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Saddle and stirrup forces of equestrian riders in sitting trot, rising trot and trot without stirrups on a riding simulator

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Abstract

Studies into horse-saddle-rider interaction demonstrate that increased vertical forces on the horse's back are potentially damaging to the musculoskeletal system, and any practice that could lead to this warrants investigation. The contribution of the stirrups in stabilising the bodyweight of the rider, and the effect of riding without stirrups on force distribution to the horse, has yet to be fully described in the literature. The current study therefore aimed to compare saddle and stirrup forces in three conditions; sitting trot, rising trot, and sitting trot without stirrups on the riding simulator. Fourteen amateur female riders of mean age 34.6 ± 10 years participated in the study and 20 seconds of data were collected for saddle and stirrup force across the three conditions. Mean and peak forces were extracted from the data for total force under the whole saddle, left and right sides of the saddle separately, left and right stirrups, and both stirrups combined. Peak vertical saddle forces were significantly higher in sitting trot without stirrups than with ($P=0.011$). Higher mean and peak saddle forces were seen on the right hand side in all conditions ($P<0.001$) and there was an overall tendency for higher left stirrup forces in both sitting and rising trot with this being significant for peak force in sitting trot ($P=0.039$). The higher forces recorded when trotting without stirrups indicate that the stirrups play an important role in controlling the vertical acceleration of the rider in relation to the horse, however further studies are needed on live horses before any specific recommendations can be made regarding training practices. Asymmetrical saddle forces have a potentially negative effect on the horse and future research should also aim to identify the underlying causes of these patterns of rider asymmetry to improve both horse welfare and performance.

Key words: equestrianism, dressage, horse-rider interactions, biomechanics, kinetics

The authors declare no conflict of interest

1 Introduction

2 The impact of the rider on equine locomotion has received increased interest over the last 15
3 years, with a growing body of research in this area (Clayton and Hobbs, 2017). This is partly
4 due to the rise in popularity of equitation science, and the increasing availability of technologies
5 developed to assess and measure the horse-rider relationship (Pierard *et al.*, 2015). The equine
6 sector as a whole is becoming more concerned with the welfare of the ridden horse (Hemsworth
7 *et al.*, 2015) and the biomechanical effects of the rider can be an influential factor in this
8 (Clayton and Hobbs, 2017; Williams and Tabor, 2017).

9 The most significant area of force transmission between horse and rider is through the saddle
10 (Clayton and Hobbs, 2017; Greve and Dyson, 2013) with peak vertical forces of up to two and
11 a half times the rider's bodyweight being recorded in sitting trot (Bogisch *et al.*, 2014). Patterns
12 of force distribution through the saddle have been shown to follow a cyclical pattern in time
13 with the horse's stride (de Cocq *et al.*, 2010a; van Beek *et al.*, 2012) with sitting trot showing
14 two clear saddle force peaks (Bogisch *et al.*, 2014; Freuhwirth *et al.*, 2004) which are thought
15 to be caused by vertical movement of the rider in response to the vertical oscillation of the
16 horse's trunk within the trot (Bogisch *et al.*, 2014). The addition of 75 kg of dead weight in the
17 saddle has been found to increase the extension of the thoracolumbar spine (de Cocq *et al.*,
18 2004) and this can also be seen in both rising and sitting trot with a rider, although rising trot
19 allows the spine to return to flexion when the saddle is unloaded in the standing phase of the
20 stride (de Cocq *et al.*, 2010a). Rising trot can however lead to asymmetrical limb loading and
21 pelvic movement between the weight bearing and non-weight bearing diagonals, which could
22 be potentially damaging if the same diagonal is used for long periods of time or when combined
23 with rider asymmetries (Roepstorff *et al.*, 2009).

24 A number of recent studies into rider biomechanics have reported the presence of force
25 asymmetry; riders have been shown to preferentially weight bear on the left ischial tuberosity
26 (seat bone) when seated on a flat, static platform (Guire *et al.*, 2017) and to weight bear
27 asymmetrically whilst sitting astride a stationary saddle horse (Nevison and Timmis, 2013) and
28 whilst riding their own horse at sitting trot (Hampson and Randle, 2015). This leads to uneven
29 loads on the horse's back (de Cocq *et al.*, 2009) which has implications for welfare and
30 performance (Greve and Dyson, 2013).

