

## RVC OPEN ACCESS REPOSITORY – COPYRIGHT NOTICE

This article may be used for non-commercial purposes in accordance with [Wiley Terms and Conditions for Self-Archiving](#).

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

TITLE: Agreement between two inertial sensor gait analysis systems for lameness examinations in horses

AUTHORS: T. Pfau, H. Boultbee, H. Davis, A. Walker, M. Rhodin

JOURNAL TITLE: Equine Veterinary Journal

PUBLISHER: Wiley

PUBLICATION DATE: April 2016

DOI: [10.1111/eve.12400](https://doi.org/10.1111/eve.12400)

1 **Agreement between two inertial sensor gait analysis systems for lameness exams in horses**

2 Thilo Pfau<sup>1</sup>, Harriet Boulton<sup>1</sup>, Hanna Davis<sup>1</sup>, Anna Walker<sup>1</sup>, Marie Rhodin<sup>2</sup>

3 <sup>1</sup>Department of Clinical Science and Services, The Royal Veterinary College, University of London

4 <sup>2</sup>Department of Clinical Sciences, Swedish University of Agricultural Sciences, SE-750 07, Uppsala,  
5 Sweden

6 **\*Correspondence:** [tpfau@rvc.ac.uk](mailto:tpfau@rvc.ac.uk)

7 Keywords: horse, lameness, gait analysis, movement symmetry

8

9 **Declarations:**

10 Ethical Considerations: The project was granted approval by the Royal Veterinary College's Ethics  
11 and Welfare Committee. Owners of privately owned horses gave signed consent for the use of their  
12 horses in the study.

13 Competing Interests: The authors of this paper have no financial or personal relationships with other  
14 people or organisations that could inappropriately influence or bias the content of this paper.

15 Source of funding: Funding was provided by the Swedish-Norwegian Foundation for Equine Research  
16 and the Royal Veterinary College (as part of Harriet Boulton's and Hanna Davis' 3<sup>rd</sup> year research  
17 project).

18 Acknowledgements: The authors thank Professor Kevin Keegan for constructive criticism on the  
19 manuscript and Constanza Gómez Álvarez and Line Greve for help with data collection.

20

21

22

23

24

25 **Summary**

26 Gait analysis is gaining in popularity for quantification of lameness and two commonly used inertial  
27 sensor systems assess trunk movement symmetry: can these be used interchangeably in multi  
28 centre studies?

29 We compared head and pelvic movement symmetry between two inertial sensor gait analysis  
30 systems in 13 horses equipped simultaneously with the two systems. The first system quantified  
31 dorso-ventral movement in the local reference frame (System A), the other system global vertical  
32 movement (System B). Widths of limits of agreement were calculated employing a well-established  
33 regression method dealing with systematically changing differences over the range of measured  
34 values.

35 Widths of limits of agreement between system A and system B were narrower for pelvic movement  
36 than for head movement. For head movement, they ranged from 6.4 to 6.9mm for in-hand trot and  
37 from 7.3 to 9.7mm in the lunge and for pelvic movement from 2.5 to 4.4mm in-hand and from 3.6  
38 to 5.3mm on the lunge.

39 Widths of limits of agreement between the two investigated inertial sensor gait analysis systems are  
40 of comparable magnitude (some equivalent, some marginally higher) to the currently proposed  
41 thresholds of 6mm for head and 3mm for pelvic movement used in lameness investigations.

42 Differences in measurements with two different systems (A and B) obtained from the same horse  
43 falling within the reported values should not be seen as a sign of a change in lameness.

