TITLE: Alterations in body lean angle in lame horses before and after diagnostic analgesia in straight lines in hand and on the lunge

AUTHORS: Greve, L; Pfau, T; Dyson, S

JOURNAL: Veterinary Journal

PUBLISHER: Elsevier

PUBLICATION DATE: 18 July 2018 (online)

DOI: https://doi.org/10.1016/j.tvjl.2018.07.006

Title: Alterations in body lean angle in lame horses before and after diagnostic analgesia in straight lines in hand and on the lunge

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

PII: S1090-0233(18)30386-1
DOI: https://doi.org/10.1016/j.tvjl.2018.07.006
Reference: YTVJL 5179

To appear in:

Received date: 4-12-2017
Revised date: 27-5-2018
Accepted date: 15-7-2018

Please cite this article as: L.Greve, T.Pfau, S.Dyson, Alterations in body lean angle in lame horses before and after diagnostic analgesia in straight lines in hand and on the lunge (2018), https://doi.org/10.1016/j.tvjl.2018.07.006

Original Article

Alterations in body lean angle in lame horses before and after diagnostic analgesia in straight lines in hand and on the lunge

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, United Kingdom*
[b]*Department of Clinical Science and Services, The Royal Veterinary College, University of London, Hawkshead Lane, North Mymms, Hatfield AL9 7TA, United Kingdom*

* Corresponding author. Tel.: +46 720036263.
E-mail address: Line.greve@evidensia.se (L. Greve).

Highlights

- This study evaluated the influence of equine lameness on body lean in trot on the lunge
- Body lean was quantified using a global position system-aided inertial measurement unit attached to the tubera sacrale
- Lameness was associated with asymmetry in body lean angles between left and right reins
- Body lean became more symmetrical between reins after improvement in lameness
- Asymmetric body lean may highlight the presence of lameness

Abstract

Altered body lean has been subjectively observed during lungeing in lame horses. The objectives were to quantify the influence of lameness on body lean in trot on the lunge and to investigate the influence of improvement in lameness on the differences in body lean between reins. Thirteen lame horses were trotted in straight lines and lunged on a 10m-diameter circle on both reins before and after lameness was subjectively substantially improved by diagnostic analgesia. A global position system-aided inertial measurement unit attached to the tubera sacrale quantified body lean. Differences between reins in body lean before and after diagnostic analgesia were calculated and means were determined.

Five and eight horses had unilateral and bilateral hindlimb lameness, respectively. Two of five horses with unilateral and three of eight horses with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the inside of the circle (difference between reins 5-8°). Two of five horses with unilateral and two of eight horses with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the outside of the circle (4-10°). Four horses, one with unilateral and three with bilateral lameness, had only 1° difference in body lean angle between left and right reins. When lameness was improved by diagnostic analgesia, the body lean changed significantly towards similar leaning on left and right reins (mean angle changed from 8.8º to 10.0º (*P*=0.03) on one rein and 13.4º to 10.8º (*P*=0.002) on the other rein). It was concluded that body lean becomes more symmetrical between reins after improvement in lameness using diagnostic analgesia.

Keywords: Balance; Global positioning system; Inertial measurement units; Lameness; Musculoskeletal coordination; Pelvic roll

Introduction

Circles are an important part of lameness investigation (Ross, 2011; Greve and Dyson, 2016). During lungeing of horses, differences in body lean angle between turn directions have been observed and it was suggested that this may be due to subclinical lameness or motor lateralities (Brocklehurst et al., 2014). Musculoskeletal pain impairs postural control and stability in man (Hirata et al., 2011). Movement symmetry is altered during circular motion (Starke et al., 2012; Robartes et al., 2013; Pfau et al., 2016; Rhodin et al., 2016). Previous studies in horses have used sensor axial rotation of a sacrum-mounted global position system (GPS)-enhanced inertial measurement unit (IMU) as an indicator of whole body lean angle (Pfau et al., 2012; Brocklehurst et al., 2014). It was demonstrated that when horses move on circles, the tubera sacrale drops to a lower minimum position during the outside hindlimb stance phase compared with the inside hindlimb stance (Pfau et al., 2012; Greve et al., 2017a). This effect is exacerbated with increasing body lean angle (Pfau et al., 2012).

