

RVC OPEN ACCESS REPOSITORY – COPYRIGHT NOTICE

This is the peer-reviewed, manuscript version of the following article:

Greve, L., Pfau, T. and Dyson, S. 'Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge and the relationship with hind limb symmetry or asymmetry', *The Veterinary Journal*.

The final version is available online: <http://dx.doi.org/10.1016/j.tvjl.2017.01.003>.

© 2016. This manuscript version is made available under the CC-BY-NC-ND 4.0 license
<http://creativecommons.org/licenses/by-nc-nd/4.0/>.

The full details of the published version of the article are as follows:

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

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

JOURNAL: The Veterinary Journal

PUBLISHER: Elsevier

PUBLICATION DATE: 4 January 2017 (online)

DOI: 10.1016/j.tvjl.2017.01.003

Accepted Manuscript

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



Please cite this article as: L. Greve, T. Pfau, S. Dyson, Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge and the relationship with hind limb symmetry or asymmetry, *The Veterinary Journal* (2017), <http://dx.doi.org/doi: 10.1016/j.tvjl.2017.01.003>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Original Article**

2

3

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

6

7

8 L. Greve ^{a, b, *}, T. Pfau ^b, S. Dyson ^a

9

10 ^a *Centre for Equine Studies, Animal Health Trust, Lanwades Park, Kentford, Newmarket, Suffolk*
11 *CB8 7UU, UK*

12 ^b *Department of Clinical Science and Services, The Royal Veterinary College, University of*
13 *London, Hawkshead Lane, North Mymms, Hatfield AL9 7TA, UK*

14

15 * Corresponding author. Tel.: +44 163 8751908

16 E-mail address: line.greve@aht.org.uk (L. Greve).

17

Accepted Manuscript

18 **Highlights**

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

22 **Abstract**

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

34

35 The dorsoventral movement of the back exhibited a sinusoidal pattern with two
36 oscillations per stride. Circles induced greater asymmetry in dorsoventral movement within each
37 stride (mean \pm standard deviation, up to $9 \pm 6\%$) compared with straight lines (up to $6 \pm 6\%$).
38 The greatest amplitude of dorsoventral movement ($119 \pm 14\text{mm}$ in straight lines vs. $126 \pm 20\text{mm}$
39 in circles) occurred at T13. Circles induced greater flexion-extension ROM ($> 1.3^\circ$; $P = 0.002$),
40 lateral bending ($> 16^\circ$; $P < 0.001$), and lateral motion ($> 16\text{mm}$; $P = 0.002$) compared with

41 straight lines. Circles induced a movement pattern similar to an inside hindlimb lameness, which
42 was significantly associated with the circle-induced greater asymmetry of dorsoventral
43 movement of the thoracolumbar region ($P = 0.03$). Moving in a circle induces measurable
44 changes in thoracolumbar movement compared with moving in straight lines, associated with
45 alterations in the hindlimb gait.

46

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

48

Accepted Manuscript

49 **Introduction**

50 Equine spinal motion has been assessed in great detail in vitro (Jeffcott and Dalin, 1980;
51 Townsend et al., 1983) and to some extent in vivo (Faber et al., 2000, 2001a, b; Licka et al.,
52 2001a, b). Movement symmetry is changed when turning (Pfau et al. 2012), which may induce
53 alterations in thoracolumbosacral kinematics, however this has not been investigated.

54

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

72

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

79

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

94

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

100

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

107

108 **Materials and methods**

109 A prospective study was performed comprising sports horses, in regular work, presumed
110 by the riders to be sound. This was a convenience sample, selected based on proximity to the
111 authors. All horses were ridden by the normal rider in usual tack and had no recent history of
112 lameness or epaxial muscle pain. Age, breed, gender, height (copied from the passport), work
113 discipline and level of training or competition were recorded. The current study was approved
114 by the Ethical Review Committee of the Animal Health Trust (AHT 14.2014; 28 February
115 2014) and there was informed owner consent.

116

117 *Horse inclusion criteria*

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

121

122 *Inertial measurement units (IMUs)*

123 Objective gait assessment was performed 4 -14 days after the initial gait assessment.

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

134

135 *Dynamic assessment with IMUs*

136 Fourteen horses selected as sound were trotted in hand on a soft surface (an indoor arena
137 approximately 25 m × 60 m, with sand and fibre on a very firm base, $n = 2$; or with a very soft
138 base, $n = 10$; or an outdoor arena approximately 30 m × 70 m with sand and fibre on a firm base,
139 $n = 2$) and then lunged on the left rein followed by the right rein using a consistent lunging
140 technique, with a lunge line attached to the inside bit ring. The handlers (selected according to

141 their familiarity with the horses) were asked to use the same lunge line with a fixed length of 5 m
142 resulting in a circle diameter of approximately 10 m. The handlers were asked to allow the
143 horses to trot in hand and on the lunge at each horse's preferred speed. IMU data were collected
144 for at least 40 strides. Notes and video recordings acquired during data collection described
145 deviations from the expected movement condition, e.g., changes in gait, speed or gait quality. If
146 a horse deviated from the required movement condition (e.g., broke into a different gait) data
147 collection was repeated. One trot trial at the horse's preferred speed on the lunge on both left and
148 right reins in trot was recorded for each circumstance. Two trials were performed in four horses
149 trotting in straight lines and up to ± 5 mm difference of the median of any outcome variable
150 between trials was achieved. The video recordings of the horses were acquired from outside of
151 the circle. Video recordings of the horses were acquired during objective data acquisition for
152 subsequent assessment by SJD. Intra-assessor repeatability of the 20 horses videoed was
153 performed three times at intervals of 2 months and 100% agreement was achieved with regard to
154 the presence of lameness (yes/no). Previous intra-assessor repeatability has been documented in
155 50 horses that were randomly selected and assessed twice in a random order at an interval of 1-4
156 months; 98% correlation was achieved for lameness group (Greve and Dyson, 2014).

