and inside hindlimb stance (Fig. 1a). However, in comparison with straight lines circles did induce significantly greater amplitude of the dorsoventral movement of T13, T18 and L3 during the outside hindlimb stance compared with the inside hindlimb stance ($P = 0.03$; Fig. 2a). There was a greater maximum displacement of T13 and T18 (Fig. 3b) after outside hindlimb stance compared with the inside hindlimb ($P = 0.003$; Fig. 3a). L3 dropped less during the inside hindlimb stance compared with the outside hindlimb stance (*P* = 0.009; Fig. 3a). The withers dropped less during the inside forelimb stance compared with the outside forelimb stance and reached a higher displacement just after the inside forelimb stance compared with just after the outside forelimb stance (*P* = 0.003). The tubera sacrale dropped less during the inside hindlimb stance compared with the outside hindlimb stance in circles compared with straight lines ($P <$ 0.001) mimicking a mild inside hindlimb lameness. Circles also induced a hip hike mimicking an inside hindlimb lameness compared with straight lines ($P < 0.001$), means on circles the inside tuber coxae had a greater amplitude of movement compared with the outside tuber coxae during the outside hindlimb stance (HHD). However, the mean difference in the maximum displacement of the tubera sacrale between left and right hindlimb stance was not significantly different between circles and straight lines (*P* = 0.2; Fig. 2b).

Differences between left and right reins when moving in circles

There were no significant differences between the side-corrected means of MinDiff or MaxDiff or the means of flexion-extension ROM, axial rotation ROM, dorsoventral or lateral displacement of the thoracolumbar region between the left and right reins when moving on the lunge. The side-corrected pelvic MaxDiff mean ± SD on the right and left reins were 3 ± 5 mm and 3 ± 8 mm, respectively. The side-corrected pelvic MinDiff on the right and left reins were 15 ± 11 mm and 14 ± 10 mm, respectively. The symmetry index on the right and left reins were 0.87 ± 0.07 mm and 0.90 ± 0.08 mm, respectively. None of these symmetry parameters on the left and right reins were significantly different from each other. However, the mean ± SD of HHD on the right rein (21 ± 11 mm) was significantly different from HHD on the left rein (12 ± 10 mm; *P* = 0.05). In addition, lateral bending was on average greater on the right rein compared with the left rein for tubera sacrale (mean ± SD right rein 31° ± 7° vs. left rein 26° ± 3°; P = 0.04), for T18 (right rein 31° ± 7° vs. left rein 26° ± 4°; P = 0.02) and the withers (right rein 32° ± 7° vs. left rein 26° ± 7°; P = 0.004). The data from all the horses is provided in supplementary information (Appendix A).

All the horses were divided into three symmetry categories for each thoracolumbar region based on the symmetry in straight lines in-hand. Horses with larger movement amplitude during LH-RF stance compared with RH-LF stance in straight lines had even greater asymmetry on circles on the right rein compared with symmetrical horses. Similarly horses with larger movement amplitude during RH-LF stance in straight lines compared with LH-RF stance had even greater asymmetry on circles to the left compared with symmetrical horses (Fig. 4).

Association of thoracolumbar movement with pelvic symmetry

Looking at both straight lines and circles there was a linear association between the differences in the upward movement amplitude of the thoracolumbar region (T13, T18, L3) during the LH stance compared with the RH stance and the difference in the upward movement amplitude of the pelvis (tubera sacrale) during the LH stance compared with the RH stance. So for example, if the pelvis had less movement amplitude during the RH stance (either by dropping less [MinDiff] or less upward movement [MaxDiff]) compared with the LH stance, the thoracolumbar region also exhibited less upward movement amplitude during the RH stance compared with the LH stance. The thoracic region was mostly sensitive to the dropping of the pelvis (MinDiff) rather than upward movement of the pelvis (MaxDiff), whereas the lumbar region in straight lines alone was more sensitive to upward movement of the pelvis (MaxDiff) rather than dropping of the pelvis (MinDiff). Ten mm difference in the MaxDiff of both hindlimbs caused 12% greater asymmetry between the first and second halves of the movement amplitudes of L3 (Table 2). There was no influence of surfaces.

The maximum and minimum displacements of T13 were linearly associated with HHD, pelvic MinDiff and pelvic MaxDiff. On a circle, alteration in HHD resulted in up to six times more change in the movement of T13 compared with comparable alterations in magnitude of either pelvic MinDiff and pelvic MaxDiff.

Comparing straight lines with circles, the changes in HHD best reflected changes in thoracolumbar upward movement symmetry between the left and right halves of the stride (Table 3). There was also a strong relationship between movement of the tubera sacrale and the thoracolumbar region. The tubera sacrale dropped less during the inside hindlimb stance compared with the outside hindlimb stance in circles, with both the lumbar and caudal thoracic regions (L3 and T18) following an identical pattern, Figs. 5a, b. However, the mid and cranial thoracic regions (T13 and withers) exhibited the opposite pattern, Fig. 6a, b. For example, on the left rein the pelvis, lumbar and caudal thoracic regions drop more during the RH stance (outside hindlimb) compared with LH stance (inside hindlimb, i.e., positive MinDiff), and the mid- and cranial thoracic regions drop more during the LH (inside hindlimb) stance compared with the RH (outside hindlimb) stance (i.e., negative MinDiff).