44

45 **Introduction**

46 Equine gait analysis and in particular quantitative assessment of gait parameters in lame horses –  
47 e.g. head nod (Buchner et al. 1996) and hip hike (May and Wyn-Jones 1987)– is increasingly  
48 performed with systems based on inertial sensors (Keegan et al. 2004, Marshall et al. 2012,  
49 McCracken et al. 2012, Starke, et al. 2012a, Maliye et al. 2013, Pfau et al. 2014, Rungsri et al. 2014).  
50 These systems are based on wireless technology allowing assessment with minimal infrastructure:  
51 Inertial sensors mounted on the horse and a laptop computer nearby. Increasing numbers of  
52 publications address clinically relevant exercises such as lungeing (Starke et al. 2011, Pfau et al.  
53 2012, Rhodin et al. 2013, Starke et al. 2013, Brocklehurst et al. 2014). In order to avoid  
54 misinterpretations of differences between systems in the framework of evidence based medicine,  
55 e.g. when a horse is referral to a specialist centre, it is essential to quantify the differences between  
56 these two systems. This knowledge is also important for multi-centre research studies when data is  
57 collected with different systems. In the context of inertial sensor based systems, potential sources of  
58 differences could be related to differences in sensor hardware, the filtering and processing  
59 algorithms to derive displacement from the recorded acceleration signals as well as from the  
60 selection of strides.

61 Aim of this study was to quantify the differences between two inertial sensor based gait analysis  
62 systems used in clinical practice and research environments under practically relevant conditions.  
63 Both systems quantify head and pelvic movement symmetry from inertial sensors mounted over the  
64 poll and over the midline of the horse at the level of the tuber sacrale. The first system (System A<sup>1</sup>)  
65 uses two uni-axial accelerometers mounted on head and pelvis and additionally a uni-axial  
66 gyroscope attached to the right forelimb to facilitate identification of stride events. The other  
67 system (System B<sup>2</sup>) uses two inertial sensors each containing one tri-axial accelerometer, one tri-  
68 axial gyroscope, and one tri –axial magnetometer per sensor. System A records movement in the  
69 direction of the uni-axial accelerometer while system B calculates vertical movement. This difference

70 is particularly relevant on the lunge when horses lean into the circle (Pfau et al. 2012, Brocklehurst  
71 et al. 2014) potentially affecting agreement between the two systems.

72 Our objectives were (1) to quantify limits of agreement for movement asymmetry quantified with  
73 the two systems in trot during in-hand assessment on the straight and during lungeing. We  
74 hypothesized, that widths of limits of agreement (Bland and Altman 1986) would be similar to  
75 reported values comparing between system B and optical motion capture (Warner et al. 2010) and  
76 similar to currently proposed thresholds for system A for the lameness exam: 6 mm for head, 3 mm  
77 for pelvic movement asymmetry (McCracken et al. 2012).

## 78 **Materials and Methods**

### 79 Animals and facilities

80 Thirteen horses were recruited from a single riding yard featuring an indoor arena with a sand/fibre  
81 based riding surface and an outdoor area with a hard flat surface suitable for trotting horses. The  
82 horses were used for a variety of equestrian activities (see table S1) and comprised horses perceived  
83 to be sound and well-functioning (i.e. in regular work and in the opinion of their owners not  
84 perceived to have performance issues) as well as horses with a previous history of injury (see table  
85 S1 for details about horses). The project was approved by the Royal Veterinary College's Ethics and  
86 Welfare Committee.

### 87 Data collection

88 Each horse was simultaneously equipped with two inertial sensor based gait analysis systems.  
89 System A<sup>1</sup> comprised of three uni-axial inertial sensors: one uni-axial gyroscope attached to the right  
90 forelimb pastern region facilitating stride segmentation and two uni-axial accelerometers mounted  
91 over poll and over the midline of the horse at the level of the tuber sacrale to quantify head and

92 pelvis movement symmetry. Uni-axial acceleration (dorso-ventral) was recorded at 200 Hz with 8 bit  
93 digital resolution and over a range of +/-6 times gravitational acceleration (Keegan et al. 2011).  
94 System B<sup>2</sup> comprised two six degree of freedom-inertial sensors (Pfau et al. 2005, Warner et al.  
95 2010), one mounted over the poll and one over the midline of the horse at the level of the tuber  
96 sacrale; both sensors attached immediately behind the corresponding sensor of system A. Sensor  
97 data of each of the nine channels (3x acceleration: range +/-18 times gravitational acceleration, 3x  
98 angular velocity: range +/-1200 degree/s, 3x magnetic field: range +/-750mGauss) were recorded at  
99 100 Hz and with 16 bit resolution. Data of both systems were transmitted wirelessly from the horse  
100 to a nearby laptop computer running the corresponding proprietary data collection software.  
101 Horses were trotted in-hand and while being lunged on a soft equestrian sand/fibre based surface in  
102 an indoor riding arena. Lungeing was performed in both directions with a circle radius of  
103 approximately 5-7 m. Multiple lungeing trials were acquired for most horses in order to capture  
104 stretches of data encompassing steady state locomotion (horse moving at consistent speed and  
105 circle radius; judged subjectively). Data collection was manually started and stopped at  
106 approximately the same time for the two inertial sensor systems. Data collection was continued until  
107 at least 25 strides of steady state locomotion – judged subjectively by the experimenters at the time  
108 of data collection – were available for each of the exercise conditions.