157

158 *Data processing*

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

162

163 *Quantification of kinematic symmetry measures*

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

173

174 *Three-dimensional kinematics of the vertebral column*

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

183

184 *Outcome variables*

185 Angular movement (a change in orientation) of the withers, T13, T18 and L3 was assessed
186 in three planes measured in degrees as ROM: flexion-extension ROM, which is the body rotation

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

197

198 $SI = ([\text{Amplitude up1} - \text{Amplitude up2}] / \text{maximum}[\text{amplitude up1}; \text{up2}] + 1,$

199

200 where maximum [amplitude up1; up2] is the maximum of the two (Starke et al. 2012).

201 Guidelines are $SI < 0.83$ is left hindlimb lameness and $SI > 1.17$ is right hindlimb lameness

202 (Starke et al. 2012), however, this has not been verified scientifically. Asymmetry was defined as

203 the absolute value of $(1 - SI) \times 100\%$. In addition, the differences between the two peaks

204 (maxima) [MaxDiff] and two troughs (minima) [MinDiff] of the vertical movement signal were

205 measured. $SI < 1$, $\text{MinDiff} < 0$ and $\text{MaxDiff} > 0$ indicates left-sided asymmetry. $SI > 1$, $\text{MinDiff} > 0$

206 and $\text{MaxDiff} < 0$ indicates right-sided asymmetry. Non-directional asymmetry measures were

207 determined by taking the absolute value of the directional asymmetry measures.

208

209 *Sample size calculation*

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

219

220 *Statistical analysis*

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

230

231 **Results**

232 The animals ranged in age from 3 to 13 years (mean, 7 years; median, 6.5 years) and

233 comprised 10 geldings, one stallion and three mares. Horses were used for dressage ($n = 12$) and
234 show jumping ($n = 2$). Breeds represented were Warmbloods ($n = 12$) and ponies ($n = 2$).
235 Bodyweights ranged from 400 to 630 kg (mean, 564 kg; median, 590 kg) and in height from 1.48
236 to 1.74 m (mean, 1.66 m; median, 1.69 m).

237

238 *Quantification of thoracolumbar movement*

239 The means \pm standard errors for the outcome variables are shown in Table 1.

240

241 *Straight lines*

242 The dorsoventral (z) displacement had two peaks per stride and exhibited a sinusoidal
243 pattern with two almost symmetrical oscillations in straight lines. The amplitude of movement in
244 straight lines was greatest at T13, with less movement amplitude cranially (withers) and caudally
245 (L3; Fig. 1a). The dorsoventral ROM of movement ranged from 75-125 mm for the withers,
246 94-138 mm at T13, 92-134 mm at T18 and 76-122 mm at L3. In contrast displacement in a
247 lateral (y) direction had only one peak and one trough per stride. The ranges of displacement
248 were 18-88 mm for the withers, 14-53 mm at T13, 17-50 mm at T18 and 19-81 mm at L3.
249 Flexion-extension ROM was smaller than axial rotation ROM for all the sensor locations (Fig.
250 1c-d). Flexion-extension ROM and axial rotation ROM were greatest towards the withers. The
251 axial rotation ROM ranged from 13-28° for the withers, 5-14° at T13, 5-16° at T18 and 7-19° at
252 L3 (Fig. 1c). The flexion-extension ROM ranged from 4-11° for the withers, 3-5° at T13, 2-7° at
253 T18 and 4-7° at L3 (Fig. 1d). The lateral bending ranged from 6-11° for the withers, 3-6° at T13,
254 3-8° at T18 and 3-8° at L3. In straight lines, there were small asymmetries in the dorsoventral
255 movement between the two halves of the stride (at T13 the symmetry was [mean \pm SD] $95 \pm 4\%$)

256 and slightly less symmetry cranially and caudally (withers, T18 and L3 up to $94 \pm 6\%$; Fig. 2a).
257 The mean \pm SD (range) in straight lines of the absolute pelvis MinDiff was 4.9 ± 5.3 mm (0 mm,
258 18 mm), pelvis MaxDiff was 3.5 ± 3.5 mm (0 mm, 14 mm) and HHD was 6.1 ± 5.9 mm (0 mm,
259 17 mm; Fig. 2b).

