

Central Lancashire Online Knowledge (CLoK)

Title	Rider skill affects time and frequency domain postural variables when performing shoulder-in
Type	Article
URL	https://clock.uclan.ac.uk/id/eprint/39947/
DOI	https://doi.org/10.1016/j.jevs.2021.103805
Date	2021
Citation	Baxter, Joanna, Hobbs, Sarah Jane, Alexander, Jill, St George, Lindsay Blair, Sinclair, Jonathan Kenneth, Chohan, Ambreen and Clayton, Hilary M. (2021) Rider skill affects time and frequency domain postural variables when performing shoulder-in. <i>Journal of Equine Veterinary Science</i> . ISSN 0737-0806
Creators	Baxter, Joanna, Hobbs, Sarah Jane, Alexander, Jill, St George, Lindsay Blair, Sinclair, Jonathan Kenneth, Chohan, Ambreen and Clayton, Hilary M.

It is advisable to refer to the publisher's version if you intend to cite from the work.
<https://doi.org/10.1016/j.jevs.2021.103805>

For information about Research at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLoK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the <http://clock.uclan.ac.uk/policies/>

1 **Rider skill affects time and frequency domain postural variables when performing shoulder-in**

2 Joanna Baxter¹, Sarah Jane Hobbs^{2*}, Jill Alexander², Lindsay St George², Jonathan Sinclair², Ambreen
3 Chohan², Hilary M. Clayton³,

4 1 Land based Department, Craven College, Gargrave Road, Skipton, BD23 1US, UK.

5 2 Research Centre for Applied Sport, Physical Activity and Performance, University of Central Lancashire,
6 Preston, PR1 2HE, UK.

7 3 Sport Horse Sciences, 3145 Sandhill Road, Mason, MI 48854, USA.

8

9 * Corresponding author

10

11 **ABSTRACT**

12

13 In equestrian sports the novice rider learns first to follow the movements of the horse's back and then how to
14 influence the horse's performance. One of the rider's challenges is to overcome inherent horse/rider asymmetry
15 patterns when riding in straight lines, mirroring the movements on the left and right sides when turning. This
16 study compares the performance of novice and advanced riders when riding in sitting trot on straight lines and
17 when riding shoulder-in to the left and right sides. Eight novice and eight advanced horse-rider combinations
18 performed sitting trot in a straight line, shoulder-in left and shoulder-in right while wearing a full body set of
19 inertial sensors. An experienced dressage judge indicated when the movements were being performed correctly
20 and assigned scores on a scale of 0-10 for the quality of performance. Kinematic data from the inertial sensors
21 were analysed in time and frequency domain. Comparisons were made between trotting on the straight,
22 shoulder-in left and shoulder-in right. Advanced riders received higher dressage scores on all three movements,
23 but significantly ($p<0.05$) lower scores were found for shoulder-in right across the two groups. When riding
24 shoulder-in, advanced riders had greater hip extension (advanced= -5.8 ± 17.7 ; novice= 7.8 ± 8.9 degrees) and
25 external rotation (advanced= -32.4 ± 15.5 ; novice= -10.8 ± 13.2 degrees) in the outside leg compared with novices
26 ($p<0.05$) and reflects an important cue in achieving the required body rotation in the horse. Lower scores for
27 shoulder-in right may be linked to significant ($p<0.05$) changes in harmonics of trunk to pelvis rotation.

28

29 **Key words:** Horse riding, dressage, asymmetry, shoulder-in, posture, rider performance.

30

31

32

33

34

35

36

37

38 **1.0 INTRODUCTION**

39 Within the discipline of dressage, the rider's position and correct application of the cues applied by
40 the legs, hands and seat aids are the basis for communicating with the horse to achieve and maintain
41 optimal performance (Hobbs et al, 2020). The classical riding position for dressage dates to Xenophon
42 430-354 BC (Podhajsky, 1994), with modern literature stating that riders must maintain their seat
43 over the horse's centre of gravity to develop and maintain horse-rider harmony (Mrozkowiak and
44 Ambroży, 2014; Auty, 2007). In dressage, rider performance is largely determined by the ability to
45 influence the horse's performance (Hobbs et al, 2020; Fédération Equestre Internationale (FEI) 2020)
46 which is the focus of scoring criteria for a dressage test. Signals or "aids" from the rider pass
47 information to the horse. An imbalanced riding posture can lead to incorrect application and/or timing
48 of the hand, leg and/or seat aids, which confuses the horse (Podhajsky, 1994; McClean and
49 McGreevy, 2010), and can, therefore, negatively impact horse-rider performance.

50

51 To date, rider and horse-rider performance in dressage has been studied mostly during sitting trot.
52 Trot is a symmetrical gait, characterised by its two-beat, diagonally coordinated rhythm, which results
53 in alternate support and suspension phases (Hobbs et al, 2016). When trotting in a straight line, rider
54 symmetry is required to ensure minimal disruption to the horse and to provide optimal synchronicity
55 (Byström et al, 2015; Engell et al, 2016). Rider skill is also differentiated in sitting trot by enhanced
56 dynamic postural control of the trunk and pelvis during the large vertical and longitudinal variations
57 in accelerations and decelerations of the horse (Byström et al, 2015). A recent scoping review (Hobbs
58 et al, 2020) acknowledged the need for further investigation into rider skills, and their effects on
59 performance in the horse, particularly during lateral movements. Shoulder-in is a lateral exercise that
60 is considered valuable to trainers and riders, as it assists with suppleness, collection and straightness,
61 thereby improving the horse's performance (Mendonça et al, 2020). It is also a required lateral
62 movement in dressage tests of an intermediate or advanced level of difficulty. Shoulder-in is ridden
63 in left and right directions and is often performed in sitting trot, and requires the rider to mirror the
64 leg, hand and seat aids when performing to the left and right sides (see Figure 1). The aids for
65 shoulder-in refer to the inside/outside hand and leg in accordance with the concave/convex sides of
66 the horse. The rider's pelvis remains parallel with the horse's haunches while the rider's trunk, head
67 and arms turn towards the inside, so the outside rein lies against the horse's neck. The rider's inside
68 leg remains in position close to the girth and applies pressure. The combination of inside leg pressure
69 and outside rein tension moves the horse sideways along the track. The rider's outside leg is retracted
70 from the hip and lies against the horse's ribcage where it can apply pressure, if necessary, to prevent
71 the haunches from swinging to the outside Kyrklund and Lemkow (1998).

72 During a dressage test, horse and rider performance are judged during the execution of movements
73 in both directions (FEI, 2020), so horse and/or rider lateral preference and/or an asymmetric posture

74 may lead to different scores in the two directions. The effect of asymmetry on human performance
75 has been investigated in other sports. For example, Li and Sanders (2005) have shown that
76 symmetrical strokes improve efficiency and therefore enhance performance in swimming. A recent
77 systematic review highlighted that asymmetry, across a range of physical qualities including inter-
78 limb differences, may have detrimental effects on sports performance (Bishop et al, 2017). Research
79 to date on rider symmetry within horse riding has found that anatomical and functional asymmetry
80 may differ between rider ability/experience levels and that riding may exacerbate rather than improve
81 asymmetry (Hobbs et al, 2014). During riding, greater right shoulder displacement associated with
82 preferred left axial shoulder rotation was found by Symes and Ellis (2009) in all gaits except right
83 canter. Evidence of laterality of both the horse and rider has been found within a right-handed
84 population, where the rein tension of the rider was different between left and right sides, with less
85 tension and range in the left rein (Kuhnke et al., 2010). Asymmetry in the rider may also influence
86 movement symmetry in the horse (MacKechnie-Guire et al., 2020), but equally asymmetric sport
87 horses are commonly found within the population (Greve and Dyson, 2014; Gunst et al., 2019).
88 Asymmetry may become more pronounced with the increased complexity of the aids required to
89 execute more advanced movements, like shoulder-in, which again may be detrimental for dressage
90 performance. One study (De Cocq et al, 2010a) has investigated leg and saddle forces in dressage
91 riders executing lateral movements. They found an increase in saddle and outside leg force when
92 performing shoulder-in and travers compared to straight trot, but left and right directions were
93 grouped in the analysis limiting their ability to investigate symmetry. As functional asymmetry is
94 known to vary between and within riders when studying the time domain (for example see, Alexander
95 et al., 2015), there may be advantages in studying asymmetry in the frequency domain. This type of
96 analysis was proposed by Peham et al. (1996) for studying asymmetry due to lameness in horses, and
97 further exploration of the harmonics of the frequency spectrum were used to investigate the
98 smoothness of human walking by Menz et al. (2003).

