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Original Research

Relationship Between Saddle and Rider Kinematics, Horse Locomotion, and Thoracolumbar Pressures in Sound Horses

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ABSTRACT

Saddle fit is considered to be a crucial factor for the health and performance of horses, yet there is a paucity of scientific data. The objective of this study was to determine the relationship between saddle and rider kinematics, horse locomotion, and thoracolumbar pressures in sound horses. Seven horses with asymmetric saddle position were tested before and after correction of the saddle positioning asymmetry. Kinematic and kinetic data were collected using motion capture, inertial sensors, and a pressure mapping system. Data of horses showing saddle roll to the right were normalized to represent saddle roll to the left. When comparing saddle roll with saddle correction in trot, this study found that once the saddle had been corrected on the rein with saddle roll to the outside (here: right rein), there was an increase in outside front fetlock hyperextension ($P = .02$) and inside hind fetlock hyperextension ($P \leq .05$); there was a reduction in peak pressures after saddle correction under the inside portion of the panel in trot ($P \leq .05$) and canter ($P = .04$), and riders showed increased thoracic side bend (lean) on the contralateral side to the direction of saddle roll ($P = .02$). The presence of saddle roll creates changes in fetlock hyperextension and hence likely force production, increases peak pressures beneath the panel on the contralateral side to the direction of saddle roll, and affects rider position, with the rider leaning in the opposite direction to saddle roll likely to optimize balance.

1. Introduction

Horse and rider interaction is of interest in improving welfare, longevity, and performance in the ridden horse [1e3]. Poor saddle fit and positioning is thought to cause back pain in horses leading to behavioral and performance problems [4]. There have been considerable advances in equestrian tack; for example, scientific studies have informed girth, bridle, and more recently saddle design to optimize pressure distribution and improve locomotor performance [5–7], along with thresholds being published representing saddle pressures that could lead to back discomfort [8]. However, there is still a paucity of objective, quantitative data on saddle kinematics and its effect on musculoskeletal disorders and performance.

During locomotion, the equine back undergoes three-dimensional translations (dorsoventral, mediolateral, and craniocaudal) and rotations (axial rotation, lateral bending, and flexion/extension) [9,10], with the saddle being positioned over the mid thoracic region. Given these movements, correct saddle fit for a horse and a rider is likely to promote unhindered back function and improved stability for the rider, facilitating positive interaction with the horse [11]. Defined with respect to the horse, saddle kinematics can include any translational (acceleration, velocity, or displacement in dorsoventral, craniocaudal, and mediolateral direction) or rotational movement (pitch, roll, yaw) [3]. Saddle kinematics have been investigated in sound horses, including the pressures associated with saddle fit and type [12,13] and the effect

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of tree and panel widths [1] and pad materials [14–16]. Saddle and rider kinematics during each phase of the stride while trotting on a treadmill [11] and over ground [17] have been investigated.

A fitted saddle should remain in balance during ridden activity with no overt signs of lateral displacement or craniocaudal movement. However, despite correct fitting, saddles can show signs of lateral displacement alluding to the challenges of saddle fitting. To date, there has been no published study in sound horses showing the effect that saddle positioning and asymmetry may have on the locomotion of the horse. A multifactorial approach as to why saddles show lateral displacement is needed, that is, taking into account laterality, conformation, saddle construction, musculoskeletal asymmetries, and rider influence. Although there are a multitude of explanations, there is evidence that saddle displacement can be associated with hind limb lameness. A recent study has shown that in 54% of cases with hind limb lameness, saddle slip (defined as a saddle being laterally displaced consistently to one side) [18] toward the lamer hind limb was observed; and after abolishing the lameness through diagnostic analgesia, an improved saddle positioning was observed visually.

In trot, the sum of force over six motion cycles has been quantified to amount to twice the body mass of the rider, and in canter, two and half times [19]. In trot, it is assumed that, with a correctly fitting saddle, these forces would be distributed on the horse's back; however, in cases where there are signs of poor fit and/or lateral saddle positioning (saddle roll), it is likely that this would cause the horse to adjust its loading to withstand the asymmetric forces particularly applied to one side of its back as a result of saddle position [19].

In trot, an asymmetric force distribution through the saddle/stirrups onto the back of the horse is likely to have an effect on asymmetry of loading between contralateral front and hind limbs, as well as on translational and rotational movements of the thoracolumbosacral region. Changes in thoracolumbosacral kinematics were found after the elimination of lameness, that is, after elimination of pelvic movement asymmetry [20] and consequently elimination of asymmetrical force production between contralateral limbs. It seems likely that horses might adapt thoracolumbar movement and fetlock hyperextension (shown to increase with increased vertical force [21]) in the presence of an asymmetrically positioned saddle. Likewise, as a function of an asymmetrically positioned saddle, angular kinematics (carpus and tarsus) may be altered in an attempt to maintain thoracolumbar stability, which is likely to be compromised due to these asymmetric forces as a result of saddle position [22].

Canter kinematics are somewhat different because of the asymmetric nature of the gait, and saddle roll is more noticeable especially when circling [15]. In gallop, during the stance phase of the lead hind limb, the horse's trunk displaces laterally away from the leading hind limb. The peak forces in the stirrup have been reported to be higher on the contralateral side to the leading limb, likely in an attempt for the jockey to maintain their center of mass as close to the midline of the horse, in doing so the jockey pushes against the stirrup on the opposite side to the leading limb [23]. Although these findings are in gallop, it seems reasonable to assume that similar mechanics could be applied in canter; saddle rolling away from the leading hind limb likely affecting thoracolumbar kinematics and creating asymmetric pressures beneath the saddle and consequently affecting rider positioning.

The aim of this study was to investigate the relationship between saddle and rider kinematics, horse locomotion, and thoracolumbar saddle pressures in sound horses. The objectives of this study were to determine the effect of an asymmetrically positioned saddle on (1) movement symmetry of the horse in hind and front, (2) pressure distribution under the saddle, and (3) rider positioning.

It is hypothesized that on the rein where the saddle position is shifted toward the outside, we will observe (1) increased fetlock hyperextension on the outside front limb along with reduced carpal and tarsal flexion on the inside limbs, in trot; (2) increased outside front limb fetlock and decreased inside hind fetlock hyperextension, in canter; (3) an asymmetric distribution in saddle pressures beneath the inside portion of the panel as a result of the saddle being brought up close to the vertebrae; and (4) asymmetric rider kinematics particularly with the rider's seat being displaced to the outside and to maintain balance, the rider will lean to the inside resulting in an increased lateral thoracic side bend.

2. Materials and Methods

The study was approved by the ethics and welfare committee of the first author's institution, project number URN 20181785-2.

