An exploration of strategies used by dressage horses to control moments around the center of mass when performing passage

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Background. Locomotion results from the generation of ground reaction forces (GRF) that cause translations of the center of mass (COM) and generate moments that rotate the body around the COM. The trot is a diagonally-synchronized gait performed by horses at intermediate locomotor speeds. Passage is a variant of the trot performed by highly-trained dressage horses. It is distinguished from trot by having a slow speed of progression combined with great animation of the limbs in the swing phase. The slow speed of passage challenges the horse's ability to control the sagittal-plane moments around the COM. Footfall patterns and peak GRF are known to differ between passage and trot, but their effects on balance management, which we define here as the ability to control nose-up/nose-down pitching moments around the horse's COM to maintain a state of equilibrium, are not known. The objective was to investigate which biomechanical variables influence pitching moments around the COM in passage. **Methods**. Three highly-trained dressage horses were captured by a 10-camera motion analysis system (120 Hz) as they were ridden in passage over 4 force platforms (960 Hz). A full-body marker set was used to track the horse's COM and measure balance variables including total body center of pressure (COP), pitching moments, diagonal dissociation timing, peak force production, limb protraction-retraction, and trunk posture. A total of twenty passage steps were extracted and partial correlation (accounting for horse) was used to investigate significant (P<0.05) relationships between variables. **Results**. Hindlimb mean protraction-retraction correlated significantly with peak hindlimb propulsive forces (R=0.821; P<0.01), mean pitching moments (R=0.546, P=0.016), trunk range of motion, COM craniocaudal location and diagonal dissociation time (P<0.05). **Discussion**. Pitching moments around the COM were controlled by a combination of kinematic and kinetic adjustments that involve coordinated changes in GRF magnitudes, GRF distribution between the diagonal limb pairs, and the moment arms of the vertical GRFs. The moment arms depend of hoof placements

relative to the COM, which were adjusted by changing limb protraction-retraction angles. Nose-up pitching moments could also be increased by providing a larger hindlimb propulsive GRF.

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4   **Abstract**

5   **Background**. Locomotion results from the generation of ground reaction forces (GRF) that cause

6   translations of the center of mass (COM) and generate moments that rotate the body around the

7   COM. The trot is a diagonally-synchronized gait performed by horses at intermediate locomotor

8   speeds. Passage is a variant of the trot performed by highly-trained dressage horses. It is

9   distinguished from trot by having a slow speed of progression combined with great animation of

10 the limbs in the swing phase. The slow speed of passage challenges the horse's ability to control

11 the sagittal-plane moments around the COM. Footfall patterns and peak GRF are known to differ

12 between passage and trot, but their effects on balance management, which we define here as the

13 ability to control nose-up/nose-down pitching moments around the horse's COM to maintain a

14 state of equilibrium, are not known. The objective was to investigate which biomechanical

15 variables influence pitching moments around the COM in passage.

16 **Methods**. Three highly-trained dressage horses were captured by a 10-camera motion analysis

17 system (120 Hz) as they were ridden in passage over 4 force platforms (960 Hz). A full-body

18 marker set was used to track the horse's COM and measure balance variables including total body

19 center of pressure (COP), pitching moments, diagonal dissociation timing, peak force production,

20 limb protraction-retraction, and trunk posture. A total of twenty passage steps were extracted and

21 partial correlation (accounting for horse) was used to investigate significant ($P<0.05$)

22 relationships between variables.

23 **Results**. Hindlimb mean protraction-retraction correlated significantly with peak hindlimb

24 propulsive forces ($R=0.821$; $P<0.01$), mean pitching moments ($R=0.546$, $P=0.016$), trunk range

25 of motion, COM craniocaudal location and diagonal dissociation time ($P<0.05$).

26 **Discussion**. Pitching moments around the COM were controlled by a combination of kinematic

27 and kinetic adjustments that involve coordinated changes in GRF magnitudes, GRF distribution

28 between the diagonal limb pairs, and the moment arms of the vertical GRFs. The moment arms

29 depend of hoof placements relative to the COM, which were adjusted by changing limb

30 protraction-retraction angles. Nose-up pitching moments could also be increased by providing a

31 larger hindlimb propulsive GRF.

32 **Introduction**

33 Horses are cursorial animals capable of performing a wide repertoire of gaits over a large range

34 of speeds. In the past, the horse's locomotor prowess was exploited in transportation, warfare and

35 agriculture but is now primarily important in equestrian sports. The growth of equestrian sports

36 has led to an upsurge of interest in the physiological and biomechanical characteristics of the

37 performance of equine athletes. Dressage is an Olympic equestrian sport in which horses perform

38 natural and artificial gaits in a variety of patterns to demonstrate an advanced level of control of

39 locomotor kinematics and kinetics. Highly-trained dressage horses offer a unique opportunity to

40 study the mechanics of equine locomotor performance and balance control.

