Equine Veterinary Education

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2020) **32** (Suppl. 10) 151-161
doi: 10.1111/eve.13102

Original Article

The effects of rider size and saddle fit for horse and rider on forces and pressure distribution under saddles: A pilot study

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Keywords: horse; thoracolumbar; back pain; horse riding; bodyweight

Summary

There is limited scientific evidence concerning the effect of rider weight on pressures under the saddle and equine performance. The objective of this prospective, crossover, randomised trial was to assess pressure distribution and magnitude in horses ridden by four riders of similar ability but differing in bodyweight and height. Six horses in regular work were ridden by four riders (rider bodyweight: horse body weight percentage > 10 ≤ 12 [L = Light], > 12 ≤ 15 [M = Moderate], > 15 ≤ 18 [H = Heavy] and > 20 [VH = Very Heavy]), performing a purpose-designed dressage test (30 min). The test was abandoned for ≥ grade 3/8 lameness or ≥ 10 behavioural markers (assessed in real-time). A calibrated force mat (Pliance) was used to record pressures under the saddle in walk, trot and canter on left and right reins. Rider position was assessed. All 13 H and VH tests and one of 12 M rider tests were abandoned (lameness, n = 12; behaviour, n = 1). At walk, the seat of rider VH extended beyond the cantle of the saddle; rider H sat on the cantle of the saddle. At trot and canter the heels of rider VH were consistently cranial to the tubera coxae and shoulders. Pressures were significantly higher under the caudal aspect of the saddle compared with cranially for rider VH in walk (P<0.05, ANOVA, Bonferroni). At rising trot pressures were higher cranially for riders L, M and H (P<0.05, ANOVA, Bonferroni), but were similar cranially and caudally for rider VH. The highest maximum peak pressure was recorded for rider VH in canter. A limitation was that speed can alter pressure measurements, but was not controlled or recorded. We concluded that there were differences in magnitude and distribution of pressures among the four riders according to their size, which may have contributed to the development of musculoskeletal pain. This may also have been influenced by saddle fit for riders and their positions.

Introduction

Force mats have been used to quantify pressures at the saddle horse interface to assess saddle fit (De Cocq *et al.* 2006), the effect of panel size (Martin *et al.* 2017) or tree width (Meschan *et al.* 2007), the influence of saddle pads on a saddle which fits (Kotschwar *et al.* 2010a) and a saddle with too wide a tree (Kotschwar *et al.* 2010b) and to assess pressure distribution in Icelandic horses with three different saddle types (Ramseier *et al.* 2013). The influence of girth strap placement and flocking material (Byström *et al.* 2010) and the relationship between pressure and clinical signs associated with ill-fitting saddles has also been evaluated (Von Peinen *et al.* 2010). The influence of gait (Fruehwirth *et al.* 2004; Bogisch *et al.* 2014), rider position (De Cocq *et al.* 2009) and rising versus sitting trot on pressure magnitude and distribution (De Cocq *et al.* 2010; Peham *et al.* 2010; Martin *et al.* 2017) has also been assessed. The effect on gait of reduction in pressures at the level of the 10th to 13th thoracic vertebrae by alteration of saddle fit was measured (Murray *et al.* 2017). However, limited work has been done on the effect of rider weight on pressure measurements.

Pressure measurements are influenced not only by the fit of the saddle to the horse, but also by the weight of the rider and the distribution of the rider's weight, as well as the horse's locomotion (Byström *et al.* 2011; Greve and Dyson 2013). In addition, it has been suggested that the fit of the saddle for each rider may have a major influence on rider weight distribution (Schleese 2014) and thereby pressures under different regions of the saddle. The presence or absence of saddle flaps and effect on rider position may also be influential (Clayton 2018).

Several studies (Sloet van Oldruitenborgh-Oosterbaan *et al.* 1995; Powell *et al.* 2008; Matsuura *et al.* 2013a,b, 2016; Gunnarsson *et al.* 2017; Stefánsdóttir *et al.* 2017) have investigated the effect of the weight of a rider with additional dead weight on the gait characteristics of horses and other physiological parameters. However, no previous studies have specifically compared the effect of riders of varying weights or heights on force magnitude and pressure distribution under the saddle during over ground exercise in both straight lines and circles.

The aims of the study were to: (1) quantify the magnitude and distribution of pressures under the saddle for six horses with riders of four different sizes; (2) relate saddle fit to the horses and saddle movement to the pressure measurements; and (3) relate rider position in the saddle to pressure measurements. It was hypothesised that there would be differences in the magnitude and distribution of pressures among the four riders. The study aimed to mimic the real-life situation when frequently riders are riding in saddles which do not fit them.

Materials and methods

The study was approved by the Clinical Ethics Review Committee of the Animal Health Trust (AHT 28-2016). Eight horses (six test horses and two reserves), volunteered by their owners, were selected based on the absence of forelimb lameness or absence of hindlimb lameness > grade 1/8. Horses were assessed in hand at walk and trot and ridden by their normal rider in walk, trot and canter by a Royal College of Veterinary Surgeons Specialist in Equine Orthopaedics. The horses were capable of being worked 'on the bit' at trot and canter for a minimum of 30 min twice daily. Horses were selected based on a body weight category 500–600 kg, so that for the study the rider bodyweight: horse body weight percentage was $>10 \leq 12$ (L = Light), $>12 \leq 15$ (M = Moderate), $>15 \leq 18$ (H = Heavy) and >20 (VH = Very heavy). Saddle fit was assessed by a qualified saddle fitter (C.M.) up to 1 month before the study and adjustments were made to improve fit when required; on the day prior to commencement of the study saddle fit was rechecked and further adjustments made if necessary. This study was part of a larger study which assessed the influence of rider size on equine gait and behaviour (Dyson *et al.* 2018a, 2019), other physiological variables (Roberts *et al.* 2018) and changes in the reaction to thoracolumbar palpation pre- and post-exercise and changes in thoracic dimensions with exercise (Quiney *et al.*, unpublished data). The riders were all capable of riding in balance and were suitably fit; none were familiar with the test horses, but all were accustomed to riding a variety of horses.