#### 109 Data processing

110 Data were processed with the corresponding software packages for each system. For both systems  
111 this procedure comprised filtering, stride segmentation and double integration from acceleration to  
112 displacement (Keegan et al. 2001, Keegan et al. 2004, Pfau et al. 2005, Warner et al. 2010, Starke, et  
113 al. 2012b). Sensor based (System A) or vertical (System B) displacement values calculated over each  
114 stride cycle were then used to determine movement symmetry for each stride cycle. Movement  
115 symmetry was characterized in both systems by calculating the differences in minimum and

116 maximum head and pelvic displacement that occurs during and after stance of right and left halves  
117 of each full stride cycle (HDmin, HDmax, PDmin, PDmax, (Kramer et al. 2004, Keegan et al. 2011), or  
118 MinDiff, MaxDiff, (Starke et al. 2011)). For each horse a mean value for all strides was calculated for  
119 each exercise condition (i.e. for each trial representing one of the exercise conditions, trot in straight  
120 line or on left or right rein). Prior to further statistical analysis values for HDmax and PDmin for  
121 system A were multiplied by -1 to match the sign convention of system B: positive values for MinDiff  
122 for left hind and right forelimb lameness and for MaxDiff for right hind and left forelimb lameness,  
123 negative values for the MinDiff for right hind and left forelimb lameness and for MaxDiff for left hind  
124 and right forelimb lameness.

#### 125 Data analysis

126 Head and pelvic movement symmetry measures were compared between the systems based on  
127 procedures described previously for method comparison studies (Bland and Altman 1986). Averages  
128 of and differences between the mean symmetry values quantified for the two systems were  
129 calculated for each trial. Evaluation of scatter plots of the difference values over the mean values  
130 (Bland and Altman, 1986) showed that differences between the two systems were systematically  
131 affected by the measurement value: increasingly negative differences with increasing mean value. As  
132 a consequence a published regression method (Bland and Altman 1999) was employed to take into  
133 account this systematic difference when establishing widths of limits of agreement values for each  
134 symmetry measure. In brief, rather than calculating limits of agreement that are constant over the  
135 range of measurements (Bland and Altman, 1986), non-constant estimates of mean difference and  
136 upper and lower limits of agreement are calculated based on regression (Bland and Altman, 1999). In  
137 order to facilitate calculation of matched movement symmetry values for the two systems, taking  
138 into account the identified systematic differences between the two systems, we also fitted linear  
139 regression lines to scatter plots of system A values versus system B values and present slope and  
140 intercept of these.

141 **Results**

142 A total of 81 trials were successfully recorded for 12 out of the 13 horses providing mean movement  
143 symmetry values for >25 strides per trial for both systems. Operator error during data collection  
144 prevented use of the data of one horse for further analysis.

145 Limits of agreement

146 Figure 1 illustrates the limits of agreement established by the regression method (Bland and Altman  
147 1999) showing both the mean difference between the two systems and the upper and lower limit of  
148 agreement (mean difference  $\pm$  2 SD of differences) over the range of observed movement  
149 symmetry measures for each parameter. All four show a systematic difference between the systems,  
150 indicating a decrease in difference with increasing symmetry value. Width of limits of agreement  
151 values (difference between upper and lower limit) are smaller for the pelvic measures (3-5mm, Table  
152 1, 'all') than for the head symmetry measures (7-9 mm, Table 1, 'all').