41 During locomotion, the limbs generate ground reaction forces (GRF) that translate the center of

42 mass (COM) and create turning forces (moments) around the COM. Sagittal plane moments

43 around the COM cause pitching rotations of the horse's body in a nose-up or nose-down

44 direction. When traveling at constant speed, the sagittal plane moments within a stride fluctuate

45 as the fore-aft distance between the COM and body center of pressure (COP) changes (Lee,

46 Bertram & Todhunter,1999; Biewener et al., 2009; Hobbs, Bertram & Clayton, 2016). In

47 quadrupeds locomotor function is related to posture (Alexander, 1984). Trunk and neck postural

48 stability and synchrony are important in trotting horses, as this helps to maintain the vestibular

49 apparatus orientation relative to gravity (Dunbar et al., 2008), so pitching moments are controlled

50 to ensure that their effect is small. Roll and yaw moments may also destabilize the body and need

51 to be managed, but in dogs and goats sagittal plane pitching moments were found to be larger

52 (Biewener et al., 2009). For cursorial mammals with vertically oriented limbs and a high COM,

53 the ability to balance pitching moments in the direction of motion is therefore important (Hobbs,

54 Bertram & Clayton, 2016).

55 In horses trotting at moderate speed, three fundamental motor control strategies are used to

56 balance sagittal-plane pitching moments (Hobbs, Bertram & Clayton, 2016). The first motor

57 control strategy is temporal dissociation of the diagonal limbs at landing (diagonal dissociation),

58 the second motor control strategy is adjustment of craniocaudal hoof contact position relative to

59 the COM by changing limb protraction-retraction, and the third motor control strategy is

60 alteration of the vertical force distribution between concurrently-loaded fore- and hindlimbs.

61 Dressage horses are trained to maintain the trunk in a more nose-up posture and to control

62 pitching rotation around the COM. In equestrian terminology, this is described as being in an

63 uphill balance and is one of the components of collection and self-carriage (Holmström,

64 Fredricson & Drevemo, 1995). One of the most challenging movements performed by dressage

65 horses is a slow, majestic type of trot called passage, which demonstrates the highest degree of

66 collection, elevation of the forehand, cadence and suspension in the trot (Fédération Equestre

67 Internationale, 2014). These requirements present a challenge with regard to managing pitching

68 moments and some dressage horses fail to reach the highest levels of competition due to an

69 inability to learn the skills necessary to stabilize their trunk in passage.

70 Although passage is defined as a two-beat gait, hind-first diagonal dissociation occurs

71 consistently on landing (Holmström, Fredricson & Drevemo, 1994; Clayton, 1997; Weishaupt et

72 al., 2009) and this has been shown to influence pitching moments at trot (Hobbs, Bertram &

73 Clayton, 2016). Postural characteristics of passage that distinguish it from trot include reduced

74 ranges of limb protraction-retraction (Holmström, Fredricson & Drevemo, 1995; Weishaupt et al.,

75 2009). Reduced limb protraction-retraction affects the hoof contact positions relative to the

76 proximal limb segments and to the COM location throughout stance. Also, all limbs generate

77 higher vertical impulses in passage than in trot with a relatively greater increase in the hindlimbs

78 compared with the forelimbs (Holmström, Fredricson & Drevemo, 1995; Clayton, Schamhardt &

79 Hobbs, 2017). These findings suggest that horses may use all three of the motor control strategies

80 described for the trot to manage their posture and control pitching moments when performing the

81 technically difficult movement of passage.

82 This study was designed to explore the intricacies of controlling sagittal plane trunk orientation

83 and rotation in passage, which will lead to a better understanding of the mechanisms available to

84 quadrupeds for managing moments around the COM. On a practical level, the insights gained

85 will elucidate understanding the training challenges and inherent physical limitations that make it

86 difficult for some horses to perform passage. The specific aim was to identify biomechanical

87 variables that affect control of moments around the COM when performing passage. We predict

88 that all three motor control strategies, which involve manipulation of temporal kinematics, linear

89 kinematics and GRFs, will have a demonstrable effect on the horse's posture, represented in the

90 sagittal plane by the orientation of the trunk, and the moments around the COM. Thus, the

91 experimental hypotheses are that diagonal dissociation, limb protraction-retraction, and fore:hind

92 vertical force distribution affect trunk inclination and pitching moments around the horse's COM

93 during passage.

94 **Materials and Methods**

95 The study was performed with approval from the Michigan State University Institutional Animal

96 Care and Use Committee under protocol number 02/08-020-00.

Experimental Data Collection

97

98 Three highly-trained Lusitano dressage horses; mass 607 ± 9 kg ridden by the same highly

99 experienced rider; mass 61.5 kg were used for the study. All horses were judged by an

100 experienced veterinarian to be free from lameness when trotting in a straight line. They were

101 accustomed to the laboratory environment before data collection commenced.

102 Retro-reflective markers secured to the skin were tracked at 120 Hz using a 10-camera Motion

103 Analysis System (Motion Analysis Corporation, Santa Rosa, California, USA) to acquire a full

104 body kinematic model of the horse as described in (Hobbs, Richards & Clayton, 2014) with the

105 omission of trunk tracking markers T10-T18. The horses warmed up in a riding arena prior to

106 data collection. Once suitably prepared they performed a series of trials of passage along a

107 runway in which a series of four force plates (Bertec Corporation, Columbus, Ohio, USA)

108 recording at 960 Hz were embedded. Successful trials were those in which the horses moved

109 straight and consistently through the data collection volume with only one hoof at a time being in

110 contact with each force plate.