Exercise test

Each horse was ridden by each of the four riders (L, M, H, VH) in randomised order in the horse's normal tack (a general purpose saddle); the riders were all of good, similar ability. Each horse-rider combination performed a standardised test (Dyson *et al.* 2019), comprising walk, rising trot (including 20 m diameter circles and serpentines) and canter for 30 min in a 60×20 m indoor arena. In the original study design, the tests for riders M and VH were to be repeated; however, all the tests for riders H and VH were terminated prematurely because of lameness ($\geq$ grade 3/8; Dyson 2011) (n = 12) or the demonstration of ≥ 10 behavioural markers (n = 1) (Dyson *et al.* 2018b). It was deemed ethically inappropriate to repeat the tests for riders H and VH, therefore repeats were performed for riders L and M. However, only the data for the first tests of each rider on each horse were analysed in this study.

Pressure measurements

All horses were tacked up by two people (L.R. and C.M.). A calibrated force mat (Pliance[1]) was placed under the saddle, consisting of two halves, each with 128 sensors in a 16×8 (longitudinal $\times$ transverse) array. Each sensor had a size of 4.7×3.1 cm (14.6 cm^2). The force mat was zeroed on a horizontal surface before application to each horse and was recalibrated when required or at least after every fourth test. Each rider mounted from a purpose-designed mounting block (maximum height 103 cm; 2nd step 69 cm) to minimise disturbance of the force mat. Recordings were acquired for each gait for one complete lap around the arena and one complete 20 metre circle, on both the left and the right reins, for riders L and M. The duration of recording for riders H and VH was shorter because of early abandonment of the tests, however recordings were split according to sections (first walk, first trot etc.) for 'equal' comparison. Frame rates of 480 Hz (TiF and Qualysis) and 60 Hz (Pliance-X) were used. The duration of data collection varied among gaits (**Table 1**).

Rider position

The saddle fit to each horse was reassessed on the first day of testing (C.M.). The position of the seat of the rider was subjectively determined to be in the middle of the saddle, on the cantle of the saddle or overhanging the cantle of the saddle by consensus (S.D. and saddle fitters, D.F., E.L., S.N.). The alignment of each rider's shoulders, tubera coxae ('hips') and heels was assessed subjectively by British Horse Society Instructors (S.D., A.B.).

High definition video footage (Panasonic HDC-SD600, Panasonic[2]) was acquired from two predetermined sites in the arena during standardised sections of each test. Video footage was reviewed retrospectively subjectively, by a British Horse Society Instructor (A.B.) to assess rider position. Freeze frame lateral images at identical phases of the stride cycle of each horse and rider were assessed subjectively from walk, trot and canter on the left and right reins. Objective measurements of rider and saddle movement were also performed. Markers were applied to the horse's left and right tubera coxae and the caudal aspect of the tuber sacrale on the midline. Tape was applied vertically to the midline of the saddle cantle. The riders wore snugly fitting jackets with a vertically positioned central line on the back (Visualise™, Visualise Technical Sportswear[3]). Using the Equine Motion Analysis System[4] (EMAS™) software tool (Gandy *et al.* 2012), frames of the same phase of each stride cycle (left hindlimb and right hindlimb mid stance, respectively, with the rider sitting) at trot on both reins from the rear were selected for analysis. As far as possible, the strides were selected when the horse was parallel to the sides of the arena, straight and moving on two tracks; however, in some cases, the horse remained crooked and on three or four tracks. Using the rear-view frames, data points corresponding to the marker positions were selected by an experienced operator (A.B.) for the midline of the horse (tuber sacrale marker), saddle cantle and rider (the distal aspect of the stripe on the jacket). The distance between the left and right tubera coxae was expressed as horse width (HW). Lateral displacement of the saddle or rider midlines relative to the horse midline was expressed as a percentage of HW, with a negative value indicating displacement to the left and positive indicating displacement to the right (Bondi 2017).

TABLE 1: Mean duration (s = seconds) of pressure data collection for four riders of variable weight (L = Light, M = Moderate, H = Heavy and VH = Very Heavy) riding six horses at walk, rising trot and canter (riders L, M and H)

Gait and rein	Average duration, s
Medium walk left arena	90–110
Medium walk right arena	90–110
Working trot left arena	35–56
Working trot right arena	35–56
Working canter right arena	28–38
Working canter left arena	28–38
Working trot right circle	16–26
Working trot left circle	16–26
Working canter right circle	12–20
Working canter left circle	12–20

Arena refers to the periphery of a 20×60 m arena; circles were of 20 m diameter. The large variability among trot times reflects early abandonment of tests for riders H and VH because of lameness or ≥ 10 behaviours (Dyson *et al.* 2018b).

Centre of pressure analysis

Centre of maximum pressure along the longitudinal and transverse axes of the whole pressure mat was measured in [mm] from a fixed origin point at the caudal right-hand corner of the pressure mat (Martin *et al.* 2017). The positive direction for the transverse axis was from the right side to the left starting at 12.5 mm line from the right and ending at 407.5 mm from the right, with the centre of mat line located at 210 mm (*y* axis origin point on x = 210).

Statistical analysis

Data were analysed for normal distribution (Kolmogorov-Smirnov) and significance level was set as P<0.05. The statistical software used was SPSS (23, 2015[5]) or JASP (0.8.6, 2018[6]).

As saddle fit in relation to rider is likely to play an important role in pressure results, but data relating to rider effect were not analysed as paired/related, analysis of variance (ANOVA) between groups was therefore used as the main statistical test (as opposed to repeated measures). Comparison of differences in saddle movement (to left or right of the centre point) within horses was analysed using paired *t*-tests. To assess saddle movement according to rider, ANOVA (post-hoc Bonferroni or Tukey) was applied.