31 It is a popular opinion amongst equestrian coaches that riding without stirrups is beneficial in
32 stabilising a rider's seat (Print, 2011) and encourages them to sit more centrally (Loch, 2003).
33 Yet there is no empirical evidence to support these ideas and the impact of working without
34 stirrups on the forces distributed to the horse is not yet known. Van Beek *et al.* (2012) were the
35 first to describe stirrup force patterns, demonstrating that the loading of the stirrups was
36 temporally associated with loading of the saddle in both sitting and rising trot. The peaks in
37 stirrup force occurred at the same point in the stride as the peaks in saddle force in the sitting
38 trot (van Beek *et al.*, 2012), indicating that the rider may be using the stirrups to control their
39 downward acceleration. When stirrups are removed from the rider it is therefore possible that
40 there would be increased forces directly on the horse's epaxial musculature as a result of less
41 controlled downward acceleration of the rider. This could have potentially negative
42 consequences for equine musculoskeletal health. As would be expected van Beek *et al.* (2012)
43 also showed that the peaks in stirrup force within the rising trot were associated with a reduction
44 in saddle force, and were significantly greater than the stirrup force peaks seen within the sitting
45 trot, as the rider takes the whole bodyweight on the stirrups in the standing portion of the stride.
46 Due to a sensor malfunction data were only collected from one stirrup during this study,
47 meaning that the total proportion of bodyweight supported by the stirrups and information on
48 the patterns of force distribution between left and right stirrups, including any possible

49 asymmetries, could not be described (van Beek *et al.*, 2012). Data collected from both left and
50 right stirrups simultaneously has not been presented in the peer reviewed literature to date.

51 The current study firstly aimed to compare the total saddle and stirrup forces between rising
52 trot, sitting trot, and trot without stirrups, testing the hypotheses that there would be a difference
53 in saddle force between the three trot types and a difference in stirrup force between sitting and
54 rising trot in line with the previous literature. Additional aims were; to describe the total force
55 that riders place on the stirrups in relation to bodyweight, to describe the relationship between
56 left and right stirrup force in both sitting and rising trot and to determine if force asymmetry
57 was present for saddle and stirrup forces in this population.

58 **Methods**

59 *Participants*

60 A self-selecting convenience sample of 14 female riders of mean age 34.6 ± 10 years (\pm SD),
61 mean height 166.7 ± 6.5 cm, and mean weight 68.9 ± 9.9 kg took part in the study, of which
62 85.7% (n=12) were right handed and the remainder left handed. Participants were recruited via
63 an advertisement on social media, detailing the aims, inclusion and exclusion criteria. Ethical
64 approval for the study was granted by Hartpury University Centre Ethics Committee.

65 The inclusion criteria required all participants to be female, as spinopelvic anatomy, which may
66 impact on the results of this study, differs between the sexes (Janssen *et al.*, 2009; Rissech *et al.*,
67 2003). Participants were aged between 18 and 60 years to reduce the potential impact of
68 growth (Mac-Thiong *et al.*, 2004) or age related joint changes (Johnson *et al.*, 2004; Leunig *et al.*,
69 2003) on the measured variables. Participants were also required to weigh less than 102kg,
70 as this is the weight limit for the riding simulator. Riders at different levels have been shown
71 to exhibit different pelvic movements (Munz *et al.*, 2014), thus riders were required to be
72 competent at British Dressage Preliminary or Novice level, with those above or below this
73 standard being excluded. Exclusion criteria removed participants who were currently injured,
74 or had previous injury to the pelvic region or hip joints as this can lead to development of
75 compensatory movement patterns (Hammoud *et al.*, 2014) which would impact the validity of
76 the study.

77 Prior to commencement of data collection, informed consent was gained from each participant
78 in line with the General Data Protection Regulations 2018 (GDPR). The anthropometric
79 measurements were then taken; height (cm) was recorded without shoes using a Leicester
80 Portable Height Measure and bodyweight (kg) was recorded using a Tanita Body Composition
81 Analyser BF-350. Participants were required to wear a correctly fitted riding hat to current
82 safety standard (PAS 015, ASTM F1163:04a or Snell E2001) and riding boots with a smooth
83 sole and a small heel for the data collection on the riding simulator. A second bodyweight
84 measurement was then taken, with riding hat and boots to use for calibration purposes.

85

86 *Equipment and Protocol*

87 Horses designated as sound by their owners have been shown to display movement asymmetry
88 in some cases (Rhodin *et al.*, 2017; Starke *et al.*, 2012) which could affect the transfer of forces
89 between horse and rider, therefore the data collection for the current study took place on a
90 riding simulator (Racewood Ridemaster Pro) to remove these effects. This riding simulator
91 model consists of a reinforced plastic horse form which sits on top of a motorised platform and
92 moves to mimic the equine gaits of walk, trot and canter. This particular model has two speeds
93 of the trot gait termed as 'collected trot' and 'medium trot'. This simulator has leg sensors on

94 both sides which allows it to detect the rider's leg aids and a sensor system built into the
95 articulation between the head and the neck which allows it to respond to the rein aids, thus the
96 rider can change between the gaits as they would on a live horse. There is also a manual control
97 panel consisting of 'up' and 'down' buttons on the side of the simulator which allows the
98 researcher to select the required gait. The simulator moves in a repeatable and symmetrical
99 manner within all gaits, meaning that there is no indication on which 'diagonal' a rider should
100 be rising on in the trot.