260

261 *Differences between straight lines and circles*

262 Circles induced significantly greater flexion-extension ROM (mean 5.3°) compared with
263 straight lines (mean 4.0°) for T13 ($P < 0.001$), for T18 (mean circles 5.1° vs. straight lines 4.0° ;
264 $P = 0.002$) and for L3 (mean circles 7.1° vs. straight lines 5.3° ; $P = 0.001$; Fig. 1d). Circles also
265 induced significantly greater lateral bending (mean 29°) compared with straight lines (mean 8°)
266 for withers ($P < 0.001$), for T13 (mean circles 29° vs. straight lines 5° ; $P < 0.001$), for T18 (mean
267 circles 28° vs. straight lines 5° ; $P < 0.001$) and for L3 (mean circles 29° vs. straight lines 5° ; $P <$
268 0.001). There were no differences in axial rotation ROM for any sensor location between circles
269 and straight lines (Fig. 1c). The displacements in a lateral (y) direction were significantly greater
270 on the lunge for T13 (mean 46 mm) compared with straight lines (mean 30 mm; $P < 0.001$) and
271 for T18 on the lunge (mean 48 mm) compared with straight lines (mean 36 mm; $P = 0.002$; Fig.
272 1b). Circles did not induce any significantly different amplitude of dorsoventral displacement
273 compared with straight lines when considering the mean of the two oscillations during outside
274 and inside hindlimb stance (Fig. 1a). However, in comparison with straight lines circles did
275 induce significantly greater amplitude of the dorsoventral movement of T13, T18 and L3 during
276 the outside hindlimb stance compared with the inside hindlimb stance ($P = 0.03$; Fig. 2a). There
277 was a greater maximum displacement of T13 and T18 (Fig. 3b) after outside hindlimb stance
278 compared with the inside hindlimb ($P = 0.003$; Fig. 3a). L3 dropped less during the inside

279 hindlimb stance compared with the outside hindlimb stance ($P = 0.009$; Fig. 3a). The withers
280 dropped less during the inside forelimb stance compared with the outside forelimb stance and
281 reached a higher displacement just after the inside forelimb stance compared with just after the
282 outside forelimb stance ($P = 0.003$). The tubera sacrale dropped less during the inside hindlimb
283 stance compared with the outside hindlimb stance in circles compared with straight lines ($P <$
284 0.001) mimicking a mild inside hindlimb lameness. Circles also induced a hip hike mimicking an
285 inside hindlimb lameness compared with straight lines ($P < 0.001$), means on circles the inside
286 tuber coxae had a greater amplitude of movement compared with the outside tuber coxae during
287 the outside hindlimb stance (HHD). However, the mean difference in the maximum displacement
288 of the tubera sacrale between left and right hindlimb stance was not significantly different
289 between circles and straight lines ($P = 0.2$; Fig. 2b).

290

291 *Differences between left and right reins when moving in circles*

292 There were no significant differences between the side-corrected means of MinDiff or
293 MaxDiff or the means of flexion-extension ROM, axial rotation ROM, dorsoventral or lateral
294 displacement of the thoracolumbar region between the left and right reins when moving on the
295 lunge. The side-corrected pelvic MaxDiff mean \pm SD on the right and left reins were 3 ± 5 mm
296 and 3 ± 8 mm, respectively. The side-corrected pelvic MinDiff on the right and left reins were 15
297 ± 11 mm and 14 ± 10 mm, respectively. The symmetry index on the right and left reins were
298 0.87 ± 0.07 mm and 0.90 ± 0.08 mm, respectively. None of these symmetry parameters on the
299 left and right reins were significantly different from each other. However, the mean \pm SD of
300 HHD on the right rein (21 ± 11 mm) was significantly different from HHD on the left rein ($12 \pm$
301 10 mm; $P = 0.05$). In addition, lateral bending was on average greater on the right rein compared

302 with the left rein for tubera sacrale (mean \pm SD right rein $31^\circ \pm 7^\circ$ vs. left rein $26^\circ \pm 3^\circ$; $P =$
303 0.04), for T18 (right rein $31^\circ \pm 7^\circ$ vs. left rein $26^\circ \pm 4^\circ$; $P = 0.02$) and the withers (right rein 32°
304 $\pm 7^\circ$ vs. left rein $26^\circ \pm 7^\circ$; $P = 0.004$). The data from all the horses is provided in supplementary
305 information (Appendix A).

306

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

313

314 *Association of thoracolumbar movement with pelvic symmetry*

315 Looking at both straight lines and circles there was a linear association between the
316 differences in the upward movement amplitude of the thoracolumbar region (T13, T18, L3)
317 during the LH stance compared with the RH stance and the difference in the upward movement
318 amplitude of the pelvis (tubera sacrale) during the LH stance compared with the RH stance. So
319 for example, if the pelvis had less movement amplitude during the RH stance (either by dropping
320 less [MinDiff] or less upward movement [MaxDiff]) compared with the LH stance, the
321 thoracolumbar region also exhibited less upward movement amplitude during the RH stance
322 compared with the LH stance. The thoracic region was mostly sensitive to the dropping of the
323 pelvis (MinDiff) rather than upward movement of the pelvis (MaxDiff), whereas the lumbar
324 region in straight lines alone was more sensitive to upward movement of the pelvis (MaxDiff)

325 rather than dropping of the pelvis (MinDiff). Ten mm difference in the MaxDiff of both
326 hindlimbs caused 12% greater asymmetry between the first and second halves of the movement
327 amplitudes of L3 (Table 2). There was no influence of surfaces.