Pressure readings were amalgamated according to area of saddle (left, right, cranial and caudal) and total mean pressure (N/area) per gait (walk, trot and canter) and within the gait (straight, circle). Mean pressures are reported in kilo Pascals (kPa) per area.

Overall means for walk, trot and canter (whole force-pad area) were analysed using ANOVA with a post-hoc Least Significant Difference test.

Centre of pressure (COP), as [mm] from the reference point, was analysed separately for horses working on a straight line, by defining median, mode, maximum and minimum distance for points of maximum pressure, as well as 'range' per horse per rider (n = 6 × 4). For maximum transverse (side to side) pressure the deviation distance [mm] from the longitudinal centre axis (intercept at x = 210) was calculated for analysis. Data were normally distributed and analysed using ANOVA (post-hoc, Bonferroni) tests.

Results

All tests for riders H (n = 6) and VH (n = 7) were terminated after a mean of 16.6 min (range 9.0–25.5 min) and 8.3 min (range 6.0–19.0 min) respectively and only one of the VH rider tests was repeated. Only four horses cantered with rider H and only one horse cantered with rider VH. This meant that there were insufficient data for statistical comparison of pressure data for rider VH in canter and only the first trot on both reins and circle could be compared for all riders and horses resulting in a total of 148 recordings for walk and trot and 108 for canter before amalgamation of data (mean or maximum per horse per rider and per gait on the straight and in a circle).

Subjective observations on rider positions and saddle fit

At halt, riders L and M were positioned in the middle of the saddle for all horses, whereas the seat of rider H was positioned at the rear (influenced partly by his long legs) for all but horse 1 and the seat of rider VH hung over the cantle of the saddle for all horses. The shoulders, tubera coxae ('hips') and heels were not in alignment for riders H and VH (**Fig 1**). During the tests, the shoulders, tubera coxae and heels were consistently not in alignment for riders VH and H (**Figs 2a** and **b**). The heels of rider VH remained in front of the shoulders and tubera coxae, particularly in the sitting phase of trot and in canter. The position of rider H was variable. This rider demonstrated anterior tilt of the pelvis with forward inclination of the torso, with the shoulders close to alignment with the heels in trot on five of six horses, but on the sixth horse and in canter on all horses the torso was more upright with the heels in front of the shoulders and tubera coxae.

No saddle fitted each horse ideally, despite recent fitting (3 months prior to the start of the study) by professional saddle fitters (Horses 1 and 4) and adjustments made by a saddle fitter (C.M.) from 1 month before the study. The flocking of horse 1's saddle was too soft, resulting in lateral and longitudinal saddle instability. The gullet of horse 2's saddle was narrow and the panels were asymmetrically flocked. Horse 4's saddle was narrow at the front and, when combined with the horse's normal sheepskin pad, created bridging. The seat of horse 5's saddle tipped backwards and was corrected by caudal shims, but these created a ridge of

***Fig 1:** The positions of four riders of varying bodyweights, (a) light, (b) moderate, (c) heavy and (d) very heavy, on Horse 3. The light and moderate riders are sitting in the centre of the saddle, with the right shoulder, tuber coxae and heel in vertical alignment; the heavy rider is sitting on the cantle of the saddle and the very heavy rider is sitting over the cantle of the saddle, each with their right heel cranial to the shoulder and tuber coxae.*

Fig 2: *a) The positions of four riders of varying bodyweights (light, moderate, heavy and very heavy) on Horse 4 during the sitting phase of rising trot on the left rein at the same phase of the stride cycle (freeze frame images from the video recordings). The light and moderate riders have alignment of their right shoulder, tuber coxae and heel. The heel of the heavy and very heavy riders is cranial to the shoulder and tuber coxae. The seat of the heavy rider is on the cantle of the saddle and the seat of the very heavy rider extends beyond the cantle of the saddle. b) The positions of four riders of varying bodyweights (light, moderate, heavy and very heavy) on Horse 4 during the rising phase of rising trot on the left rein at the same phase of the stride cycle (freeze frame images from the video recordings). The light and moderate riders have alignment of their right shoulder, tuber coxae and heel. There is closer alignment of the shoulder, tuber coxae and heel for the heavy and very heavy riders compared with in the sitting phase (a). Note that riders H and VH have the distal aspect of their right leg further caudal compared with the sitting phase.*

pressure at their cranial margins. Horse 6's saddle bridged and when used with the horse's normal under-saddle-cushion pad was too narrow, resulting in dry spots under the cranial aspect of the saddle. The flocking was compressed hard. The saddles of horses 3, 5 and 6 slipped to the right to variable degrees.

Total area mean pressures

Overall, the mean pressure under the saddle for all horse-rider combinations was higher in walk than in trot and canter (ranging from 5.4 kPa [walk] to 5.0 kPa [canter]). The mean maximum pressure ranged from 7.7 kPa for walk to 13.6 kPa in canter (**Table 2**). The actual maximum pressure recorded was 26.4 kPa.

Effect of rider

Analysis of overall mean pressure (entire pad, all movements) according to gait showed that rider L exerted significantly less pressure ($P<0.001$, ANOVA, Bonferroni) compared with all other riders. Rider VH exerted significantly more pressure ($P<0.001$, ANOVA, Bonferroni) compared with all other riders. There were no significant differences between riders M and H for mean pressure recordings (**Fig 3**). There was no interaction between gait and riders (Multivariate ANOVA). Overall maximum pressure (entire pad, all movements) was similar among riders. The mean maximum pressure increased between gaits within riders (see **Fig 3** capital letter annotations), between walk and trot for riders L, M, H and VH and between trot and canter for riders M and H. The highest maximum pressure was recorded for rider VH at 26.4 kPa in canter.