2.1. Horses

A convenience sample of seven adult sports horses was used in this study. Horses and riders were recruited via Facebook asking for riders to volunteer to participate. Inclusion criteria were saddle “slip” confirmed by Society of Master Saddler Qualified Saddle Fitters (SMSQSFs) and the horse free from lameness as perceived by the owner, in competitive work and within a 2-hour journey time of the proposed data collection site. The horses were all geldings from a variety of disciplines (n = 4 dressage, 1 working hunter, and 2 eventers). They ranged in height at the withers (1.63–1.80 m with a mean ± SD of 1.69 ± 0.07 m), body mass (495–590 kg with a mean ± SD 523 ± 47 kg), and age (6–12 years with a mean ± SD 9 ± 2.8 years). Horses underwent a veterinary assessment performed by two veterinary surgeons, including flexion tests of all four limbs, and no lameness was observed subjectively. The horses' gait was also assessed quantitatively on a hard surface with a validated sensor-based system (4× Xsens MTw; Xsens, Enschede, The Netherlands) [24,25]. Data were collected in hand, in trot, and data analyzed from a total of 40 strides per horse.

Six riders (four females and two males [one female rode two horses]) were of an experienced level all competing at (British Dressage) advanced medium or above, height (mean ± SD) 1.52 m ± 0.05, and body mass (mean ± SD) 67 ± 11 kg. Information such as height, fitness, handedness, and body mass along with medical information—in particular previous injuries—was obtained by questionnaires. All riders at the time of the study were free from any injuries. Informed consent was obtained, and riders could withdraw from the study at any point should they wish to do so.

2.2. Saddles

The horses' own saddles were used (five dressage and two general purpose), which had been checked for fi t before the study. On the day of the study, following the SMS static and dynamic saddle fitting guidelines, each horse and saddle was assessed by four SMSQSFs. The static assessment was performed following a published protocol for which each SMSQSF completed the seven points of saddle fitting and documented their responses, independently from each other using an observation sheet [26].

2.3. Study Protocol

Each horse underwent a warmup period self-prescribed by the rider lasting 15 minutes, followed by a prescribed rising trot and seated canter protocol lasting 8 minutes, during which saddle-horse-rider kinematics were quantified along with saddle-horse kinetics. Horses were tested with their own saddle displaying "saddle roll" first, and then data collection was repeated after the saddle had been corrected by an SMSQSF; all corrections were made by the same SMSQSF. Data were collected during straight line locomotion in rising trot left rein, rising trot right rein, canter left lead, and canter right lead. All measurements were performed on the same outdoor school on the same surface (Martin Collins, Berkshire, UK), which was groomed prior and in between each horse trial in the same way. Three repeats on the left and right rein were collected with "saddle roll" and then saddle corrected. If the horse lost straightness, tripped, or made an obvious alteration in the gait pattern (e.g., shying), the trial was repeated. Asymmetric saddle positioning was corrected with the use of shims (Prolite), which were positioned underneath the saddle. The shims are designed and contoured to fit beneath the saddle panel. In brief, saddles that rolled were fitted with either a thin shim (5 mm thick) or a thick shim (10 mm thick) underneath the saddle. Saddles that rolled to the left were fitted with a shim under the caudal portion of the left panel and cranial portion of the right panel, and saddles that rolled to the right were fitted with a shim under the caudal portion of the right panel and cranial portion of the left panel. An SMSQSF was responsible for determining the thickness of the shims to be used dependent on the degree of observed saddle asymmetry.

2.4. Horse, Rider, and Saddle Kinematics

2.4.1. Kinematics—Two-Dimensional Motion Capture

Kinematic data were recorded with a high-speed video camera system, using 24 skin markers (30 mm; Quintic Consultancy, West Midlands, UK) placed on each horse using double-sided tapes. Marker locations were identified by manual palpation of anatomical landmarks identifying joint centers and segment ends; once located, white skin paint was used to mark each reference point. Markers were located on (1) scapular spine, (2) head of humerus (cranial), (3) lateral condyle of humerus, (4) lateral metacarpal condyles, (5) distal aspect of the metacarpus over the lateral collateral ligament (LCL) of the metacarpophalangeal joint, (6) origin of the LCL of the distal interphalangeal joint, (7) tuber sacrale, (8) greater trochanter of the femur, (9) lateral condyle of the femur, (10) talus, (11) distal aspect of the metatarsus over the LCL of the metatarsophalangeal joint, and (12) origin of the LCL of the distal interphalangeal joint (Fig. 1) on both sides of the horse.

Two high-speed cameras (Quintic) were positioned at a 10-m distance from the experiment track, capturing simultaneously left and right sides of the horse at 400 Hz (spatial resolution 1300 × 400, 400 fps at 10 m distance), with a field of view capturing two complete strides in trot and canter. A halogen light was used to illuminate the markers. High-speed video data were recorded and downloaded to a laptop (Sony Vaio) and processed using two-dimensional motion capture (Quintic Biomechanics, Quintic Consultancy, West Midlands, UK). This experimental technique has been described previously [5–7]. Automatic marker tracking was used to investigate maximum carpal flexion [palmar angle between (3) lateral condyle of humerus, (4) lateral metacarpal condyles, and (5) distal aspect of the metacarpus over the LCL of the metacarpophalangeal joint], maximum tarsal flexion [angle between (9) lateral condyle of the femur, (10) talus, and (11) distal aspect of the metatarsus over the LCL of the metatarsophalangeal joint] during the swing phase and maximum fetlock extension during stance for front [palmar angle between (4) lateral metacarpal condyles, (5) distal aspect of the metacarpus over the LCL of the metacarpophalangeal joint, and (6) origin of the LCL of the distal interphalangeal joint] and hind limbs [palmar angle between (10) talus, (11) distal aspect of the metatarsus over the LCL of the metatarsophalangeal joint, and (12) origin of the LCL of the distal interphalangeal joint] (Fig. 1). All raw data were smoothed using a Butterworth low-pass filter with a cutoff frequency of 10 Hz [27] .

2.4.2. Kinematics—Inertial Measurement Units

Horses were instrumented with four MTw inertial measurement units (IMUs) (Xsens). These were attached over the sacrum and left and right tuber coxae using custom-built pouches and double-sided tapes and over the poll using a custom-made Velcro attachment. Sensor data were collected at 80 Hz per individual sensor channel and transmitted, via the proprietary wireless data transmission protocol (Xsens), to a receiver station (Awinda, Xsens) connected to a laptop computer running MTManager (Xsens) software.