The amount of body lean can be predicted by speed and circle radius. The smaller the radius and the greater the speed, the more the tubera sacrale will drop to a lower minimum position during the outside hindlimb stance phase compared with the inside hindlimb stance (Pfau et al., 2012). It is therefore important to standardise speed and circle radius in order to compare lameness parameters and body lean angles between circle directions (left versus right reins). A recent study in thirteen non-lame dressage horses demonstrated no differences between reins in the difference between measured body lean angle and predicted body lean based on speed and radius of the circle (Greve and Dyson, 2016). Lameness may affect body lean angle, however this remains to be investigated. To date, there have been no studies which quantified the difference between circle directions on the lunge in body lean angle and symmetry measures in horses with lameness before and after reduction in pain by diagnostic analgesia.

Previous studies have estimated body lean angle from the pelvic roll (i.e., the axial rotation of the pelvis around the craniocaudal axis) averaged over a stride cycle termed ‘pelvic roll bias’ or ‘mean pelvic roll’ for an individual horse (Pfau et al., 2012; Brocklehurst et al., 2014). In a group of horses considered sound by their owners the ‘pelvic roll bias’ of the group of horses as a whole had good correlation to predicted lean angle, based on the speed of the horse and the radius of the circle (Pfau et al., 2012; Brocklehurst et al., 2014). No work has yet been done in lame horses. Horses with hindlimb lameness alter their pelvic and thoracolumbar range of motion and symmetry of motion (Gómez Álvarez et al., 2008; Greve et al., 2017b). The pelvis, lumbar and caudal thoracic region can be described as a rigid body with regard to axial rotation in non-lame horses (Faber et al., 2001). Although it is possible that some horses with lameness in straight lines exhibit a ‘pelvic roll bias’ that is different from the trunk, it was demonstrated that on average the pelvic asymmetry patterns observed in horses with varying degrees of lameness can be explained by a simple rigid body model, without the need to alter pelvic roll bias (Starke et al., 2015).

The objectives of this study were: (1) to assess the influence of limb pain on equine postural control and stability, measured as mean pelvic roll by a GPS-enhanced IMU, on the lunge comparing left and right reins in trot; and (2) to investigate the influence of alleviation of limb pain on the differences in body lean angle between left and right reins. It was hypothesised that: (1) lame horses lean more on one rein compared with the other; and (2) that alleviation of limb pain reduces the differences in body lean between left and right reins during lungeing.

Materials and methods

A prospective study was performed at the Animal Health Trust (AHT) and Royal Veterinary College (RVC). The study was approved by the Ethical Review Committee of the AHT (Approval number 39 2014; Approval date 12 September 2014) and there was informed owner consent. Six consecutive horses with hindlimb lameness at the RVC and seven at the AHT were included. The same sample of horses had been used to assess thoracolumbosacral movement before and after improvement in lameness by diagnostic analgesia (Greve et al., 2017b). Diagnosis was assigned based on the results of a comprehensive clinical evaluation, diagnostic analgesia and imaging. Age, breed, gender, body mass (determined using a weighbridge), height (copied from the passport) and work discipline were recorded.

Inertial measurement units

Each horse was instrumented with eight MTx (18xgravity, 1200 degree/s) miniaturised inertial measurement units (IMUs) (MTi-G, Xsens Technologies). 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, the withers, the 13th and 18th thoracic vertebrae, and the 3rd lumbar vertebra and one combined IMU/global positioning system (GPS) sensor (MTi-G, Xsens Technologies) at the level of the tubera sacrale (TS) that measured stride-time, speed and radius of the circle during lungeing. For this study, only data from the poll, the tuber sacrale and the left and right tuber coxae were used. 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 to the horse's body during lungeing. Sensors were attached in two strings (1: head; 2: left and right tubera coxae, tubera sacrale (TS) to the Xbus (Xsens Technologies) transmitting IMU data at a sampling rate of 100Hz per individual sensor channel.

Dynamic assessment

All the horses were trotted in-hand on a hard surface and then lunged on the left and right reins on a soft surface using a consistent lungeing technique, with a lunge line attached via couplings to the bit rings. The handlers were asked to keep the same lunge line length throughout the entire examination resulting in a circle diameter of approximately 10 m. IMU data were collected for at least 20 s. 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 on both left and right reins in trot were recorded for each circumstance. All horses were examined by experienced lameness clinicians (Royal College of Veterinary Surgeons Specialist in Equine Orthopaedics, SD; Diplomate of the European College of Veterinary Surgeons, AFJ, RS). The presence of lameness was graded on a 0-8 scale (Dyson, 2011) under each circumstance before and after diagnostic analgesia. To avoid potential inconsistencies between different grading systems as reported by Hewetson et al. (2006), lameness grading at both centres was performed by one person (LG). All horses were handled by experienced people who were asked to allow the horses to trot at their preferred speeds in hand and on the lunge. The speed was not standardised among horses. The same person handled an individual horse throughout its investigation. All horses were assessed in hand and on the lunge before and after each nerve block. Diagnostic analgesia was performed in all lame limbs and IMU data were collected for at least 20 s under all circumstances after each nerve block.