153 Differences between straight line and lungeing

154 In order to establish whether agreement was different for straight line and lungeing, we analysed  
155 the widths of limits of agreement values separately for the straight-line and for the lungeing trials.  
156 This is illustrated in Figure 1 with different colors (blue: lunge; red: in-hand). As a consequence of the  
157 systematic differences the widths of the limits of agreement varied as a function of the measured  
158 value, i.e. the lines illustrating upper and lower limit in figure 1 are not parallel to the x-axis. In order  
159 to present one representative value for the agreement per condition an average value for the  
160 widths of limits of agreement was calculated over a range of symmetry values from -20 mm to +  
161 20mm; this range covers more than 95% of the movement symmetry values measured in this study.  
162 Table 1 shows that the widths of limits of agreement vary between  $\pm$ 2.5 mm (PDmax, straight line)  
163 and  $\pm$ 9.7mm (HDmax, lungeing) with smaller values for pelvic movement ( $\pm$ 2.5mm to  $\pm$ 5.3mm)  
164 than for head movement ( $\pm$ 6.4mm to  $\pm$ 9.7mm). Average limits of  $\pm$  6.2mm were quantified



165 across all four measures for the combined data set, of +/- 6.5mm for lungeing and +/- 5.1mm for  
166 straight line trials. Finally, table 2 presents slope and intercept values for linear regression lines fitted  
167 to scatter plots of system A versus system B values. The presented values allow calculation of system  
168 B values from system A values.

## 169 **Discussion**

170 Here we have compared two commonly used inertial sensor based equine gait analysis systems that  
171 quantify head and pelvic movement symmetry and we established limits of agreement after  
172 correcting for systematic differences between the systems (Bland and Altman 1986, Bland and  
173 Altman 1999).

174 A 'worst case scenario' study design was chosen to reflect the practical scenario we have in mind: a  
175 horse gets transferred between veterinarians, e.g. from first opinion practice using one system to a  
176 specialist referral centre using the other system. The question is then when comparing movement  
177 symmetry values whether the horse shows an improvement, a worsening or no change.

178 Synchronization between the systems was hence implemented by recording approximately the same  
179 series of strides with each system by starting and stopping the recording simultaneously (no  
180 hardware synchronization) since in the above scenario, no information about the selected strides  
181 will be available. With this 'worst case scenario' approach we have— in our opinion — achieved  
182 promising results.

183 Studying the scatter plots in Figure 1 (Bland and Altman 1986) and slope values presented in table 2  
184 between system A and system B values it becomes apparent that system A consistently  
185 underestimates the amount of movement asymmetry compared to system B: decreasing differences  
186 with increasing asymmetry values. System B has been shown previously to marginally overestimate  
187 displacement compared to an optical motion capture system by 0.7 to 2% ((Warner et al. 2010),  
188 table 1). Here, the slopes of the regression lines of figure 1 as well as the slope values found in table

189 2 suggest that system B overestimates asymmetry by considerably more than 2% compared to  
190 system A. As a consequence, system A would underestimate the 'true' amount of asymmetry were it  
191 to be compared to motion capture.

192 By using the suggested regression method (Bland and Altman 1999) it was possible to take into  
193 account the systematic differences between the two systems and to establish average width of limits  
194 of agreement values across a range of movement symmetry values. We chose to calculate the  
195 widths of limits of agreement over a range of symmetry value from -20mm to +20mm hence  
196 including over 95% of the values presented here during trot in-hand and on the lunge for a range of  
197 horses with/without history of musculoskeletal problems (table S1).

198 By comparing the widths of limits of agreement (the 95% confidence interval) to threshold values  
199 used in the context of the clinical lameness exam (McCracken et al. 2012), it is possible to make a  
200 judgement about the interchangeability of measurements for the task of classifying horses into  
201 'sound' and 'lame'. If the disagreement is higher than the thresholds, then a classification into sound  
202 and lame will statistically result in discrepancies in more than 5% of cases. In a study with system A,  
203 thresholds of 6 mm for HDmin or HDmax and 3 mm for PDmin or PDmax have been presented  
204 (McCracken et al. 2012). The widths of limits of agreement values of +/-8.8 mm and +/-7.2 mm for  
205 HDmax and HDmin and of +/-3.4 mm and +/-5.2 mm for PDmax and PDmin observed across all  
206 exercise conditions (Table 1) suggest that the limit of agreement values are equivalent (PDmax) or  
207 marginally outside (all others) these threshold values. However the widths of limits of agreement  
208 values on the straight (Table 1) are with +/-6.9 mm and +/-6.4 mm for HDmax and HDmin and +/-2.5  
209 mm and +/-4.4 mm for PDmax and PDmin closer (HDmax, HDmin, PDmin) or even marginally below  
210 (PDmax) these thresholds and it should be emphasized that the thresholds (McCracken et al. 2012)  
211 have been defined based on straight line trot.