TABLE 2: Summary overview of mean pressure and standard deviation (s.d.) and mean maximum pressure in kilo Pascal (kPa) recorded for the overall area under the saddle for six horses when ridden by four riders of different weights (n = 148 recordings for walk and trot; n = 108 recordings for canter)

	Mean pressure			Mean maximum pressure		
	Walk	Trot	Canter	Walk	Trot	Canter
Mean pressure (kPa)	5.4	5.1	5.0	7.7	12.1	13.6
s.d.	1.7	1.5	1.2	2.3	3.4	3.2
Minimum	2.0	2.0	3.0	3.0	7.0	7.0
Maximum	11.0	10.0	9.0	15.0	25.0	26.0

Pressure according to area under saddle

In both walk and trot, pressures on the left and right sides were similar for all riders. In walk, for rider VH, there was significantly higher pressure under the saddle caudally compared with cranially ($P<0.001$, ANOVA, Bonferroni. **Fig 4a**). In rising trot, for riders L, M and H, there was less pressure under the saddle caudally compared with cranially ($P<0.01$, ANOVA), but there was no significant difference for rider VH (**Fig 4b**).

Relative alterations in pressure according to rider weight

The increase in riders' bodyweights correlated well with increased pressure in all gaits (**Fig 5**). The ratio of increase in bodyweight from rider H to VH was × 1.5 but the increase in pressure under the saddle was × 1.3. For riders L and H, the ratios for bodyweight and maximum pressure increase were identical at × 1.5.

The overall maximum pressure (26.4 kPa, top circle **Fig 5**) for rider VH in canter was 1.3× more pressure than rider H, whereas the bodyweight increase for VH was 1.5 × rider H's

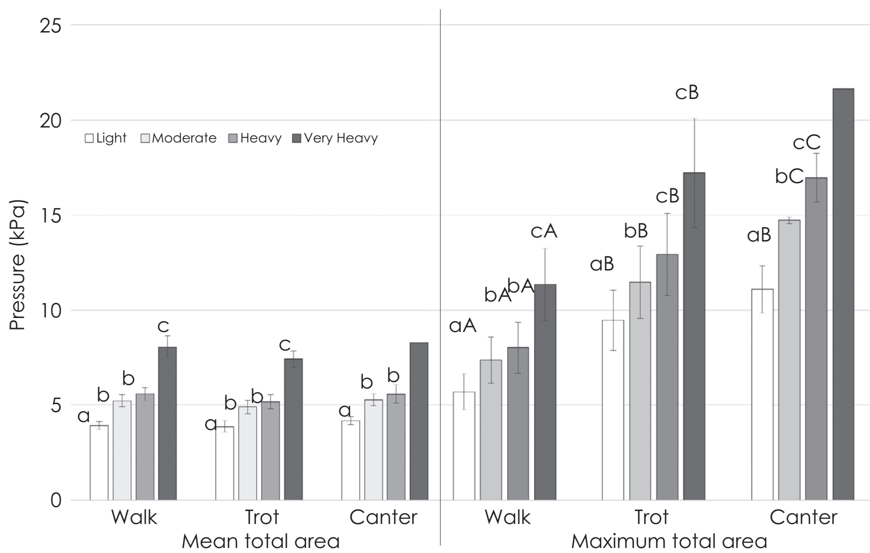

Fig 3:* *Overall mean pressure and maximum pressure (kPa) for total area under the saddle for six horses, ridden by four riders (light, moderate, heavy, very heavy) in walk (n = 6), trot (n = 6) and canter (n = 6 for L and M, n = 4 for rider H and one horse with rider VH). Trot and canter were recorded on the straight and on a circle. Differences in small letter annotations represent significant differences between riders within a gait (P<0.001, ANOVA, Bonferroni) and differences in capital letter annotations represent significant differences within the same rider between gaits (P<0.05, ANOVA, Tukey).

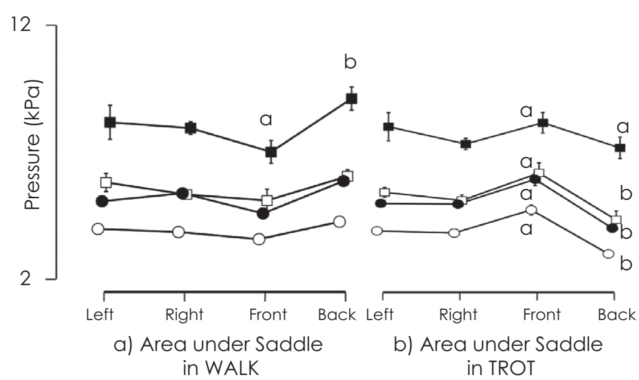

Fig 4:* *Mean pressure (kPa) in (a) Walk and (b) Trot according to the region of the saddle (Left – left of gullet, Right – right of gullet, Front – cranial half of saddle, Back – caudal half of saddle) and according to four riders (Light = white circle; Moderate = black circle; Heavy = white square; Very heavy = black square), when riding six horses. Letters indicate significant differences within riders between the cranial and caudal parts of the saddle, P<0.05, ANOVA, Bonferroni).

bodyweight. The increase of maximum pressure was lower than the increase in bodyweight from riders H to VH, indicating that the lighter the rider was, the greater the pressure in relation to bodyweight. In canter, there was an increased pressure of 2.2 × bodyweight for rider H, 2.3 × bodyweight for rider M and 2.6 × bodyweight for rider L.

Saddle movement and rider alignment in trot

The saddles of horses 3 and 6 had significantly more movement to the right, measured caudally as a percentage of horse width (HW) on both the right rein (17%HW, t = 4.1, P<0.01) and on the left rein (11%HW, t = 2.7, P<0.05) respectively (**Fig 6**). The saddle of horse 5 had a very wide range of side to side movement. The mean movement of all riders on horses 3 and 6 was also to the right on all reins (horse 3 14.0%HW, t = 4.1, P<0.01, horse 6 10.0%HW, t = 2.5, P<0.05). For all horses, saddle movement and rider movement were significantly positively correlated on both reins (P<0.01, left rein R^2 = 0.6, right rein R^2 = 0.8). Overall there was no significant difference in saddle or rider movement among riders. For all riders, on the left rein there was a significantly greater movement of the saddle to the right (8.0%HW) than to the left (2.0%HW, P<0.001). On the right rein, there was no significant difference in saddle movement to the left and to the right, but riders moved more to the left (4.5%HW) than to the right (1.7%HW, P<0.001).