Discussion

The results of our study supported the hypothesis that circles induce symmetrical asymmetry between the left and right reins in the thoracolumbar movement and in the hindlimb gait, with the exception of HHD, in sound horses. The hypothesis that left and right asymmetries in the thoracolumbar amplitudes between the first and second halves of the stride are associated with left and right asymmetries in the hindlimb gait was also supported by our findings. The method used for measuring thoracolumbar movement and the hindlimb gait provided an objective means of investigating the relationship between hindlimb and thoracolumbar kinematics. Several studies have described limb kinematics in trot, which is a two beat, symmetrical, diagonal gait with two periods of suspension per stride cycle (Hildebrand 1965, Back et al., 1995a,b), but there are only a few studies which have used biomechanical methods to study the influence of hindlimb gait on the movement of the thoracolumbar region (Faber, 2001, Gómez Álvarez et al., 2007, 2008).

Consistent with previous studies (Audigié et al., 1999; Buchner et al., 2000; Faber et al., 2000, 2001, 2002, Warner et al., 2010), there was a double sinusoidal pattern for dorsoventral displacement of the thoracolumbosacral region and a sinusoidal pattern for lateral-lateral displacement for each stride. There were large ranges in angular movement (up to 19°), except at the withers, which showed up to 28° for axial rotation. This represents only ± 14°, which is quite small when considering that the withers area is less 'rigid' than other sites at which measurements were acquired. There were also large ranges in dorsoventral (75-128 mm) and lateral (18-88 mm) amplitudes of movement among the horses included in the study, emphasising that even within normal sound horses there is considerable variation in thoracolumbosacral movement. The range of movement was slightly more in circles (up to 80 mm) compared with straight lines (up to 70 mm). There were considerably smaller ranges of movement in six research ponies, 40–47 mm for dorsoventral and 16–37 mm for lateral movement, respectively (Warner et al., 2010). This probably reflects the different study populations: ponies vs. sports horses and here the use of animals that have undergone a comprehensive lameness examination including flexion tests. The inclusion of horses with lameness may affect the rotational thoracolumbosacral ROM and symmetry of motion (Greve L., Dyson S., Pfau T. Unpublished data). We made no attempt to scale the data between different sizes of horses, but this merits further investigation. In Franches-Montagnes stallions there was a similar magnitude of movement as in the current study for movement in the dorsoventral direction (mean ± SD, 97 ± 9 mm) and for the movement in the lateral direction at the level of the 12th thoracic vertebra (35 ± 10 mm; Heim et al., 2015). In the current study the greatest range of dorsoventral displacement was found at T13 (94-138 mm), which is closely related to the movement of the body centre of mass (Buchner et al., 2000). It has been previously demonstrated that horses with hindlimb lameness and a convex shape at the level of T18 or T13 had a higher risk of saddle slip than horses with other thoracolumbar shapes (Greve and Dyson, 2013, 2014). This may reflect that the maximal range of vertical displacement and the greatest difference in maximum and minimum heights between left and right halves of the stride occurs at T13, where the equine body centre of mass is aligned with the rider's centre of mass (Buchner et al., 2000). In addition, in the current study the circle-induced differences in the minimum height of T13 during the left and right hindlimb stance phases showed an opposite pattern compared with T18 and L3, indicating that sound horses alter the movement of the mid thoracic region in circles differently to the caudal thoracic and lumbar regions. This means that for example on the left circle where the pelvis shows a higher maximum displacement during inside (left) hind limb stance, potentially a sign of reduced weight bearing with the inside hindlimb, the mid thoracic region shows a higher maximum displacement during outside hindlimb stance, i.e. during inside (left) forelimb stance, potentially a sign of reduced weight bearing with the inside forelimb. Forces in forelimbs and hindlimbs have been correlated with head MinDiff (Keegan et al., 2012) and pelvic MinDiff (Bell et al., 2016), respectively, for lame horses trotting in straight lines, but there is no similar data relating pelvis movement to limb forces during movement in circles for either sound or lame horses. The pattern observed would be consistent with an ipsilateral compensatory movement, which has been reported previously in induced hindlimb lameness on the lunge (Rhodin et al., 2013). In the present study, we observed that the symmetry of the thoracolumbar movement was reduced in circles compared with straight lines for all sensor locations, with greater amplitude of the dorsoventral movement during the outside hindlimb stance in comparison with the inside hindlimb stance. This may explain why a saddle normally moves slightly more in circles compared with straight lines (Bystrom et al., 2009), and why saddle slip in horses with hindlimb lameness is usually worse in circles compared with straight lines (Greve and Dyson, 2013, 2014).