328

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

333

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

345

346 **Discussion**

347 The results of our study supported the hypothesis that circles induce symmetrical
348 asymmetry between the left and right reins in the thoracolumbar movement and in the hindlimb

349 gait, with the exception of HHD, in sound horses. The hypothesis that left and right asymmetries
350 in the thoracolumbar amplitudes between the first and second halves of the stride are associated
351 with left and right asymmetries in the hindlimb gait was also supported by our findings. The
352 method used for measuring thoracolumbar movement and the hindlimb gait provided an objective
353 means of investigating the relationship between hindlimb and thoracolumbar kinematics. Several
354 studies have described limb kinematics in trot, which is a two beat, symmetrical, diagonal gait
355 with two periods of suspension per stride cycle (Hildebrand 1965, Back et al., 1995a,b), but there
356 are only a few studies which have used biomechanical methods to study the influence of hindlimb
357 gait on the movement of the thoracolumbar region (Faber, 2001, Gómez Álvarez et al., 2007,
358 2008).

359
360 Consistent with previous studies (Audigié et al., 1999; Buchner et al., 2000; Faber et al.,
361 2000, 2001, 2002, Warner et al., 2010), there was a double sinusoidal pattern for dorsoventral
362 displacement of the thoracolumbosacral region and a sinusoidal pattern for lateral-lateral
363 displacement for each stride. There were large ranges in angular movement (up to 19°), except at
364 the withers, which showed up to 28° for axial rotation. This represents only $\pm 14^\circ$, which is quite
365 small when considering that the withers area is less 'rigid' than other sites at which
366 measurements were acquired. There were also large ranges in dorsoventral (75-128 mm) and
367 lateral (18-88 mm) amplitudes of movement among the horses included in the study,
368 emphasising that even within normal sound horses there is considerable variation in
369 thoracolumbosacral movement. The range of movement was slightly more in circles (up to 80
370 mm) compared with straight lines (up to 70 mm). There were considerably smaller ranges of
371 movement in six research ponies, 40–47 mm for dorsoventral and 16–37 mm for lateral

372 movement, respectively (Warner et al., 2010). This probably reflects the different study
373 populations: ponies vs. sports horses and here the use of animals that have undergone a
374 comprehensive lameness examination including flexion tests. The inclusion of horses with
375 lameness may affect the rotational thoracolumbosacral ROM and symmetry of motion (Greve L.,
376 Dyson S., Pfau T. Unpublished data). We made no attempt to scale the data between different
377 sizes of horses, but this merits further investigation. In Franches-Montagnes stallions there was a
378 similar magnitude of movement as in the current study for movement in the dorsoventral
379 direction (mean \pm SD, 97 ± 9 mm) and for the movement in the lateral direction at the level of
380 the 12th thoracic vertebra (35 ± 10 mm; Heim et al., 2015). In the current study the greatest range
381 of dorsoventral displacement was found at T13 (94-138 mm), which is closely related to the
382 movement of the body centre of mass (Buchner et al., 2000). It has been previously demonstrated
383 that horses with hindlimb lameness and a convex shape at the level of T18 or T13 had a higher
384 risk of saddle slip than horses with other thoracolumbar shapes (Greve and Dyson, 2013, 2014).
385 This may reflect that the maximal range of vertical displacement and the greatest difference in
386 maximum and minimum heights between left and right halves of the stride occurs at T13, where
387 the equine body centre of mass is aligned with the rider's centre of mass (Buchner et al., 2000).
388 In addition, in the current study the circle-induced differences in the minimum height of T13
389 during the left and right hindlimb stance phases showed an opposite pattern compared with T18
390 and L3, indicating that sound horses alter the movement of the mid thoracic region in circles
391 differently to the caudal thoracic and lumbar regions. This means that for example on the left
392 circle where the pelvis shows a higher maximum displacement during inside (left) hind limb
393 stance, potentially a sign of reduced weight bearing with the inside hindlimb, the mid thoracic
394 region shows a higher maximum displacement during outside hindlimb stance, i.e. during inside

395 (left) forelimb stance, potentially a sign of reduced weight bearing with the inside forelimb.
396 Forces in forelimbs and hindlimbs have been correlated with head MinDiff (Keegan et al., 2012)
397 and pelvic MinDiff (Bell et al., 2016), respectively, for lame horses trotting in straight lines, but
398 there is no similar data relating pelvis movement to limb forces during movement in circles for
399 either sound or lame horses. The pattern observed would be consistent with an ipsilateral
400 compensatory movement, which has been reported previously in induced hindlimb lameness on
401 the lunge (Rhodin et al., 2013). In the present study, we observed that the symmetry of the
402 thoracolumbar movement was reduced in circles compared with straight lines for all sensor
403 locations, with greater amplitude of the dorsoventral movement during the outside hindlimb
404 stance in comparison with the inside hindlimb stance. This may explain why a saddle normally
405 moves slightly more in circles compared with straight lines (Bystrom et al., 2009), and why
406 saddle slip in horses with hindlimb lameness is usually worse in circles compared with straight
407 lines (Greve and Dyson, 2013, 2014).

408
409 We observed that circles induced mild asymmetry of the movement of the pelvis in sound
410 horses mimicking subtle inside hindlimb lameness, consistent with the results of other studies
411 (Starke et al. 2012; Rhodin et al. 2013, 2016, Halling Thomsen et al. 2014). The circle-induced
412 asymmetry in thoracolumbar and pelvis movement were significantly associated. The maximum
413 and minimum displacements of T13 were linearly associated with HHD, pelvic MinDiff and
414 pelvic MaxDiff. On a circle, alteration in HHD resulted in up to six times more change in the
415 movement of T13 compared with comparable alterations in magnitude of either pelvic MinDiff
416 and pelvic MaxDiff. When measuring pelvic movement symmetry parameters (MinDiff,
417 MaxDiff, HHD) quantifying the response to diagnostic analgesia in horses with hindlimb

418 lameness, the most sensitive and consistent changes were observed in HHD (Pfau et al. 2014).