Inertial measurement unit data were processed following published protocols [24]. In brief, triaxial sensor acceleration data were rotated into a gravity (z: vertical) and horse-based (x: craniocaudal and y: mediolateral) reference frame and double integrated to displacement. Displacement data were segmented into individual strides based on vertical velocity of the sacrum sensor [28] and

Fig. 1. Markers were located over the (1) scapular spine, (2) head of humerus (cranial), (3) lateral condyle of humerus, (4) lateral metacarpal condyles, (5) distal aspect of the metacarpus over the lateral collateral ligament (LCL) of the metacarpophalangeal joint and (6) origin of the LCL of the distal interphalangeal joint, (7) tuber sacrale, (8) greater trochanter of the femur, (9) lateral condyle of the femur, (10) talus, (11) distal aspect of the metatarsus over the LCL of the metatarsophalangeal joint, and (12) origin of the LCL of the distal interphalangeal joint on both sides of the horse along with a pressure mat (Pliance) beneath the saddle and inertial measuring units positioned over the sacrum, left and right tuber coxae, and the poll using custom-made pouches.

median values for the following kinematic variables were calculated over all strides for each exercise condition for both saddle roll and saddle-corrected conditions. Inertial measurement unit data were generated using displacement data (deviation from a zero average position) as opposed to positional data based on high-pass filtering and double integration from acceleration data [24].

- Range of motion (ROM): maximum−minimum value over a stride cycle for x, y, and z displacement for trot and canter.
- Minimum difference (MinD): difference between the two minima in vertical (z) displacement observed during the two diagonal stance phases in trot [29].
- Maximum difference (MaxD): difference between the two maxima in vertical (z) displacement observed after the two diagonal stance phases in trot [29].
- Hip hike difference (HHD): difference between vertical upward movement amplitude of left and right tuber coxae during contralateral stance [30].

To allow interpretation of the effect of saddle roll, IMU-derived kinematic variables were compared between reins: ROM variables were subtracted from each other (left rein value − right rein value), and movement symmetry values (MinD, MaxD, and HHD) were added up (left rein value + right rein value). This procedure ensures that for horses performing symmetrically between reins, values near zero are expected because head and pelvic movement symmetry values show directional circle-dependent tendencies (positive for one rein, negative for the other) [29].

2.4.3. Kinetic Data—Pressure Distribution

Kinetic data under the saddle were recorded using a pressure mapping system (Pliance System, Novel, MSA600, sampling rate 50 Hz; Novel, Pliance, München, Germany). The pressure mat consisted of 256 sensors arranged into 8 columns and 16 rows, left and right. The mat was divided into two halves with no sensors over the vertebrae. Before measuring, the pad was zeroed without the saddle, girth, or rider [31] and was fitted so that the pressure mat was on top of the horse's skin and beneath the numnah and saddle as previously described [5–7]. Peak pressures (kPa) and maximum force (N) in trot and canter for both saddle roll and saddle correction were collected. Data were included from 11 repeated strides, with both the start and end points being determined by maximal protraction of the inside hind limb on both reins. Data were then split into left and right sides denoting the left and right portion (panel) of the saddle.

2.4.4. Rider Kinematics

Rider kinematics in relation to the horse were quantified by applying 30-mm spherical markers positioned on the midline of the cantle, between the two tubera sacrale and caudal aspect of the croup with riders wearing a posture jacket (Visualise), with lines positioned horizontally across the upper scapula and down the spine of the rider; this jacket acted as a body suit so the rider's anatomical locations could easily be identified. A high-speed camera (240 Hz) was positioned on a tripod that remained in the same position caudal to the horse, capturing straight line locomotion in trot and canter on both reins with saddle roll to the outside (right) and saddle roll to the inside (left). With the camera zoom remaining the same from a caudal view, the riders' trunk and leg position were quantified with saddle roll and after saddle correction. Two angles were measured: (1) the angle between the *acromion*, *greater trochanter (dorsal)*, and the lateral *femoral condyle* (ventral) representing the rider's trunk angle and (2) from the horizontal, the angle between the ventral aspect of both the inside and outside stirrups representing the rider's heel position (Fig. 2). Data were collected from five consecutive strides when the inside hind limb was maximally protracted on both reins in trot and canter.

2.4.5. Data Normalization

To make optimal use of the sample of n = 7 horses, all kinetic and kinematic data were "normalized" with respect to the direction of saddle roll. Data of horses with saddle roll to the right (n = 2) were combined with data of horses with saddle roll to the left (n = 5). This data normalization process required (1) inverting IMU asymmetry and saddle pressure data for horses with saddle roll to the right and (2) expressing movement conditions and limbs with respect to the side of the saddle roll as inside or outside rather than left or right. As a consequence, "rein with saddle roll to the outside" was used to express the direction of movement for a horse with saddle roll to the left on the right rein (or a horse with saddle roll to the right on the left rein) and "rein with saddle roll to the inside" for a horse with saddle roll to the left on the left rein (or a horse with saddle roll to the right on the right rein). This process effectively assesses the two horses showing saddle roll to the right through a mirror.

2.5. Data Analysis

2.5.1. Data Collection

From the two-dimensional kinematic analysis, data were collected from two consecutive strides with three repeats, totaling six strides used for analysis for both trot and canter on both inside and outside reins for each horse for both conditions. Outcome parameters for each condition were (1) maximum fetlock hyperextension front and hind during stance, (2) maximum carpal flexion, and (3) maximum tarsal flexion.

From IMUs and pressure distribution, measurements were started/stopped at the same time; data were matched in relation to movement condition and collected from 11 consecutive strides from three repeats, totaling mean ± SD of 33 ± 3 strides being used for analysis, in trot and canter on both inside and outside reins for each horse, for each condition. For the IMUs, outcome parameters were craniocaudal, vertical, and mediolateral ROM of the (1) inside and outside tuber coxae, (2) sacrum, and (3) hip hike difference and differences in movement symmetry between saddle roll and after saddle correction; and for pressure distribution outcome parameters were differences in saddle pressures, that is, (1) pressure beneath the inside panel and (2) pressures beneath the outside panel between saddle roll and after saddle correction.

2.6. Statistical Analysis

Statistical analysis was performed in SPSS (version 22; IBM, Armonk, USA). Kinetic and kinematic outcome parameters were assessed for normality using histograms that were inspected visually for fit of normal distribution and for presence of outliers.

Differences in outcome parameters for saddle roll and saddle correction were assessed using a paired *t*-test with a significance level set at $P \leq .05$. A mixed model was used to determine the influence of speed on outcome parameters. For the assessment of saddle fit, Fleiss Kappa statistics was calculated to assess agreement between observers averaging the Kappa values over two pairs; agreement was categorized values < 0 as indicating no agreement and 0–0.20 as slight, 0.21−0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81−1 as almost perfect agreement [26].