111 The timings of hoof contacts and lift offs were identified from the force data using a threshold of

112 50 N. Diagonal steps for the left forelimb and right hindlimb pair (LFRH) and the right forelimb

113 and left hindlimb pair (RFLH) were extracted when both limbs of the diagonal pair made valid

114 contacts with different force plates. Summed fore- and hindlimb GRF for each diagonal step were

115 calculated and the time of zero summed longitudinal force (Tzero) was used to separate braking

116 and propulsive phases.

117   Variables of interest were chosen based on those identified by Hobbs, Bertram & Clayton (2016)

118   as being important to the management of pitching moments during trotting. Craniocaudal COM

119   location relative to the diagonal hoof placements was calculated from the distance by which the

120   COM was behind (caudal to) the grounded fore hoof divided by the distance between the

121   diagonal fore and hind hooves. Body center of pressure (COP) location was determined based on

122   the magnitudes of the vertical forces in the fore- and hindlimbs combined with the COP locations

123   of concurrently-loaded hooves. The instantaneous location of the body COP was then expressed

124   relative to the base of support as the relative distance from the position of the grounded fore hoof

125   divided by the distance between the diagonal fore and hind hooves. The body's COM and COP

126   locations were therefore reported as ratios with higher values indicating greater proximity to the

127   hind hoof.

128   Moments about the COM due to the effect of GRFs (MGRF) (Nm/kg) were determined over time

129   for each diagonal step (Hobbs, Richards & Clayton, 2014) and mean values were calculated

130   separately for braking and propulsive phases with positive values representing a nose-down

131   moment. Peak vertical force (GRFV) (N/kg) and the time taken to reach peak force (T) (%

132   stance) were measured for each limb.

133   Diagonal dissociation time (DIS) (s) was calculated as the time elapsing between hind and fore

134   contacts of each diagonal pair with the value of hind-first contacts being designated positive and

135   fore-first contacts being designated negative. Limb protraction and retraction angles were

136   measured relative to the vertical by representing the forelimb/hindlimb as a line from the tuber

137   spinae scapulae/greater femoral trochanter to the center of rotation of the distal interphalanegeal

138   joint. Protraction was negative, retraction was positive. Mean protraction-retraction angles over

139   the entire stance phase were calculated for the fore ($P\text{-}R_F$) and hind ($P\text{-}R_H$) limbs.

140   Trunk orientation was represented by a line from the cervical C6/C7 junction to the second

141   coccygeal vertebra (CA2). Trunk inclination was the angle between that line and a horizontal line

142   through the C6/C7 junction. Positive values indicated CA2 was higher than C6/C7 junction. The

143   range of trunk angular motion (ROM_T) and mean trunk inclination (INC_T) during each diagonal

144   step (degrees) were calculated to represent measures of dynamic posture, as described by Hobbs,

145   Bertram & Clayton (2016). All variables of interest were calculated in Visual 3D (C-Motion Inc.,

146   Germantown, Maryland, USA).

147   **Data Analysis**

148   Tabulated data were imported into SPSS (IBM Corporation, Armonk, New York, USA) for

149   analysis. Data were tested for normality using a Kolmogorov–Smirnov test and all variables were

150   found to be normally distributed except mean forelimb protraction-retraction angle, which was

151   log transformed. Partial correlations (Morrison, 1976) controlling for horse were used to

152   determine the relationships between variables and to evaluate balance strategies where significant

153   relationships existed. Significance was set at $P<0.05$.

154   **Results**

155   All variables of interest were pooled, which provided a total of 20 steps from the 3 horses, (10

156   steps from each diagonal pair). Mean and standard deviation (s.d.) are reported for each variable

157   for the pooled data in Table 1, together with the correlations between variables, significance

158   levels and a subjective classification of the variables into the three motor control strategies

159   previously identified (Hobbs, Bertram & Clayton, 2016). Standing COP location was (mean ±

160   s.d.) 0.4 ± 0.00 (ratio), indicating that the fore:hind vertical force distribution ratio was 60:40.

161   Standing trunk inclination was 11.9 ± 0.01 degrees for the three horses.

162   The COM moved forward at an average speed of 1.22 ± 0.18 m/s. Relative to the grounded limbs

163   it was positioned at approximately 70% of the distance from forelimbs to hindlimbs at the start of

164   stance then progressed forward to a position 20-40% of diagonal distance behind the forelimb at

165   lift off. Greater mean hindlimb protraction, which indicates use of the second motor control

166   strategy, placed the hind hoof significantly (R=-0.771; P<.01) closer to the COM and

167   significantly (R=0.546; P<.05) increased nose up moments during propulsion (Table 1).

168   The hind hoof was predominantly the first of the diagonal pair to contact the ground, and when

169   this occurred the COP initially coincided with the hind hoof position, then moved forward

170   gradually until it coincided with the position of the fore hoof, which was always the last hoof to

171   lift off. Through most of stance the COP tracked the COM quite closely (Figure 1), which was

172   achieved by adjusting the relative distribution of the vertical GRF between the fore- and

173   hindlimbs; as the COP moved closer to the fore hoof, the forelimb supported a greater proportion

174   of the total vertical GRF.