419

420 Differences in the maximum displacement of the tubera sacrale just after the left and right

421 hindlimb stance had the biggest influence on the movement of L3. Movement of the lumbar

422 vertebral column is controlled by both the hypaxial and epaxial muscles. The hypaxial lumbar

423 muscles function as flexors of the coxofemoral joint, the lumbosacral junction and provide

424 stability to the

425 lumbosacral region (Sisson 1975; Clayton 2012; van Weeren 2014) and may contribute to the

426 engagement of the hindlimbs (meaning that the lumbosacral joint is flexed and the hindlimbs are

427 protracted under the body; Dyson, 2016;¹), but their exact function has not yet been investigated.

428 The epaxial muscles act as extensor muscles. It is a common clinical observation that many

429 horses with hindlimb lameness exhibit epaxial muscle soreness and hypertonicity in the lumbar

430 region (Landman et al., 2004; Zimmerman et al., 2011), although the pathophysiology of muscle

431 pain and the association with limb movement and lameness are not well understood. In the

432 present study, the kinematics of the hindlimbs and the thoracolumbar regions were closely

433 linked. It has also been observed that lameness can induce thoracolumbar stiffness and limited

434 hindlimb impulsion, or a restricted gait in all limbs (Dyson, 2016) and that primary

435 thoracolumbar pain can induce similar symptoms (Girodroux et al., 2009). Based on the results

436 of the current study it is important to be able to detect lameness at an early stage to avoid

437 increased asymmetry of thoracolumbosacral movement which might induce additional pain.

438

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

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

447

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

462

463 Conclusions

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

472

473 Conflict of interest statement

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

476

477 Acknowledgements

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

480

481 Supplementary material

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

483 ...

484

485 **References**

- 486 Abrams, D. M., Panaggio, M.J., 2012. A model balancing cooperation and competition can
487 explain our right-handed world and the dominance of left-handed athletes. *Journal of the Royal*
488 *Society Interface* 9, 2718-2722.
- 489
490 Audigié, F., Pourcelot, P., Degueurce, C., Denoix, J.M., Geiger, D., 1999. Kinematics of the
491 equine back: Flexion–extension movements in sound trotting horses. *Equine Veterinary Journal*
492 31, 210–213.
- 493
494 Back, W., Schamhardt, H. C., Savelberg, H. H., van den Bogert, A. J., Bruin, G., Hartman, W.,
495 Barneveld, A., 1995a. How the horse moves: 1. Significance of graphical representations of
496 equine forelimb kinematics *Equine Veterinary Journal* 27, 31-8.
- 497
498 Back, W., Schamhardt, H. C., Savelberg, H. H., van den Bogert, A. J., Bruin, G., Hartman,
499 W.Barneveld, A., 1995b. How the horse moves: 2. Significance of graphical representations of
500 equine hind limb kinematics *Equine Veterinary Journal* 27, 39-45
- 501
502 Bell, R.P., Reed, S.K., Schoonover, M.J., Whitfield, C.T., Yonezawa, Y., Maki, H., Pai, P.F.,
503 Keegan, K.G., 2016. Associations of force plate and body-mounted inertial sensor measurements
504 for identification of hind limb lameness in horses. *American Journal of Veterinary Research* 77,
505 337-345
- 506
507 Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C., Barneveld, A., 1996. Head and trunk
508 movement adaptations in horses with experimentally induced fore or hind limb lameness. *Equine*
509 *Veterinary Journal* 28, 71–76.
- 510
511 Buchner, H.H.F. Ohermuller. Scheidl, M., 2000. Body centre of mass involvement in the sound
512 horse. *The Veterinary Journal* 160, 225-234.
- 513
514 Bystrom, A., Rhodin, M., von Peinen, K., Weishaupt, M.A., Roepstorff, L., 2009. Basic
515 kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. *Equine*
516 *Veterinary Journal* 41, 280–284.
- 517
518 Clayton, H.M., Sha D.H., 2006. Head and body centre of mass movement in horses trotting on a
519 circular path. *Equine Veterinary Journal* 38, (Suppl 36), 462-467.
- 520
521 Clayton, H. M. 2012. Equine back pain reviewed from a motor control perspective. *Comparative*
522 *Exercise Physiology*, 8, 145-152.
- 523
524 Dyson, S., 2011. Can lameness be reliably graded? *Equine Veterinary Journal* 43, 379-382.
- 525
526 Dyson, S., 2016. Evaluation of poor performance in competition horses: a musculoskeletal
527 perspective. Part 1 Clinical assessment. *Equine Veterinary Education* 28, 284-293.
- 528
529 Faber, M., Schamhardt, H., Weeren, R. van, Johnston, C., Roepstorff, L., Barneveldt, A., 2000.
530 Basic threedimensional kinematics of the vertebral column of horses walking on a treadmill.