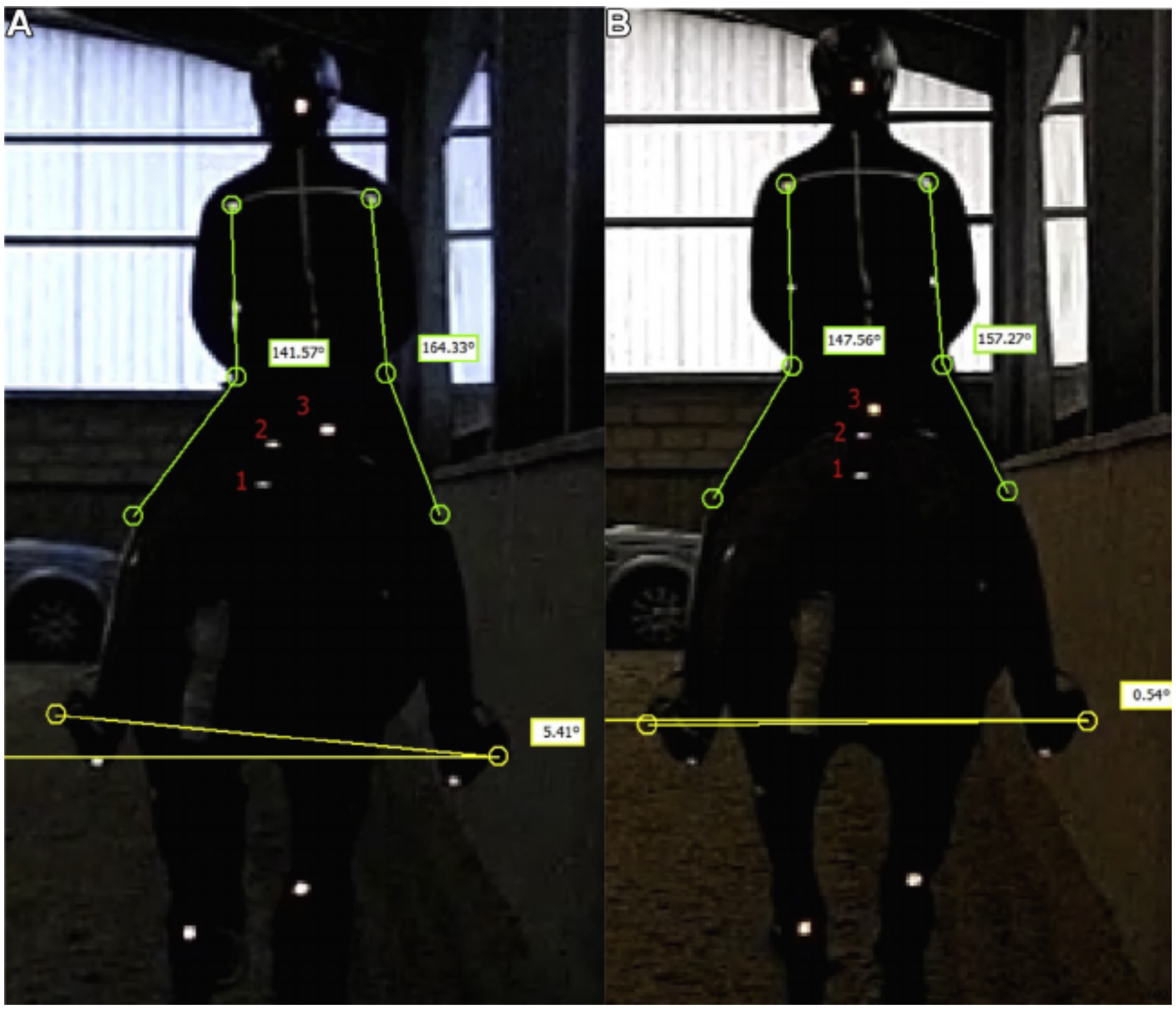

Fig. 2. (A) Showing the rider position with saddle roll (here: right) with 30-mm spherical markers positioned on the midline of the cantle (3), between the two tubera sacrale (2), and caudal aspect of the croup (1) with riders wearing a posture jacket (Visualise), with lines positioned horizontally across the upper scapula and down the spine of the rider. (B) Showing the same rider, same horse after saddle correction. Two angles were measured: (i) the angle between the *acromion*, *greater trochanter (dorsal)*, and the lateral *femoral condyle* (ventral) representing the rider's trunk angle and (ii) from the horizontal, the angle between the ventral aspect of both the inside and outside stirrups representing the rider's heel position.

3. Results

3.1. Speed

No significant difference was found in any of the outcome parameters when speed was included in the mixed model.

3.2. Horse Inclusion

All horses underwent a full lameness evaluation by two veterinary surgeons. Horses were trotted in hand on a firm level surface; all horses were deemed fit to perform. From the objective measures, horses had mean ± SD asymmetry values: HD_{min} −2.37 ± 2.71 and HD_{max} 0.05 ± 2.85, PD_{min} −3.11 ± 4.80 and PD_{max} 2.15 ± 4.82, and HHD 1.27 ± 8.98 [32] (Appendix 1).

3.3. Saddler Observations

Saddle asymmetries were subjectively scored by four SMSQSFs in rising trot and canter on both reins for each horse, for each condition. Five saddles displayed left roll and two displayed right roll before correction. There was complete agreement between the four SMSQSFs with both the static and dynamic evaluation in respect of saddle fit and direction of saddle roll. Visually, asymmetric positioning (saddle roll) was more noticeable on the rein with saddle roll to the outside, using an SMS subjective scoring system where saddle roll was categorized as 0 = no signs of saddle roll, 1 = mild signs of saddle roll, 2 = moderate signs of saddle roll, 4 = severe signs of saddle roll, and 5 = extreme signs of saddle roll, and saddle position was evaluated on both reins.

On the rein where the saddle had rolled to the outside, saddle roll ranged from 3 to 5, the lateral saddle displacement was more noticeable (trot 3.2 ± 0.55 and canter 4.20 ± 0.45), and once corrected the subjective assessment of the displacement of the saddle ranged from 0 to 2 and was significantly "improved" (trot 1.20 ± 0.45, $P = .03$; canter 1.40 ± 0.55, $P = <.001$).

On the rein where the saddle rolled to the inside, visually the saddle asymmetries were less noticeable (trot 1.80 ± 0.45; canter 1.80 ± 0.45) and after saddle correction were unchanged (trot 1.80 ± 0.45; canter 1.70 ± 0.30; $P \leq .05$).