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 Inc).

Body lean angle

The mean value of pelvic roll was used as an estimate of body lean angle.

Quantification of kinematic symmetry measures

The following kinematic symmetry measurements were determined: The difference between the two peaks (maxima) (MaxDiff) and two troughs (minima) (MinDiff) of the vertical movement signal for the head and TS were measured and the HipHike Difference (HHD), defined as the difference in upward movement of each tuber coxae during contralateral hindlimb stance (mm). A horse moving perfectly symmetrically would have MinDiff, MaxDiff and HHD values of 0. Detailed description of the calculations can be found elsewhere (Pfau et al., 2012).

Statistical analysis

Sample size calculation

See Appendix: Sample size.

Straight lines

The mean ± standard deviations (SDs) for the directional values of the pelvic roll bias ‘body lean angle’ before and after improvement in lameness by diagnostic analgesia were determined. Data were assessed for normal distribution using the Shapiro-Wilk test. A paired *t* test was used to determine the difference between the values before and after all diagnostic analgesia.

Lungeing

The differences between left and right reins in body lean angle, speed and stride time were calculated for before and after diagnostic analgesia. Data of body lean angle, speed and normalised stride time on the left and right reins and the differences between reins before and after diagnostic analgesia were assessed for normal distribution using the Shapiro-Wilk test. Mean ± SDs for normally distributed data and median and interquartile range (IQR) for none normally distributed data were determined. Two mixed-effect linear regression models were performed to assess the effect of diagnostic analgesia on the difference in body lean angle between reins with either speed or stride time as covariates. All analyses were adjusted for the clustering effect of the horse by including horse as random effect. Those variables that were statistically significant at $P<0.20$ were put forward for inclusion in a multivariable, mixed-effects linear model. Final model results were reported as mean and *P*-values. All statistical analyses were performed using SPSS Statistics 20 (IBM) with significance set at $P<0.05$.

Results

Horse data

See Appendix: Supplementary Table 1.

Subjective grading of lameness

Five and eight horses had unilateral and bilateral hindlimb lameness, respectively. Three and two horses had concurrent sacroiliac joint region pain or forelimb lameness, respectively, and one horse had both. The range of the subjective hindlimb lameness grade before diagnostic analgesia for all the horses was 0 to 5 both in hand in straight lines (See Appendix: Supplementary Table 1) and on the lunge on the right rein, and 0 to 3 on the lunge on the left rein (*n*=13) (See Appendix: Supplementary Tables 2 and 3). The most frequent hindlimb lameness grade was 2 in hand in straight lines and during lungeing on the right rein and grade 1 on the left rein. Five horses had predominantly right hindlimb lameness (three bilateral and two unilateral). Eight horses had predominantly left hindlimb lameness (five bilateral and three unilateral). Lameness data is more comprehensively summarised, See Appendix: Tables S1, S2 and S3.

Quantification of pelvic roll bias in straight lines

The average pelvic roll bias (body lean angle) in straight lines in lame horses before and after diagnostic analgesia was normally distributed with a mean of 0º and a SD of 1.6º. No horse changed its body lean angle in straight lines when lameness was improved by diagnostic analgesia (*P*=1) (Table 1).

Quantification of body lean angle

Before diagnostic analgesia

The mean±SD speed and stride time of lungeing were 3.20±0.26 m/s and 0.73±0.04 s, respectively. The mean difference in speed and stride time between left and right reins were 0.12±0.17 m/s and 0.02±0.02 s, respectively. There were significant differences between the body lean angle on the left and right reins before diagnostic analgesia (*P*<0.001). The mean±SD (range) of the body lean angle on the rein on which the horses leaned more was 13.4±2.3º (10º –

16º) and on the rein where the horses leaned less was 8.8±2.3º (6º - 13º) (Table 2). Two/five horses with unilateral lameness and three/eight horses with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the inside of the circle. Two/five (40%) horses with unilateral lameness and two/eight with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the outside of the circle before diagnostic analgesia. Four horses, one with unilateral and three with bilateral lameness respectively, had only 1° difference in body lean angles between left and right reins (Table 2).