212 The widths of limits of agreement values are also similar (slightly larger for head movement and  
213 slightly smaller for pelvic movement) to the values presented previously for a comparison between

214 system B and an optical motion capture system ( $\pm 4$  and  $\pm 8$ mm, (Warner et al. 2010)). The two  
215 inertial sensor systems hence agree similarly well than system B with the optical system. This seems  
216 interesting to note since – in contrast to the earlier study (Warner et al. 2010) where exact  
217 synchronization between inertial sensors and motion capture was performed – here with our  
218 practical ‘worst case scenario’ approach we made use of the automated stride selection provided by  
219 the different inertial sensor software packages. The influence of exact time synchronization when  
220 comparing between different inertial sensor systems should be further investigated.

221 An additional source of ‘mismatch’ between the two systems is the physical location; here we placed  
222 system B sensors directly behind the corresponding system A sensor (approximately 0.05m between  
223 sensors). Only limited variation has been documented from inertial sensor measurements placed  
224 along the spine (Warner et al, 2010) with inter-sensor distances of approximately 0.15 to 0.2m.  
225 Abaxial misplacement of motion capture markers (Starke et al, 2012c) has been shown to have more  
226 influence on movement symmetry measurements (up to 11mm when misplaced by 0.07m; typical  
227 inter- and intra-operator variation in marker placement has been reported to be considerably less  
228 than 0.07m (Weller et al, 2006)). Care should hence be taken to place sensors in the midline of the  
229 horse since the sensing elements (in particular relevant here accelerometers, gyroscopes) may not  
230 be in the centre of the physical sensor housing.

231 The horses used in this study varied in breed, age, sex, use and presence/history of musculoskeletal  
232 problems (see table S1). In the context of the study design employed here – comparing two gait  
233 analysis systems simultaneously mounted on the same horse – the variability between horses is not  
234 a disadvantage since comparisons are made within horses. On the contrary, if all horses had been  
235 completely sound, i.e. showing symmetrical movement on the straight and only small asymmetries  
236 on the lunge (see e.g. (Starke et al. 2011, Pfau et al. 2012)), then the comparison between the  
237 systems would likely have covered a much smaller range of values (x-axis in Figure 1). Estimates of  
238 the limits of agreement would then only have been applicable for the small range of values observed

239 in sound horses. Here average values of movement symmetry measures between the two systems  
240 cover a range of approximately +/-25 mm for head movement and of up to +/-15mm for pelvic  
241 movement (x-axis, Figure 1). This is similar to what has been reported previously for similar lungeing  
242 conditions (Pfau et al. 2012) and we have used a similar range of +/-20 mm to calculate widths of  
243 limits of agreement from the regression approach, which covers more than 95% of the symmetry  
244 values in this study.

## 245 **Conclusions**

246 After regression based correction for systematic differences between the two systems, the widths of  
247 limits of agreement values for comparison of straight line trials are within or marginally outside  
248 currently proposed thresholds of detecting lameness in horses (6mm for head movement, 3mm for  
249 pelvic movement). Differences in measurements between the two systems obtained from the same  
250 horse that fall within the widths of limits of agreement values reported here should not be seen as a  
251 sign of a change in movement symmetry in this horse. These are +/-6.9 mm and +/-6.4 mm for  
252 HDmax and HDmin and +/-2.5 mm and +/-4.4 mm for PDmax and PDmin on the straight. On the  
253 lunge these are +/-9.7mm and +/-7.3mm for HDmax and HDmin or +/-3.6mm and +/-5.3mm for  
254 PDmax and PDmin.