3.4. Relationship Between Saddle Pressure Distribution, Axial Kinematics, and Limb Kinematics—on the Rein with Saddle Roll to the Outside

3.4.1. Kinematics—Two-Dimensional Motion Capture

With the rider on the correct diagonal (sitting as the outside forelimb and inside hind limb were in stance) with saddle roll to the outside, the outside front fetlock hyperextension was reduced compared with the inside front fetlock hyperextension. When the saddle had been corrected, there was a significant increase (saddle roll 250.9° ± 7.7°, saddle corrected 252.9° ± 7.4°, $P = .02$) in outside front fetlock hyperextension. After the saddle had been corrected, the inside hind fetlock hyperextension increased (saddle roll 242.76° ± 13.1°, saddle corrected 246.76° ± 11.9°, $P \leq .05$). No significant differences (all, $P > .06$) were found in canter for any of the 2D kinematic outcome parameters between before and after saddle correction (Tables 1 and 2).

3.4.2. Kinematics—Inertial Measurement Units

Smaller values were found after saddle correction for craniocaudal ROM of the outside tuber coxae (saddle roll

Table 1
Simultaneous motion capture providing kinematic data collected from six strides from the left and right side during rising trot for both saddle roll and saddle-corrected conditions on both left and right reins.

Parameter	Rein with Saddle Roll to Inside (Here: Left Rein)			Rein with Saddle Roll to Outside (Here: Right Rein)		
	Asymmetric Saddle	Saddle Corrected	P Value $\leq .05$	Asymmetric Saddle	Saddle Corrected	P Value $\leq .05$
Inside—maximal carpal flexion (°) (mean ± SD)	100.9 ± 5.9	99.5 ± 6.1	.13	97.3 ± 2.7	97.7 ± 1.8	.78
Outside—maximal carpal flexion (°) (mean ± SD)	97.2 ± 2.3	96.6 ± 1.9	.10	100.1 ± 6.9	98.6 ± 5.0	.11
Inside—front maximum fetlock hyperextension (°) (mean ± SD)	250.8 ± 7.8	250.2 ± 6.3	.54	248.8 ± 8.2	247.1 ± 7.9	.81
Outside—front maximum fetlock hyperextension (°) (mean ± SD)	253.5 ± 15.0	249.9 ± 9.4	.37	250.9 ± 7.7	252.9 ± 7.4	.02
Inside—maximal tarsal flexion (°) (mean ± SD)	116.9 ± 6.5	118.5 ± 5.6	.05	112.7 ± 14.4	118.7 ± 3.4	.27
Outside—maximal tarsal flexion (°) (mean ± SD)	117.5 ± 4.3	118.5 ± 4.7	.13	118.7.5 ± 4.3	117.3 ± 4.7	.27
Inside—hind maximum fetlock hyperextension (°) (mean ± SD)	246.3 ± 3.5	247.0 ± 3.7	.22	242.7 ± 13.1	246.7 ± 11.9	.05
Outside—hind maximum fetlock hyperextension (°) (mean ± SD)	241.5 ± 11.0	241 ± 14.3	.95	246.5 ± 4.5	246.0 ± 4.1	.64

All data mirrored to represent saddle roll left.

35.4 ± 5.7 mm, saddle corrected 31.2 ± 4.5 mm, P = .02). In canter, no significant differences were found (all P > .15) (Tables 3 and 4).

3.4.3. Kinetic Data—Pressure Distribution

In rising trot, differences in peak pressures were observed between saddle roll and after saddle correction; after saddle correction, a significant reduction in peak pressure beneath the inside portion of the panel (saddle roll 66.2 ± 10.2 kPa, saddle correction 58.6 ± 11.2 kPa, $P \leq .05$) was found. In canter, peak pressures were reduced beneath the inside portion of the panel of the saddle (saddle roll 60.8 ± 12.1 kPa, saddle correction 56.0 ± 12.8 kPa, P = .04) (Table 5).

3.4.4. Relationship Between Saddle and Rider Kinematics

Asymmetric saddle positioning affected rider kinematics significantly; in canter on the rein with saddle roll to the outside (for both the inside and outside of the trunk angle between the *acromion*, *greater trochanter*, and the lateral *femoral condyle*), the inside trunk angle of the rider was less when compared with the outside trunk angle (outside 153.27° ± 7.26°, inside 141.93° ± 3.36°, P = .02). After saddle correction, the inside trunk angle increased (P = .01) in effect increasing symmetry between the inside and outside trunk with no significant difference ($P \leq .05$) between inside and outside angles after saddle correction (outside 149.27° ± 10.68°, inside 148.60° ± 2.24°). When the saddle rolled to the outside, measured from the horizontal, the rider's outside stirrup was significantly (P = .02) lower than their inside stirrup (saddle roll 6.25° ± 2.21°, saddle correction 1.67° ± 1.23°).

3.5. Relationship Between Saddle Pressure Distribution, Axial Kinematics, and Limb Kinematics—on the Rein with Saddle Roll to the Inside

3.5.1. Kinematics—Two-Dimensional Motion Capture

In trot on the rein with saddle roll to the inside, a larger angle was found for the inside maximum tarsal flexion (saddle roll 116.9° ± 6.5°, saddle corrected 118.5° ± 5.6°, $P \leq .05$) after saddle correction. No significant differences (all P > .11) were found in trot or canter for any of the remaining outcome parameters after saddle correction (Tables 1 and 2).

3.5.2. Kinematics—Inertial Measurement Units

Larger values were found after saddle correction for mediolateral ROM of the sacrum (saddle roll 42.7 ± 17.6 mm, saddle correction 47.1 ± 18.4 mm, P = .03) and the outside tuber coxae (saddle roll 40.7 ± 7.9 mm, saddle correction 50.4 ± 11.2 mm, P = .03) and in a craniocaudal direction for the inside tuber coxae (saddle roll 27 ± 3.4 mm, saddle correction 32.4 ± 3.0 mm, P = .001) (Table 3).

In canter, after saddle correction smaller values were found for sacrum ROM (saddle roll 121.4 ± 17.1 mm, saddle correction, 115.2 ± 13.2 mm, P = .04) and the outside tuber coxae ROM (saddle roll 113 ± 13.0 mm, saddle correction 104.8 ± 13.8 mm P = .04) in a craniocaudal direction after saddle correction (Table 4).

3.5.3. Kinetic Data—Pressure Distribution

In canter, after saddle correction, reduced peak pressures were found beneath the outside portion of the panel of the saddle (saddle roll 59.7 ± 7.2 kPa, saddle correction 54.5 ± 5.6 kPa, P = .02) (Table 5).

Table 2
Simultaneous motion capture providing kinematic data collected for the left and right side during canter for both saddle roll and saddle-corrected conditions on both left and right reins.