After diagnostic analgesia

The mean±SD speed and stride time of lungeing was 3.19±0.34 m/s and 0.73±0.04 s, respectively. The mean differences in speed and stride time between left and right reins were 0.11±0.13 m/s and 0.01±0.02 s, respectively, which were not significantly different from before diagnostic analgesia. There were no significant differences between speeds and stride time before and after diagnostic analgesia (mean difference between before and after diagnostic analgesia ± SD [*P*-value], 0.01 ± 0.2 m/s, [*P*=0.8] and 0.2 ± 0.2 s [*P*=0.6].

In the two mixed effect models (one with speed as a fixed covariate; and one with stride time as a fixed covariate), only diagnostic analgesia retained significance (*P*=0.002) and speed (*P*=0.5), stride time (*P*=0.4) and horse specific characteristics (*P*=0.8) were not significant. There were no identified interactions between variables in the model. The final of each model both contained the difference in body lean angle between turn directions before diagnostic analgesia which was mean ± SD 4.9° ± 0.78° versus 1.8° ± 0.78° after diagnostic analgesia, (*P*=0.002) (Figure 1). When lameness was improved by diagnostic analgesia, the body lean changed significantly towards similar leaning on the left and right reins (from mean 8.8º to 10º [*P*=0.03] on one rein and from 13.4º to 10.8º [*P*=0.002] on the other rein). After diagnostic analgesia, there were no significant differences between the body lean angles for the left and right reins (*P*=0.1). Figure 1 illustrates how body lean angle became more similar between reins after diagnostic analgesia. The mean±SD (range) of the body lean angle after diagnostic analgesia on the rein where the horses leaned more was 10.8±1.7º (7º to 13º) and on the rein where the horses leaned less was 10±1.2º (10º to 12º) (Table 2). In 11 horses (85%) improvement in lameness decreased the difference in body lean angle between turn directions, whereas two horses (15%) had no change in body lean angles between before and after diagnostic analgesia (Table 2).

Discussion

In accordance with our hypothesis, we demonstrated that lame horses lean more on one rein compared with the other, however the direction of increased or reduced lean was not predictable. Some horses leaned more with the lame(r) limb on the inside of a circle and some with the lame(r) limb on the outside of a circle. Improvement of limb pain reduced the differences in body lean angles between left and right reins during lungeing, providing supporting evidence for our hypothesis.

The mechanisms of adaptation of body posture in the horse on the lunge have not been determined objectively. Examination of both still photographs and video recordings indicate that there are a variety of adaptations that influence body lean. In the authors’ experience, it appears that the whole trunk leans, however a horse may also adapt by altering the position of the head and neck, with both the head and neck turning in the opposite direction. This may influence balance. In some horses the body lean appears to be accentuated by the inside limb crossing in under the trunk during protraction, towards the contralateral forelimb.

It has been proposed that a difference in body lean angle in horses between turn directions could be due to asymmetries in strength, suppleness and neural programming (Clayton and Sha, 2006). Specific adaptations were observed in individual horses presumed to be non-lame by the owners at the trot when comparing left and right reins (Dyson and Greve, 2016); it was suggested that this was due to either motor laterality or subclinical lameness. A recent study found that older, non-lame dressage horses, which have been trained more and thus developed a better core stability and muscular strength, were able to maintain a more vertical orientation of the body when turning compared with young, untrained, non-lame horses that are less well-balanced and coordinated (Greve and Dyson, 2016). The study was restricted to non-lame horses selected based on a comprehensive lameness examination. The horses were lunged using a similar technique to that used in the current study. These non-lame horses, irrespective of age, had no significant differences in the leaning pattern between the left and right reins, with a mean body lean angle of 10º. This amount of leaning was comparable to the horses in the current study after diagnostic analgesia (mean body lean angle was 10.4º).

Some horses in the current study with either unilateral or bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the inside of the circle, whereas others leaned more on the rein with the lame or lamer hindlimb on the outside of the circle before diagnostic analgesia. Trot in circles compared with straight-lines introduces altered symmetry of the head and trunk (Starke et al., 2012) and thoracolumbosacral movement (Greve et al., 2017a) as a function of body lean angle (Pfau et al., 2012), influencing common symmetry parameters used to quantify lameness (Walker et al., 2010). It was proposed that in general movement asymmetries of head and pelvic on the circle are related to distribution of loading to the outside limbs (Pfau et al., 2012). In sound horses, there was greater peak vertical force in the outside forelimb compared with the inside forelimb on a circle in trot (Chateau et al., 2013), whereas the inside hindlimb exhibited increased inclination (Hobbs et al., 2011) and may experience higher extrasagittal joint torques caused by increasing ground reaction force moment arms. This could explain why some lame horses avoid leaning into the circle when the lame limb is on the inside of the circle because it is then at a more acute angle to the ground (Hobbs et al., 2011). This, however, was not consistent with the observations in the current study in all horses. While the medial or lateral location of pain causing lameness may be influenced differently by the limb angulation, we currently cannot fully explain the variability in adaptation to pain among horses.