Centre of pressure

For median COP among riders along the transverse axis, the maximum COP of rider H was further to the left compared with all other riders (P<0.001, F = 13), but the median COP was only significantly more to the left compared with rider VH (P<0.05, F = 2.5, ANOVA; **Fig 7**). For the longitudinal COP, rider VH had a median COP significantly more towards the caudal aspect of the saddle compared with all other riders (P<0.01, F = 3.2, ANOVA) (**Fig 7**).

Analysis of transverse COP according to horse, revealed significant differences among all horses (P<0.05, F = 20, ANOVA, Bonferroni), which are in line with the subjective saddle shift and fit identified above. Horse 3 had a strong COP shift to the left, whereas horse 5 had a strong COP shift to the right (**Fig 6**). Both horses 3 and 5 had a high range of movement of the saddle with the median COP ranging by 17 and 19 mm respectively (versus a mean 11 mm for other horses). For all horses the COP was more central during the trot, compared with either walk or canter (**Fig 8**). In the longitudinal axis horses 3 and 5 had significantly greater COP distribution towards the caudal aspect of the saddle compared with the other horses (P≤0.01, F = 2.8, ANOVA, Bonferroni; **Fig 9**).

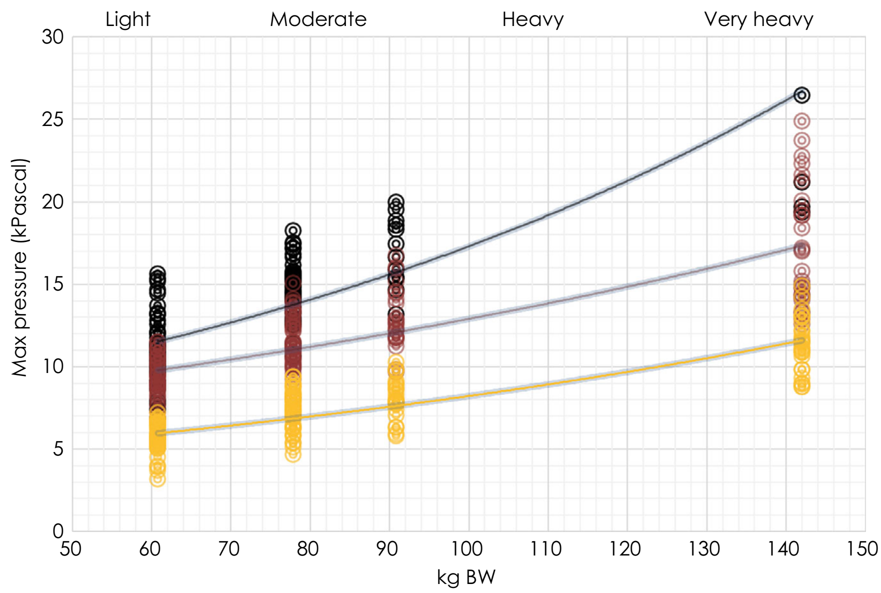

***Fig 5:** Relationship between actual rider bodyweight (BW) (x-axis) in kilograms (kg) and mean maximum pressure (Max Pressure, kPa) measured under the saddle during walk (light-yellow circles), trot (medium-brown circles) and canter (black circles) (Exponential lines fitted).*

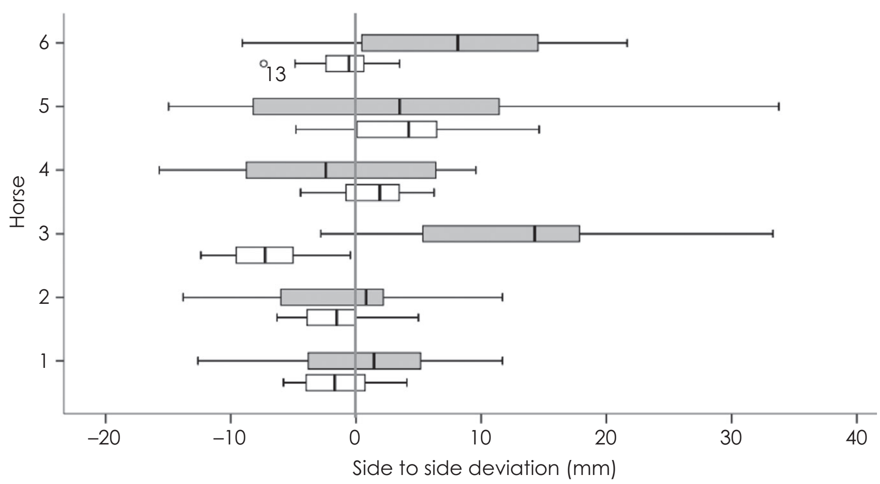

***Fig 6:** Side to side deviation of the saddle from the dorsal midline measured as (a) Grey Boxes: sideways displacement of the saddle using video analysis from the centre of the cantle and (b) White Boxes: sideways (transverse) movement of the location of centre of pressure (maximum pressure) from the centre line measured by the force mat for six horses (1–6) ridden by four riders of varying bodyweight.*

Discussion

Despite the fact that tests were abandoned for riders H and VH because of lameness or demonstration of ≥10 behavioural markers, satisfactory data were collected for walk and trot, but data were incomplete for canter. In accordance with our hypotheses, differences in the magnitude and distribution of pressures among the four riders were observed.

Every saddle is shaped to accommodate the rider of a certain size (Schleese 2014). If a rider's size exceeds the size of the horizontal surface of the seat, their weight on the cantle will result in higher pressure under the caudal part of the saddle. There was a significant difference in pressure distribution for rider VH, with caudal pressure exceeding cranial in walk, whereas for the other riders the pressures were more evenly distributed, despite rider H sitting on the cantle because of his long leg length relative to the sizes of the saddles. The influence of leg length is discussed elsewhere (Dyson *et al.* 2019).