101 An under saddle pressure mat (Tekscan CONFORMat) was placed directly onto the back of
102 the simulator and a dressage saddle weighing 7.5kg complete with stirrups was placed directly
103 on top. The saddle was then attached to the girth buckles present on the sides of the simulator
104 by two research assistants simultaneously from either side, ensuring neither the pressure mat
105 nor saddle were pulled to one side. Ahead of data collection the saddle pressure mat was
106 calibrated to the weight of the saddle using the Force Calibration function within the Tekscan
107 CONFORMat version 7.6x software (Tekscan, 2013 pp139-150). This software was then used
108 to view the under saddle force measurements within the Real Time viewing window, using the
109 'panes' tool to separate the 32 x 32 sensor array into two 32 x 16 sensor panes, corresponding
110 to the left and right sides of the saddle. The left and right girth straps were then adjusted until
111 the force difference between the left and right panes displayed in the Real Time window was
112 no greater than one Newton. This process was repeated before each participant to ensure any
113 saddle movement caused by one participant was corrected prior to the next rider mounting.

114 The Pliance stirrup force sensors (Novel gmbh), consisting of two 11cm x 5cm pressure mats,
115 each housed within its own rubber protective sleeve, were fitted to the left and right stirrups.
116 Prior to data collection the stirrup force sensors were calibrated using the weight of an 86kg
117 adult using the Bipedal calibration function within the Loadsol app via an Android smartphone
118 (Novel gmbh, 2017 pp26-7).

119 Riders were mounted onto the simulator from the left hand side, using a mounting block to
120 minimise disruption to the sensors. Riders underwent a standardised four minute warm up,
121 consisting of one minute in each 'walk', 'collected trot', 'medium trot' and 'canter' settings on
122 the simulator. The simulator was then returned to halt. The saddle pressure mat was recalibrated
123 at this stage for each rider, using the Force Calibration function as previously described,
124 calibrating to the weight of the rider with hat and boots, plus the weight of the saddle. This
125 ensured no drift in calibration throughout the data collection period (de Cocq *et al.*, 2009). The
126 stirrup sensors were also unloaded and zeroed at this stage for each rider to eliminate the effects
127 of any movement on the sensors and ensure accurate readings could be obtained (Novel gmbh,
128 2017 p29).

129 The simulator was set to 'medium trot' for the data collection element, and was controlled by
130 the researcher using the control panel to ensure that riders' position was not disrupted by trying
131 to locate the leg sensors. Once the rider had verbally confirmed that they were comfortable in
132 the trot, 20 seconds of data were recorded from each the saddle and stirrup pressure sensors,
133 for each the sitting trot, rising trot and the sitting trot without stirrups. Between each pace the
134 simulator was returned to the 'walk' setting by the researcher, the participant was then briefed
135 on the next condition to be measured, which included removal of stirrups for the without
136 stirrups condition. The simulator was then returned to the 'medium trot' setting and the next
137 20 seconds of data collected. On completion of the trial participants were then given a one
138 minute cool down period in walk before dismounting and being debriefed.

139 The medium trot setting on this model has a stride frequency of 0.93 seconds, in which time
140 the plastic horse form raises and lowers twice to emulate the stance phases of each diagonal

141 pair of limbs, each time followed by the short suspension phase as seen in the trot stride of the
142 live horse (Barrey, 2001). The saddle force data were recorded at a frequency of 100Hz and
143 the mat is accurate to 0.1N (Tekscan, 2013), the stirrup force data were also recorded a
144 frequency of 100Hz and the stirrup sensors are accurate to the nearest 10N (Novel gmbh, 2017).
145 Due to the two measurement systems being by different manufacturers, automatic
146 synchronisation of data collection was not possible, the systems were manually synchronised
147 in that data collection for both systems was started at the same time. Due to the potential for
148 human error in this process, analysis was conducted on mean and peak values found over the
149 20 second data collection window and no analysis of the relationship between saddle and
150 stirrup force at specific time points was included.

151 *Data Analysis*

152 Saddle pressure data were analysed within the Tekscan CONFORMat v7.6x software, total
153 force (N) over the whole saddle pressure mat, and on the left and right sides of the saddle
154 separately, was then extracted in Microsoft (MS) Excel. Left and right stirrup force data (N)
155 were collected using the Novel Loadsol app via an Android smartphone and later downloaded
156 into MS Excel, these were then combined within MS Excel to create a total stirrup force
157 variable.