99
100 Previous studies that have quantified rider posture and/or harmony have typically used inertial
101 measurement unit (IMU) or motion capture technology to calculate phasic rider-horse movement
102 (Münz et al, 2014; Baillet et al, 2017) or rider synchronicity specific to gaits (Peham et al, 2001;
103 Wolframm et al, 2013; Byström et al, 2015). Motion capture studies have often utilised treadmill or
104 mechanical horse methods (Byström et al, 2015) to collect multiple strides, however fewer have
105 employed ridden tests during over ground locomotion; predominantly due to the camera configuration
106 necessary to obtain a calibration volume large enough to capture multiple strides from a moving horse
107 and rider. Studies investigating phasic relationships have successfully evidenced differences between
108 novice and advanced levels of rider (Lagarde et al, 2005; Peham et al, 2001). Postural studies have

109 identified more upright postures in advanced riders compared to novice or inexperienced riders, and
110 differences in joint angles that relate to skilled rider characteristics (Schils et al, 1993; Lovett et al,
111 2005; Kang et al, 2010; Eckardt and Witte, 2017; 2016; Hobbs et al, 2020). Despite this, further
112 research is required to quantify the impact of the rider on horse performance and dressage scores
113 during over ground lateral movements.

114

115 The aims of this study were to compare rider posture in the time and frequency domain between i)
116 straight-line trot and lateral (shoulder-in) movements, and ii) advanced and novice riders. It was
117 hypothesized that significant differences in rider posture will be found between rider level (novice
118 and advanced) and between shoulder-in (left and right).

119

120 **2.0 METHODS**

121 *2.1 Participants and Horses*

122 Ethical approval was obtained from the host university (MScSp&ExSci2011/JB). Prior to the study,
123 riders were fully informed of the requirements, benefits, risks and procedures involved. Written
124 informed consent was provided by all riders/horse owners prior to study inclusion. Riders completed
125 a short questionnaire on their rider experience, previous injuries, handedness and information on their
126 horse including level of training. None of the riders had been injured or were receiving treatment for
127 injury in the year prior to collection. A total of 20 riders volunteered to participate and they were
128 grouped into novice and advanced categories, based on their highest level of competition experience.
129 Advanced riders were considered to be those who regularly perform shoulder-in in competition.
130 Novice riders (n=10; Age: 28 ± 12 years; sex: male n=2, female n=8; Height: 168 ± 7 cm; Mass:
131 65 ± 10 kg) were competing at Open Novice to Elementary level (British Dressage Rider Groups 6-7)
132 at the time of the study. Advanced level riders (n=10; Age: 29 ± 6 years; sex: female n=10, Height:
133 163 ± 7 cm; Mass: 67 ± 6 kg) were competing in medium to advanced (British Dressage Rider Groups
134 2-5) at the time of the study.

135

136 The novice group rode one of three “schoolmaster” type horses (Age: 17 ± 2 years;
137 Height: 165 ± 3 cm Gender: mares n=2, gelding n=1; Breed: Thoroughbred n=1, Warmblood n=2), that
138 were deemed sound by their owners. Horses were selected based on their previous level of training
139 and competition experience (Elementary = 1; Medium = 2). An experienced rider (British Horse
140 Society Level 4 Coach, British Dressage Group 5 rider) trained these horses over a four-week period,
141 prior to the commencement of the study. The advanced group rode their own competition horses,
142 allowing varying levels of trained horses (Age = 12 ± 2 years; Height = 167 ± 5 cm; Gender = mare x1,
143 geldings x8, stallion x1; Breed = British Sports x1, Andalusian x1, Warmblood x7, Welsh Section D

144 Cross x1). All horses were ridden in their normal dressage saddle and bridle, equipped with a snaffle
145 bit (Novice Group n = 10, Advanced Group n = 8), or double bridle (Advanced Group n = 2).

146

147 *2.2 Equipment*

148 An MVN Biomech full body IMU system from XsensTM (Netherlands) was used to measure
149 three-dimensional movement from riders during the ridden test on the horse following previous
150 published protocols (Munz et al, 2013). This system can be used in varying light conditions and
151 allowed riders to mount and execute normal riding posture without interference from the sensors.
152 The system includes a full-body suit, equipped with IMU sensors that provide six-degree-of-freedom
153 tracking. Orientation and position of body segments were calculated by integration of the gyroscope
154 and accelerometer data (Roetenberg et al., 2013). Data were recorded during the motion trials at 120
155 Hz. To mitigate integration drift, additional global positioning sensors (magnetometers) are
156 incorporated into the sensor system, which, together with constant feedback from the kinematic
157 model, update and correct the position and orientation of the segments on a frame-by-frame basis
158 (Roetenberg et al., 2013).

159

160 *2.3 Procedures*

161 Riders wore normal riding breeches, boots and a tight-fitting top to ensure secure application
162 of the sensors. A belt was used to hold the system battery packs in place and additional tape was
163 placed around each sensor to limit displacement whilst mounting and riding. Anthropometric
164 measurements were taken from anatomical landmarks and used to develop a model for each rider. A
165 full calibration was performed prior to mounting the horse using the four poses suggested by the
166 manufacturer; neutral pose (N pose), anatomical pose (T pose), squat and hand touch, which
167 determine “sensor to segment” alignments based upon the methods described by Roetenberg et al.
168 (2013).

169

170 Riders mounted the horses using a mounting block, taking care that sensors were kept in place.
171 Prior to data collection, the riders were asked ride the horse in walk for 2-minutes to allow the
172 calibration algorithm to accrue enough data to maintain the relative position of segments within the
173 global coordinate system. Bent leg stirrup irons were used to avoid interference with the foot sensors.
174 Riders were given 15 minutes to familiarise themselves with wearing the sensors and to warm up
175 which included shoulder-in movements. Trials were then recorded during straight line trot (both reins)
176 and shoulder-in movements in the left (left-rein on the inside) and right (right-rein on the inside)
177 direction/reins. The first trial was always straight-line trot, but then subsequent trials were recorded
178 in a random order. All trials were executed in sitting trot along the track and riders were asked to ride

179 at a collected trot and to apply aids to the horse as they would normally when training or competing.
180 Four trials of each condition were recorded whilst the movements were observed and scored by one
181 dressage judge (BHS Stage 4 Senior Coach in Complete Horsemanship, UKCC Level 3, BD list 6
182 judge), in accordance with British Dressage (2020) and FEI (2020) dressage judging guidelines on a
183 scale of 0-10 points. Each trial consisted of three strides, defined visually, using consecutive impacts
184 of the horse's outside hind leg to define gait cycles. The use of coloured bandages aided visual
185 identification of the stride pattern (see Figure 2). During shoulder-in, data acquisition began when
186 the horse moved forwards on three tracks and the movement was deemed to achieve minimum judged
187 score of 6, which is indicative that the performance is satisfactory. If a dressage score of 6 was not
188 reached, the trial was discounted and repeated.

189

190 *2.4 Data Analysis*

191 Motion capture data from standing and dynamic trials were exported into Visual 3D software
192 (C-Motion, USA) for analysis. The static (standing) trial was used to develop a model for each rider,
193 which was applied to all dynamic trials for that participant. Dynamic trials were smoothed with a 4th
194 order Butterworth low pass filter (Robertson and Dowling, 2003) with 6 Hz cut off frequency. Stride
195 segmentation was conducted using maximum vertical displacement of the rider's head segment. This
196 peak-to-peak event detection technique also served to convey the vertical displacement pattern of the
197 horse's trot stride, as depicted by Bystrom et al, (2009) and De Cocq et al, (2010b). Some horse-rider
198 combinations had missing trials due to data quality issues, so the number of trials for each condition
199 varied between horse-rider combinations.

200 Two strides were extracted from each of the available trials for each movement. This provided
201 between two and eight strides (most often four strides) of data for each horse-rider
202 combination/movement for further analysis in the time domain. For frequency domain variables, the
203 first stride from each trial was used in the analysis, so this provided between one and four strides of
204 data (which was most often two strides).

205 Rotations between reconstructed segments were calculated from the dynamic data using an
206 XYZ Cardan sequence, where X=flexion extension, Y=ab-adduction and Z=internal-external (axial)
207 rotation. Time domain variables included mean right and left hip flexion-extension and mean internal-
208 external rotation, trunk to pelvis flexion-extension ROM and mean axial rotation, mean difference
209 between right and left anterior superior iliac spine (ASIS) vertical height (right minus left), mean
210 difference between right and left acromion process vertical height (right minus left) and range of
211 motion (ROM) for left and right knee flexion-extension. The sign conventions for mean posture
212 variables were as follows:

- 213 • flexion and internal rotation positive.