- 531 American Journal of Veterinary Research 61, 399-406.
532
- 533 Faber, M., Johnston, C., Schamhardt, H.C., Weeren, P.R. van, Roepstorff, L., Barneveldt, A.,
534 2001a. Threedimensional kinematics of the equine spine during canter. Equine Veterinary
535 Journal 33, 145-149.
536
- 537 Faber, M., Johnston, C., Schamhardt, H.C., Weeren, P.R. van, Roepstorff, L., Barneveldt, A.,
538 2001b. Basic three dimensional kinematics of the vertebral column of horses trotting on a
539 treadmill. American Journal of Veterinary Research 62, 757-764.
540
- 541 Faber, M., Johnston, C., Weeren, P.R. van, Barneveldt, A., 2002. Repeatability of back
542 kinematics in horses during treadmill locomotion. Equine Veterinary Journal 34, 235-241.
543
- 544 Girodroux, M., Dyson, S., Murray, R., 2009. Osteoarthritis of the thoracolumbar synovial
545 intervertebral articulations: clinical and radiographic features in 77 horses with poor performance
546 and back pain. Equine Veterinary Journal 41, 130-138.
547
- 548 Gómez Álvarez, C.B., Wennerstrand, J., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van
549 Weeren, P.R., 2007. The effect of induced forelimb lameness on thoracolumbar kinematics
550 during treadmill locomotion. Equine Veterinary Journal 39, 197-201.
551
- 552 Gómez Álvarez, C.B., Wennerstrand, J., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van
553 Weeren, P.R., 2008. The effect of induced hindlimb lameness on thoracolumbar kinematics
554 during treadmill locomotion. Equine Veterinary Journal 40, 147-152.
555
- 556 Greve, L. Dyson, S., 2013. An investigation of the relationship between hindlimb lameness and
557 saddle-slip. Equine Veterinary Journal 45, 570-577.
558
- 559 Greve, L., Dyson, S., 2014. The interrelationship of lameness, saddle-slip and back shape in the
560 general sports horse population. Equine Veterinary Journal 46, 687-94
561
- 562 Greve, L., Dyson, S., 2015. A longitudinal study of back dimension changes over 1 year in sports
563 horses. The Veterinary Journal 203, 65-73
564
- 565 Halling Thomsen, M., Sahl-Tjørnholm, C., Sørensen, H., Tolver Jensen, A., 2014. Effect of
566 lungeing and circle size on movement symmetry in sound riding horses. Equine Veterinary
567 Journal 46, 49-50.
568
- 569 Heim, C., Pfau, T., Gerber, V., Schweizer, C., Doherr, M., Schüpbach-Regula, G., Witte, S.,
570 2016. Determination of vertebral range of motion using inertial measurement units in 27
571 Franches-Montagnes stallions and comparison between conditions and with a mixed population.
572 Equine Veterinary Journal 48, 509-516.
573
- 574 Hildebrand, M., 1965. Symmetrical gaits in horses. Science 150, 701-708.
575
- 576 Hobbs, S.J., Licka, T., Polman, R., 2011. The difference in kinematics of horses walking, trotting

- 577 and cantering on a flat and banked 10 m circle. *Equine Veterinary Journal* 43, 686-694.
578
- 579 Jeffcott L. B., Dalin, G., 1980. Natural rigidity of the horses' backbone. *Equine Veterinary*
580 *Journal* 12, 101-108.
581
- 582 Johnson, J.L., Moore-Colyer, M., 2009. The relationship between range of motion of
583 lumbosacral flexion-extension and canter velocity of horses on a treadmill. *Equine Veterinary*
584 *Journal* 41, 301-303.
585
- 586 Keegan, K.G., Pai, P.F., Wilson, D.A., Smith B. K., 2001. Signal decomposition method of
587 evaluating head movement to measure induced forelimb lameness in horses trotting on a
588 treadmill. *Equine Veterinary Journal* 33 (Suppl. 5), 446-451.
589
- 590 Keegan, K.G., MacAllister, C.G., Wilson, D. A., Gedon, C.A., Kramer, J., Yonezawa, Y., Maki,
591 H., 2012. Comparison of an inertial sensor system with a stationary force plate for evaluation of
592 horses with bilateral forelimb lameness. *American Journal of Veterinary Research* 73, 368-374.
593
- 594 Kramer, J., Keegan, K.G., Kelmer, G., Wilson, D.A. 2004. Objective determination of pelvic
595 movement during hind limb lameness and pelvic height differences. *American Journal*
596 *Veterinary Research* 65, 741-747.
597
- 598 Landman, M.A., de Blaauw, J.A., van Weeren, P.R., Hofland, L.J., (2004) Field study of the
599 prevalence of lameness in horses with back problems. *Veterinary Record* 155, 165-168.
600
- 601 Licka, T., Peham, C., Zohmann, E., 2001a. Range of back movement at trot in horses without
602 back pain. *Equine Veterinary Journal* 33 (Suppl. 33), 150-153.
603
- 604 Licka, T., Peham, C., Zohmann, E., 2001b. Treadmill study of the range of back movement at the
605 walk in horses without back pain. *American Journal of Veterinary Research* 62, 1173-1179.
606
- 607 May, S.A., Wyn-Jones, G., 1987. Identification of hindleg lameness. *Equine Veterinary Journal*
608 19, 185-188.
609
- 610 McGreevy, P.D., Rogers, L.J., 2005. Motor and sensory laterality in thoroughbred horses.
611 *Applied Animal Behaviour Science* 92, 337-352.
612
- 613 McGreevy, P.D., Thomson, P. C., 2006. Differences in motor laterality between breeds of
614 performance horse. *Applied animal behaviour Science* 99, 183-190.
615
- 616 Peham, C., Scheidl, M., Licka, T., 1996. A method of signal processing in motion analysis of the
617 trotting horse. *Journal Biomechanics* 29, 1111-1114.
618
- 619 Pfau, T., Witte, T.H., Wilson, A.M., 2005. A method for deriving displacement data during
620 cyclical movement using an inertial sensor. *Journal Experimental Biology* 208, 2503-2514.
621
- 622 Pfau, T., Stubbs, N., Kaiser, L., Brow, L., Clayton, H., 2012. Effect of trotting speed and circle