## 255 **Manufacturers' addresses**

256 <sup>1</sup>LamenessLocator, Equinosis, LLC, Columbia, Missouri, United States of America

257 <sup>2</sup>MTx, Xbus system, Xsens Technologies B.V., Enschede, The Netherlands

258

## 259 **References**

260 Bland, J.M., Altman, D.G. (1986) Statistical methods for assessing agreement between two methods  
261 of clinical measurement. *Lancet* **1**, 307–10

- 262 Bland, J.M., Altman, D.G. (1999) Measuring agreement in method comparison studies. *Stat Methods*  
263 *Med Res* **8**, 135–160
- 264 Brocklehurst, C., Weller, R., Pfau, T. (2014) Effect of turn direction on body lean angle in the horse in  
265 trot and canter. *Vet. J.* **199**, 258–262
- 266 Buchner, H.H., Savelberg, H.H., Schamhardt, H.C., Barneveld, a (1996) Head and trunk movement  
267 adaptations in horses with experimentally induced fore- or hindlimb lameness. *Equine Vet. J.* **28**, 71–  
268 76
- 269 Keegan, K.G., Kramer, J., Yonezawa, Y., Maki, H., Pai, P.F., Dent, E. V, Kellerman, T.E., Wilson, D.A.,  
270 Reed, S.K. (2011) Assessment of repeatability of a wireless inertial sensor-based lameness evaluation  
271 system for horses. **72**, 1156–1163
- 272 Keegan, K.G., Pai, P.F., Wilson, D.A., Smith, B.K. (2001) Signal decomposition method of evaluating  
273 head movement to measure induced forelimb lameness in horses trotting on a treadmill. *Equine Vet.*  
274 *J.* **33**, 446–451
- 275 Keegan, K.G., Yonezawa, Y., Pai, P.F., Wilson, D. a, Kramer, J. (2004) Evaluation of a sensor-based  
276 system of motion analysis for detection and quantification of forelimb and hind limb lameness in  
277 horses. *Am. J. Vet. Res.* **65**, 665–670
- 278 Kramer, J., Keegan, K.G., Kelmer, G., Wilson, D.A. (2004) Objective determination of pelvic  
279 movement during hind limb lameness and pelvic height differences. *Am. J. Vet. Res.* **65**, 741–747
- 280 Maliye, S., Voute, L., Lund, D., Marshall, J.F. (2013) An inertial sensor-based system can objectively  
281 assess diagnostic anaesthesia of the equine foot. *Equine Vet. J.* **45**, 26–30
- 282 Marshall, J.F., Lund, D.G., Voute, L.C. (2012) Use of a wireless , inertial sensor-based system to  
283 objectively evaluate flexion tests in the horse. *Equine Vet. J.* **44**, 8–11
- 284 May, S.A., Wyn-Jones, G. (1987) Identification of hindleg lameness. *Equine Vet. J.* **19**, 185–188
- 285 McCracken, M.J., Kramer, J., Keegan, K.G., Lopes, M., Wilson, D.A., Reed, S.K., LaCarrubba, A., Rasch,  
286 M. (2012) Comparison of an inertial sensor system of lameness quantification with subjective  
287 lameness evaluation. *Equine Vet. J.* **44**, 652–656
- 288 Pfau, T., Spicer-Jenkins, C., Smith, R.K., Bolt, D.M., Fiske-Jackson, A., Witte, T.H. (2014) Identifying  
289 optimal parameters for quantification of changes in pelvic movement symmetry as a response to  
290 diagnostic analgesia in the hindlimbs of horses. *Equine Vet. J.* **46**, 759-763
- 291 Pfau, T., Stubbs, N.C., Kaiser, L.J., Brown, L.E.A., Clayton, H.M. (2012) Effect of trotting speed and  
292 circle radius on movement symmetry in horses during lunging on a soft surface. *Am. J. Vet. Res.* **73**,  
293 1890–1899
- 294 Pfau, T., Witte, T.H., Wilson, A.M. (2005) A method for deriving displacement data during cyclical  
295 movement using an inertial sensor. *J. Exp. Biol.* **208**, 2503–2514
- 296 Rhodin, M., Pfau, T., Roepstorff, L., Egenvall, A. (2013) Effect of lungeing on head and pelvic  
297 movement asymmetry in horses with induced lameness. *Vet. J.* **198**, e39–45