175   Trunk inclination had strong negative correlations with the positions of both the COM and COP

176   (Table 1), such that greater elevation of the forehand was associated with closer proximity of the

177   COM and COP to the hind hoof.

178   The moments around the COM due to the vertical and longitudinal GRFs tended to act in

179   opposite directions through much of stance, which had the effect of keeping the total moments

180   around the COM relatively small (Figure 2). The net moment was nose-down in early diagonal

181   stance and nose-up in late stance. Post hoc correlations were performed between limb

182   protraction-retraction angles and peak longitudinal forces to further explore the influence of hoof

183 placement on balance. A strong relationship was found between a more retracted mean angle of

184 the hindlimb and peak hindlimb longitudinal propulsive (R=0.821; P<.01) and braking (R=0.654;

185 P<.01) forces. There was also a significant relationship between having a less protracted mean

186 forelimb angle and a higher peak forelimb propulsive force (R=0.581; P<.01).

187 **Discussion**

188 Dressage training develops the horse's ability to move with good posture, which involves

189 maintaining the trunk in an uphill (nose-up) orientation, and minimizing the sagittal plane trunk

190 rotations. Under these conditions the horse is described as being in good balance and self-carriage

191 (Fédération Equestre Internationale, 2014). The study described here has advanced our

192 understanding of how dressage horses achieve these objectives by identifying kinematic and

193 kinetic variables that are associated with elevation of the forehand and reduction of pitching

194 moments around the COM in passage. The results also indicate areas in which horses that fail to

195 learn the passage might be deficient in strength or coordination.

196   Dressage doctrine indicates the desirability of the hind hoof stepping further forward relative to

197 the trunk segment in all gaits. In passage less protraction and less retraction are reported in the

198 hind limb compared with trot (Holmström, Fredricson & Drevemo, 1995), but the mean hindlimb

199 protraction-retraction angle reported here is similar to that for horses trotting in hand (Hobbs,

200 Bertram & Clayton, 2016). This indicates that the hind hoof does not step or remain further

201 forwards in passage compared to trot. Our findings do, however, support the importance of foot

202 contact position, the second motor control strategy, for adjusting moments around the COM in

203 passage by showing that, if hindlimb protraction is limited, for example by conformation, the

204 horse will have difficulty performing passage. Adjustment of limbprotraction-retraction has been

205 used to control velocity and maintain fore-aft stability in trotting quadrupedal robots (Raibert,

206   1986; Raibert, 1990) and more recently as an additional mechanism to successfully negotiate

207   uneven ground at high speed trot (Palmer & Orin, 2007) In robots though, these limb adjustments

208   are made to ensure that synchronous diagonal contacts are achieved between fore and hindlimbs,

209   which controls pitch and roll moments (Palmer & Orin, 2007). Quadrupedal mammals are not

210   constrained in this way, as diagonal dissociation, the first motor control strategy may be used to

211   maintain stability during trotting (Hobbs, Bertram & Clayton, 2016). In passage, the majority of

212   diagonal contacts were hind-first, but they appeared to play a relatively minor role in managing

213   sagittal plane moments. Subtle differences in contact timing between fore and hindlimbs have

214   been reported previously in dogs (Lee, Bertram & Todhunter, 1999), but these were associated

215   with morphological and mass distribution differences between the breeds that were tested

216   (Greyhounds and Labrador Retrievers). In horses, diagonal dissociation has been shown to

217   change the inter-limb timing of force production during stance, which affects the relative GRF

218   contributions of the fore and hind limbs (Hobbs, Bertram & Clayton, 2016). In passage, peak

219   forelimb GRF occurred earlier when hind-first dissociation was greater, but this did not influence

220   the relative GRF contributions either. Instead, evidence suggested that hind-first dissociation

221   influenced trunk and limb posture. A greater elevation of the forehand, as indicated by a trunk

222   angle closer to zero, greater hindlimb protraction and an increased trunk ROM were found when

223   a longer time elapsed between hind and forelimb contacts. Greater elevation of the forehand also

224   occurs with greater forelimb protraction. Forelimb posture may dictate trunk pitch on hindlimb

225   landing, after which loading and trunk pitch then influence hindlimb compression (Deng et al.,

226   2010). The overall effect is that an earlier hindlimb landing and greater trunk pitch increase the

227   trunk ROM. This may be a key demand on the hindlimbs when performing passage.

228   For a horse moving at constant speed, longitudinal GRFs and COM moments over an entire stride

229   should sum to zero. Pitching moments are due to the effects of the GRFs acting at a distance from

230   the COM and to the inertial effects associated with movements of the body segments (Hobbs,

231 Richards & Clayton, 2014). With regard to GRF moments, hindlimb vertical GRF and

232 longitudinal braking GRFs create nose-down moments, whereas forelimb vertical GRF and

233 longitudinal propulsive GRFs create nose-up moments. The moment arms of the vertical force

234 components depend on the longitudinal proximity of the hoof to the COM. The moment arms of

235 the longitudinal GRFs are related to limb lengths. Greater hindlimb protraction places the hind

236 hoof closer to the COM, thereby reducing the moment arm of its vertical GRF.