- 214 • trunk to pelvis axial rotation - in the transverse view, right shoulder rotated towards
215 the left side positive (counter-clockwise rotation when looking from above), left
216 shoulder rotated towards the right side negative (clockwise rotation when looking
217 from above).
- 218 • difference in height of ASIS and acromion process -higher on right positive, higher on
219 left negative

220 For frequency domain variables, firstly the magnitude of 3D rotational motion of the trunk
221 relative to the pelvis was calculated from the three rotational components (i.e. X,Y,Z). This variable
222 was used in preference to each orthogonal component, as the frequency of overall 3D motion could
223 be investigated. To calculate the magnitude, firstly, an arbitrary value of 100 degrees was added to
224 all signal components to ensure that all values were positive. The square root of the sum of the squares
225 was calculated and the waveform was centred around zero by subtracting its mean value over the
226 stride cycles. This was calculated for each data point in the time series as shown in Eqn. 1

$$227 \theta_{3D} = \sqrt{((\theta_x + 100)^2 + (\theta_y + 100)^2 + (\theta_z + 100)^2)} - \overline{d\theta_{3D} \text{ 2 strides}} \dots\dots \text{Eqn.1}$$

228 where θ_{3D} is 3D Trunk to Pelvis Rotation, θ_x , θ_y and θ_z are Trunk to Pelvis rotational
229 components, and $\overline{d\theta_{3D} \text{ 2 strides}}$ is the mean value of θ_{3D} over two strides.

230
231 To compare the frequency content of 3D Trunk to Pelvis Rotation between riders, firstly the
232 time of two strides for each trial was determined (range = 1.33-1.74 s). This was converted to a
233 frequency (range = 0.574-0.750Hz) and used as the base frequency in the analysis which provided
234 harmonics related to strides, steps, higher frequency components and inter-stride components.
235 Discrete Fourier Transformation was then used to calculate the harmonic content of each 3D Trunk
236 to Pelvis Rotation waveform for each stride individually.

237 The frequency domain analysis included an analysis of the power spectrum (see Figure 3).
238 From each power spectrum mean frequency and total signal power were calculated. Mean frequency
239 was the integral of the frequency-power curve (or area under the curve) divided by the total signal
240 power. Total signal power was the sum of the amplitudes across the complete power spectrum. A
241 higher mean frequency would indicate that higher frequency components within the signal had a
242 higher amplitude and greater total signal power would suggest that the amplitudes of the frequency
243 components overall were higher. For example, if there was a large amount of trunk pitch at the step
244 frequency in one rider, due to being less stable (Byström et al, 2015) this would increase the mean
245 frequency and total signal power compared to a rider with a stable trunk.

246 The harmonic content of the signal (see Figure 4) was explored further by examining the
247 power content of the even (symmetric) harmonics compared to the odd (asymmetric) harmonics. The

248 even harmonics are the sine components of the signal at each of the frequencies used in the analysis,
 249 the odd components are the cosine components of the signal at each of the frequencies used in the
 250 analysis. .One might expect that when riding sitting trot, 3D trunk to pelvis motion should contain
 251 symmetrical (sine wave) pelvis and trunk motion pitching motion per stride and asymmetrical (cosine
 252 wave) lateral flexion/axial rotation per stride to follow the motion of the horses' trunk (Byström et al
 253 2009). An example from one trial of the harmonic waves from the stride and step frequency
 254 components plotted over time are shown in Figure 5. Other asymmetric harmonics might include
 255 altered rotation between one stride and the next that may be due to a loss of balance or limitations in
 256 following the motion of the horse. Harmonics at higher frequency may also be evident, particularly
 257 with increased stiffness in the rider (Alexander et al., 2015). For this analysis, firstly an overall
 258 harmonic ratio was calculated as the sum of squares of the even harmonics divided by the sum of
 259 squares of the odd harmonics (Menz et al., 2003), as shown in Eqn 2.

260
$$Harmonic Ratio_{stride} = \frac{\sum_{stride} Sin Harmonics^2}{\sum_{stride} Cosine Harmonics^2} \dots\dots\dots Eqn. 2$$

261 As pelvic motion is primarily used in pitch and roll to damp the large accelerations and
 262 decelerations of the horse (Byström et al 2009), which has both symmetric and asymmetric
 263 components, it was anticipated that the harmonic ratio would be close to 1 in more skilled riders.
 264 Riders with greater symmetrical pelvic or trunk pitch might have a higher ratio than 1, whereas riders
 265 with inferior balance may have more asymmetrical harmonics and a ratio less than 1. To explore these
 266 data further, harmonic ratios of the square root of the sum of squares of all trials from each rider/at
 267 each frequency component were calculated up to the step frequency (see Equation 3) and then the
 268 sum of squares of spectral components from 3.195-7.029 Hz were calculated.

269
$$Harmonic Ratio_{frequency} = \frac{\sqrt{\sum_{trials} Sin Harmonics^2}}{\sqrt{\sum_{trials} Cosine Harmonics^2}} \dots\dots\dots Eqn. 3$$

270 The square root of the sum of squares was used to reduce the effect of over inflation of a ratio
 271 due to squared values increasing for harmonics over 1 and decreasing for harmonics below 1.

272

273 *2.5 Statistical Analysis*

274 Descriptive statistics were calculated for time and frequency domain variables and dressage
 275 scores (mean ± standard deviation and/or median, interquartile range) for straight trot. For shoulder-
 276 in left and right, the difference between shoulder-in and straight trot were calculated (shoulder-in
 277 minus straight trot) for the descriptive statistics. Dressage scores were retained as absolute values for
 278 shoulder-in. Data were grouped by side (left and right) and level (novice and advanced). A Shapiro-
 279 Wilk test confirmed normal distributions for each outcome measure. A repeated measures model was
 280 used to determine the effect of side within the riders, with rider level as a between-subjects factor to
 281 assess the interaction between side and level. Independent samples t-tests were used to compare

282 between rider levels for straight trot and shoulder-in. Partial eta squared (η^2) values were calculated
283 to estimate effect sizes for all significant main effects and interactions, and classified as small (0.01–
284 0.059), moderate (0.06-0.137) or large (>0.138) (Cohen, 1988). Non-parametric data were compared
285 using Wilcoxon Signed Rank Test (between left and right shoulder-in) and Mann Whitney U test
286 (between rider level). Harmonic ratios of spectral components between novice and advanced riders
287 and between straight trot and shoulder-in were explored post hoc using the same statistical methods.
288 All statistical procedures were performed in SPSS version 26.0 (IBM SPSS, Chicago USA). Values
289 of $p < 0.05$ were considered significant.

290

291 **3.0 RESULTS**

292 Descriptive statistics for each outcome measure across rider level (novice and advanced) and
293 movements (straight trot and left and right shoulder-in differences to straight trot) are presented in
294 Tables 1 and 2. Two riders were removed from each group prior to data analysis, due to data quality
295 issues, so the results are presented for eight riders in each group. All riders included in the study were
296 right-handed. Non-parametric variables were; in straight trot all frequency domain variables except
297 for higher frequency harmonic ratios, and for shoulder-in data dressage score, stride time and all
298 frequency domain variables except for 3D Trunk to Pelvis Rotation signal power in shoulder-in left
299 and higher frequency domain harmonic ratios in shoulder-in right. No significant main effects from
300 the repeated measures model were found for level ($F(5)=1.099$, $p=0.488$, $\eta^2=0.687$), side ($F(5)=0.959$,
301 $p=0.556$, $\eta^2=0.657$), or the interaction between side and level ($F(5)=2.253$, $p=0.191$, $\eta^2=0.818$) for
302 the variables included in the model. Significant differences ($p < 0.05$) were evident for key variables,
303 as shown in Tables 1 and 2 and described below, and significant interactions ($p < 0.05$) were evident
304 for mean right and left hip flexion-extension and internal-external rotation.

305

306 *3.1 Dressage scores*

307 For straight trot significant differences were found between dressage score (see Table 1), with
308 higher scores for the advanced group ($p < 0.01$). Dressage score was also significantly higher ($p < 0.05$)
309 for the advanced group during shoulder-in movements and significantly higher scores ($p < 0.01$) were
310 found for shoulder-in left compared to shoulder-in right.

311

312 *3.2 Time domain variables*

313 A significantly ($p < 0.05$) smaller trunk to pelvis flexion-extension ROM in shoulder-in left
314 compared to straight trot is evident in the advanced group compared to the novice group (see Table
315 1). In addition, significant ($p < 0.05$) time domain variables between groups and movements are found
316 at the hip joint. In the advanced group in particular, hip mean flexion-extension are mirrored for left

317 and right shoulder-in with greater extension compared to straight trot in the left hip for shoulder-in
318 right and the right hip for shoulder-in left. For shoulder-in right, significantly ($p<0.05$) greater
319 external rotation is found in the left hip and significantly ($p<0.05$) less external rotation in the right
320 hip compared to straight trot in the advanced group. This is mirrored for shoulder-in left but was only
321 significant for the right hip.