- 623 radius on movement symmetry in horses during lungeing on a soft surface. *American Journal of*
624 *Veterinary Research* 73, 1890-1899.
- 625
- 626 Pfau, T., Spicer-Jenkins, C., Smith, R.K., Bolt, D.M., Fiske-Jackson, A., Witte, T.H., 2014.
627 Identifying optimal parameters for quantification of changes in pelvic movement symmetry as a
628 response to diagnostic analgesia in the hindlimbs of horses. *Equine Veterinary Journal* 46, 759-
629 763.
- 630
- 631 Pfau, T., Fiske-Jackson, A., Rhodin, M. 2016. Quantitative assessment of gait parameters in
632 horses: Useful for aiding clinical decision making? *Equine Veterinary Education*, 28(4), 209-
633 215.
- 634
- 635 Rhodin, M., Pfau, T., Roepstorff, L., Egenvall, A., 2013. Effect of lungeing on head and pelvic
636 movement asymmetry in horses with induced lameness. *The Veterinary Journal* 198, 39-45.
- 637
- 638 Rhodin, M., Roepstorff, L., French, A., Keegan, K. G., Pfau, T., Egenvall, A., 2016. Head and
639 pelvic movement asymmetry during lungeing in horses showing symmetrical movement on the
640 straight. *Equine Veterinary Journal* 48, 315-320.
- 641
- 642 Sisson, S., 1975. Equine myology. In Getty, R., eds., *Sisson and Grossman's Anatomy of*
643 *domestic animals*, 5th Ed., Philadelphia, USA: Saunders (W.B.), 433-435.
- 644
- 645 Starke, S.D., Willems, E., May, S. Pfau, T., 2012. Vertical head and trunk movement adaptations
646 to sound horses trotting in a circle on a hard surface. *The Veterinary Journal* 193, 73-80.
- 647
- 648 Starke, S.D., Merritt, J.S., Stubbs, N., Pfau T., Clayton, H.M. 2014. Is foot placement related to
649 body movement asymmetry during circular locomotion? In: *Proceedings of the Annual Meeting*
650 *of the International Conference on Equine Exercise Physiology*. Chester, UK, p. 48-49
- 651
- 652 Townsend, H. G. G., Leach, D. H., Fretz, P. B. 1983. Kinematics of the equine thoracolumbar
653 spine. *Equine Veterinary Journal* 15, 117-122.
- 654
- 655 Uhler, C., Licka, T., Kübber, P., Peham, C., Scheidl, M., Girtler, D., 1997. Compensatory
656 movements of horses with a stance phase lameness. *Equine Veterinary Journal* 29 (Suppl. 23),
657 102–105.
- 658
- 659 van Heel, M.C.V., Kroekenstoel, A.M., van Dierendonck, M.C., van Weeren, P.R., Back, W.,
660 2006. Uneven feet in a foal may develop as a consequence of lateral grazing behaviour induced
661 by conformational traits. *Equine Veterinary Journal* 38, 646-651.
- 662
- 663 van Weeren, P.R. 2014. Kinematics of the equine back and pelvis. In Hodgson, D.R., McKeever,
664 K., McGowan C., eds., *The Athletic Horse: Principles and Practices of Equine Sports Medicine*.
665 2nd Ed., St Louis, USA: Elsevier, 282-292.
- 666
- 667 Warner, S.M., Koch, T.O., Pfau, T., 2010. Inertial sensors for assessment of back movement in
668 horses during locomotion over ground. *Equine Veterinary Journal* 42, 417–424.

- 669
670 Wennerstrand, J., Johnston, C., Roethlisberger- Holm, K., Erichsen, C., Eksell, P., Drevemo, S.,
671 2004. Kinematic evaluation of the back in the sport horse with back pain. *Equine Veterinary*
672 *Journal* 36, 707–711.
- 673
674 Wennerstrand, J., Gómez Alvarez, C.B., Meulenbelt, R., Johnston, C., van Weeren, P.R.,
675 Roethlisberger-Holm, K., Drevemo, S., 2009. Spinal kinematics in horses with induced back
676 pain. *Veterinary Comparative Orthopaedics and Traumatology* 22, 448-454.
- 677
678 Zimmerman, M., Dyson, S., Murray, R., 2011. Close, impinging and overriding spinous
679 processes in the thoracolumbar spine: The relationship between radiological and scintigraphic
680 findings and clinical signs. *Equine Veterinary Journal* 44, 178-184.
- 681

Accepted Manuscript

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

697

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

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

718

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

728 was greater during the inside hindlimb stance in comparison with the outside hindlimb stance (P
729 = 0.009)**.