158 For both saddle and stirrup data the mean value was calculated for left, right, and total force
159 within each of the trot conditions over the entire 20 seconds of recorded data, with the obvious
160 exception of stirrup force data for the ‘without stirrups’ condition. The data were then
161 partitioned into strides, each stride lasting 0.93 seconds which was the average (mean, mode
162 and median) time between high (standing) stirrup force peaks in the rising trot. A peak value
163 for left, right, and total force was then extracted for each stride (0.93 second window) within
164 the 20 seconds and a mean of these peak values taken. All data were then normalised to the
165 bodyweight of the rider. Thus twelve variables were created; mean normalised saddle force
166 (left, right, and total) mean normalised stirrup force (left, right, and total), peak normalised
167 saddle force (left, right, and total) and peak normalised stirrup force (left, right, and total) and
168 extracted into IBM SPSS Statistics v21 for all remaining analyses.

169 Symmetry indices (SI) were calculated for mean normalised saddle and stirrup forces, using
170 the formula;

$$171 \quad SI(\%) = 100[(X_R - X_L) / 0.5(X_R + X_L)]$$

172 *Where X=measured parameter, R=right mean, L=left mean*

173 (Alexander *et al.*, 2015; Carpes *et al.*, 2010; Robinson *et al.*, 1987).

174 Symmetry indices were produced as both directional and non-directional variates to allow
175 comparison for both direction and overall degree of asymmetry between the conditions. For
176 the directional SI a positive sign indicates higher force on the right and a negative sign indicates
177 higher force on the left. Non-directional SI use only the value, with the sign removed, giving a
178 percentage asymmetry for a variable but without direction of asymmetry.

179 Normality of all variables was confirmed using the Kolmogorov-Smirnov test. Differences in
180 total mean and peak saddle force and saddle SI between the conditions were analysed using the
181 repeated measures Analysis of Variance (RM ANOVA) with Bonferroni correction applied to
182 the *post hoc* testing ($\alpha=0.017$). Differences in total mean and peak stirrup force and stirrup SI
183 between the sitting and rising conditions were analysed using the paired t-test ($\alpha=0.05$) due to
184 there being only two conditions in which this variable could be measured. Differences between
185 left and right mean and peak values for both saddle and stirrup force were also analysed using

186 the paired t-test ($\alpha=0.05$). In order to further investigate the relationship between stirrup force
 187 and participant bodyweight the Pearson's product moment correlation was then used to test for
 188 association between non- normalised mean and peak stirrup force and bodyweight in both
 189 sitting and rising trot ($\alpha=0.05$).

190 **Results**

191 Data shown are the averages for 14 participants of mean and peak saddle and stirrup force
 192 recorded at 100Hz for 20 seconds continuously, equivalent to 21 complete stride cycles, in each
 193 sitting trot, rising trot and trot without stirrups.

194 *Saddle forces*

195 Mean total saddle force did not significantly differ between the three conditions of rising trot,
 196 sitting trot and trot without stirrups (Table 1). There was a significant difference in peak total
 197 saddle force with pairwise comparisons showing the force in the without stirrups condition to
 198 be significantly higher than sitting trot with stirrups ($P=0.011$). There was a trend for peak
 199 total saddle force in rising trot to be higher than that in sitting trot, but the pairwise comparison
 200 was not significant ($P=0.031$) when the Bonferroni correction was applied ($\alpha=0.017$).

201

202 Table 1: Results of RM ANOVA showing main effects for total normalised saddle force and
 203 saddle force symmetry index across the three conditions of sitting trot, rising trot and trot
 204 without stirrups on the riding simulator (n=14)

Variable	Sitting Trot (Mean \pm SD)	Rising Trot (Mean \pm SD)	Without Stirrups (Mean \pm SD)	F	P
Mean Force (%bwt)	76.49 \pm 4.7	76.43 \pm 5.2	77.42 \pm 4.9	0.384	0.685
Peak Force (%bwt)	187.79 \pm 18.5 ^a	198.15 \pm 26.6 ^{ab}	195.78 \pm 28.7 ^b	4.437	0.022*
Symmetry Index (%)	+41.21 \pm 10.7	+39.87 \pm 10.3	+40.54 \pm 13.4	0.092	0.913

205 Directional SI; negative= higher force left, positive= higher force right
 206 *= $P<0.05$ **= $P<0.001$; superscript letters reflect significant difference on pairwise comparison
 207 bwt= bodyweight

208

209 When comparing saddle force between left and right hand sides of the saddle a significantly
 210 higher mean and peak force was recorded on the right hand side in all of the conditions (Table
 211 2). There were no significant differences in SI between the three conditions (Table 1). As all
 212 saddle forces were higher on the right hand side of the saddle for all riders in the sample across
 213 all conditions directional and non-directional SI would yield the same results, therefore only
 214 one set were analysed.