322

323 *3.3 Frequency domain variables*

324 For overall frequency domain variables, a significantly ($p<0.05$) higher 3D Trunk to Pelvis
325 Rotation mean frequency was found for shoulder-in left compared to shoulder-in right with shoulder-
326 in right much more similar to straight trot. When comparing harmonic ratios for spectral components
327 (see Table 3), a significant differences ($p<0.05$) between shoulder-in left and shoulder-in right were
328 found at stride, inter-stride and step frequencies. For all three component groups a higher ratio was
329 found for shoulder-in right, so the motion became more symmetrical. The power spectra are
330 illustrated for straight trot and shoulder-in for both groups in Figure 3 and an example of the odd and
331 even harmonics and 3D rotational motion of the trunk relative to the pelvis for a low scoring novice
332 rider and a high scoring advanced rider are provided in Figure 4.

333

334

335 **Table 1.** Mean (standard deviation (s.d.)) for dressage scores (absolute), stride time (s) and time domain
336 variables for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in
337 separated by rider level. Bold values are significant between rider levels. Shaded boxes are significant between
338 shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used and
339 median (inter quartile ranges) are also provided for non-parametric data. Number of trials for the group
340 included in the analysis (n). For these variables (n) includes two strides. Anterior superior iliac spine (ASIS).
341

Kinematic Movement	Magnitude		Difference between Shoulder-In and Straight Trot (except Dressage Score)				p-value (Shoulder-In Left – Shoulder-in Right)
	Straight Trot		Shoulder-in Left		Shoulder-in Right		
	Nov mean (s.d.)	Adv mean (s.d.)	Nov mean (s.d.)	Adv mean (s.d.)	Nov mean (s.d.)	Adv mean (s.d.)	
	n=22	n=18	n=17	n=13	n=18	n=17	
Dressage score	6.44 (0.15)	7.36 (0.69)	6.43 (0.16)	7.17 (0.66)	6.14 (0.15)	6.90 (0.84)	0.002*
Median (inter quartile range)			6.50 (0.25)	7.00 (0.38)	6.13 (0.25)	6.71 (6.71)	
p-value (Nov-Adv)	0.007		0.005*		0.038*		
Stride Time (s)	0.78 (0.04)	0.79 (0.04)	-0.01 (0.04)	-0.02 (0.04)	-0.01 (0.03)	-0.001 (0.02)	0.289*
Median (inter quartile range)			-0.03 (0.03)	-0.01 (0.03)	0.00 (0.03)	0.00 (0.02)	
p-value (Nov-Adv)	0.577		0.878*		0.798*		
Trunk to pelvis flexion-extension ROM (deg)	19.9 (9.0)	21.6 (3.5)	-1.9 (2.4)	-5.4 (3.3)	-1.5 (5.3)	-3.9 (3.1)	0.197
p-value (Nov-Adv)	0.646		0.032		0.274		
Mean Trunk to Pelvis Axial Rotation (deg)	-4.0 (7.3)	0.64 (7.3)	-0.1 (4.6)	1.2 (9.0)	-3.6 (6.7)	-4.2 (8.8)	
p-value (Nov-Adv)	0.225		0.726		0.877		0.095
R-L Mean Difference in Acromion Process Height (mm)	0.4 (15.3)	0.9 (32.4)	0.6 (15.1)	-3.9 (16.8)	-1.5 (12.6)	7.7 (22.4)	
p-value (Nov-Adv)	0.971		0.588		0.326		
R-L Mean Difference in ASIS Height (mm)	-2.6 (9.5)	-0.7 (19.7)	-2.6 (9.0)	4.7 (15.7)	16.5 (19.0)	2.7 (22.9)	0.132
p-value (Nov-Adv)	0.808		0.272		0.211		
Mean Left Hip Flexion-Extension (deg)	6.0 (10.1)	5.4 (12.7)	-1.0 (4.9)	1.0 (8.7)	-0.3 (2.5)	-12.0 (7.0)	
p-value (Nov-Adv)	0.915		0.576		0.001		0.041
Mean Right Hip Flexion-Extension (deg)	9.3 (6.5)	6.5 (10.9)	0.8 (2.6)	-11.4 (10.7)	-0.02 (5.2)	4.7 (6.1)	
p-value (Nov-Adv)	0.538		0.015		0.121		
Mean Left Hip Internal-External Rotation (deg)	-18.6 (9.7)	-22.9 (12.7)	-0.6 (5.1)	9.4 (13.8)	0.8 (5.7)	-11.6 (12.2)	0.026
p-value (Nov-Adv)	0.459		0.087		0.021		
Mean Right Hip Internal-External Rotation (deg)	-8.8 (9.9)	-20.7 (16.5)	5.3 (6.4)	-9.5 (17.1)	1.1 (5.7)	14.8 (6.4)	
p-value (Nov-Adv)	0.100		0.047		<0.001		0.009

Left Knee Flexion-Extension ROM (deg)	8.4 (2.8)	7.9 (2.9)	<0.01 (1.5)	0.78 (3.1)	-0.2 (2.2)	-0.3 (1.1)	0.205
p-value (Nov-Adv)	0.729		0.536		0.874		
Right Knee Flexion-Extension ROM (deg)	9.4 (3.6)	6.9 (2.7)	0.2 (3.7)	-1.7 (1.8)	-0.3 (1.6)	0.4 (3.0)	0.329
p-value (Nov-Adv)	0.146		0.204		0.554		

342

343

344 **Table 2.** Median (inter quartile ranges) for frequency domain variables for straight trot and differences between
345 shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant
346 between rider levels. Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks
347 are where non-parametric statistical tests were used. Number of trials for the group included in the analysis
348 (n). For these variables (n) includes one stride.

349

Kinematic Movement	Magnitude		Difference between Shoulder-In and Straight Trot (except Dressage Score)				p-value (Shoulder-In Left – Shoulder-in Right)
	Straight Trot		Shoulder-in Left		Shoulder-in Right		
	Nov mean (s.d.)	Adv mean (s.d.)	Nov mean (s.d.)	Adv mean (s.d.)	Nov mean (s.d.)	Adv mean (s.d.)	
	n=22	n=18	n=17	n=13	n=18	n=17	
3D Trunk to Pelvis Rotation Mean Frequency (Hz)	3.12 (0.28)	3.16 (0.28)	0.35 (0.34)	0.05 (0.37)	0.07 (0.28)	0.01 (0.53)	0.049*
p-value (Nov-Adv)	0.721*		0.161*		0.505*		
3D Trunk to Pelvis Rotation Signal Power (deg ² *s)	51.5 (180.0)	93.3 (81.9)	-24.6 (49.6)	-49.3 (61.7)	-17.7 (76.2)	-33.5 (57.0)	0.215*
p-value (Nov-Adv)	1.000*		0.727		1.000*		
Harmonic Ratio	1.03 (0.10)	0.98 (0.09)	-0.02 (0.16)	0.04 (0.16)	-0.07 (0.20)	0.00 (0.16)	0.234*
p-value (Nov-Adv)	0.161*		0.234*		0.234*		

350

351

352 **Table 3.** Median (inter quartile ranges) for harmonic ratios for each spectral component for straight trot and
 353 differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded
 354 values are significant between rider levels. Asterisks are where non-parametric statistical tests were used.
 355 Number of trials for the group included in the analysis (n). For these variable (n)includes one stride.
 356

Kinematic Movement	Magnitude		Difference between Shoulder-In and Straight Trot (except Dressage Score)				p-value (Shoulder-In Left – Shoulder- in Right)
	Straight Trot		Shoulder-in Left		Shoulder-in Right		
	Nov mean ± (s.d.)	Adv mean ± (s.d.)	Nov mean ± (s.d.)	Adv mean ± (s.d.)	Nov mean ± (s.d.)	Adv mean ± (s.d.)	
	n=22	n=18	n=17	n=13	n=18	n=17	
Two stride frequency	0.57 (0.83)	1.80 (1.63)	0.10 (0.70)	-0.59 (2.18)	0.96 (1.24)	1.73 (1.92)	0.098*
p-value (Nov-Adv)	0.161*		0.328*		0.442*		
Stride frequency	1.10 (1.48)	0.70 (2.01)	-0.26 (0.87)	0.56 (2.73)	1.29 (1.49)	2.73 (5.49)	0.034*
p-value (Nov-Adv)	0.234*		0.442*		0.442*		
Inter-stride frequency	0.87 (1.23)	0.71 (0.76)	-0.34 (0.92)	-0.11 (0.79)	1.38 (2.18)	0.94 (0.75)	0.030*
p-value (Nov-Adv)	0.645*		0.878*		0.798*		
Step frequency	1.12 (1.19)	1.89 (0.68)	0.12 (1.22)	0.76 (3.02)	0.93 (2.84)	0.42 (3.95)	0.469*
p-value (Nov-Adv)	0.195*		0.574*		0.645*		
Higher frequencies	0.95 (0.40)	0.79 (0.20)	0.05 (0.61)	0.03 (0.65)	1.09 (1.10)	0.97 (0.89)	0.007*
p-value (Nov-Adv)	0.468		0.878*		0.405		

357

358

359 4.0 DISCUSSION

360 This study used IMU technology to compare riders with different ability levels in terms of
 361 their dynamic posture in the time and frequency domain with the horse at sitting trot and shoulder-in.
 362 Not surprisingly, advanced riders received higher scores for all movements and showed better
 363 performance than novice riders with regard to several posture variables. These findings, together with
 364 a main effect of level support our first hypothesis. Significant differences were also found between
 365 shoulder-in left and right which supports our second hypothesis.