730

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

751

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

758

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

769

770

771

772

773 **Table 1.** The mean \pm standard error (SE) for the non-directional symmetry of the left and right oscillations during one stride in 14
 774 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 (%)

| Region | Mean \pm SE | | Mean \pm SE | |
|---------|----------------|--|----------------|----------------|
| | Straight lines | | Right rein | Left rein |
| Withers | 6.1 \pm 1.6 | | 8.2 \pm 1.7 | 8.9 \pm 1.8, |
| T13 | 4.5 \pm 1.0 | | 6.6 \pm 1.1 | 5.3 \pm 1.2 |
| T18 | 5.9 \pm 1.4 | | 8.5 \pm 1.5 | 6.8 \pm 1.3 |
| L3 | 5.8 \pm 1.4 | | 11.1 \pm 1.6 | 7.4 \pm 1.5 |
| TS | 6.4 \pm 1.6 | | 13 \pm 1.7 | 10.1 \pm 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 \pm 1.5 | -0.3 \pm 1.2 | 12.6 \pm 2.7 | 8.1 \pm 1.6 | -10.4 \pm 2.6 | -6.9 \pm 1.6 |
| T13 | -1 \pm 1.2 | 1.2 \pm 1.0 | 2.5 \pm 1.4 | 9.6 \pm 1.8 | -2.4 \pm 1.9 | -5.6 \pm 1.4 |
| T18 | -1.4 \pm 1.4 | 1.5 \pm 1.3 | -3 \pm 1.5 | 6.9 \pm 1.5 | 2.3 \pm 1.7 | -4.1 \pm 1.4 |
| L3 | -0.7 \pm 1.5 | 0.7 \pm 1.3 | -7.7 \pm 2.1 | 3.4 \pm 1.5 | 6.4 \pm 1.8 | -0.4 \pm 1.5 |
| TS | 0.5 \pm 1.9 | 0.8 \pm 1.3 | -14.9 \pm 3.0 | -2.9 \pm 1.4 | 14.3 \pm 2.7 | 3.7 \pm 2.3 |

Displacement (mm)

| | Straight lines | | Right rein | | Left rein | |
|---------|----------------|-----------------|--------------|-----------------|--------------|-----------------|
| | Dorsoventral | Lateral-lateral | Dorsoventral | Lateral-lateral | Dorsoventral | Lateral-lateral |
| Withers | 101 \pm 4 | 42 \pm 5 | 111 \pm 6 | 55 \pm 6 | 104 \pm 4 | 48 \pm 5 |
| T13 | 119 \pm 4 | 30 \pm 3 | 128 \pm 7 | 47 \pm 4 | 125 \pm 4 | 45 \pm 3 |
| T18 | 114 \pm 4 | 36 \pm 2 | 122 \pm 6 | 51 \pm 5 | 117 \pm 3 | 45 \pm 4 |
| L3 | 102 \pm 4 | 44 \pm 4 | 114 \pm 6 | 54 \pm 6 | 109 \pm 3 | 45 \pm 3 |
| TS | 115 \pm 4 | 41 \pm 7 | 127 \pm 6 | 50 \pm 4 | 122 \pm 4 | 44 \pm 3 |

775 TS, Tubera sacrale.

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

| Region | Condition | Hindlimb variable (10mm increase) | Increase in outcome | <i>P</i> |
|--|----------------|-----------------------------------|---------------------|----------|
| Outcome: Flexion-extension ROM in ° (the body rotation about the transverse [lateral-lateral] axis). | | | | |
| | Straight Lines | Pelvis MaxDiff | 3.7° | 0.004 |
| Withers | 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 |

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

782

783

784 **Table 3.** Significant results of multivariable mixed effect linear regression analysis of the
 785 association between hindlimb gait and thoracolumbar movement, when the outcomes* and
 786 variables** used are found by subtracting the mean value for straight lines from the mean values
 787 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 | Δ Dorsoventral displacement | Δ HHD | 5.2mm | 0.03 |
| | | Δ MinDiff | 1.4° | 0.001 |
| T13 | Δ Flexion-extension ROM | Δ HHD | -1.5° | 0.02 |
| | Δ The asymmetry of the left and right oscillations during one stride (%) | Δ HHD | 1.6% | 0.04 |
| | Δ Laterolateral displacement | Δ HHD | 4.5mm | 0.02 |
| T18 | Δ The asymmetry of the left and right oscillations during one stride (%) | Δ HHD | 2.6% | 0.003 |
| | Δ Laterolateral displacement | Δ HHD | 5.4mm | 0.02 |
| L3 | Δ The asymmetry of the left and right oscillations during one stride (%) | Δ HHD | 2.8% | 0.004 |
| | | Δ MinDiff | 3.2% | 0.05 |
| | Δ Dorsoventral displacement | Δ HHD | 6.2mm | 0.04 |

788 For example, looking at the first row of the table: 10 mm increase in the variable Δ HHD results
 789 in 5.2 mm increase in the outcome Δ Dorsoventral displacement ($P = 0.03$) of the withers.
 790 Δ , The measured mean value for straight lines subtracted from the mean value for circles;
 791 Flexion-extension ROM (range of motion), the body rotation about the transverse (lateral-lateral)
 792 axis; MinDiff and MaxDiff, the differences in minimum and maximum displacement of the
 793 pelvis, respectively; HHD, the difference in upward movement of each tuber coxae during
 794 contralateral hindlimb stance.
 795