215

216 Table 2: Results of paired t-test between left and right mean and peak normalised saddle
 217 forces across the three conditions of sitting trot, rising trot and trot without stirrups on the
 218 riding simulator (n=14)

Condition	Variable	Left (Mean ±SD)	Right (Mean ±SD)	t	P
Sitting Trot	Mean Force (%bwt)	30.37±2.8	46.12±3.3	-14.77	<0.001**
	Peak Force (%bwt)	86.34±11.5	112.48±11.9	-9.05	<0.001**
Rising Trot	Mean Force (%bwt)	30.64±3.3	45.79±3.1	-15.36	<0.001**
	Peak Force (%bwt)	84.34±15.0	114.22±17.9	-5.73	<0.001**
Without Stirrups	Mean Force (%bwt)	30.75±2.7	46.46±4.1	-11.50	<0.001**
	Peak Force (%bwt)	93.14±15.9	118.48±15.9	-7.58	<0.001**

219 *=P<0.05 **=P<0.001

220 bwt= bodyweight

221

222 *Stirrup forces*

223 Stirrup loading was seen to follow the cyclical pattern of the stride within both sitting trot
 224 (Figure 1) and rising trot (Figure 2) as described by van Beek *et al.* (2012), with the current
 225 study also allowing consideration of each left and right stirrup separately.

226 Within the sitting trot the group mean demonstrated a tendency for a higher left stirrup force
 227 (Figure 1C) and asymmetry in stirrup force could be seen in individual participants (Figure
 228 1D). Within rising trot the left and right mean forces appear fairly similar at a group level
 229 (Figure 2C), however Figure 2D demonstrates a commonly seen movement pattern in
 230 individual participants in which the stirrup force is higher on one stirrup in the sitting phase of
 231 the stride (low peak) and then on the opposite stirrup when standing (high peak).

232

233 *Figure 1: Normalised stirrup force data in sitting trot for left stirrup (A) and right stirrup (B) showing*
 234 *mean (solid line) ± 1SD (dotted line) across all participants (n=14) and left and right stirrup composite*
 235 *graphs showing the mean of all participants (C) and an example of an individual participant (D) where*
 236 *solid line represents the left stirrup, dotted line represents the right. Please note the stirrup force*
 237 *measurement system used reports data to the nearest 10 Newtons, hence the staircase pattern in the*
 238 *individual participant data.*

239

240

241

242 *Figure 2: Normalised stirrup force data in rising trot for left stirrup (A) and right stirrup (B) showing*
 243 *mean (solid line) ± 1SD (dotted line) across all participants (n=14) and left and right stirrup composite*
 244 *graphs showing the mean of all participants (C) and an example of an individual participant (D) where*
 245 *solid line represents the left stirrup, dotted line represents the right. Note the high peak in the second*
 246 *half of the stride indicating the standing phase of the rising trot.*
 247

248 Both mean and peak total normalised stirrup forces were significantly higher in rising trot than
 249 sitting trot (Table 3). Mean stirrup SI was calculated at -8.9% for both sitting and rising
 250 conditions, demonstrating a propensity within the group for a higher left stirrup force (Table
 251 3), however this was only shown to be significant for peak forces within sitting trot (Table 4)
 252 where 71.4% of the sample showed a higher force on the left stirrup. There were no significant
 253 differences in stirrup SI between rising and sitting trot conditions. It was also noted that
 254 standard deviations for mean stirrup forces were more than double those for mean saddle force,
 255 demonstrating a greater inter-participant variability in this measure.

256 Table 3: Results of paired t-test for total normalised stirrup force and stirrup force symmetry
 257 index between sitting and rising trot on a riding simulator (n=14)

Variable	Sitting Trot (Mean ±SD)	Rising Trot (Mean ±SD)	t	P
Mean Force (%bwt)	22.33±6.8	37.06±8.4	-9.495	<0.001**
Peak Force (%bwt)	39.70±9.6	123.75±13.4	-24.184	<0.001**
Symmetry Index directional (%)	-8.92 ±22.2	-8.91 ±32.9	0	1.0
Symmetry Index non directional (%)	19.6 ±12.8	26.02±21.0	-1.035	0.320

258 Directional SI; negative= higher force left, positive= higher force right

259 *=P<0.05 **=P<0.001

260 bwt= bodyweight

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270 Table 4: Results of paired t-test between left and right mean and peak normalised stirrup
 271 forces in both sitting and rising trot on a riding simulator (n=14)