366 The fact that higher dressage scores were awarded to horses ridden by advanced riders is
 367 consistent with them having better posture and a higher skill level than novices, which facilitates
 368 better performance and higher scores.

369 The trot is an inherently symmetrical gait with the limbs moving in a diagonally synchronized
 370 pattern. The horse's body undergoes a vertical excursion in each diagonal step (Buchner et al., 2000;
 371 Hobbs et al., 2013) and the rider is subjected to large accelerations due to the synchronized motion
 372 and force generation of the diagonal limb pairs (Clayton and Hobbs, 2017). Additionally, the horse's

373 trunk rotates around its centre of mass in a nose up direction in early diagonal stance, reversing to
374 nose down rotation in late diagonal stance (Dunbar et al., 2008; Hobbs et al., 2013). Rotations of the
375 rider's pelvis are the primary mechanism for the rider to absorb the horse's movements and
376 communicate with the horse (Hobbs et al., 2020). The rider's pelvis pitches in the opposite direction
377 and rolls in the same direction as the horse's back (Byström et al 2009).

378 The acetabulum of the hip joint is an integral part of the pelvis. When the rider's pelvis tilts
379 anteriorly or posteriorly, it rocks onto the front or back, respectively, of the tubera ischii with the
380 acetabulum rotating in the same direction. One of the skills acquired by the experienced rider is to be
381 able to actively pitch the pelvis to follow the movement of the horse without changing the leg position.
382 This implies that the rider allows the hip joints to flex and extend as necessary, so the position of the
383 thigh is independent of pelvic pitching.

384 During shoulder-in, the rider positions the horse by turning the axis of the horse's shoulders
385 to one side while the haunches remain straight. In this position, with the horse's shoulders at an angle
386 to the line of motion, the inside forelimb crosses the outside forelimb each time it steps forward while
387 the hind limbs continue to move straight along the original line. The riders inside leg acts in a forward
388 position to maintain the bend in the horse's trunk, but the outside leg should move back along the
389 horse's side and apply pressure to prevent the haunches from swinging outwards. The right leg should
390 move back when performing left shoulder-in and the left leg should move back when performing
391 right shoulder-in. Failure to move the outside leg back and use it to guard the haunches is a common
392 rider mistake, especially in novice riders. The results presented here show symmetrical flexion-
393 extension angles for the rider's left and right hips when riding on the straight as would be expected.
394 In shoulder-in, the outside hip was significantly more extended (11.7° in shoulder-in left, 13.2° in
395 shoulder-in right) in the advanced riders which has the effect of moving that leg back to control the
396 haunches. The novice riders showed $\leq 1^\circ$ change in left or right hip angle when performing shoulder-
397 in which likely represents the difference in level of skill with the novices failing to control the horse's
398 haunches.

399 The rider's leg should be draped around the horse's trunk, which is somewhat oval in cross-
400 section and widest around the height of the rider's knee. Since the rider's knee joints are mainly
401 confined to rotate in flexion and extension, they cannot simply adduct their knee to wrap their calves
402 around the horse. Therefore, in order to maintain contact with the saddle/horse with both the thigh
403 and calf, the rider must either rotate the hip externally and/or flex the knee. We did not find
404 differences in knee flexion between rider levels, whereas internal-external hip rotation values showed
405 greater variability and were sometimes different between rider groups. This may indicate that hip
406 rotation is used preferentially to adjust leg position and contact with the saddle. Furthermore, it has
407 been stated that, in order to increase the horse's level of engagement whilst sitting in an upright

408 dressage posture, riders must externally rotate their hips and, by doing so, they are able to absorb
409 greater vertical movement of the horse's centre of mass and apply more consistent aids to the horse
410 (Auty, 2007).

411 When riding in straight lines, left-right symmetry is highly valued, and riders strive to
412 overcome their inherent sidedness patterns. The only positional variable that we observed to be
413 asymmetrical when trotting on the straight was that the left hip was more externally rotated than the
414 right hip in the novice riders, but this was not tested for significance. This observation agrees with
415 Gandy et al. (2014) who used IMUs to evaluate 12 riders at rising trot on straight lines and circles. All
416 riders showed asymmetrical external hip rotation with differences between left and right limbs in the
417 range of 1-27°, which is in the same range as we report here. Furthermore, 83% of riders showed
418 greater external rotation of the right hip regardless of the direction of motion or which diagonal they
419 were rising on. In a study comparing ballet dancers with non-dancers, strength, work, and angle
420 specific torque of the hip external rotator muscles were reported to be greater on the right side than
421 the left ($p = 0.007$) in both groups (Gupta et al., 2004). Thus, differences in hip rotation between the
422 left and right legs may be a manifestation of inherent sidedness patterns. When performing shoulder-
423 in, the advanced riders had greater outside hip external rotation and a reduction in external rotation
424 of the inside hip. This would have the effect of turning the toe outwards in the outside leg and slightly
425 more inwards in the inside leg which is in accordance with their functions of guarding the haunches
426 vs bending the horse. Novice riders did not have a consistent pattern.

427 The equestrian literature emphasizes the importance of the rider's seat as the foundation for
428 good performance, where the seat can be defined by hip and pelvis posture and motion, and lumbar
429 spine mobility (Schusdziarra and Schusdziarra, 1993). Several scientific studies have confirmed that
430 the phase synchrony between movements of the rider's pelvis with those of the horse is a key
431 contributor to the impression of harmony (Eckardt and Witte, 2017; Lagarde et al., 2005; Münz et
432 al., 2014; Peham et al., 2001). In this study we investigated 3D trunk to pelvis rotation harmonics to
433 assess rider skill in the frequency domain, as no data were available from the horse. Together with a
434 significant finding between shoulder-in left and right for mean frequency, there were interesting
435 findings when exploring the spectral components. We predicted that harmonic ratios would be close
436 to 1 in straight trot, due to the pitch, roll and yaw of the pelvis and trunk that occur within a stride
437 (Byström et al, 2009; 2015). Indeed, this was the case in both groups, although from Figure 4 it is
438 clear that the symmetric and asymmetric harmonics included in the ratio are not exclusively related
439 to the stride and step frequencies. For shoulder-in left, a higher mean frequency is evident compared
440 to straight trot, particularly in the novice group, but with lower signal power, whereas for shoulder-
441 in right there is only a slight reduction in signal power. The changes for shoulder-in left may reflect
442 the change in motion to give seat aids to the horse. When exploring the spectral components in more

443 detail, harmonic ratios at the stride, inter-stride and step frequencies were higher for shoulder-in right,
444 suggesting a more symmetric pattern. These alterations are also assumed to reflect the way riders give
445 seat aids for shoulder-in right, but as they carry a lower dressage score could be considered less
446 desirable. It could therefore be surmised that lower dressage scores for shoulder-in right in the
447 advanced group relate to less desirable motion patterns that are produced as a result of seat aids,
448 whereas lower dressage scores in the novice group are due to incorrect leg aids and undesirable
449 motion to produce seat aids. A notable difference in magnitude and variability of the spectral
450 components are illustrated between the rider groups in Figures 3 and 4, but unfortunately the
451 relatively small group size and the variability, particularly in the novice riders, has limited our ability
452 to analyse these data. Further work exploring the harmonics of both horse and rider motion,
453 particularly at elite level, may prove fruitful in the development of determinants of dressage
454 performance.

455 At the time these data were collected (year 2011) inertial sensor suits were not commonly
456 used for biomechanical data collection from riders. A pilot study was therefore conducted to compare
457 the inertial sensor data to data collected from a 3D motion capture system. The pilot test results found
458 comparable ranges of motion between systems but highlighted how crucial sensor or tracking marker
459 position on a segment are in extracting absolute angles (unpublished data). Such methodological
460 issues have been reported in the literature (Leardini et al., 2005). Two additional methodological
461 challenges are most evident when calculating axial rotation at the hip joint. Firstly, using an XYZ
462 Cardan sequence, the Z axis is the third in the series of rotations to be extracted, introducing potential
463 cross talk errors (Sinclair et al., 2012). Secondly, the model used in this study is based on rigid body
464 mechanics, but the thigh segment, particularly the quadriceps muscles are quite deformable. As such,
465 measured external rotation may include an artefact of a change in quadriceps position relative to the
466 femur rather than modelled rotation of the femur at the hip joint. Due to these methodological
467 limitations the analysis was focussed on comparisons between rider groups and movements, as any
468 systematic errors are likely to be present throughout the dataset. Our scrutiny of the dataset also meant
469 that riders and trials were missing from the analysis, which reduced the statistical power. Data quality
470 issues were only evident during data processing, so collecting additional data was not possible for
471 this study. The variability in the dataset may also be in part due to the difference between horses, tack
472 and potential asymmetries within horses. Horses in this study were not screened to assess asymmetry
473 prior to data collection. Finally, in this study multiple testing was not corrected for, based on the work
474 of (Sinclair et al., 2013).