We observed that circles induced mild asymmetry of the movement of the pelvis in sound horses mimicking subtle inside hindlimb lameness, consistent with the results of other studies (Starke et al. 2012; Rhodin et al. 2013, 2016, Halling Thomsen et al. 2014). The circle-induced asymmetry in thoracolumbar and pelvis movement were significantly associated. The maximum and minimum displacements of T13 were linearly associated with HHD, pelvic MinDiff and pelvic MaxDiff. On a circle, alteration in HHD resulted in up to six times more change in the movement of T13 compared with comparable alterations in magnitude of either pelvic MinDiff and pelvic MaxDiff. When measuring pelvic movement symmetry parameters (MinDiff, MaxDiff, HHD) quantifying the response to diagnostic analgesia in horses with hindlimb lameness, the most sensitive and consistent changes were observed in HHD (Pfau et al. 2014).

Differences in the maximum displacement of the tubera sacrale just after the left and right hindlimb stance had the biggest influence on the movement of L3. Movement of the lumbar vertebral column is controlled by both the hypaxial and epaxial muscles. The hypaxial lumbar muscles function as flexors of the coxofemoral joint, the lumbosacral junction and provide stability to the lumbosacral region (Sisson 1975; Clayton 2012; van Weeren 2014) and may contribute to the engagement of the hindlimbs (meaning that the lumbosacral joint is flexed and the hindlimbs are protracted under the body; Dyson, 2016;[1]), but their exact function has not yet been investigated. The epaxial muscles act as extensor muscles. It is a common clinical observation that many horses with hindlimb lameness exhibit epaxial muscle soreness and hypertonicity in the lumbar region (Landman et al., 2004; Zimmerman et al., 2011), although the pathophysiology of muscle pain and the association with limb movement and lameness are not well understood. In the present study, the kinematics of the hindlimbs and the thoracolumbar regions were closely linked. It has also been observed that lameness can induce thoracolumbar stiffness and limited hindlimb impulsion, or a restricted gait in all limbs (Dyson, 2016) and that primary thoracolumbar pain can induce similar symptoms (Girodroux et al., 2009). Based on the results of the current study it is important to be able to detect lameness at an early stage to avoid increased asymmetry of thoracolumbosacral movement which might induce additional pain.

[1] See: FEI Dressage Rules, 2016. https://inside.fei.org/sites/default/files/DRE-Rules_2016_GA-approved_clean.pdf (Accessed 31 December 2016).

Moving on a circle induced a symmetrical asymmetry between left and right reins in the movement of the thoracolumbar region and the pelvic MaxDiff, MinDiff, but not a symmetrical asymmetry in HHD between reins compared with trotting in hand in straight lines in horses selected based on a comprehensive lameness examination by an expert. The difference in HHD may be the result of the circle size and shape not being absolutely identical on the left and right reins. It could also reflect functional motor laterality (the preference of one side of the body or limb compared with the other) in some horses (McGreevy and Rogers 2005; McGreevy and Thomson 2006; van Heel et al. 2006, 2011; Abrams and Panaggio 2012).

This study had some limitations. The measurements were obtained on a soft arena surface and therefore do not represent movement symmetry data on a hard surface or on a different type of arena surface. Data collection was limited to upper body landmarks and did not provide detailed quantification of spatiotemporal limb movement parameters or limb angles, which have been reported (Clayton et al., 2006, Hobbs et al., 2011), however it can be argued based on the principle of Newtonian mechanics that upper body movement asymmetry is closely linked to force production on the ground (Pfau et al., 2016). Preliminary data from six horses demonstrated that foot placement relative to body position and line of travel did not differ markedly between straight lines and circles and cannot solely account for the observed upper body movement asymmetry (Starke et al., 2014). More detailed studies with a larger number of horses and simultaneous measurement of limb forces would complement the understanding of circular movement mechanics. The results of the current study relate mainly to dressage horses and further studies are required to determine if similar results would be obtained with horses from other work disciplines such as eventing and showjumping.

Conclusions

The results of this study have increased our understanding of thoracolumbar movement in sound sports horses, determined the difference between straight lines and lunging exercise and described the effect of left and right reins. Moving on a circle induces measurable changes in thoracolumbar movement compared with moving in straight lines, associated with alterations in the hindlimb gait. Development and determination of objective thoracolumbar movement parameters and establishing the association with the hindlimb gait for sound horses is important to be able to distinguish normal from abnormal and to be able to use the parameters in future lameness investigations.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

Acknowledgements

We thank Ruby Yu-Mei Chang for statistical advice and the many horses and their owners who participated in the study.

Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi: …

References

Abrams, D. M., Panaggio, M.J., 2012. A model balancing cooperation and competition can explain our right-handed world and the dominance of left-handed athletes. Journal of the Royal Society Interface 9, 2718-2722.