Condition	Variable	Left (Mean ±SD)	Right (Mean ±SD)	t	P
Sitting Trot	Mean Force (% bwt)	11.71±3.9	10.62±3.3	1.847	0.088
	Peak Force (% bwt)	21.90±5.6	19.21±5.2	2.299	0.039*
Rising Trot	Mean Force (% bwt)	19.50±6.1	17.57±4.9	1.005	0.333
	Peak Force (% bwt)	62.55±9.7	61.71±16.5	0.135	0.895

272 *=P<0.05 **=P<0.001

273 bwt= bodyweight

274 For the non-normalised stirrup force data correlated with rider bodyweight (68.9 ±9.9kg); peak
 275 total force in rising trot showed a significant positive correlation (r=0.804, P=0.001), however
 276 peak total force in sitting trot did not (r=0.047, P=0.873). Mean total stirrup force did not
 277 correlate with rider weight in either sitting trot (r=0.005, P=0.987) or rising trot (r=0.231,
 278 P=0.427).

279

280 Discussion

281 Saddle Forces

282 Significantly increased peak vertical saddle force was seen in the trot without stirrups condition
 283 compared to sitting trot with stirrups, supporting the original hypothesis. This is likely evident
 284 of the rider having less ability to control their downward acceleration relative to the saddle in
 285 this condition, this is in line with the findings of Lagarde *et al.* (2005) who demonstrated that
 286 an experienced rider uses flexion of the ankle to dampen the effects of vertical oscillations of
 287 the horse, which would be ineffective in the without stirrups condition. Whilst sitting trot is
 288 widely considered to be beneficial to rider posture (Loch, 2003; Print, 2011), there is growing
 289 interest within the literature on the negative effects of increased forces from the saddle on the
 290 horse (Clayton and Hobbs, 2017; Greve and Dyson, 2013). This finding demonstrates that
 291 future research is warranted to combine assessment of saddle force with three dimensional
 292 kinematic assessments of riders working without stirrups in order to gain a more complete
 293 picture of the potential impact of this common training activity on the horse.

294 Peak vertical saddle forces were higher in the rising trot than the sitting trot, although this was
 295 not significant. Previous studies have demonstrated the opposite with higher peak forces in the
 296 sitting trot when measured directly for one rider, riding multiple horses on a treadmill (Peham
 297 *et al.*, 2010) and for multiple riders on two different horses overland (de Cocq *et al.*, 2010b). It
 298 has however been seen that the equine spine flexes within the standing phase of the rising trot
 299 and extends within the sitting phase (de Cocq *et al.*, 2010a; Roepstorff *et al.*, 2009). The current

300 study took place on a riding simulator which is rigid and cannot absorb or displace any of the
301 vertical force from the movement of the rider, it may be that be that in extending the
302 thoracolumbar spine at the moment of impact of the rider's seat with the saddle, the live horse
303 attenuates some of this force, explaining why the forces described here are not consistent with
304 those seen previously in the live horse (de Cocq *et al.*, 2010b; Peham *et al.*, 2010).

305 There was no difference in saddle force symmetry index between the three conditions. This is
306 in agreement with Peham *et al.* (2010) who stated that the centre of pressure at the horse-saddle
307 –rider interface did not differ in position or variability between rising and sitting trot. This lack
308 of change also indicates that riders in this sample were able to stabilise their weight distribution
309 easily without stirrups, which is perhaps a factor of experience level, with all participants being
310 accustomed to working without stirrups. Novice riders may show a greater degree of
311 variability. It is possible that the short time period for which this exercise was used, along with
312 reduced biomechanical demands of the simulator (Ure *et al.*, 2018) was not enough to require
313 the rider to make postural adjustments to centralise their weight within the saddle for increased
314 stability. Alternatively it could be the completion of exercises developed to improve the seat
315 whilst working without stirrups that makes the difference to rider stability (Loch, 2003; Print,
316 2011) and not solely the removal of support for the legs.

317 All riders in the sample showed increased force on the right hand side of the saddle in all
318 conditions, however this was a relatively small sample size and care should be taken not to
319 over interpret the findings (Clayton and Hobbs, 2017). Great care was taken to ensure the
320 saddle was positioned centrally on the pressure mat and total force under each side of the saddle
321 was measured, which represents rider bodyweight distribution (de Cocq *et al.*, 2009), not
322 pressure or contact area as these variables would be more affected by saddle fit. An under
323 saddle pressure system cannot distinguish between vertical and shear forces (Janura *et al.*,
324 2012) therefore the right hand force increase detected could have been due to shear forces
325 associated with saddle roll to the left. Whilst no visible saddle roll was seen in the current study,
326 Guetjens *et al.* (2008) found that mounting a live horse from the left side caused increased force
327 under the right hand side of the saddle at the withers, even when using a high mounting block.
328 It may be that this slight movement of the saddle is never completely reversed when on the
329 simulator, as there is no movement of the back musculature which may naturally right the
330 saddle, also the girth does not completely encircle the horse, instead the saddle is anchored on
331 both sides, this may lead to a different pattern of saddle movement on the simulator as
332 compared to the live horse. A small number of studies have described the differences in rider
333 kinematics between the simulator and the live horse (Dumbell *et al.*, 2015; Ure *et al.*, 2018),
334 but future studies could investigate the kinetic differences to build a more complete picture of
335 the validity of the riding simulator as an alternative to the live horse within biomechanical
336 studies. It would also be useful consider the impact of mounting from the opposite side on
337 saddle force distribution, both on the simulator and the live horse.