Body lean is also influenced by speed and circle radius, so one could speculate that if horses lean more evenly between reins after pain has been reduced/eliminated by diagnostic analgesia, this could simply be because they move at more similar speeds than before diagnostic analgesia. However, this was not the case. There were no significant differences between speeds or the differences in speed between turn directions comparing before and after diagnostic analgesia. It is possible that different trunk leaning patterns, limb inclinations and limb flexion patterns alter limb forces and reduce pain. Alterations in body lean potentially induce changes in propulsive and transversal forces, vertical impulse, loading rate, peak moment around longitudinal and vertical axes and kinetic moment around longitudinal and vertical axes (Chateau et al., 2005, 2013). Combining the dynamometric horseshoe (Chateau et al., 2013) to measure ground reaction force (GRF) or, more accurately, the hoof action force (the opposite of the GRF) of limbs, with measuring kinematics and body lean angle would enable us to understand the limb kinetics associated with variable degree of body lean on the circle.

Horses with an underlying lameness may adapt differently to lungeing, depending on whether the affected limb is on the inside or outside of the circle (Pfau et al., 2016). Increasing body lean angle when the affected limb is on the inside of the circle or on the outside of the circle may be a mechanism to reduce pain, despite there potentially being more torque acting around the joints of the limbs. In experimentally-induced forelimb lameness, the cranial thoracic region flexes during the sound forelimb stance in association with the downward movement of the neck and head and the thoracolumbar region is extended during the lame forelimb stance (Gómez Álvarez et al., 2007). Reduced lumbosacral range of motion and an extended thoracolumbosacral region has been observed in both experimentally-induced hindlimb lameness (Gómez Álvarez et al., 2007) and naturally occurring hindlimb lameness (Greve et al., 2017a). This may be a protective mechanism; with reduced lateral bending there may inevitably be more body lean. In association with hindlimb lameness, horses also adapt by being more on the forehand i.e., with the centre of gravity further forwards, presumably to reduce loading of the hindlimbs by shifting the impulse forward towards the forelimb (Weishaupt et al., 2004). Future studies should investigate whether there is a link between body lean angle and specific limb movements that can be observed in horses with hindlimb lameness and their effect on upper body movement (mechanics). The effect of unilateral or bilateral forelimb lameness on body lean angle has not been investigated.

It is well documented in humans that pain may be detrimental to the motor (movement, strength, activation) and sensory (proprioception, balance) components of muscle function (Hassan et al., 2002; Zhang et al., 2015). It has been shown that knee osteoarthritis impairs balance (Hinman et al., 2002), increases the risk of falling (Foley et al., 2006), and increases static postural sway in several directions compared with age-matched controls (Hassan et al., 2001; Masui et al., 2006; Hirata et al., 2013). Pain in legs induces postural instability (Hinman et al., 2002; Hirata et al., 2010, 2012). A complex mechanism exists between sensory information and the motor system controlling the body centre of mass and posture (Hassan et al., 2001). In the presence of a painful condition, the central nervous system may increase the gain of sensory information from the non-affected areas and have altered proprioceptive information from the impaired structure, which provide alternative mechanisms for compensatory postural control (Hirata et al., 2013). Presumably, in horses, the alleviation of pain by diagnostic analgesia may result in altered neuromuscular function, thus avoiding compensatory postural control and consequently the horses lean similarly when turning left and right, as demonstrated in the current study, albeit in a small number of horses. Reducing lameness by diagnostic analgesia permitted investigation of the relationship between limb pain and body lean in horses, however we cannot necessarily conclude from this ‘inverse model’ that development of lameness would create identical compensatory postural control mechanisms. However, it seems likely that lameness may lead to altered postural control in horses comparable to the mechanisms described in man (Hinman et al., 2002; Hirata et al., 2010, 2012).

We investigated the relationships between movements of the trunk and pelvis by quantifying pelvic roll bias before and after diagnostic analgesia in lame horses trotting on the straight. There was no change after diagnostic analgesia, supporting the use of pelvic roll to estimate body lean angle in lame horses (Starke et al., 2015).