Audigié, F., Pourcelot, P., Degueurce, C., Denoix, J.M., Geiger, D., 1999. Kinematics of the equine back: Flexion–extension movements in sound trotting horses. Equine Veterinary Journal 31, 210–213.

Back, W., Schamhardt, H. C., Savelberg, H. H., van den Bogert, A. J., Bruin, G., Hartman, W., Barneveld, A., 1995a. How the horse moves: 1. Significance of graphical representations of equine forelimb kinematics Equine Veterinary Journal 27, 31-8.

Back, W., Schamhardt, H. C., Savelberg, H. H., van den Bogert, A. J., Bruin, G., Hartman, W.Barneveld, A., 1995b. How the horse moves: 2. Significance of graphical representations of equine hind limb kinematics Equine Veterinary Journal 27, 39-45

Bell, R.P., Reed, S.K., Schoonover, M.J., Whitfield, C.T., Yonezawa, Y., Maki, H., Pai, P.F., Keegan, K.G., 2016. Associations of force plate and body-mounted inertial sensor measurements for identification of hind limb lameness in horses. American Journal of Veterinary Research 77, 337-345

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C., Barneveld, A., 1996. Head and trunk movement adaptations in horses with experimentally induced fore or hind limb lameness. Equine Veterinary Journal 28, 71–76.

Buchner, H.H.F. Ohermuller. Scheidl, M., 2000. Body centre of mass involvement in the sound horse. The Veterinary Journal 160, 225-234.

Bystrom, A., Rhodin, M., von Peinen, K., Weishaupt, M.A., Roepstorff, L., 2009. Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. Equine Veterinary Journal 41, 280–284.

Clayton, H.M., Sha D.H., 2006. Head and body centre of mass movement in horses trotting on a circular path. Equine Veterinary Journal 38, (Suppl 36), 462-467.

Clayton, H. M. 2012. Equine back pain reviewed from a motor control perspective. Comparative Exercise Physiology, 8, 145-152.

Dyson, S., 2011. Can lameness be reliably graded? Equine Veterinary Journal 43, 379-382.

Dyson, S., 2016. Evaluation of poor performance in competition horses: a musculoskeletal perspective. Part 1 Clinical assessment. Equine Veterinary Education 28, 284-293.

Faber, M., Schamhardt, H., Weeren, R. van, Johnston, C., Roepstorff, L., Barneveldt, A., 2000. Basic threedimensional kinematics of the vertebral column of horses walking on a treadmill.

American Journal of Veterinary Research 61, 399-406.

Faber, M., Johnston, C., Schamhardt, H.C., Weeren, P.R. van, Roepstorff, L., Barneveldt, A., 2001a. Threedimensional kinematics of the equine spine during canter. Equine Veterinary Journal 33, 145-149.

Faber, M., Johnston, C., Schamhardt, H.C., Weeren, P.R. van, Roepstorff, L., Barneveldt, A., 2001b. Basic three dimensional kinematics of the vertebral column of horses trotting on a treadmill. American Journal of Veterinary Research 62, 757-764.

Faber, M., Johnston, C., Weeren, P.R. van, Barneveldt, A., 2002. Repeatability of back kinematics in horses during treadmill locomotion. Equine Veterinary Journal 34, 235-241.

Girodroux, M., Dyson, S., Murray, R., 2009. Osteoarthritis of the thoracolumbar synovial intervertebral articulations: clinical and radiographic features in 77 horses with poor performance and back pain. Equine Veterinary Journal 41, 130-138.

Gómez Álvarez, C.B., Wennerstrand, J., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van Weeren, P.R., 2007. The effect of induced forelimb lameness on thoracolumbar kinematics during treadmill locomotion. Equine Veterinary Journal 39, 197-201.

Gómez Álvarez, C.B., Wennerstrand, J., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van Weeren, P.R., 2008. The effect of induced hindlimb lameness on thoracolumbar kinematics during treadmill locomotion. Equine Veterinary Journal 40, 147-152.

Greve, L. Dyson, S., 2013. An investigation of the relationship between hindlimb lameness and saddle-slip. Equine Veterinary Journal 45, 570-577.

Greve, L., Dyson, S., 2014. The interrelationship of lameness, saddle-slip and back shape in the general sports horse population. Equine Veterinary Journal 46, 687-94

Greve, L., Dyson, S., 2015. A longitudinal study of back dimension changes over 1 year in sports horses. The Veterinary Journal 203, 65-73

Halling Thomsen, M., Sahl-Tjørnholm, C., Sørensen, H., Tolver Jensen, A., 2014. Effect of lungeing and circle size on movement symmetry in sound riding horses. Equine Veterinary Journal 46, 49–50.