338 Whilst the effect of mounting on the saddle may impact force distribution, consistent patterns
339 of rider asymmetry have also been reported in other studies. Riders have been shown to display
340 a marked pelvic tilt, most usually to the right with a corresponding left trunk tilt (Alexander *et al.*,
341 2015) and to axially rotate to the left whilst showing a greater right shoulder displacement
342 (Symes and Ellis, 2009). Asymmetrical rider posture is known to have an impact on saddle
343 force asymmetry (de Cocq *et al.*, 2009) and patterns such as those described could have
344 contributed to the tendency of this group to have a higher force on the right hand side of the
345 saddle. Several potential causes of rider asymmetry have been proposed including innate
346 laterality, musculoskeletal pain, and training effects (Clayton and Hobbs, 2017; Hobbs *et al.*,
347 2014) and whilst there have been a number of studies which attempt to remedy rider asymmetry

348 using a variety of techniques (Alexander *et al.*, 2015; Hampson and Randle, 2015; Nevison and
349 Timmis, 2013) there has been little investigation into the various potential causes in order to
350 assess their relative contribution and the ultimate effect of this on forces transferred to the
351 horse.

352

353 *Stirrup Forces*

354 It was noted that there was a tendency for one stirrup to bear more weight throughout the sitting
355 trot, in the case of this sample population a greater proportion of riders (71.4%) placed more
356 weight in the left stirrup. This could indicate a potential effect of pelvic limb laterality
357 (footedness) on the stirrup force data, as this value closely agrees with the proportion of the
358 population thought to have a left ‘stabilising’ limb, which is the limb naturally better
359 conditioned to supporting the body weight, whilst the opposite ‘mobilising’ limb carries out a
360 movement task (Previc, 1991; Sadeghi *et al.*, 2000). Future studies of rider laterality could
361 focus on footedness rather than handedness, which may help to better understand some of the
362 common asymmetries seen in the literature.

363 Van Beek *et al.* (2012) hypothesised that the right and left stirrups would be alternately loaded
364 in the sitting trot with a high peak on the right being associated with a low peak on the left and
365 vice versa. This exact pattern was not seen in the current study, with one stirrup showing higher
366 force in both peaks (Figure 1D), however when considering the group as a whole it was seen
367 that the force peaks did appear to increase and decrease in opposition to each other, without
368 actually overlapping (Figure 1C). It could be that the resolution of the stirrup force sensors
369 (10N) made this subtle difference difficult to discern for individual participants. Van Beek *et al.*
370 (2012) did suggest that the expected pattern of alternating left and right stirrup force could
371 be due to the rotation of the saddle about the vertical axis (yaw) as a result of the alternating
372 stance phases of the horse’s hind limbs. The current study was conducted on a simulator, which
373 whilst trying to approximate equine locomotion as closely as possible, is not capable of
374 producing the rotational motion of the saddle, therefore the pattern proposed by van Beek *et al.*
375 (2012) may be more clearly evident on the live horse.

376 Alternating higher and low peaks were however clearly seen in the rising trot with individual
377 riders demonstrating more force on one stirrup in the seated phase of the stride, and then the
378 opposite stirrup in the standing phase (Figure 2D). This could be linked to the muscle
379 movement pattern associated with rising on a particular ‘diagonal’ (Print, 2011) with the rider
380 unconsciously maintaining their centre of gravity more towards the side of the supporting hind
381 limb (that which is in stance) when in rising trot on a live horse. If this alternating pattern is
382 generated by rider movement and not the specific motion of the horse itself, this would explain
383 why it persists on the simulator. Individual asymmetries in stirrup force seen within the
384 participants in rising trot showed no significant differences when considered at the sample
385 level. This may partly have been due to the necessity to consider ‘left’ and ‘right’ as the main
386 groupings, rather than ‘inside’ and ‘outside’ as there is no limb movement, and therefore no
387 difference between a left and right diagonal stance phase. This means that it cannot be
388 determined if rider asymmetries in the rising trot are true asymmetries, or if they are associated
389 with unconsciously rising on specific diagonal.