237 Trotting dogs have been shown to balance the sagittal plane moments by adjusting the fore and

238 hind limb GRFs (Lee, Bertram & Todhunter, 1999). In trotting horses, hindlimb vertical GRF is

239 the main contributor to a nose-down moment (Hobbs, Richards & Clayton, 2014) but this was not

240 the case in passage in which pitching was controlled by manipulating both the vertical and

241 longitudinal GRF moments (Figure 2). Hindlimb propulsive force, which contributes to the nose-

242 up moment, is larger in passage than collected trot (Clayton, Schamhardt & Hobbs, 2017) and is

243 correlated with increased hindlimb retraction. The ability to use the longitudinal GRF to generate

244 a larger nose-up moment during hindlimb retraction offers a mechanism to combat the increase in

245 nose-down moment associated with the higher hindlimb vertical GRF. Thus, horses may also use

246 the third motor control strategy of adjusting the GRFs to control moments around the COM.

247 Positioning the hindlimb closer to the COM might be expected to increase its weight-bearing

248 responsibility (Holmström, Fredricson & Drevemo, 1994) but, in fact, hindlimb protraction-

249 retraction was not related to hindlimb peak vertical GRF. In contrast, mean forelimb angulation is

250 more protracted in passage than collected trot (Weishaupt et al., 2009), which positions the

251 forelimb further away from the COM and forelimb angulation was correlated with a higher peak

252 vertical GRF in the hindlimbs. So the increased weight-bearing responsibility of the hindlimbs is

253 effected by positioning the forelimbs further from the COM throughout the stance phase.

254   In trotting horses, COP position changes only a little during the middle part of stance with the

255   largest movement occurring in horses that show hind-first diagonal dissociation (Hobbs, Bertram

256   & Clayton, 2016). At the same time, the COM is moving forward at almost constant speed and,

257   consequently, the position of the COP relative to the COM changes continuously through stance

258   (Hobbs & Clayton, 2013). In passage, the COP tracks the COM much more closely as a

259   consequence of continual adjustments in the vertical GRF ratio between the diagonal limbs such

260   that the relative contribution of the forelimb increases as stance progresses. This causes the COP

261   to move closer to the forelimb at a rate similar to the forward progression of the COM (Hobbs,

262   Bertram & Clayton, 2016). When the COP follows the COM more closely, it decreases the

263   moment arm lengths of the vertical GRF, which may be a strategy to reduce moments around the

264   COM. A similar technique is used by trotting dogs during moderate acceleration and deceleration

265   (Lee, Bertram & Todhunter, 1999). Their study found that during acceleration the limbs act in a

266   more retracted position that favours the development of longitudinal propulsive forces, and

267   during deceleration the limbs are held in a more protracted position to facilitate the application of

268   braking forces. The skewed limb positions help to align the resultant GRF vector so it passes

269   close to the COM, thereby reducing the effective moment arm length and, therefore, moments

270   around the COM.

271   In galloping horses the function of the leading, more protracted forelimb is to provide an impulse

272   that deflects the COM from forwards to upwards (Bertram & Gutmann, 2009). Greater mean

273   protraction of the forelimb in passage is likely required to deflect the COM upwards and, together

274   with increased vertical impulses (Holmström, Fredricson & Drevemo, 1995; Clayton,

275   Schamhardt & Hobbs, 2017), produce a larger vertical COM excursion. Unlike the gallop, this

276   limb posture is not associated with an increase in braking impulse compared to collected trot

277   (Clayton, Schamhardt & Hobbs, 2017), but this may be because the forward velocity is slower in

278   passage.

279   It is difficult to identify owners who are willing to make top quality horses available for research

280   and the opportunity to work with horses of this calibre using these techniques is unusual, though

281   the small number of horses is acknowledged as a limitation to the present study. All horses were

282   of the same breed and ridden by the same rider. Although this may be considered a limitation, a

283   previous study (Clayton, Schamhardt & Hobbs, 2017) reported no significant differences in the

284   GRFs generated in passage by Lusitano horses versus Dutch warmblood horses, suggesting that

285   passage is performed similarly across breeds. Finally, the control of balance is not limited to the

286   sagittal plane, but our study did not take into account the influence of altered kinetics and

287   kinematics on medio-lateral balance. Medio-lateral GRF are reported to be highly variable during

288   trotting (Merkens et al., 1993), so trunk roll and yaw may be more sensitive to the changes

289   reported here and will be an interesting topic for future study.

290   **Conclusions**

291   The mean pitching moments around the horse's COM were managed differently in passage than

292   during trotting, although evidence of all three balancing strategies were found in both gaits. In

293   passage, both the timing (control strategy 1) and position (control strategy 2) of limb contacts

294   play a key role. Adjustments in the fore- and hindlimb vertical GRF (control strategy 3), together

295   with a slower forward COM velocity allowed the COP to track the COM more closely in passage

296   than in trot. Since this reduced the effective moment arm lengths of the vertical GRFs, pitching

297   moments were particularly sensitive to vertical force magnitudes. In trotting, the largest

298   contributor to the nose-down moment is the hindlimb vertical GRF. In passage, the effect of a

299   relative increase in hindlimb vertical GRF in creating a nose-down moment was somewhat

300   countered by either; a more protracted hindlimb position which shortened its moment arm, or by

301   an increase in hindlimb longitudinal propulsive GRF which increased the nose-up moment. Given

302   the complexity of the kinematic and kinetic adjustments required to control pitching moments in

303   passage, it is not surprising that some horses fail to learn the biomechanical skills necessary to

304   perform this movement well.