Heim, C., Pfau, T., Gerber, V., Schweizer, C., Doherr, M., Schüpbach-Regula, G., Witte, S., 2016. Determination of vertebral range of motion using inertial measurement units in 27 Franches-Montagnes stallions and comparison between conditions and with a mixed population. Equine Veterinary Journal 48, 509-516.

Hildebrand, M., 1965. Symmetrical gaits in horses. Science 150, 701–708.

Hobbs, S.J., Licka, T., Polman, R., 2011. The difference in kinematics of horses walking, trotting and cantering on a flat and banked 10 m circle. Equine Veterinary Journal 43, 686-694.

Jeffcott L. B., Dalin, G., 1980. Natural rigidity of the horses' backbone. Equine Veterinary Journal 12, 101-108.

Johnson, J.L., Moore-Colyer, M., 2009. The relationship between range of motion of lumbosacral flexion-extension and canter velocity of horses on a treadmill. Equine Veterinary Journal 41, 301-303.

Keegan, K.G., Pai, P.F., Wilson, D.A., Smith B. K., 2001. Signal decomposition method of evaluating head movement to measure induced forelimb lameness in horses trotting on a treadmill. Equine Veterinary Journal 33 (Suppl. 5), 446–451.

Keegan, K.G., MacAllister, C.G., Wilson, D. A., Gedon, C.A., Kramer, J., Yonezawa, Y., Maki, H., 2012. Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness. American Journal of Veterinary Research 73, 368-374.

Kramer, J., Keegan, K.G., Kelmer, G., Wilson, D.A. 2004. Objective determination of pelvic movement during hind limb lameness and pelvic height differences. American Journal Veterinary Research 65, 741-747.

Landman, M.A., de Blaauw, J.A., van Weeren, P.R., Hofland, L.J., (2004) Field study of the prevalence of lameness in horses with back problems. Veterinary Record 155, 165-168.

Licka, T., Peham, C., Zohmann, E., 2001a. Range of back movement at trot in horses without back pain. Equine Veterinary Journal 33 (Suppl. 33), 150-153.

Licka, T., Peham, C., Zohmann, E., 2001b. Treadmill study of the range of back movement at the walk in horses without back pain. American Journal of Veterinary Research 62, 1173-1179.

May, S.A., Wyn-Jones, G., 1987. Identification of hindleg lameness. Equine Veterinary Journal 19, 185-188.

McGreevy, P.D., Rogers, L.J., 2005. Motor and sensory laterality in thoroughbred horses. Applied Animal Behaviour Science 92, 337-352.

McGreevy, P.D., Thomson, P. C., 2006. Differences in motor laterality between breeds of performance horse. Applied animal behaviour Science 99, 183-190.

Peham, C., Scheidl, M., Licka, T., 1996. A method of signal processing in motion analysis of the trotting horse. Journal Biomechanics 29, 1111–1114.

Pfau, T., Witte, T.H., Wilson, A.M., 2005. A method for deriving displacement data during cyclical movement using an inertial sensor. Journal Experimental Biology 208, 2503-2514.

Pfau, T., Stubbs, N., Kaiser, L., Brow, L., Clayton, H., 2012. Effect of trotting speed and circle radius on movement symmetry in horses during lungeing on a soft surface. American Journal of Veterinary Research 73, 1890-1899.

Pfau, T., Spicer-Jenkins, C., Smith, R.K., Bolt, D.M., Fiske-Jackson, A., Witte, T.H., 2014. Identifying optimal parameters for quantification of changes in pelvic movement symmetry as a response to diagnostic analgesia in the hindlimbs of horses. Equine Veterinary Journal 46, 759-763.

Pfau, T., Fiske-Jackson, A., Rhodin, M. 2016. Quantitative assessment of gait parameters in horses: Useful for aiding clinical decision making? Equine Veterinary Education, 28(4), 209-215.

Rhodin, M., Pfau, T., Roepstorff, L., Egenvall, A., 2013. Effect of lungeing on head and pelvic movement asymmetry in horses with induced lameness. The Veterinary Journal 198, 39-45.

Rhodin, M., Roepstorff, L., French, A., Keegan, K. G., Pfau, T., Egenvall, A., 2016. Head and pelvic movement asymmetry during lungeing in horses showing symmetrical movement on the straight. Equine Veterinary Journal 48, 315-320.

Sisson, S., 1975. Equine myology. In Getty, R., eds., Sisson and Grossman's Anatomy of domestic animals, 5th Ed., Philadelphia, USA: Saunders (W.B.), 433-435.

Starke, S.D., Willems, E., May, S. Pfau, T., 2012. Vertical head and trunk movement adaptations to sound horses trotting in a circle on a hard surface. The Veterinary Journal 193, 73-80.

Starke, S.D., Merritt, J.S., Stubbs, N., Pfau T., Clayton, H.M. 2014. Is foot placement related to body movement asymmetry during circular locomotion? In: Proceedings of the Annual Meeting of the International Conference on Equine Exercise Physiology. Chester, UK, p. 48-49

Townsend, H. G. G., Leach, D. H., Fretz, P. B. 1983. Kinematics of the equine thoracolumbar spine. Equine Veterinary Journal 15, 117-122.