Alteration in the distribution of pressure has the potential to adversely affect thoracolumbar movement and hindlimb gait. In a small study which compared a standard-fitting saddle with one with panels which were 10 cm shorter, there was increased pressure under the middle and caudal thirds of the saddle and caudal displacement of the COP with the shorter saddle (Martin *et al.* 2015). This was associated with reduced range of motion in the caudal thoracic and lumbar

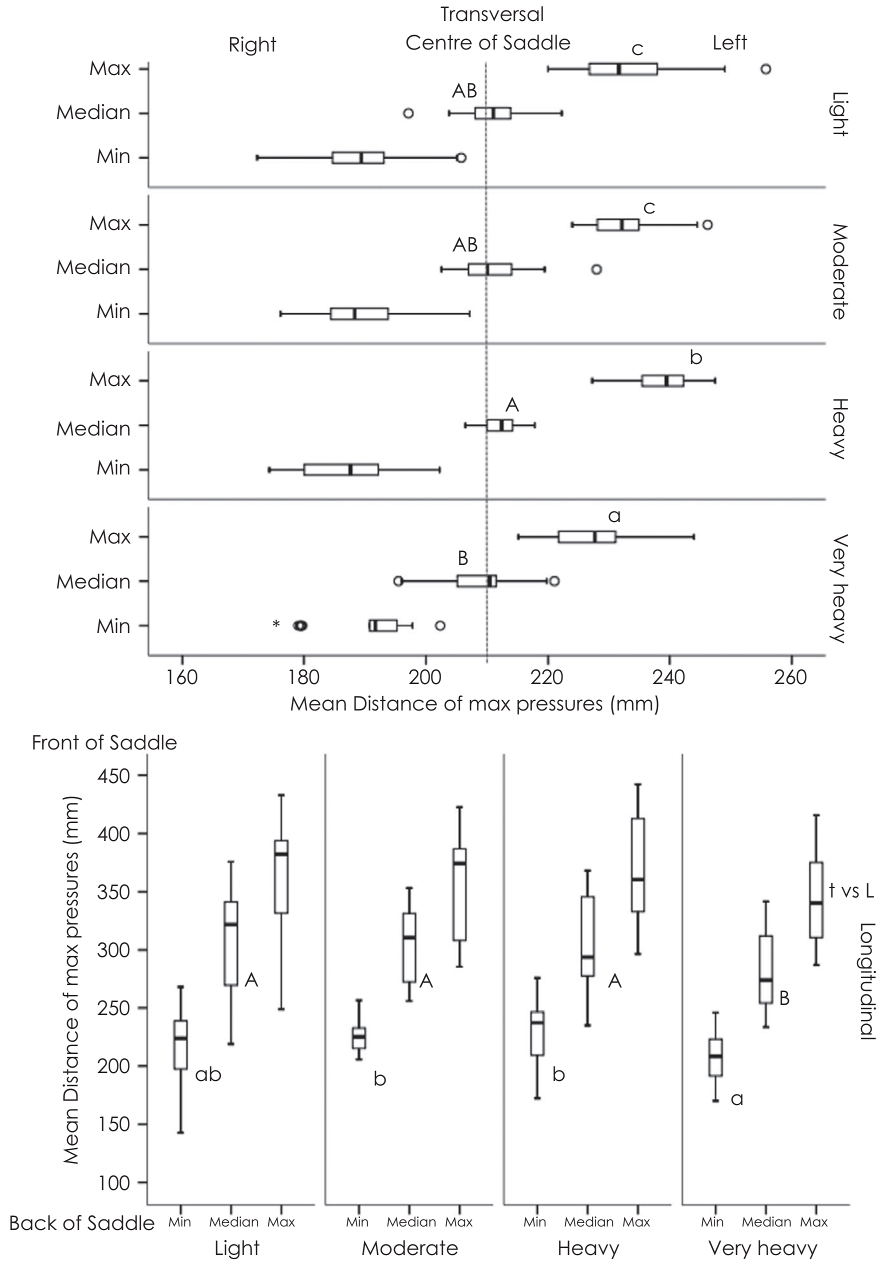

***Fig 7:** Minimum, median and maximum location of the greatest Centre of Pressure for transverse and longitudinal axes for four riders of different bodyweights (light, moderate, heavy and very heavy). Higher the COP on the transverse axis, further the shift to the left (centre of pressure mat under the saddle at 210). Higher the COP on the longitudinal axis, further COP was forward on the saddle. Values within the same measures for each axis which do not share superscripts are significantly different (P<0.05, ANOVA; Least significant difference; t = trend: P<0.08; L = Light rider).*

regions and reduced hindlimb protraction. The more caudal distribution of the COP for horses 3 and 5 may have caused additional discomfort for these horses when ridden by riders H and VH.

At rising trot, the weight of the rider is shifted to the stirrups when rising once per cycle and loading is higher in the sitting diagonal compared with the rising diagonal (De Cocq *et al.* 2010; Peham *et al.* 2010). At rising trot for rider VH, caudal pressure was similar to cranial pressure, whereas for all other riders cranial pressure exceeded caudal at rising trot. The transverse COP location in trot was closer to the centre than in walk and canter for all riders, (**Fig 7**), reflecting the symmetry and biomechanical forces of each gait. The minimal total force is lower at sitting trot than rising trot, but the maximal total force is higher in sitting trot than rising trot (Peham *et al.* 2010). However, the craniocaudal shift of the centre of pressure is greater in sitting trot than rising trot (Peham *et al.* 2010). It could be argued that the use of sitting trot may give more information about pressure distribution among the riders of different weights/sizes, because for a 'normal' rider, pressure is distributed evenly among the four quadrants of a