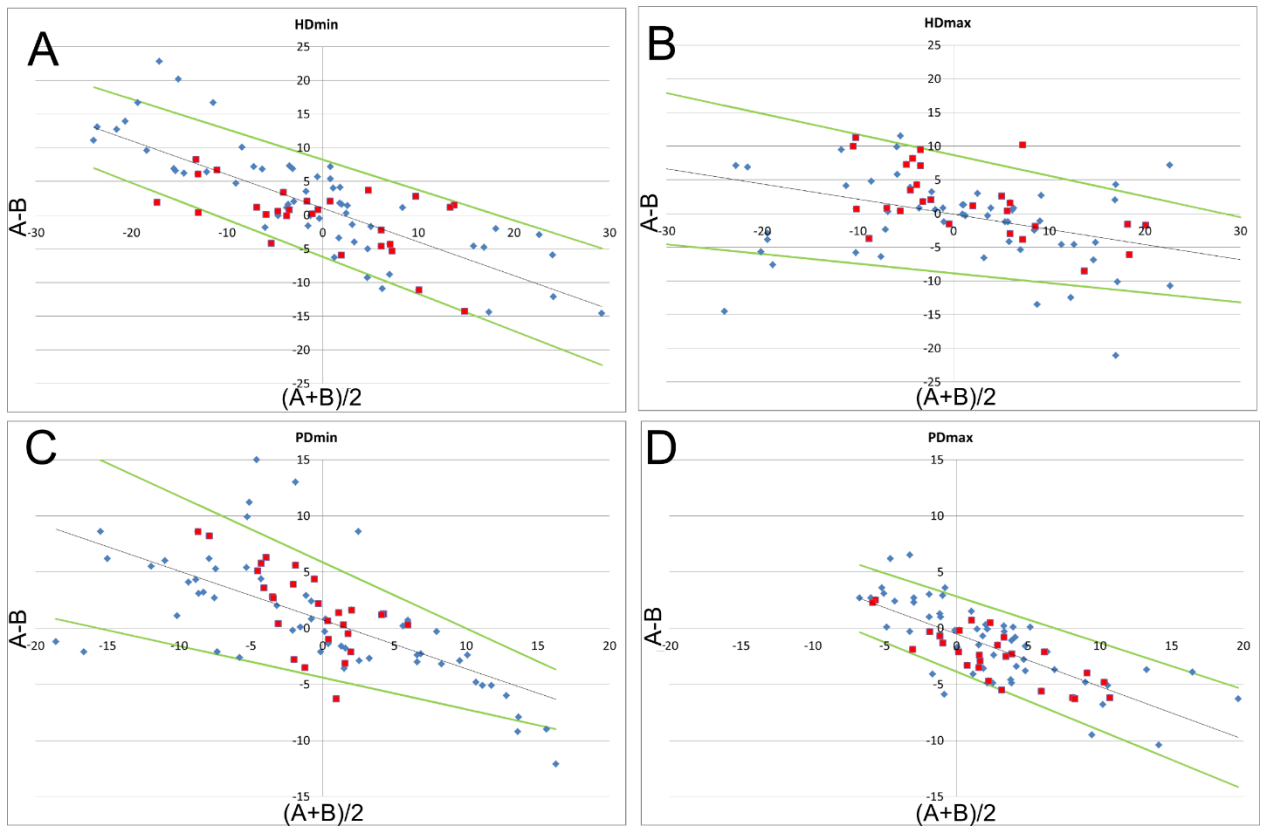
- 298 Rungsri, P.K., Staecker, W., Leelamankong, P., Estrada, R.J., Schulze, T., Lischer, C.J. (2014) Use of  
299 Body-Mounted Inertial Sensors to Objectively Evaluate the Response to Perineural Analgesia of the  
300 Distal Limb and Intra-articular Analgesia of the Distal Interphalangeal Joint in Horses With Forelimb  
301 Lameness. *J. Equine Vet. Sci.* **34**, 972–977
- 302 Starke, S.D., Raistrick, K.J., May, S.A., Pfau, T. (2013) The effect of trotting speed on the evaluation of  
303 subtle lameness in horses. *Vet. J.* **197**, 245-252
- 304 Starke, S.D., Willems, E., Head, M., May, S.A., Pfau, T. (2012a) Proximal hindlimb flexion in the horse:  
305 effect on movement symmetry and implications for defining soundness. *Equine Vet. J.* **44**, 657–663
- 306 Starke, S.D., Witte, T.H., May, S.A., Pfau, T. (2012b) Accuracy and precision of hind limb foot contact  
307 timings of horses determined using a pelvis-mounted inertial measurement unit. *J. Biomech.* **45**,  
308 1522–1528
- 309 Starke, S.D., McDonald, J., May, S.A., Pfau, T. (2012c) Effect of inaccurate equipment placement on  
310 displacement trajectories and asymmetry features in horses at walk and trot. 7th International  
311 Conference on Canine and Equine Locomotion (ICEL 7), Stroemsholm, Sweden. Starke, S.D., Willems,  
312 E., May, S.A., Pfau, T. (2011) Vertical head and trunk movement adaptations of sound horses trotting  
313 in a circle on a hard surface. *Vet. J.* **193**, 73–80
- 314 Warner, S.M., Koch, T.O., Pfau, T. (2010) Inertial sensors for assessment of back movement in horses  
315 during locomotion over ground. *Equine Vet. J.* **42 Suppl 3**, 417–24
- 316 Weller, R., Pfau, T. Babbage, D., Brittin, E., May, S. A., Wilson, A.M. (2006) Reliability of  
317 conformational measurements in the horse using a three-dimensional motion analysis system,  
318 *Equine Vet J*, **38**, 610-615