The measurements were obtained on a soft arena surface and therefore do not represent the body lean angle and movement symmetry data on a hard surface, or on a different type of arena surface. Data collection was limited to four upper body landmarks and did not provide detailed quantification of spatiotemporal limb movement parameters or limb angles, which have been reported (Clayton and Sha, 2006; Hobbs et al., 2011). More detailed studies with simultaneous measurement of limb forces would complement the understanding of circular movement mechanics. We have not described how the horses effectuated this leaning when meeting the ground, because this was outside the scope of the current study.

Conclusions

This study has increased our understanding of body lean angle. Some horses adapt to lameness by increasing body lean angle on one rein compared with the other during lungeing. Asymmetry of body lean angle may indicate the presence of a pain-related problem. Following improvement in lameness using diagnostic analgesia the difference in body lean angle on the left and right reins becomes more symmetrical.

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 the many horses and their owners who participated in the study and Roger Smith and Andrew Fiske-Jackson for performing clinical lameness examinations. Line Greve was funded by a Royal Veterinary College PhD-studentship through the Mellon Trust.

Supplementary material

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

References

Brocklehurst, C., Weller, R., Pfau, T., 2014. Effect of turn direction on body lean angle in the horse in trot and canter. The Veterinary Journal 199, 258-262.

Chateau, H., Degueurce, C., Denoix, J.M., 2005. Three-dimensional kinematics of the equine distal forelimb: Effects of a sharp turn at the walk. Equine Veterinary Journal 37, 12-18.

Chateau, H., Camus, M., Holden-Douilly, L., Falala, S., Ravary, B., Vergary, C., Lepley, J., Denoix, J.-M., Pourcelot, P., Crevier-Denoix, N., 2013. Kinetics of the forelimb in horses circling on different ground surfaces at the trot. The Veterinary Journal 198, 20-26.

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, 462-467.

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

Dyson, S., Greve L., 2016. Subjective gait assessment of 57 sports horses in normal work: A comparison of the response to flexion tests, movement in hand, on the lunge and ridden. Journal of Equine Veterinary Science 38, 1-7.

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

Foley, S.J., Lord, S.R., Srikanth, V., Cooley, H., Jones, G., 2006. Falls risk is associated with pain and dysfunction but not radiographic osteoarthritis in older adults: Tasmanian Older Adult Cohort study. Osteoarthritis and Cartilage 14, 533-539.

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., 2016. Body lean angle in sound dressage horses in-hand, on the lunge and ridden. The Veterinary Journal 217, 52-57.

Greve, L., Pfau, T., Dyson, S., 2017a. Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge. The Veterinary Journal 220, 95-104.

Greve, L., Dyson, S., Pfau, T., 2017b. Alterations in thoracolumbosacral movement when pain causing lameness has been improved by diagnostic analgesia. The Veterinary Journal doi:10.1016/j.tvjl.2017.03.009

Hassan, B.S., Mockett, S., Doherty, M., 2001. Static postural sway, proprioception, and maximal voluntary quadriceps contraction in patients with knee osteoarthritis and normal control subjects. Annals of the Rheumatic Diseases 60, 612-618.

Hassan, B.S., Doherty, S.A., Mockett, S., Doherty, M., 2002. Effect of pain reduction on postural sway, proprioception, and quadriceps strength in subjects with knee osteoarthritis. Annals of the Rheumatic Diseases 61, 422-428.

Hewetson, M., Christley, R., Hunt, I., Voute, L., 2006. Investigation of the reliability of observational gait analysis for the assessment of lameness in horses. Veterinary Record 158, 852-858.

Hinman, R.S., Bennell, K.L., Metcalf, B.R., Crossley, K.M., 2002. Balance impairments in individuals with symptomatic knee osteoarthritis: A comparison with matched controls using clinical tests. Rheumatology (Oxford) 41, 1388-1394.

Hirata, R.P., Arendt-Nielsen, L., Graven-Nielsen, T., 2010. Experimental calf muscle pain attenuates the postural stability during quiet stance and perturbation. Clinical Biomechanics 25, 931-937.

Hirata, R.P., Ervilha, U.F., Arendt-Nielsen, L., Graven-Nielsen, T., 2011. Experimental muscle pain challenges the postural stability during quiet stance and unexpected posture perturbation. Journal of Pain 12, 911-919.

Hirata, R.P., Arendt-Nielsen, L., Shiozawa, S., Graven-Nielsen, T., 2012. Experimental knee pain impairs postural stability during quiet stance but not after perturbations. European Journal of Applied Physiology 112, 2511-2521.