Parameter	Rein with Saddle Roll to Inside (Here: Left Rein)			Rein with Saddle Roll to Outside (Here: Right Rein)		
	Asymmetric Saddle	Saddle Corrected	P Value $\leq .05$	Asymmetric Saddle	Saddle Corrected	P Value $\leq .05$
Inside—maximal carpal flexion (°) (mean ± SD)	109.8 ± 5.3	108.4 ± 6.4	.40	108.9 ± 7.1	109.1 ± 6.5	.79
Outside—maximal carpal flexion (°) (mean ± SD)	110.6 ± 4.3	111.2 ± 5.8	.62	111.9 ± 9.4	110.9 ± 8.7	.18
Inside—front maximum fetlock hyperextension (°) (mean ± SD)	249.7 ± 9.4	247.5 ± 9.4	.29	243.1 ± 11.9	245.6 ± 11.3	.33
Outside—front maximum fetlock hyperextension (°) (mean ± SD)	247.1 ± 6.6	246.5 ± 6.7	.22	252.9 ± 4.1	250.0 ± 5.8	.57
Inside—maximal tarsal flexion (°) (mean ± SD)	129.6 ± 4.0	131.8 ± 10.2	.44	128.8 ± 8.5	131.8 ± 8.8	.06
Outside—maximal tarsal flexion (°) (mean ± SD)	127.9 ± 4.4	129.5 ± 4.7	.11	128.7 ± 4.4	128.6 ± 5.6	.93
Inside—hind maximum fetlock hyperextension (°) (mean ± SD)	244.1 ± 3.4	246.9 ± 3.4	.23	239.5 ± 11.1	238.0 ± 13.3	.66
Outside—hind maximum fetlock hyperextension (°) (mean ± SD)	119.4 ± 11.6	120.0 ± 13.7	.74	244.3 ± 5.2	246.6 ± 7.1	.10

All data mirrored to represent saddle roll left.

Table 3
Kinematic data during trot on the left and right rein with saddle roll left and after saddle correction.

Parameter	Rein with Saddle Roll to Inside (Here: Left Rein)			Rein with Saddle Roll to Outside (Here: Right Rein)		
	Asymmetric Saddle	Saddle Corrected	*P* Value ≤ .05	Asymmetric Saddle	Saddle Corrected	*P* Value ≤ .05
Sacrum ROMY (mean ± SD)	42.7 ± 17.6	47.1 ± 18.4	.03	44.7 ± 17.0	44.1 ± 17.6	.69
LTC ROMX (mean ± SD)	27 ± 3.4	32.4 ± 3.0	.001	35.4 ± 5.7	31.2 ± 4.5	.02
LTC ROMY (mean ± SD)	35 ± 10.0	38.4 ± 11.3	.10	46.1 ± 9.9	48.8 ± 6.2	.92
LTC ROMZ (mean ± SD)	125.4 ± 19.6	126.8 ± 18.4	.51	118 ± 20.7	121 ± 22.1	.23
RTC ROMX (mean ± SD)	31.4 ± 6.3	35.7 ± 6.2	.07	31.5 ± 3.9	32.2 ± 6.2	.70
RTC ROMY (mean ± SD)	40.7 ± 7.9	50.4 ± 11.2	.03	37.5 ± 9.3	36.2 ± 9.6	.39
RTC ROMZ (mean ± SD)	121.8 ± 18.4	121.2 ± 17.0	.68	126.5 ± 14.8	128.4 ± 19.8	.60
LTC MinD (mean ± SD)	5.1 ± 25.0	7.1 ± 24.4	.31	−2.3 ± 20.2	− 0.6 ± 21.1	.43
RTC MinD (mean ± SD)	0.4 ± 21.8	2.3 ± 21.6	.05	−7.2 ± 26.3	−5.6 ± 26.3	.50

Abbreviations: ROMY, range of motion in mediolateral direction; ROMX, range of motion craniocaudal direction; ROMZ, range of motion in vertical direction; MinD, difference between the two minima in vertical displacement.

3.5.4. Relationship Between Saddle and Rider Kinematics

In canter, no significant differences were seen in the rider's inside trunk angle compared with the outside trunk angle (inside 147.27 ± 6.56°, outside 149.43 ± 2.56°, $P > .05$) before or after saddle correction. No significant differences were found in the rider's inside/outside stirrup position (saddle roll 1.47 ± 1.31°, saddle correction 1.56 ± 1.21°) before and after saddle correction.

4. Discussion

The aim of this study was to determine the relationship between saddle kinematics, horse locomotion, saddle pressures, and rider kinematics in nonlame horses. Although some differences have been reported here, the authors appreciate that this study is limited in its sample size. As such, to make optimal use of the small sample size, data processing methods involved converting data from n = 2 horses (showing saddle roll to the right) effectively resulting in saddle roll to the left for n = 7 horses. In addition, data analysis categorized data with respect to whether the shift in saddle positioning (saddle roll) occurred to the inside or outside irrespective of the actual direction of roll (to left or to right). The authors appreciate riders' handedness, and horse laterality might affect data normalization; however, all subjects were right handed. Future studies, with greater sample size, should look to investigate handedness and laterality and its influence on saddle position.

Given that speed can influence stride characteristics [33], it is possible that any alterations in locomotion were related to a change in speed [34]; however, in this study, speed did not affect any of the outcome parameters between the two conditions (with/without saddle roll). The saddles used in this study had uniform and symmetrical panels, were wool flocked, free from lumps or cavities and regularly serviced by an SMSQSF preceding the study, and were deemed to fit and be in good working order by four SMSQSFs [26]. Therefore, in this study, the presence of saddle roll could not be explained by incorrectly fitting saddles.

The effect that saddles have on the locomotor system has been previously explored with respect to pressures associated with saddle fit and type [12,13,35] and the effect of tree and panel widths [1] and pad materials [14–16]. However, there is a paucity of quantitative research on the effect that a saddle (out of balance) has on the locomotion of sound horses. Studies have investigated the association between hind limb lameness and saddle slip where it was shown after resolution of hind limb lameness, and saddle roll (slip) was eliminated [15,18]. The association of asymmetrical or reduced ROM of thoracolumbar kinematics has been investigated where, after the elimination of lameness, increased ROM of the thoracolumbar was reported [20], thus likely to help support the ability for the saddle to remain in balance.

In our preliminary study, it was hypothesized that with saddle roll bias to one side, there would be increased front fetlock hyperextension, a sign of increased vertical ground reaction forces [21], generating greater forces on the side that the saddle and rider weight had rolled to. In contrast to our hypothesis—in trot on the rein with saddle roll to the outside—a decrease in outside front fetlock hyperextension and a decrease in inside hind fetlock hyperextension were observed.