390 The only stirrup force variable which showed a significant positive correlation with rider
391 weight was peak force in the rising trot condition. This indicates that downward force on the
392 stirrups in the standing phase of rising trot is mostly a function of the rider’s body mass
393 combined with the downward acceleration of the limb into the stirrup required to push the body
394 out of the saddle. Mean forces in rising trot, which describe the whole stride cycle, and both

395 mean and peak forces in sitting trot were not significantly correlated with body weight. This,
396 coupled with the high degree of variability in the proportion of body weight supported by the
397 stirrups indicates a large degree of individual difference in riders' load bearing patterns when
398 seated in the saddle. These differences could be related to riding level, with more experienced
399 riders being shown to have a more open hip angle and a straighter leg alignment in line with
400 classical riding guidelines (Kang *et al.* 2010; Schils *et al.*, 1993) and more effectively use the
401 ankle to dampen the acceleration caused by vertical movement of the horse's trunk (Lagarde
402 *et al.*, 2005), both factors which could impact on stirrup force. Whilst rider competence was
403 controlled within the sample, this was self-reported and the number of years' riding experience
404 was very variable, therefore this could have been a confounding factor. There are several
405 commonly observed rider faults, such as bracing into the stirrup, or having an unstable lower leg
406 (Loch, 2003), which could potentially influence mean stirrup force and have not yet been
407 investigated. Terada (2000) also found that riders with poor core muscle activation showed an
408 increase in activation of the adductor magus muscle, which would lead to the movement of
409 gripping with the knees. This is highly likely to reduce stirrup force and increase force
410 variability. Further research in this area could consider the relationship between stirrup forces
411 and rider kinematics to determine the how asymmetrical or variable stirrup loading relates to
412 the rider's posture and performance.

413

414 *Limitations*

415 This study did not include any male riders, in an attempt to control as many potential
416 confounding variables as possible at this early stage in the research. Males show different
417 spinopelvic anatomy to females (Janssen *et al.*, 2009; Rissech *et al.*, 2003) which may impact
418 on movement patterns at the rider-saddle interface. Female athletes in other sports have been
419 shown to have a greater propensity for internal hip rotation and a higher asymmetry in hip
420 abductor muscle strength when compared to males (Brophy *et al.*, 2009). These factors have
421 the potential to influence the force distribution across the saddle and stirrups when riding,
422 therefore the findings of the current study may not be as applicable to a sample of male riders.

423 This is the first peer reviewed study using this particular model of stirrup force sensor, thus the
424 protocol in terms of calibration, fitting and usage may require further development. Within this
425 trial the sensors were only calibrated once, prior to commencement of data collection, future
426 validation studies may be necessary to determine how much these single sensors are subject to
427 drift in calibration. Also this technology outputs the results to the nearest 10N, which may
428 mean that subtle differences in stirrup force are missed, especially in the lighter weight riders.
429 As the research area progresses more sensitive technologies may be required, however this
430 provides some useful preliminary data to support the development of future studies. The fact
431 that the saddle and stirrup force sensors could not be synchronised within this study also limits
432 the potential applications of this work and would be a valuable addition to future research to
433 fully describe the temporal relationships between these variables.

434 Some potential limitations and unknown factors with relation to the use of the simulator to
435 emulate the movement of a live horse have already been highlighted. It is also worth noting
436 that the trot stride duration of the simulator (0.93 seconds) is markedly longer than commonly
437 seen on the live horse, with 0.8 seconds being reported for collected trot and 0.7 for medium
438 trot (Walker *et al.*, 2017). This difference in the stride duration could potentially give riders
439 longer to react to the movement of the horse and to stabilise themselves. The movement is also
440 very predictable from stride to stride. These factors together could make it easier for the rider
441 to co-ordinate their movement pattern and this may help to explain why the peak forces shown

442 here are consistently lower than those seen in similar studies using live horses (Bogisch *et al.*,
443 2014; de Cocq *et al.*, 2010a).

444

445 **Conclusion**

446 Sitting trot without stirrups is a common practice in rider training, however this study
447 demonstrates that this could lead to increased peak vertical forces on the horse's back, the
448 effects of this force increase on the horse are not yet known and this highlights an important
449 area for future study. Predictable patterns of stirrup loading in time with the stride can be seen,
450 however the variability of stirrup force and the lack of relationship between this and rider
451 bodyweight, points to a great degree of variation between riders in how much weight they place
452 in the stirrups. Marked asymmetries in saddle and stirrup force across the population add to the
453 number of studies reporting significant asymmetry in equestrian riders. There are several
454 potential causes for rider asymmetry discussed in the literature including laterality,
455 musculoskeletal pain, and training effects. Future research should focus on characterising
456 common rider asymmetry patterns within a larger sample population and investigating the
457 underlying causes, so as to better support riders and minimise the potential for damage to the
458 horse from uneven force distribution.

459

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463

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