475 Despite the greater movement observed in advanced compared to novice riders, a key finding
476 in the current study is the ability of the advanced riders to maintain and stabilise 'ideal' posture
477 through their trunk and lower limbs, whilst absorbing motion through the pelvis and gaining higher

478 dressage scores because of this. Future research should consider further investigation of other
479 dressage movements and the balance between postural control and mobility in order to achieve greater
480 performance outcomes in dressage tests across several levels.

481

482 **5.0 CONCLUSION**

483 This study has highlighted a difference in performance of the shoulder-in between advanced and
484 novice riders in hip extension, and consequently the position of the outside leg to prevent the haunches
485 swinging out. This is likely to have contributed to higher scores in the advanced riders. Since the
486 difference was mirrored on the left and right sides, it is regarded as a voluntary part of the rider's
487 technique. Lower dressage scores for shoulder-in right are likely to be linked to changes in harmonics
488 of 3D trunk to pelvis rotation due to the application of seat aids. Results from the current study have
489 implications for equitation coaches and for horse and rider dressage performance.

490

491 **Acknowledgements**

492 The authors would like to thank the horse owners and riders for taking part in this study. We would
493 like to acknowledge Rob Ditchfield Photography for the photograph of the advanced rider.

494

495 **Funding**

496 The authors received no funding for this study.

497

498 **Author contribution**

499 JB: Study design, data collection, data analysis, practical interpretation, manuscript preparation.

500 SJH: Study design, data collection, data analysis, statistical analysis, manuscript preparation.

501 JA: Data analysis, manuscript preparation.

502 LSG: Data analysis, manuscript preparation.

503 JS: Statistical analysis.

504 AC: Data collection, manuscript review.

505 HMC: Data analysis, practical interpretation, manuscript preparation.

506

507 **Figure and Table Captions**

508

509 **Figure 1:** Illustration of the correct position of the horse from above in straight trot and shoulder-in
510 and an image showing one of the novice riders in the study performing shoulder-in left.

511 **Figure 2:** An advanced rider equipped with the XSENS suit and a corresponding reconstruction of
512 the data for one trial for that rider.

513 **Figure 3:** Mean and standard deviation for novice A) and advanced B) riders of the 3D trunk to pelvis
514 rotation power spectrum. Straight trot = dark blue, shoulder-in left = grey, shoulder-in right = cyan.

515 **Figure 4:** 3D trunk to pelvis rotation (degrees) and corresponding harmonics in straight trot and
516 shoulder-in for A) and C) a low scoring novice rider, and B) and D) a high scoring advanced rider.
517 Straight trot = dark blue, shoulder-in left = grey, shoulder-in right = cyan.

518 **Figure 5:** An example of the harmonics from a 3D trunk to pelvis rotation (degrees) from one trial at
519 the A) stride frequency and B) step frequency.

520

521 **Table 1.** Mean (standard deviation (s.d.)) for dressage scores (absolute), stride time (s) and posture
522 time domain variables for straight trot and differences between shoulder-in and straight trot for left
523 and right shoulder-in separated by rider level. Bolded values are significant between rider levels.
524 Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks are where non-
525 parametric statistical tests were used and median (inter-quartile ranges) are also provided for non-
526 parametric data. Number of trials for the group included in the analysis (n), where each trial includes
527 two strides. Anterior superior iliac spine (ASIS).

528 **Table 2.** Harmony Mean (standard deviation (s.d.)) for frequency domain variables for straight trot
529 and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider
530 level. Bolded values are significant between rider levels. Shaded boxes are significant between
531 shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used
532 and median (inter-quartile ranges) are also provided for non-parametric data. Number of trials for the
533 group included in the analysis (n), where each trial includes one stride.

534 **Table 3.** Mean (standard deviation (s.d.)) for harmonic ratios for each spectral component for straight
535 trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by
536 rider level. Bolded values are significant between rider levels. Asterisks are where non-parametric
537 statistical tests were used and median (inter-quartile ranges) are also provided for non-parametric
538 data. Number of trials for the group included in the analysis (n), where each trial includes one stride.

539

540

541

542 **References**

543 Auty I. The BHS manual of equitation. Shrewsbury: Kenilworth Press; 2007:35-41.

544 Baillet H, Thouwarecq R, Verin E, Tourny C, Benguigui N, Komar J, Leroy D. Human energy
545 expenditure and postural coordination on the mechanical horse. *J Motor Behav* 2017;49:441-457.

546 Bishop C, Turner A, Read P. Effects of inter-limb asymmetries on physical and sports performance:
547 a systematic review. *J Sports Sci* 2017;36(10):1135-1144.

548 British Dressage. British Dressage rules. Warwickshire: British Dressage; 2020.

549 Buchner HHF, Obermüller S, Scheidl M. Body Centre of Mass Movement in the Sound Horse. *Vet J*
550 2000;160:225-234.

551 Byström A, Roepstorff, L., Geser-von Peinen, K, Weishaupt, MA, Rhodin, M. Differences in rider
552 movement pattern between different degrees of collection at the trot in high-level dressage horses
553 ridden on a treadmill. *Human Mov Sci* 2015;41:1-8.

554 Byström A, Rhodin M, Von Peinen K, Weishaupt MA, Roepstorff L. Basic kinematics of saddle and
555 rider in high-level dressage horses trotting on the treadmill. *Equine Vet J* 2009;41:280-284.

556 Clayton HM, Hobbs SJ. The role of biomechanical analysis of horse and rider in equitation science.
557 *Appl Ani Behav Sci* 2017;190:123-132.

558 Cohen J. Statistical power analysis for the behavioural sciences (2nd ed.). Hillside, NJ:Lawrence
559 Erlbaum Associates; 1988.

560 De Cocq P, Mooren M, Dortmans A, Van weeren PR, Timmerman M, Muller M, Van Leeuwen JL.
561 Saddle and leg forces during lateral movements in dressage. *Equine Vet J* 2010a;42:644-649.

562 De Cocq P, Duncker AM, Clayton HM, Bobbert MF, Muller M, Van Leeuwen JL. Vertical forces on
563 the horse's back in sitting and rising trot. *J Biomech* 2010b;43:627 -631.

564 Dunbar DC, Macpherson JM, Simmons RW, Zarcades A. Stabilization and mobility of the head, neck
565 and trunk in horses during overground locomotion: comparisons with humans and other primates. *J*
566 *Exp Biol* 2008;211(Pt 24):3889–3907.

567 Eckardt F, Witte K. Kinematic analysis of the rider according to different skill levels in sitting trot
568 and canter. *J Equine Vet Sci* 2016;39:51-57.

569 Eckardt F, Witte K. Horse-Rider Interaction: A new method based on inertial measurement units. *J*
570 *Equine Vet Sci* 2017;55: 1-8.

571 Engell M, Clayton H, Egenvall A, Weishaupt MA, Roepstorff L. Postural changes and their effects
572 in elite riders when actively influencing the horse versus sitting passively at trot. *Comp Ex Physiol*
573 2016;12:27-33.

574 Fédération Equestre Internationale (FEI). Rules for Dressage. (25th ed.) Switzerland: Fédération
575 Equestre Internationale; 2020.

576 Gandy EA, Bondi A, Hogg R, Pigott TM. A preliminary investigation of the use of inertial sensing
577 technology for the measurement of hip rotation asymmetry in horse riders. *Sports Tech* 2014;7:79-
578 88.

579 Greve L, Dyson SJ. The interrelationship of lameness, saddle slip and back shape in the general sports
580 horse population. *Equine Vet J* 2014;46:6:687-694.

581 Gunst S, Dittmann M, Arpagaus S, Roepstorff C, Latif S, Klaassen B, Pauli C, Bauer C, Weishaupt
582 M. Influence of functional rider and horse asymmetries on saddle force distribution during stance and
583 in sitting trot. *J Equine Vet Sci* 2019;78:20-28.

584 Gupta A, Fernihough B, Bailey G, Bombeck P, Clarke A, Hopper D. An evaluation of differences in
585 hip external rotation strength and range of motion between female dancers and non-dancers. *Brit J*
586 *Sports Med* 2004;38:778-783.

587 Hobbs SJ, Clayton HM. Sagittal plane ground reaction forces, centre of pressure and centre of mass
588 in trotting horses. *Vet J* 2013; 198(1):e14-19.