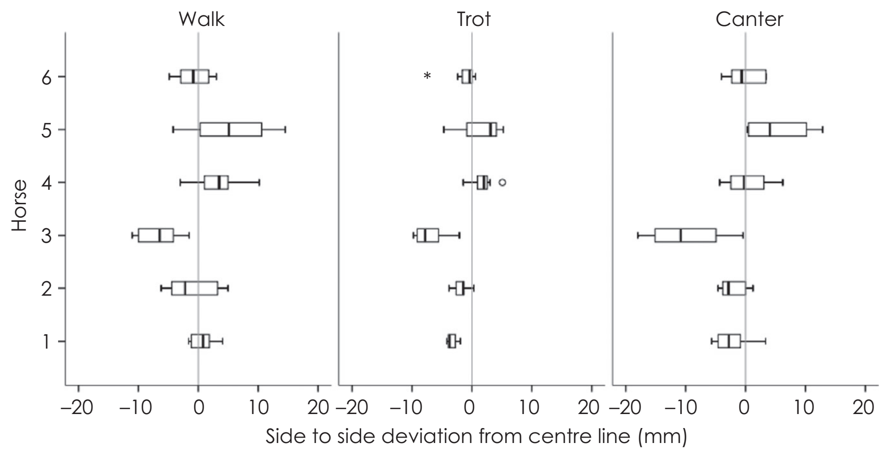

***Fig 8:** Distribution of transverse deviation of the median Centre of Pressure from the centre line (0) according to horse (1–6) and gait (walk, trot and canter) when ridden in a straight line by four riders of varying bodyweight.*

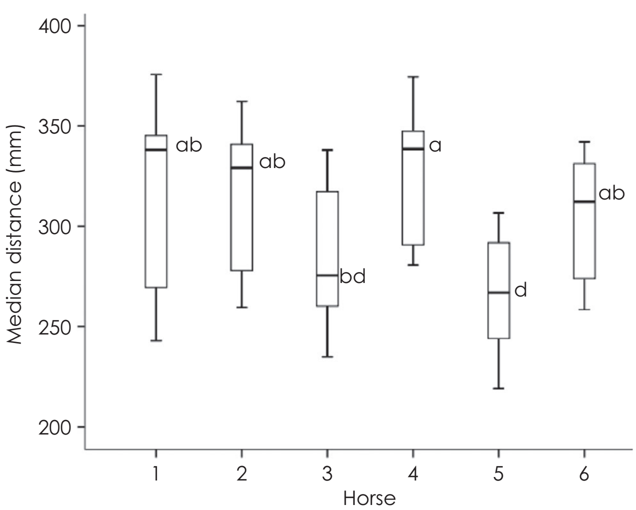

***Fig 9:** Distribution of the median longitudinal Centre of Pressure for six horses (1–6) when ridden in a straight line by four riders of varying bodyweight. Medians which do not share a superscript were significantly different ($P \le 0.01$, $F = 2.8$, ANOVA, Bonferroni).*

dressage saddle (Fruehwirth *et al.* 2004), however, we were concerned with the horses' ability to withstand continuous sitting in walk, trot and canter over 30 min. Moreover, the riders were not used to continuous periods of sitting trot and the majority of riders ride predominantly in rising trot. The riders were instructed to sit on the correct diagonal (when the outside forelimb and inside hindlimb were bearing weight), however, occasionally horses forced riders H and VH onto the incorrect diagonal, which was then corrected.

Maximum total force is the peak value of total force during a stride, whereas mean force is average value of total force over the stride. It has been debated whether mean, maximum or minimum pressures over the stride cycle are most relevant (Clayton 2013). The maximum peak pressures for each rider were significantly different between walk and trot and between trot and canter, as previously described (Von Peinen *et al.* 2010), for all except rider L at trot and canter. Force is the product of mass × acceleration and force is pressure/unit area, so higher pressures are expected for larger riders and at increased speeds of movement of the rider. At walk, pressure is continuous, whereas in rising trot, pressure is biphasic. This may have an influence on horse comfort, especially for rider VH, when pressure was the highest over the caudal quadrants of the saddle in walk and was similar for cranial and caudal quadrants at trot. It has been suggested that there are regional differences in pain threshold, with lower pressures inducing pain caudally under the saddle (mean 10.0 kPa, maximum 31.0 kPa) compared with cranially (mean 13.2 kPa, maximum 34.5 kPa) (Nyikos *et al.* 2005).

There were significant decreases in thoracic width dimensions post-exercise compared with pre-exercise for both riders H and VH, whereas there were significant increases for riders L and M (Quiney *et al.*, unpublished data). We have previously demonstrated that the mean thoracic width after 30 min of ridden exercise was greater compared with before exercise (Greve *et al.* 2015). However, mean changes were greater in horses working correctly versus those not working correctly, in those with correctly fitting versus ill-fitting saddles and in horses ridden by good > moderately > poorly skilled riders. The reductions in thoracic dimensions for riders H and VH are likely to reflect their bodyweights combined with the poor saddle fit for the riders, especially for rider VH, influencing their weight distribution. Rider VH had the highest maximum pressure under the caudal aspect of the saddle. Whereas all riders demonstrated a slight to significant shift in overall pressure to the left of the saddle, this was greatest for rider H. This asymmetry could reflect postural asymmetry of the riders (Symes and Ellis 2009; Gandy *et al.* 2014, 2018; Hobbs *et al.* 2014; Guire *et al.* 2016), either innate or secondary to injury and may play a role in the horses' movement.

In canter, the pressures are influenced by rider position: sitting in the saddle versus sitting 'light' (De Cocq *et al.* 2009). All riders in the current study sat in the saddle during canter and the maximum peak pressure was recorded for rider VH. The maximum peak pressure which was recorded for rider VH in canter is nonetheless smaller than peak pressures associated with muscle tension and atrophy (Werner *et al.* 2002), dry spots or saddle sores (Von Peinen *et al.* 2010) or pain (Byström *et al.* 2010). The pressure recordings in the current study highlighted that there is not a completely linear relationship between pressure and bodyweight of the rider (**Fig 5**).