305   **References**

306   Alexander RM. 1984. The gaits of bipedal and quadrupedal animals. International Journal of

307   Robotics Research 3:49-59.

308   Bertram JEA, Gutmann A. 2009. Motions of the running horse and cheetah revisited:

309   fundamental mechanics of the transverse and rotary gallop. Journal of the Royal Society Interface

310   6:549-559. DOI 10.1098/rsif.2008.0328

311   Biewener AA, Ros I, Lee DV, Antonnen J, Higgins T. 2009. Ground reaction force and centre of

312   mass dynamics of goats and dogs trotting and galloping. *Integrative and Comparative Biology*

313   49: E15.

314   Clayton HM. 1997. Classification of collected trot, passage and piaffe using stance phase

315   temporal variables. *Equine Veterinary Journal Supplement* 23:54-57.

316   Clayton HM, Schamhardt HC, Hobbs SJ. 2017. Ground reaction forces of elite dressage horses in

317   collected trot and passage. *Veterinary Journal* 221:30-33. doi.org/10.1016/j.tvjl.2017.01.016

318   Deng Q, Wang S, Liang Q, Mo J. 2010. The effects of body pitching on leg spring behaviour in

319   quadruped running. *Journal of Bionic Engineering* 7: 219-227.

320   Dunbar DC, MacPherson JM, Simmons RW, Zarcades A. 2008. Stabilization and mobility of the

321   head, neck and trunk in horses during overground locomotion: comparisons with humans and

322   other primates. Journal of Experimental Biology 211: 3889-3907. DOI 10.1242/jeb.020578

323   Fédération Equestre Internationale. 2014. Dressage Rules 25th edition, with updates effective 1st

324   January 2017. *Available at https://inside.fei.org/sites/default/files/DRE-*

325   *Rules_2017_GA_approved_clean.pdf*

326   Hobbs SJ, Bertram JEA, Clayton HM. 2016. An exploration of the influence of diagonal

327   dissociation and moderate changes in speed on locomotor parameters in trotting horses. *PeerJ*

328   4:e2190; DOI 10.7717/peerj.2190.

329   Hobbs SJ, Clayton HM. 2013. Sagittal plane ground reaction forces, center of pressure and center

330   of mass in trotting horses. The Veterinary Journal 198, e14-e19.

331   doi.org/10.1016/j.tvjl.2013.09.027

332   Hobbs SJ, Richards J, Clayton HM. 2014. The effect of center of mass location on sagittal plane

333   moments around the center of mass in trotting horses. *Journal of Biomechanics* 47:1278-1286.

334   doi.org/10.1016/j.jbiomech.2014.02.024

335   Holmström M, Fredricson I, Drevemo S. 1994. Biokinematic analysis of the Swedish Warmblood

336   riding horse trot. *Equine Veterinary Journal* 26:235-240.

337   Holmström M, Fredricson I, Drevemo S. 1995. Biokinematic effects of collection in the elite

338   dressage trot. *Equine Veterinary Journal* 27:281-287.

339   Lee DV, Bertram JEA, Todhunter RJ. 1999. Acceleration and balance in trotting dogs. *Journal of*

340   *Experimental Biology* 202:3565-3573.

341 Merkens HW, Schamhardt HC, van Osch GJVM, van den Bogert AJ. 1993. Ground reaction

342 force patterns of Dutch Warmblood horses at normal trot. *Equine Veterinary Journal* 25:134-137.

343 Morrison DF. 1976. IN: Multivariate statistical methods. New York: McGraw-Hill.

344 Palmer LR, Orin DE. 2007. Quadrupedal running at high speed over uneven terrain. In:

345 Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems

346 San Diego, CA, USA, Oct 29 - Nov 2, 2007. pp303-308.

347 Raibert MH. 1986. Legged robots that balance. Cambridge, MA: MIT Press.

348 Raibert MH. 1990. Trotting, pacing and bounding by a quadrupedal robot. Journal of

349 Biomechanics 23:79-98.

350 Weishaupt MA, Byström A, von Peinen K, Wiestner T, Meyer H, Waldern N, Johnston C, Van

351 Weeren R, Roepstorff L. 2009. Kinetics and kinematics of the passage. *Equine Veterinary*

352 *Journal* 41:263–267. doi: 10.2746/042516409X397226

353 **Table Legend**

354 **Table 1**: Mean and (standard deviation) for pooled data of 20 steps of passage and relationship

355 between variables (accounting for horse). Shaded boxes indicate the balance strategy

356 classifications of the variables. Significance; * P<.05, **P<.01

357 MGRF Br: sagittal plane moment around the center of mass due to ground reaction forces during

358 the braking phase; MGRF Pr: sagittal plane moment around the center of mass due to ground

359 reaction forces during the propulsive phase; ROM_T: trunk range of angular motion; INC_T: mean

360 trunk inclination angle; COM: mean center of mass location during stance; DIS: diagonal

361 dissociation; T_F: time taken to reach peak vertical GRF in the forelimb; T_H: time taken to reach

362 peak vertical GRF in the hindlimb; P-R_F: mean protraction-retraction angle of the forelimb during

363 stance; P-R_H: mean protraction-retraction angle of the hindlimb during stance; COP: mean center

364 of pressure location during stance; $GRFV_F$: peak vertical ground reaction force in the forelimb;

365 $GRFV_H$: peak vertical ground reaction force in the hind limb.