589 Hobbs SJ, Baxter J, Broom L, Rossell L-A, Sinclair J and Clayton HM. Posture, Flexibility and Grip
590 Strength in Horse Riders. *J Human Kinet* 2014;42:113-125.

591 Hobbs SJ, Bertram JE, Clayton HM. An exploration of the influence of diagonal dissociation and
592 moderate changes in speed on locomotor parameters in trotting horses. *PeerJ* 2016;30(4):e2190.

593 Hobbs SJ, St George L, Reed J, Stockley R, Thetford C, Sinclair J, Williams J, Nankervis K, Clayton
594 HM. A scoping review of determinants of performance in dressage. *PeerJ* 2020;24(8):e9022.

595 Kang DO, Ryu YC, Ryew CC, Oh WY, Lee CE, Kang, MS. (2010). Comparative analyses of rider
596 position according to skills levels during walk and trot in Jeju horse. *Human Mov Sci* 2010;29:256-
597 963.

598 Kyrklund K, Lemkow J. (1998). *Dressage with Kyra*. Trafalgar Square Publishing, North Pomfret,
599 Vermont.

600 Kuhnke S, Dumbell L, Gaulty M, Johnson JL, McDonald K, Von Borstel UK. A comparison of rein
601 tension of the rider's dominant and non-dominant hand and the influence of the horse's laterality.
602 *Comp Ex Physiol* 2010;7:57-63.

603 Lagarde J, Peham C, Licka T, Kelso JAS. Coordination dynamics of the horse-rider system. *J Motor*
604 *Behav* 2005;37(6):418-424.

605 Leardini A, Chiari L, Della Croce U, Cappozzo A, Human movement analysis using
606 stereophotogrammetry: Part 3. Soft tissue artifact assessment and compensation, *Gait Posture* 2005;
607 21:2:212-225.

608 Li S, Sanders R. Symmetry in flutter kicking in swimming. In: *ISBS Conference Proceedings*
609 *Archive*, 23 International Symposium on Biomechanics in Sport: Beijing, China 2005.

610 Lovett T, Hodson-Tole E, Nankervis K. A preliminary investigation of rider position during walk,
611 trot and canter. *Equine Comp Ex Physiol* 2005;2:71-76.

612 MacKechnie-Guire R, MacKechnie-Guire E, Fairfax V, Fisher M, Hargreaves S, Pfau T. The Effect
613 That Induced Rider Asymmetry Has on Equine Locomotion and the Range of Motion of the
614 Thoracolumbar Spine When Ridden in Rising Trot. *J Equine Vet Sci* 2020;88:102946.

615 <https://doi.org/10.1016/j.jevs.2020.102946>. McLean AN, McGreevy PD. Ethical Equitation: Capping
616 the price horses pay for human glory. *J Vet Behav* 2010;5(4):203-209.

617 Mendonça, T., Bienboire-Frosini, C., Sanchez, N., Kowalczyk, I., Teruel, E., Descout, E., Pageat, P.
618 De la Guérinière was right: shoulder-in is beneficial for the physical and mental state of horses. *J Vet*
619 *Behav* 2020;38:14-20.

620 Menz, H.B., Lord, S.R. Fitzpatrick, R.C. Acceleration patterns of the head and pelvis when walking
621 on level and irregular surfaces. *Gait Posture* 2003;18:35-46.

622 Mrozkowiak M., Ambroży D. Control and correction of horse rider's body posture. *Centr Eur J Sport*
623 *Med* 2014;6(2):21–33.

624 Münz A, Eckardt F, Heipertz-Hengst C, Peham C, Witte K. A preliminary study of an inertial sensor-
625 based method for the assessment of human pelvis kinematics in dressage riding. *J Equine Vet Sci*
626 2013;33:950-955.

627 Münz, A., Eckardt, F., Witte, K. Horse-Rider interaction in dressage riding. *Human Mov Sci*
628 2014;33:227-237.

629 Peham C, Scheidl M, Licka T. A method of signal processing in motion analysis of the trotting horse.
630 *J Biomech* 1996;29:8:1111-1114.

631 Peham C, Licka T, Kapaun M and Scheidl M. A new method to quantify harmony of the horse–rider
632 system in dressage. *Sports Eng* 2001;4:95-101.

633 Podhajsky A. The complete training of horse and rider in the principles of classical horsemanship.
634 London: The Sportsman's Press 1994.

635 Robertson DGE, Dowling JJ. Design and responses of Butterworth and critically damped digital
636 filters. *J Electromyogr and Kinesiol* 2003;13:569-573.

637 Roetenberg D, Luinge H, Slycke P. Xsens MVN: Full 6DOF Human Motion Tracking Using
638 Miniature Inertial Sensors. *Xsens Technologies* 2013; 3: 1-9.

639 Schils SJ, Greer NL, Stoner LJ. and Kobluk CN. Kinematic analysis of the equestrian – Walk, posting
640 trot and sitting trot. *Human Mov Sci* 1993;12:693-712.

641 Schusdziarra H, Schusdziarra Z. An anatomy of riding. New York: Breakthrough Publications,
642 1993;32:42-46.

643 Sinclair J, Taylor PJ, Edmundson CJ, Brooks D, Hobbs SJ. Influence of the helical and six available
644 Cardan sequences on 3D ankle joint kinematic parameters. *Sports Biomech* 2012;11:3:430-437.

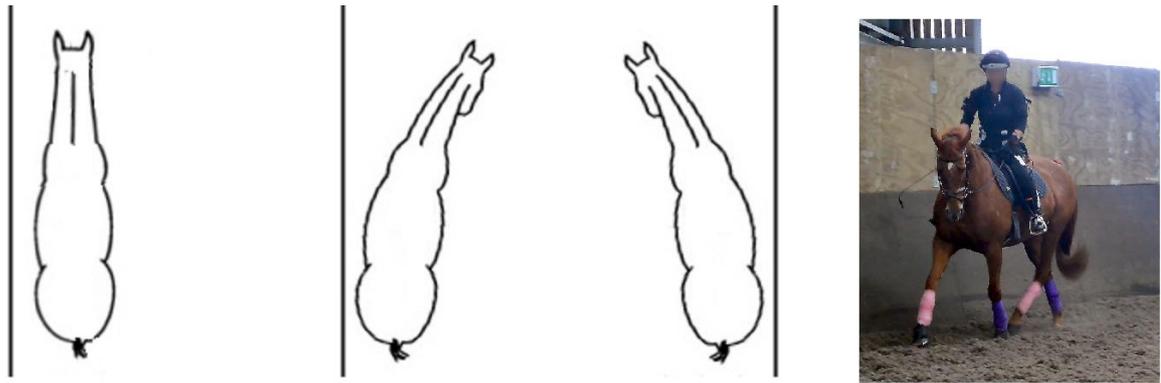
645 Sinclair J, Taylor PJ, Hobbs SJ. Alpha level adjustments for multiple dependent variable analyses
646 and their applicability—a review. *Int J Sports Sci Eng* 2013;7:1:17-20. Symes D, Ellis R. A preliminary
647 study into rider asymmetry within equitation. *Vet J* 2009;181:34-37.

648 Wolframm IA, Bosga J, Meulenbroek RG. Coordination dynamics in horse-rider dyads. *Human Mov*
649 *Sci* 2013;32:157-170.