Uhlir, C., Licka, T., Kübber, P., Peham, C., Scheidl, M., Girtler, D., 1997. Compensatory movements of horses with a stance phase lameness. Equine Veterinary Journal 29 (Suppl. 23), 102–105.

van Heel, M.C.V., Kroekenstoel, A.M., van Dierendonck, M.C., van Weeren, P.R., Back, W., 2006. Uneven feet in a foal may develop as a consequence of lateral grazing behaviour induced by conformational traits. Equine Veterinary Journal 38, 646-651.

van Weeren, P.R. 2014. Kinematics of the equine back and pelvis. In Hodgson, D.R., McKeever, K., McGowan C., eds., The Athletic Horse: Principles and Practices of Equine Sports Medicine. 2nd Ed., St Louis, USA: Elsevier, 282-292.

Warner, S.M., Koch, T.O., Pfau, T., 2010. Inertial sensors for assessment of back movement in horses during locomotion over ground. Equine Veterinary Journal 42, 417–424.

Wennerstrand, J., Johnston, C., Roethlisberger- Holm, K., Erichsen, C., Eksell, P., Drevemo, S., 2004. Kinematic evaluation of the back in the sport horse with back pain. Equine Veterinary Journal 36, 707–711.

Wennerstrand, J., Gómez Alvarez, C.B., Meulenbelt, R., Johnston, C., van Weeren, P.R., Roethlisberger-Holm, K., Drevemo, S., 2009. Spinal kinematics in horses with induced back pain. Veterinary Comparative Orthopaedics and Traumatology 22, 448-454.

Zimmerman, M., Dyson, S., Murray, R., 2011. Close, impinging and overriding spinous processes in the thoracolumbar spine: The relationship between radiological and scintigraphic findings and clinical signs. Equine Veterinary Journal 44, 178-184.

Fig. 1. The dorsovental, lateral-lateral movements, axial rotation range of motion (ROM, °) and flexion-extension ROM (°) of the thoracolumbar region of 14 subjectively sound horses examined moving in straight lines in hand and in circles on the lunge. White bars represent straight lines. Dotted grey bars represent moving on a circle which is the data for the left and right reins combined, because there was no significant difference between the two. (A) Dorsoventral movement (mm) and (B) Lateral-lateral movement (mm). (C) Axial rotation and (D) Flexion-extension. The displacements in a lateral (y) direction were significantly greater on the lunge for T13 (mean 46 mm) compared with straight lines (mean 30 mm; P <0 .001) and for T18 on the lunge (mean 48 mm) compared with straight lines (mean 36 mm; $P = 0.002$). Circles induced significantly greater flexion-extension ROM (mean 5.3°) compared with straight lines (mean 4°) for T13 ($P < 0.001$), for T18 (mean circles 5.1° vs. straight lines 4°; $P = 0.002$) and for L3 (mean circles 7.1° vs. straight lines 5.3° $P = 0.001$). Circles did not induce any significantly different dorsoventral displacement or axial rotation ROM (°) compared with straight lines. Boxes are marked as follows: line, median; box, 25th and 75th percentiles; whiskers, maxima and minima; * significantly greater movement in circles than in straight lines.

Fig. 2. The non-directional asymmetry of the first and second halves of the stride for the thoracolumbar region and the hindlimbs of 14 subjectively sound horses examined moving in straight lines in hand and in circles on the lunge. White bars represent straight lines. Dotted grey bars represent moving on a circle which is the data for the left and right reins combined, because there was no significant difference between the two. (A) The asymmetry is calculated as the movement amplitude of the first half of the stride (left hindlimb-right forelimb diagonal stance phase; LH-RF) minus the movement amplitude of the second half of the stride (right hindlimb-

left forelimb diagonal stance phase; RH-LF) and then normalised by dividing with range of motion and expressed as a percentage on the y-axis. Circles compared with straight lines induced a significantly greater amplitude of the dorsoventral movement of T13, T18 and L3 during the outside hindlimb stance compared with the inside hindlimb stance (*P* = 0.03)*. (B) HipHike difference (HHD) quantifies the difference in the movement amplitude of the tubera coxae during contralateral hindlimb stance. On circles the outside hindlimb bore more weight during the stance phase compared with the inside hindlimb (MinDiff), mimicking mild inside hindlimb lameness. There were significantly greater mean differences in weight bearing between each hindlimb (MinDiff 16 mm) and mean differences in upward movement of the tubera coxae during the contralateral stance phase (HHD 18 mm) on the lunge compared with straight lines (MinDiff 5 mm and HHD 6 mm; *P* < 0.001)*. However, the mean difference in hindlimb push off was not significantly different between circles and straight lines (lunge 4 mm vs. straight lines 6 mm; *P* = 0.2).