In effect, saddle roll to the outside reduced outside front fetlock hyperextension, a pattern observed in lameness [36], and once the saddle had been corrected, inside hind limb fetlock hyperextension increased, a pattern observed with increased loading and higher ground reaction forces. In addition, the rider's seat position became more central to the horse, and the trunk lean (displayed when saddle roll was present) was reduced. Changes in thoracolumbar mechanics have been reported with induced front limb lameness [37], and after elimination of hind limb lameness [20], increased flexion/extension of the region around the 13th thoracic vertebra and axial rotation of the thoracolumbar region was measurable. It is speculated that as a function of saddle roll, affecting front and hind (contralateral) limb fetlock hyperextension and consequently contralateral force production [21], it is likely that thoracolumbar mechanics would be altered [20,37]. Further work is needed to confirm.

It would be useful to evaluate the maximal flexion for the proximal joints, elbow, shoulder, hip, and stifle, as well as evaluating front/hind limb pro/retraction angles and stance durations [38] as these have been evaluated in relation to gait adaptations [39], thus could provide further information on how the horse compensates with an asymmetrically positioned saddle and rider.

Table 4
Horse ROM values during canter on the left and right rein with saddle roll and after saddle correction.

Parameter	Rein with Saddle Roll to Inside (Here: Left Rein)			Rein with Saddle Roll to Outside (Here: Right Rein)		
	Asymmetric Saddle	Saddle Corrected	*P* Value ≤ .05	Saddle Corrected	Asymmetric Saddle	*P* Value ≤ .05
Sacrum ROMX (mean ± SD)	121.4 ± 17.1	115.2 ± 13.2	.04	116.5 ± 19.3	115.2 ± 18.2	.61
RTC ROMX (mean ± SD)	113 ± 13.0	104.8 ± 13.8	.04	89.8 ± 15.6	91.2 ± 16.7	.55
TCD (mean ± SD)	32.2 ± 32.8	19.8 ± 28.2	.05	−20.2 ± 30.1	−26.1 ± 28.7	.21

Abbreviations: ROMX, range of motion craniocaudal direction; TCD, difference between vertical movement amplitude of left and right tuber coxae.

Table 5
Saddle pressure distribution data collected from 33 strides from beneath the saddle during trot and canter for both saddle roll and saddle-corrected conditions on both left and right reins.

Parameter		Rein with Saddle Roll to Inside (Here: Left Rein)			Rein with Saddle Roll to Outside (Here: Right Rein)		
		Asymmetric Saddle	Saddle Corrected	*P* Value ≤ .05	Asymmetric Saddle	Saddle Corrected	*P* Value ≤ 0.05
Peak pressures beneath the left panel (kPa) (mean ± SD)	Trot	61.1 ± 10.6	58.8 ± 10.9	.38	58.5 ± 9.0	53.3 ± 8.0	.09
Peak pressures beneath the right panel (kPa) (mean ± SD)	Trot	58.2 ± 4.7	54.4 ± 9.5	.15	66.2 ± 10.2	58.6 ± 11.2	.05
Peak pressures beneath the left panel (kPa) (mean ± SD)	Canter	59.6 ± 5.5	56.6 ± 6.3	.12	56.6 ± 8.2	49.7 ± 5.8	.19
Peak pressures beneath the right panel (kPa) (mean ± SD)	Canter	59.7 ± 7.2	54.5 ± 5.6	.02	60.8 ± 12.1	56.0 ± 12.8	.04

All data mirrored to represent saddle roll left and split into left and right saddle panels.

On the rein with saddle roll to the outside, the maximal flexion of the carpus or tarsal joint was not altered between the two conditions. It was hypothesized that the inside carpal and tarsal joint would have reduced flexion in an attempt to maintain trunk stability by reducing propulsion [22,40]. In contrast to our hypothesis, on the rein with saddle roll to the inside, the inside maximal tarsal flexion was less after correction; it is speculated that an increase in tarsal flexion could be associated with the hock-stifle reciprocal apparatus potentially aiding the flexion of the hip to alter pelvic function to flex the back and aid propulsion or indeed a sign of lameness. Further research is needed to confirm these gait alterations in relation to saddle position. Various riding positions and their effect on locomotion have been reported [41]. This study only looked at rising trot that could have an effect on saddle position and kinematics; however, it would be expected that if the saddle rolled because of rising trot or the seated position in canter, saddle roll would be seen on both reins; and in the present study, it was only seen on one rein. Future studies should attempt to look at various riding positions and their influence on saddle position.

The effect the rider has on the horse [3,42–44] and rider experience [1] have been investigated, in respect to saddle position; with saddle roll to the outside, the rider's seat was positioned to the outside (with the saddle), and in a likely attempt to maintain balance, by keeping their center of mass aligned as closely to the midline of the horse, the rider's trunk leant to the inside. All riders adjusted their position as a result of saddle position and when corrected they became more central. Further work is needed to determine if the rider induces saddle roll through their own asymmetries or handiness or if their position is a function of saddle position. Interestingly, one rider rode two horses, and each horse showed saddle roll in a different direction suggesting, in this case, that saddle roll was as a function of the horse and/or horse-saddle and not directly related to the rider. Future studies should look at the influence of rider position on saddle position.

Further support that saddle roll affects locomotion derived from our IMU data; while trotting, on the rein with saddle roll to the outside, smaller values were found after saddle correction for the outside tuber coxae in a craniocaudal direction. It is likely that this is related to the push-off of the contralateral hind limb (here: inside), where it was found that horses who displayed less vertical push-off, accommodated by increasing their motion in a craniocaudal direction of the contralateral limb (here: outside) [45]. Further evidence supporting this derived from our limb kinematics, where inside hind fetlock hyperextension was less before saddle correction indicating less push-off. It is speculated that, in the present study, the larger values seen on the outside tuber coxae when saddle roll was present could be an indication that the push-off of the inside hind is less, once corrected, values were smaller indicating more equal push-off. Further work, ideally with direct force measurement as described elsewhere [45], is needed to confirm this association. Thoracolumbar motion has been investigated with the positioning of IMUs along the back and beneath the saddle [46]. This study could glean further information incorporating these methods in determining changes in thoracolumbar motion before and after saddle correction; however, a lateral displacement of the saddle may influence the IMU placement, and in particular, lateral changes in positioning could lead to larger errors [47]. Differences in gallop kinematics (head and pelvis) after the induction of forelimb and hind limb lameness have been investigated where no differences between sound and lame conditions were reported [48]. This study found that while cantering on the rein with saddle roll to the inside, smaller ROM values were found for the sacrum and outside tuber coxae. The reason for this is unknown; cautiously following the principles of trot mechanics, it is speculated that this might be related to increased propulsion of the inside hind when saddle roll is present. Cautiously speculating that when the saddle is corrected, the inside hind limb reduces propulsion, given the locomotor differences between trot and canter; further work is needed to substantiate this theory. This study omitted the poll sensor data because of the noise as a result of the interaction of the rider with the horse.