366   **Figure Legends**

367   **Figure 1:** Translations of the horse's center of mass (COM) and center of pressure (COP)

368   locations during one stride of passage. Progression of the COM and COP are shown relative to

369   the grounded forelimb and expressed as a fraction of the diagonal distance.

370   **Figure 2:** Moments around the center of mass (COM) (Nm/kg) during one stride of passage.

371   MGRF: total moments around the COM due to the effect of the ground reaction forces; $MGRF_V$:

372   moments due to vertical force production; $MGRF_L$: moments due to longitudinal force

373   production.

Figure 1

Translations of the horse's center of mass (COM) and center of pressure (COP) locations during one stride of passage.

Progression of the COM and COP are shown relative to the grounded forelimb and expressed as a fraction of the diagonal distance.

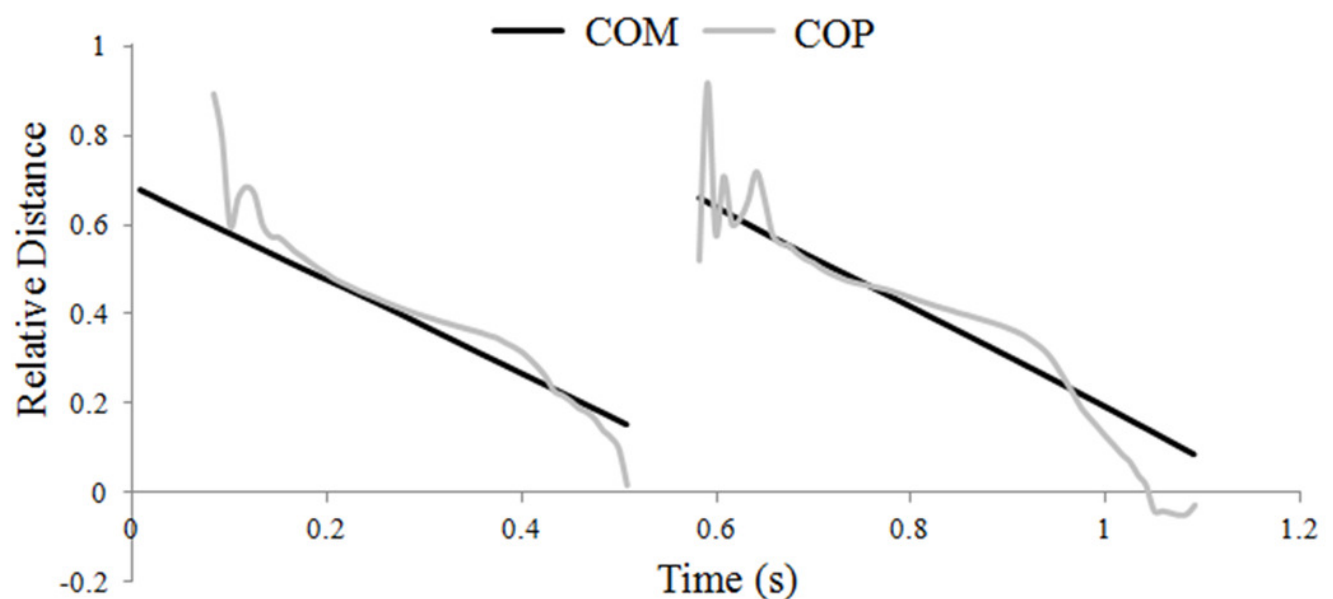
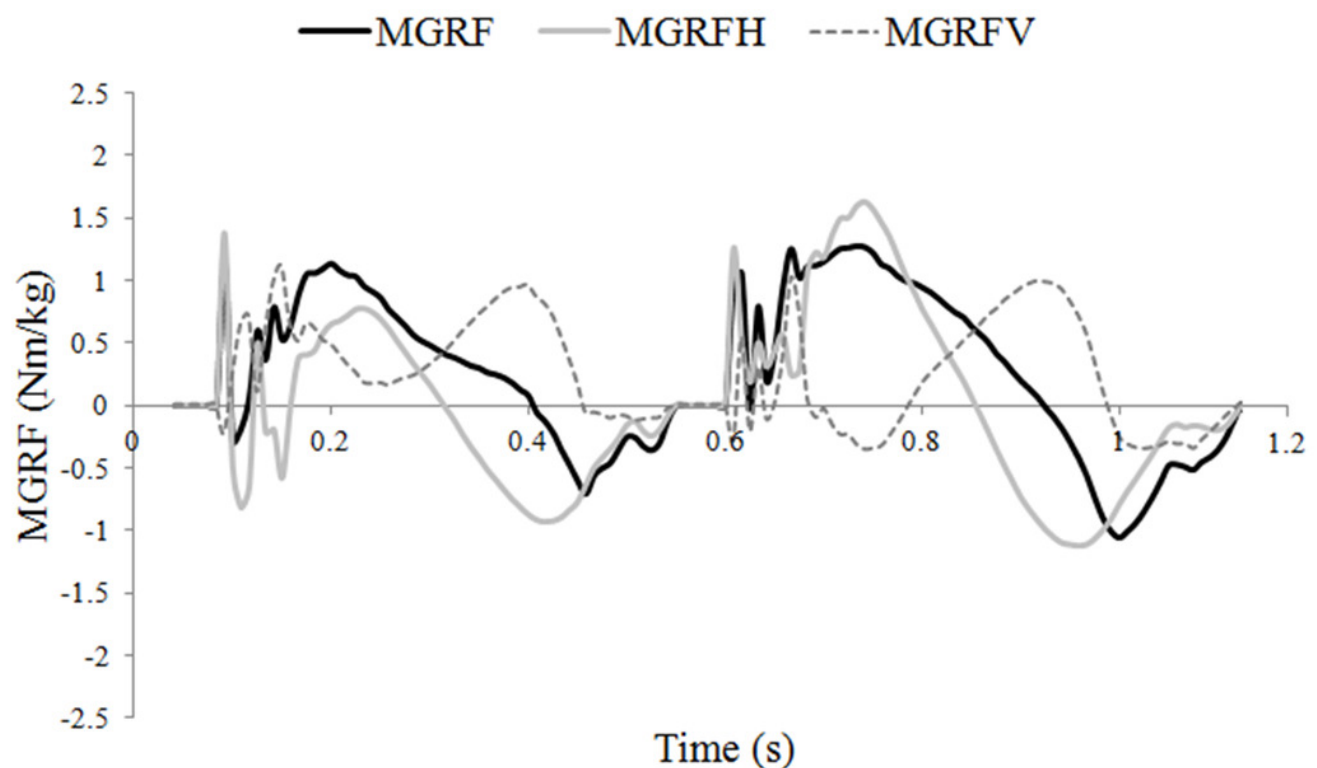