Hirata, R.P., Jorgensen, T.S., Rosager, S., Arendt-Nielsen, L., Bliddal, H., Henriksen, M., Graven-Nielsen, T., 2013. Altered visual and feet proprioceptive feedbacks during quiet standing increase postural sway in patients with severe knee osteoarthritis. PLoS One 8, e71253.

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.

Masui, T., Hasegawa, Y., Yamaguchi, J., Kanoh, T., Ishiguro, N., Suzuki, S., 2006. Increasing postural sway in rural-community-dwelling elderly persons with knee osteoarthritis. Journal of Orthopaedic Science 11, 353-358.

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

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

Pfau, T., Jennings, C., Mitchell, H., Olsen, E., Walker, A., Egenvall, A., Tröster, S., Weller, R., Rhodin, M., 2016. Lungeing on hard and soft surfaces: Movement symmetry of trotting horses considered sound by their owners. Equine Veterinary Journal 48, 83-89.

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

Robartes, H., Fairhurst, H., Pfau, T., 2013. Head and pelvic movement symmetry in horses during circular motion and in rising trot. The Veterinary Journal 198 Supplement 1, 52-58.

Ross, M.W., 2011. Movement. In: Ross, M.W. and Dyson, S.J. Eds. Diagnosis and Management of Lameness in the Horse. 2nd edn. Saunders, Philadelphia, USA, pp 64-79.

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

Starke, S. D., Witte, T. H., May, S. A., Pfau, T., 2015. Understanding hind limb lameness signs in horses using simple rigid body mechanics. Journal of Biomechanics 48, 3323-3331.

Walker, A. M., Wilson, A. M., Pfau, T., 2010. Comparison of kinematic symmetry index calculations and the effects of straight and circular trotting. Equine Veterinary Journal 42 Supplement 38, 482-487.

Weishaupt, M.A., Wiestner, T., Hogg, H.P., Jordan, P., Auer, J.A., 2004. Compensatory load redistribution of horses with induced weightbearing hindlimb lameness trotting on a treadmill. Equine Veterinary Journal 36, 727-733

Zhang, Z., Lion, A., Chary-Valckenaere, I., Loeuille, D., Rat, A.C., Paysant, J., Perrin, P.P., 2015. Diurnal variation on balance control in patients with symptomatic knee osteoarthritis. Archives of Gerontology of Gerontology and Geriatrics 61, 109-114.

Table 1

The body lean angle in thirteen lame horses (five and eight horses had unilateral and bilateral hindlimb lameness, respectively; three and two horses had concurrent sacroiliac joint region pain or forelimb lameness, respectively, and one horse had both) assessed in straight lines before and after substantial improvement in lameness by diagnostic analgesia.

Horse	Body lean angle before diagnostic analgesia [º] [a]	Body lean angle after diagnostic analgesia [º] [a]
1	3	3
2	-1	-1
3	-1	-1
4	0	0
5	0	0
6	-3	-3
7	0	0
8	2	2
9	0	0
10	-1	-1
11	-2	-2
12	-2	-2
13	0	0

[a] The mean value of pelvic roll, measured by a GPS-enhanced inertial measurement unit on the tubera sacrale, was used as an estimate of body lean angle.

Table 2
The body lean angle in thirteen lame horses assessed on the lunge on both the left and right reins before and after substantial improvement in lameness by diagnostic analgesia.