650

Figure 1

651



Straight

**Shoulder-in
right**

**Shoulder-in
left**

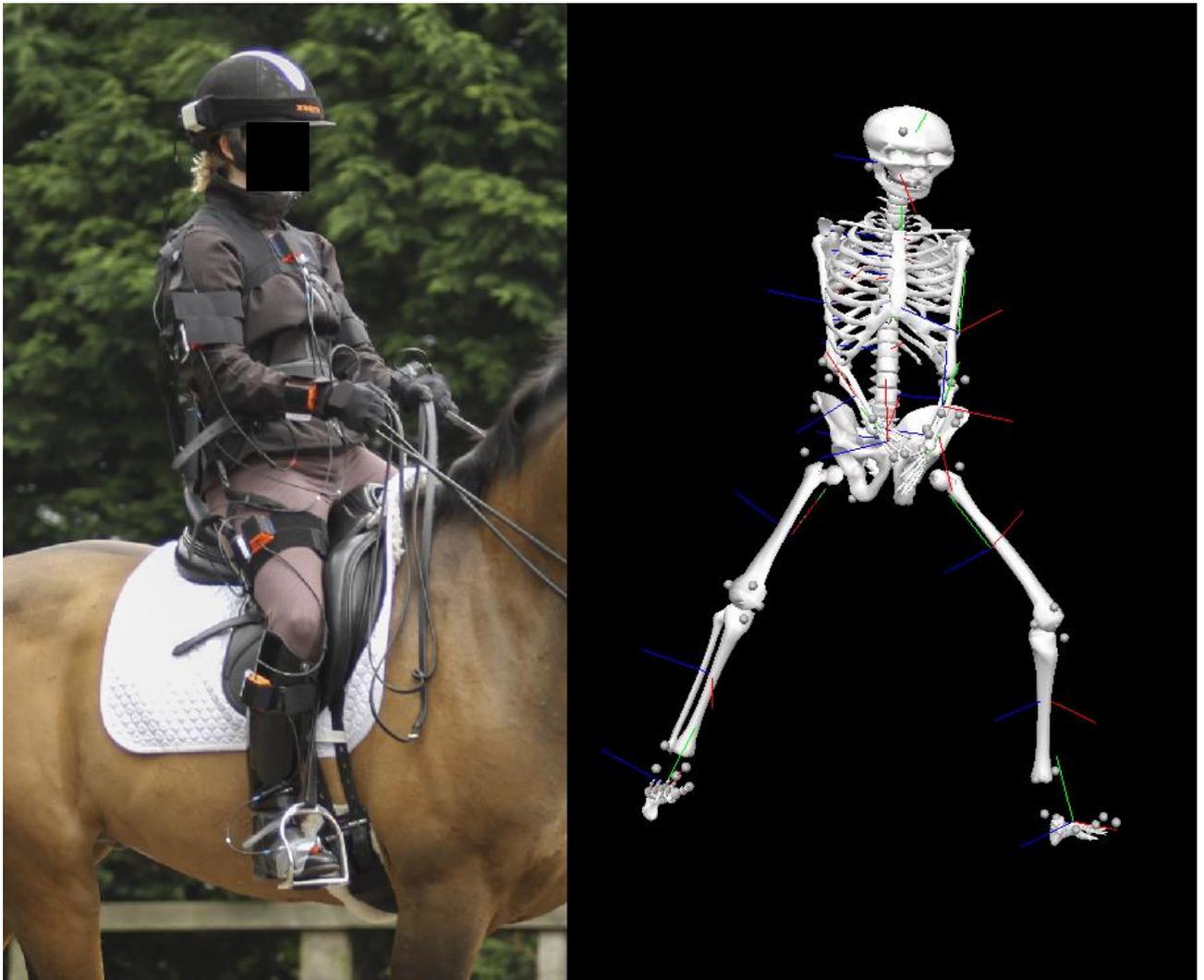
**Shoulder-in
left**

652

Figure 2

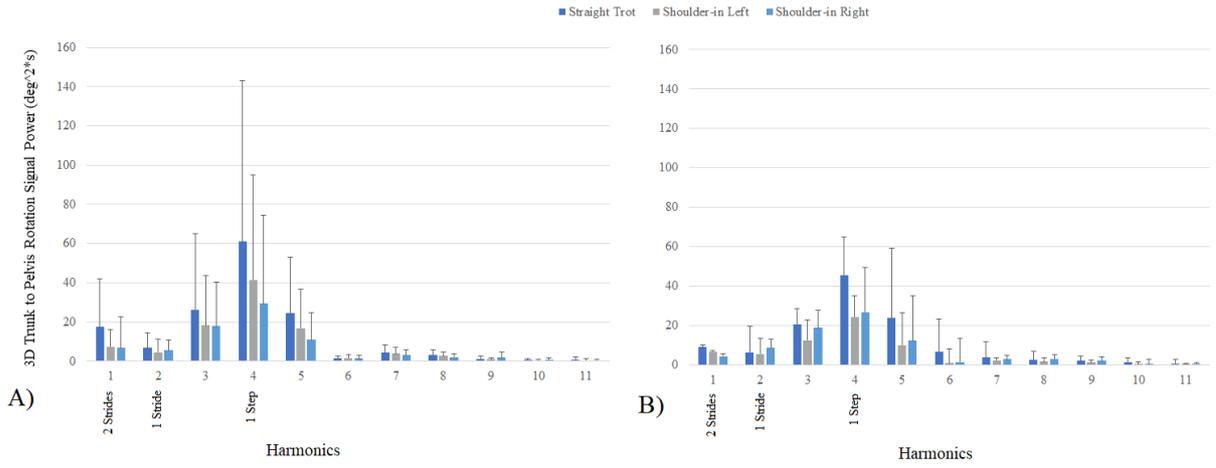
653

654

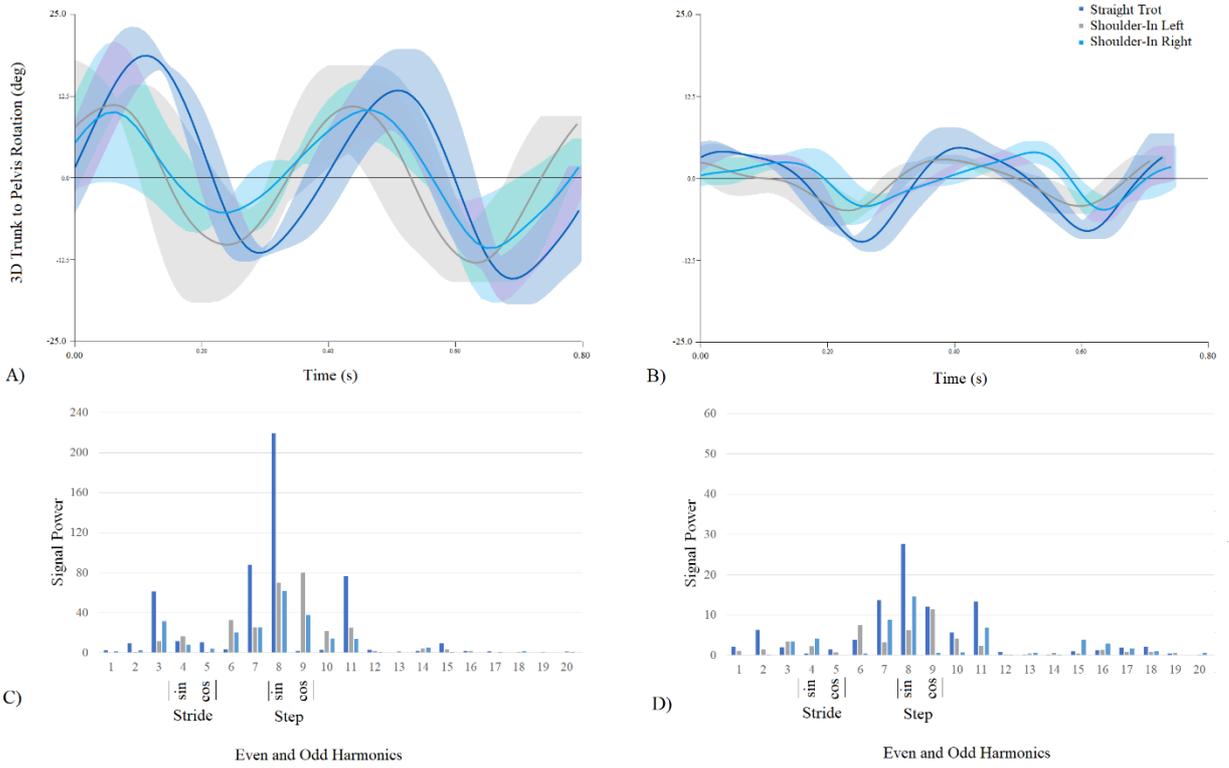


655

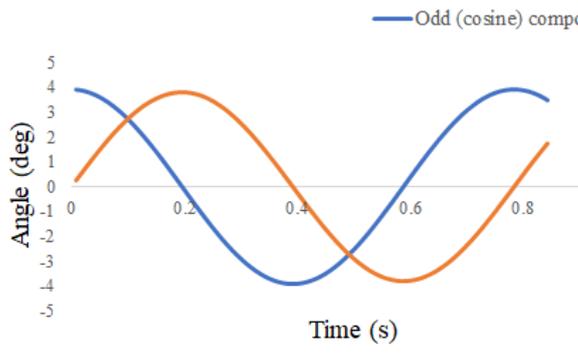
656 Figure 3



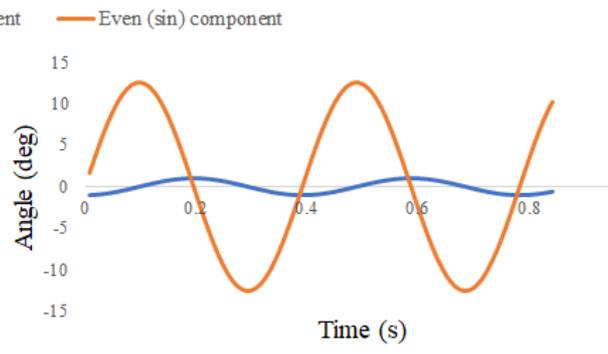
657
658
659 Figure 4



660
661
662 Figure 5



A



B

663