Figure 2

Moments around the center of mass (COM) (Nm/kg) during one stride of passage.

MGRF: total moments around the COM due to the effect of the ground reaction forces; $MGRF_V$: moments due to vertical force production; $MGRF_L$: moments due to longitudinal force production.

Mean and (standard deviation) for pooled data of 20 steps of passage and relationship between variables (accounting for horse).

MGRF Br: sagittal plane moment around the center of mass due to ground reaction forces during the braking phase; MGRF Pr: sagittal plane moment around the center of mass due to ground reaction forces during the propulsive phase; ROM_T: trunk range of angular motion; INC_T: mean trunk inclination angle; COM: mean center of mass location during stance; DIS: diagonal dissociation; T_F: time taken to reach peak vertical GRF in the forelimb; T_H: time taken to reach peak vertical GRF in the hindlimb; $P\text{-}R_F$: mean protraction-retraction angle of the forelimb during stance; $P\text{-}R_H$: mean protraction-retraction angle of the hindlimb during stance; COP: mean center of pressure location during stance; $GRFV_F$: peak vertical ground reaction force in the forelimb; $GRFV_H$: peak vertical ground reaction force in the hind limb.

Table 1

Variable	Mean (s.d.)	MGRF Br	MGRF Pr	ROM_T	INC_T	COM	DIS	T_F	T_H	$P\text{-}R_F$	$P\text{-}R_H$	COP	$GRF\ V_F$	$GRF\ V_H$
MGRF Br (Nm/kg)	0.39 (0.32)	1												
MGRF Pr (Nm/kg)	-0.19 (0.32)	-0.317	1											
ROM_T (deg)	2.71 (1.15)	0.237	-0.754**	1										
INC_T (deg)	8.03 (1.34)	0.082	-0.066	0.000	1									
COM (ratio)	0.42 (0.03)	-0.266	-0.272	0.345	-0.634**	1								
DIS (s)	0.03 (0.03)	0.125	-0.263	0.532*	-0.529*	0.481*	1							
T_F (% stance)	0.46 (0.06)	-0.040	0.097	-0.134	0.183	-0.515*	-0.468*	1						
T_H (% stance)	0.40 (0.06)	-0.156	-0.080	-0.180	0.203	0.045	-0.332	-0.074	1					
$P\text{-}R_F$ (deg)	-6.16 (1.81)	0.289	-0.019	0.143	0.538*	-0.385	-0.315	-0.016	0.208	1				
$P\text{-}R_H$ (deg)	-1.57 (2.26)	0.037	0.546*	-0.729**	0.299	-0.771**	-0.515*	0.355	-0.033	0.104	1			
COP (ratio)	0.43 (0.04)	-0.085	0.068	0.011	-0.650**	0.506*	0.440	-0.196	-0.001	-0.444	-0.238	1		
$GRFV_F$ (N/kg)	9.56 (0.94)	0.182	0.348	-0.125	0.186	0.071	-0.056	-0.496	-0.042	0.410	0.025	0.002	1	
$GRFV_H$ (N/kg)	7.68 (0.54)	0.412	-0.274	0.316	0.331	-0.136	-0.094	-0.138	-0.033	0.550*	0.032	-0.393	0.428	1

Key:	
	Balance strategy 1: Relative fore-aft contact timing
	Balance strategy 2: Foot contact position
	Balance strategy 3: Fore-aft vertical force distribution