Mass normalisation (kPa/kg bodyweight) facilitates comparisons of riders of different sizes (Clayton 2013). At walk, the overall force is approximately equivalent to the body mass of the rider (Fruehwirth *et al.* 2004). At sitting trot, the force values increase to approximately twice the body mass and reach almost 2.5 times the body mass of the rider when cantering. This is similar to the results in the current study, despite only limited results for rider VH in canter. The higher pressures recorded for riders M and H compared with rider L were associated with significantly increased epaxial muscle tension scores following exercise (Quiney *et al.*, unpublished data). There was a non significant increase in muscle pain for rider VH. Moreover, all tests for riders H and VH were abandoned because of lameness or exhibition of behavioural markers reflecting musculoskeletal pain (Dyson *et al.* 2018b). Provision of larger saddles for riders H and VH could have permitted a more uniform pressure distribution, however, such saddles would have exceeded the acceptable length relative to the horses' thoracic lengths (Harman 2005; Nyikos *et al.* 2005; Schleese 2014). The rider being too large for the saddle reflects real life, for example in riding schools and trekking centres, when adults ride children's ponies or native show ponies and with the increasing size of the population is also regularly observed clinically among the general riding community (S. Dyson, unpublished observations).

Byström *et al.* (2018) reported that in non lame horses there may be measurable mild symmetrical side to side oscillations of the caudal aspect of the saddle, more in rising trot than sitting trot, possibly influenced by both the horse and the rider. Our study showed a reduced amount of oscillation when in rising trot compared with walk and canter. Asymmetrical saddle movement associated with asymmetrical pressures was observed in seven horses that were non lame in hand, with well-fitting saddles (Mackechnie-Guire *et al.* 2018). This was corrected short-term with the use of shims, with associated improved symmetry of pressures under the saddle and measurable modifications in gait. Three horses (3, 5, 6) in the current study had a variable degree of saddle slip with all riders, which was not explained by measurable thoracic asymmetry (unpublished data) or asymmetry of the saddle. It may be associated with subclinical lameness, although the direction of slip was consistently to the right, despite episodic low-grade left hindlimb lameness observed with some riders. In 14% of horses with hindlimb lameness and saddle slip, the saddle slipped to the side of the non lame or less lame limb (Greve and Dyson 2013). Saddle pressure patterns may be altered after diagnostic analgesia has resolved hindlimb lameness (Byström *et al.* 2011). Left right asymmetry in pressure distribution under the saddle in association with saddle slip and hindlimb lameness has previously been demonstrated; pressures became symmetrical when lameness was abolished using diagnostic analgesia and saddle slip resolved (Greve and Dyson 2013). Saddle slip associated with hindlimb lameness, even if subclinical, is often apparent trotting in hand or on the lunge without a rider (S. Dyson, unpublished data). The horses in the current study were not assessed moving in hand with a saddle. Asymmetrical movement of the thoracolumbosacral region was observed in association with hindlimb lameness and became symmetrical after resolution of lameness using diagnostic analgesia (Greve *et al.* 2017). This asymmetry could induce saddle slip. However, saddle slip has also been seen in a small number of horses in which no gait abnormality was detected in hand or ridden, despite well-fitting saddles (Greve and Dyson 2014). The large displacement of the COP to the left and right respectively, for horses 3 and 5, probably reflects the wide range of saddle movement, which is probably also associated with the highly convex contour of their caudal thoracic regions (Greve and Dyson 2013).

The current study had some limitations. The study was limited to small numbers of horses and riders. The speed of each gait could not be controlled and was not measured, however tests were completed in consistent times, suggesting similar speeds. Differences in speed within a gait can alter peak forces; a 10% increase within a specified speed range resulted in + 5% (walk) and + 14% (trot) higher total saddle force peaks (Bogisch *et al.* 2014). The current technology only measures forces perpendicular to sensors (Jeffcott *et al.* 1999; Clayton 2013); there is no measurement of shear forces, which obviously can be influential. The early termination of tests for riders H and VH meant only limited data were available for canter.

In conclusion, there were differences in magnitude and distribution of pressures among the four riders according to their weight, which may have contributed to the development of musculoskeletal pain, but this may also have been influenced by the fit of the saddles to the riders. In future studies, the fit of the saddle to both horse and rider must be considered.

Authors' declaration of interests

No conflicts of interest have been declared.

Ethical animal research

The study was approved by the Clinical Ethics Review Committee of the Animal Health Trust (28-2016).

Sources of funding

World Horse Welfare, Saddle Research Trust, Frank Dyson, British Equestrian Federation, British Horse Society, Pony Club, Polocross, The Showing Council, The Showing Register, The Society of Master Saddlers, Riding for the Disabled, British Eventing, British Dressage, the British Horse Foundation, the Worshipful Company of Saddlers and Endurance GB. The funders had no influence over the conduct of the research and/or preparation of the article.

Acknowledgements

We are grateful to the owners who provided the horses and to the participating riders. Diane Fisher, Elizabeth Leggett and Sue Norton, Society of Master Saddlers qualified the saddle fitters and contributed to the saddle fitting.

Authorship

The idea for the study was conceived by S. Dyson and P. Harris. The study was designed by S. Dyson, P. Harris, A. Ellis, J.

Douglas and A. Bondi and was performed by all authors. Statistical analysis was performed by A. Ellis. The data were interpreted by S. Dyson, L. Roost, A. Bondi and A. Ellis. S. Dyson and A. Ellis wrote the paper, which was adapted and approved by all authors.

Manufacturers' addresses

[1]Novel GmbH, Munich, Germany
[2]Panasonic Corporation, Hamburg, Germany
[3]Visualise Technical Sportswear, Moreton Morrell, Warwick, UK.
[4]Equine Motion Analysis System, (EMAS), Elizabeth A. Gandy, University of Sunderland, UK.
[5]IBM
[6]University of Amsterdam

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