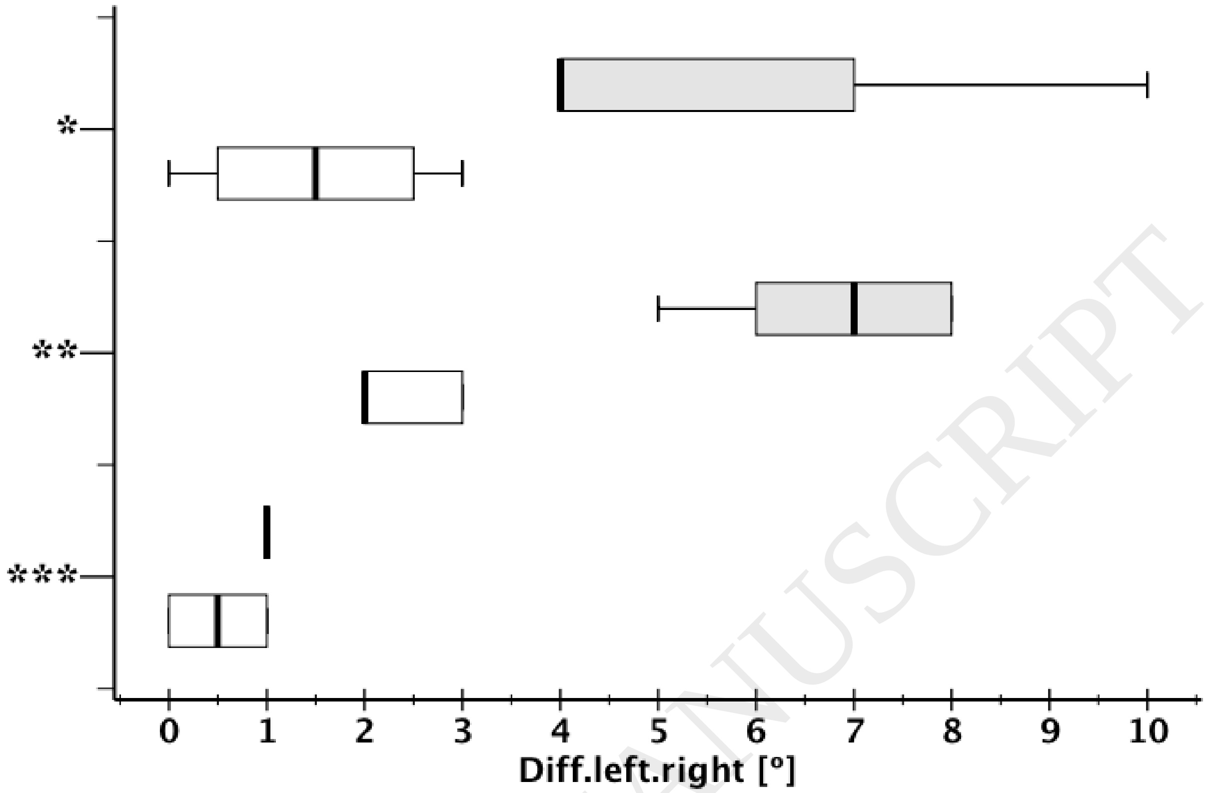
Leaning pattern	Type of hindlimb lameness	Horse	Body lean angle before diagnostic analgesia [º]			Body lean angle after diagnostic analgesia [º]		
			One rein *[, a]	The other rein**[, a]	Diff.left.right [b]	One rein*[,a]	The other rein**[, a]	Diff.left.right [b]
Leaned more when the lame(r) limb was on the outside of the circle	Unilateral left hindlimb lameness	1	6	10	4	8	9	1
		3	11	15	4	12	10	2
	Bilateral hindlimb lameness	9	5	15	10	10	7	3
		10	7	11	4	10	10	0
	Mean		7.3	12.8	5.5	10.0	9.0	1.5
Leaned more when the lame(r) limb was on the inside of the circle	Unilateral right hindlimb lameness	4	8	16	8	10	13	3
		5	8	16	8	10	13	3
	Bilateral hindlimb lameness	6	7	14	7	8	10	2
		7	10	15	5	10	12	2
		8	9	15	6	10	12	2
	Mean		8.4	15.2	6.8	9.6	12.0	2.4
Leaned the same on both reins	Bilateral hindlimb lameness	11	9	10	1	9	10	1
		12	11	12	1	12	12	0
		13	10	11	1	11	12	1
	Unilateral left hindlimb lameness	2	13	14	1	10	10	0
	Mean		10.8	11.8	1.0	10.5	11.0	0.5
Mean of all horses			8.8	13.4	4.6	10	10.8	1.5

[a] The rein where the horse leaned less* or more** compared with the other rein.

[b] Diff.left.right, Difference between the left and right reins.

Figure legends

Fig. 1. Boxplot illustrating the difference in body lean angle between the left and right reins (Diff.left.right) in thirteen horses with lameness before (grey bars, and one black vertical line) and after substantial improvement in lameness by diagnostic analgesia (white bars). *Two of five (40%) horses with unilateral lameness and two of eight (25%) with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the outside of the circle before diagnostic analgesia. **Two of five (40%) horses with unilateral lameness and three of eight (37.5%) horses with bilateral lameness leaned more on the rein with the lame or lamer hindlimb on the inside of the circle. ***Four horses, one with unilateral and three with bilateral lameness respectively, had only 1° difference in body lean angles between left and right reins. The box represents the interquartile range; the whiskers the maximum and minimum value and the black vertical line represents the median.


*
**
***
0
1
2
3
4
5
6
7
8
9
10
Diff.left.right [º]