319 **Supplementary Information Items**

320 **Table S1:** Information about horses participating in study.

321

322 **Figure legends**



323

324 **Figure 1:** Difference between system A and system B symmetry measures (A-B, y-axis) as a function  
325 of average value of both systems ((A+B)/2, x-axis) for each of the 81 trials (red: straight line trials;  
326 blue: lungeing trials) from the 12 horses for which data was successfully recorded. The widths of the  
327 limits of agreement are illustrated by the green lines including  $\pm 2$  SD of difference values over the  
328 range of observed movement symmetry values.

329 A: difference in head movement minima (HDmin), B: difference in head movement maxima  
330 (HDmax), C: difference in pelvic movement minima (PDmin), D: difference in pelvic movement  
331 maxima (PDmax).

332

333 **Tables:**

334 **Table 1:** Width of limits of agreement ( $\pm 2 \times \text{SD}$  of differences) established as an average across the  
 335 range of -20 mm to +20 mm for average values between system A and B measurements (x-axis in  
 336 Figure 1) for all four symmetry measures for data from all trials, for straight-line trials and for  
 337 lungeing trials. For all four symmetry measures the widths of the limits of agreement are narrower  
 338 for straight-line trot than for lungeing. The difference between the widths of the limits of agreement  
 339 of straight line and lungeing is also given (lunge-straight). All values are given in mm.

	All	lunge	straight	lunge-straight
<b>HDmax</b>	+/- 8.8	+/- 9.7	+/- 6.9	2.8
<b>HDmin</b>	+/- 7.2	+/- 7.3	+/- 6.4	0.9
<b>PDmax</b>	+/- 3.4	+/- 3.6	+/- 2.5	1.1
<b>PDmin</b>	+/- 5.2	+/- 5.3	+/- 4.4	0.9
<b>average</b>	+/- 6.2	+/- 6.5	+/- 5.1	1.5

340

341 **Table 2:** Slope (a) and intercept (b) values of the regression equations for calculation of system B  
 342 movement symmetry values (y) based on system A movement symmetry values (x) for straight line  
 343 ('in-hand') and lunge trials.

344 Equation used:  $y = a \cdot x + b$  based on sign convention for system B (see materials and methods for  
 345 details).

symmetry measure	straight		lunge	
	slope a	intercept b	slope a	intercept b
<b>HDmin</b>	1.2204	0.4118	1.5761	-2.3685
<b>HDmax</b>	1.2126	2.3728	1.0968	-1.4187
<b>PDmin</b>	1.2218	1.7242	1.3175	0.5894
<b>PDmax</b>	1.4545	1.8118	1.4245	0.5359

346