Fig. 3. The non-directional maximum difference (MaxDiff) and minimum difference (MinDiff) of the thoracolumbar region of 14 subjectively sound horses examined moving in straight lines in hand and in circles on the lunge. White bars represent straight lines. Dotted grey bars represents moving on a circle which is the data for the left and right reins combined, because there was no significant difference between the two. (A) MinDiff and (B) MaxDiff quantify the differences in minimum and maximum displacement of the different sensor locations reached during and after the two stance phases (Starke et al., 2012). Circles induced a greater maximum displacement of withers, T13 and T18 and minimum displacement of the withers during the outside hindlimb stance compared with the inside hindlimb stance (*P* = 0.003)*. At L3 the minimum displacement

was greater during the inside hindlimb stance in comparison with the outside hindlimb stance ($P = 0.009$)**.

Fig. 4. The symmetry of the first and second halves of the stride for the withers, T13, T18 and L3 of 14 subjectively sound horses divided into three symmetry categories based on the symmetry in straight lines in hand. The symmetry index is calculated as the movement amplitude of the first half of the stride (left hindlimb-right forelimb diagonal stance phase; LH-RF) minus movement amplitude of the second half of the stride (right hindlimb-left forelimb diagonal stance phase; RH-LF) and then normalised by dividing with range of motion. Symmetry index < 1 indicates less movement amplitude in the first half of the stride, whereas a symmetry index > 1 indicates less movement amplitude in the second half of stride. The white bars represent horses with symmetry index < 0.98 in straight lines (less movement amplitude in the first half of the stride; LH-RF diagonal stance phase). The grey bars represent horses with symmetry index > 1.02 straight lines (Greater movement amplitude during second half of the stride; RH-LF diagonal stance). The light grey bars represent horses with symmetry index = 1 ± 0.02 (equal movement amplitude between first and second halves of the stride). Open circles indicates outliers. The vertical black line at SI = 1 represents 100% symmetry. (A) the withers; (B) the thirteenth thoracic vertebra (T13); (C) the eighteenth thoracic vertebra (T18); (D) the third lumbar vertebra (L3). Horses with greater movement amplitude during LH-RF stance in straight lines (similar pattern induced by right circles) had even greater asymmetry on circles on the right rein compared with symmetrical horses. Similarly horses with greater movement amplitude during RH-LF stance in straight lines (similar pattern induced by left circles) had even greater asymmetry on circles to the left compared with symmetrical horses.

Fig. 5. The association between the motion of the third lumbar (L3) vertebra and the eighteenth thoracic vertebra (T18) and pelvic MinDiff. There was a linear association between pelvic MinDiff and (a) L3 (r =0.93; $P < 0.001$) and (b) T18 ($r = 0.58$; $P < 0.001$) in a univariable model. The tubera sacrale dropped less during the inside hindlimb stance compared with the outside hindlimb stance in circles, with both the lumbar and caudal thoracic regions (L3 and T18) following an identical pattern.

Fig. 6. The association between the motion of the thirteenth thoracic vertebra (T13) and the withers and pelvic MinDiff. There was a linear association between pelvic MinDiff and (a) T13 ($r = 0.38$; $P = 0.02$) and (b) the withers ($r = 0.82$; $P < 0.001$) in a univariable model. The tubera sacrale dropped less during the inside hindlimb stance compared with the outside hindlimb stance in circles, with both the lumbar and caudal thoracic regions (L3 and T18) following an identical pattern. However, the mid and cranial thoracic regions (T13 and withers) exhibited the opposite pattern. For example, on the right rein the pelvis, lumbar and caudal thoracic regions dropped more during the outside hindlimb stance compared with inside hindlimb, and the mid- and cranial thoracic regions dropped more during the inside hindlimb stance compared with the outside hindlimb stance.

Table 1. The mean ± standard error (SE) for the non-directional symmetry of the left and right oscillations during one stride in 14 subjectively sound horses assessed trotting in straight lines and in circles on the lunge.

Non-directional asymmetry of the oscillations during left and right hindlimb stance phase during one stride (%)						
	Mean ± SE		Mean ± SE		Mean ± SE	
Region	Straight lines		Right rein		Left rein	
Withers	6.1 ± 1.6		8.2 ± 1.7		8.9 ± 1.8,	
T13	4.5 ± 1.0		6.6 ± 1.1		5.3 ± 1.2	
T18	5.9 ± 1.4		8.5 ± 1.5		6.8 ± 1.3	
L3	5.8 ± 1.4		11.1 ± 1.6		7.4 ± 1.5	
TS	6.4 ± 1.6		13 ± 1.7		10.1 ± 1.9	
The difference between the two peaks (maxima) [MaxDiff] and two troughs (minima) [MinDiff] of the vertical movement signal (mm)						
	Straight lines		Right rein		Left rein	
	MinDiff	MaxDiff	MinDiff	MaxDiff	MinDiff	MaxDiff
Withers	-0.8 ± 1.5	-0.3 ± 1.2	12.6 ± 2.7	8.1 ± 1.6	-10.4 ± 2.6	-6.9 ± 1.6
T13	-1 ± 1.2	1.2 ± 1.0	2.5 ± 1.4	9.6 ± 1.8	-2.4 ± 1.9	-5.6 ± 1.4
T18	-1.4 ± 1.4	1.5 ± 1.3	-3 ± 1.5	6.9 ± 1.5	2.3 ± 1.7	-4.1 ± 1.4
L3	-0.7 ± 1.5	0.7 ± 1.3	-7.7 ± 2.1	3.4 ± 1.5	6.4 ± 1.8	-0.4 ± 1.5
TS	0.5 ± 1.9	0.8 ± 1.3	-14.9 ± 3.0	-2.9 ± 1.4	14.3 ± 2.7	3.7 ± 2.3
Displacement (mm)						
	Straight lines		Right rein		Left rein	
	Dorsoventral	Lateral-lateral	Dorsoventral	Lateral-lateral	Dorsoventral	Lateral-lateral
Withers	101 ± 4	42 ± 5	111 ± 6	55 ± 6	104 ± 4	48 ± 5
T13	119 ± 4	30 ± 3	128 ± 7	47 ± 4	125 ± 4	45 ± 3
T18	114 ± 4	36 ± 2	122 ± 6	51 ± 5	117 ± 3	45 ± 4
L3	102 ± 4	44 ± 4	114 ± 6	54 ± 6	109 ± 3	45 ± 3
TS	115 ± 4	41 ± 7	127 ± 6	50 ± 4	122 ± 4	44 ± 3

TS, Tubera sacrale.

Table 2. Significant results of multivariable mixed effect linear regression analysis of the effects of hindlimb gait on the thoracolumbar movement in a sound sample of the general sports horse population (n = 14) in both straight lines and circles on the lunge.

Region	Condition	Hindlimb variable (10mm increase)	Increase in outcome	*P*
Outcome: Flexion-extension ROM in ° (the body rotation about the transverse [lateral-lateral] axis).				
Withers	Straight Lines	Pelvis MaxDiff	3.7°	0.004
	Circles	HHD	1.2°	0.006
Outcome: The asymmetry of the left and right oscillations during one stride (%)				
T13	Straight Lines	Pelvis MinDiff	4.5%	0.01
	Circles	Pelvis MinDiff	2.5%	0.02
T18	Straight Lines	Pelvis MinDiff	5.8%	0.03
	Circles	Pelvis MinDiff	3.1%	0.007
		HHD	2.1%	0.006
L3	Straight Lines	Pelvis MinDiff	2.7%	0.05
		Pelvis MaxDiff	12%	0.001
	Circles	Pelvis MinDiff	3.9%	0.001
		HHD	2.6%	0.002

MinDiff and MaxDiff, Differences in minimum and maximum displacement of the pelvis, respectively; hiphike difference (HHD), defined as the difference in upward movement of each tuber coxae during contralateral hindlimb stance; ROM, range of motion.

Table 3. Significant results of multivariable mixed effect linear regression analysis of the association between hindlimb gait and thoracolumbar movement, when the outcomes* and variables** used are found by subtracting the mean value for straight lines from the mean values for circles in a sound sample of the general sports horse population (*n* = 14).

Region	Circle-induced changes in outcome variables*	Circle-induced changes in explanatory variables (10mm increase)**		*P*
Withers	ΔDorsoventral displacement	ΔHHD	5.2mm	0.03
		ΔMinDiff		
			1.4°	0.001
		ΔHHD	-1.5°	0.02
	ΔFlexion-extension ROM			
T13	ΔThe asymmetry of the left and right oscillations during one stride (%)	ΔHHD	1.6%	0.04
	ΔLaterolateral displacement	ΔHHD	4.5mm	0.02
T18	ΔThe asymmetry of the left and right oscillations during one stride (%)	ΔHHD	2.6%	0.003
	ΔLaterolateral displacement	ΔHHD	5.4mm	0.02
L3	ΔThe asymmetry of the left and right oscillations during one stride (%)	ΔHHD	2.8%	0.004
		ΔMinDiff	3.2%	0.05
	ΔDorsoventral displacement	ΔHHD	6.2mm	0.04

For example, looking at the first row of the table: 10 mm increase in the variable ΔHHD results in 5.2 mm increase in the outcome ΔDorsoventral displacement (*P* = 0.03) of the withers.
Δ, The measured mean value for straight lines subtracted from the mean value for circles; Flexion-extension ROM (range of motion), the body rotation about the transverse (lateral-lateral) axis; MinDiff and MaxDiff, the differences in minimum and maximum displacement of the pelvis, respectively; HHD, the difference in upward movement of each tuber coxae during contralateral hindlimb stance.