Pressure distribution beneath the saddle has been reported [8,31,49–51] along with changes in locomotion as a result of reduced pressures beneath the saddle and girth [5,7]. Thresholds for saddle pressures associated with back pain have been established (peak pressures of >30 and mean pressures of >11 [kPa]) [8]. It was hypothesized that as a function of saddle roll, there would be asymmetric distribution of pressure beneath the saddle. In support of this, on the rein with saddle roll to the outside, differences in peak pressures were observed beneath the inside portion of the saddle localized close to the midline in the region of 13th thoracic vertebra, beneath the points of the tree (inside) and panel (inside) (Fig. 3). These increased peak pressures were seen in rising trot (<66.2 ± 10.2 kPa) and canter (<60.8 ± 12.1 kPa) [8]. In this group of horses, the timings at which the peak pressures occurred within the stride were consistent. With saddle roll left (right rein), peak pressures occurred in trot in the cranial portion of the inside panel during the stance phase of the inside forelimb. These pressures could be due to the rider because at this moment, the rider is at maximal height during the rise. Peak pressures only occurred on the rein with saddle roll; on the opposite rein, when the saddle was straight, a more uniform pressure distribution was seen suggesting that the pressures seen in the present study were as a function of saddle position as opposed to the rider rising. This study could be improved further by investigating sitting trot which would help to determine if the peak pressures observed were as a function of riding position (rising trot) or/and saddle roll. In canter, peak pressures occurred during the stance phase of the diagonal pair (inside hind limb and outside forelimb) and the leading forelimb, and this could be related to the ground reaction forces of the diagonal pair, rotation of the thorax, thoracolumbar kinematics, and influence of the rider [23]. The direct mechanics behind this

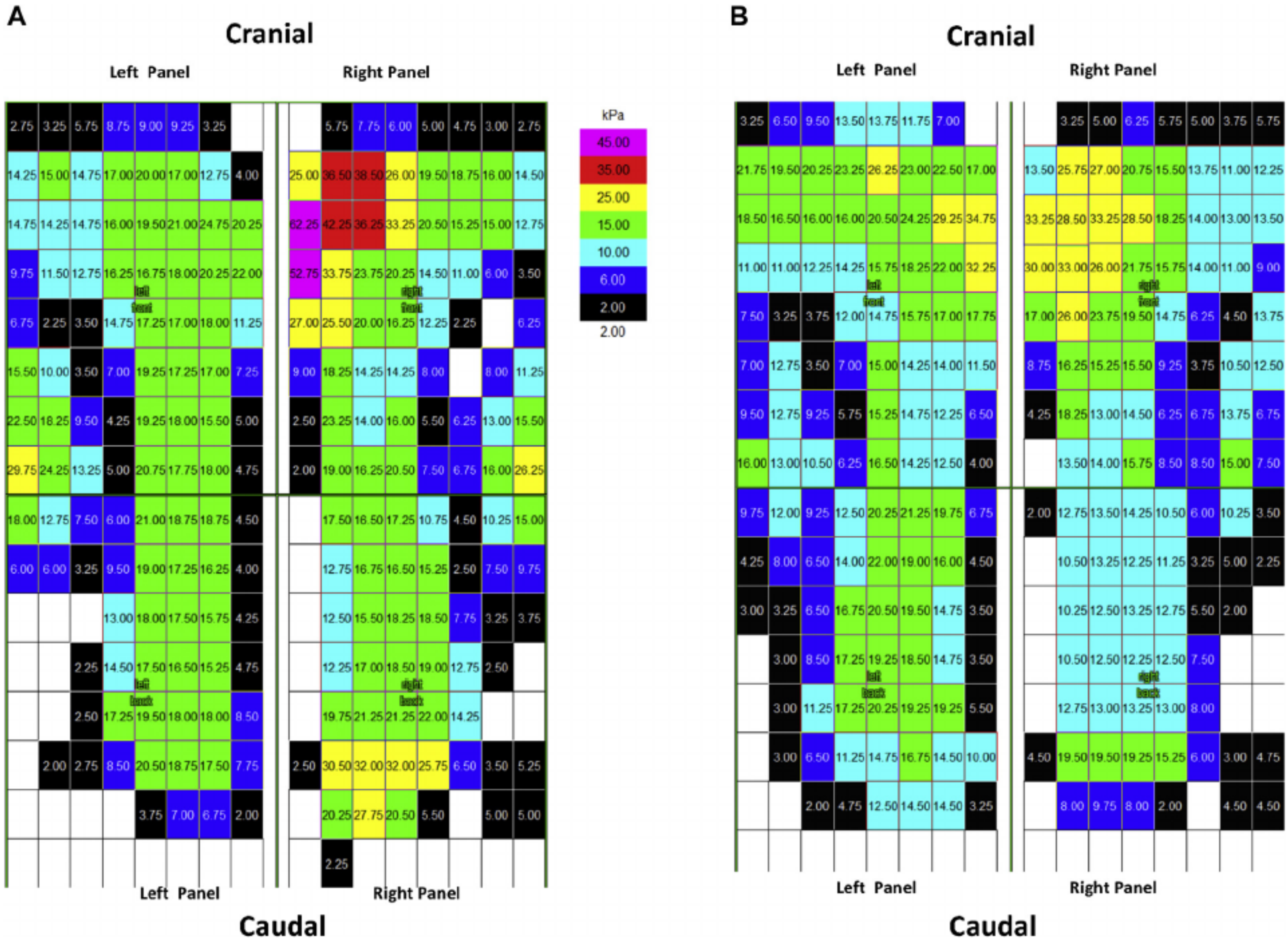

Fig. 3. Pressure distribution beneath the saddle while cantering on the rein with saddle slip to the outside (here: left). (A) Showing pressure distribution beneath a saddle that has rolled to the left, increased pressures to the right of the midline. (B) Showing pressure distribution beneath the saddle after saddle correction.

warrant further investigation. Once saddle position had been corrected with the use of shims, saddle pressures were reduced. It could seem counterintuitive to position a shim under the saddle, with the concern that a ridge of pressure would be created; in this study, saddle roll was reduced when corrected with a shim, and no ridges of pressures were seen from the use of the shim.

5. Conclusion

In a straight line, horses with an asymmetrically positioned saddle significantly altered their locomotion in trot and canter. As previously highlighted, this study is limited by its sample size; however, by using three objective measures, four qualified saddle fitters, and data processing, taking into account the side of the saddle roll and using each horse as its own control, an attempt to investigate the relationship between saddle kinematics and horse locomotion has been made. This preliminary study has shown that in these horses, saddle kinematics have a significant effect on equine locomotion; asymmetry in fetlock angles that is likely affecting force production; increased pressures beneath the panel contralateral to the direction of saddle roll; changes in pelvic ROM as a result of saddle position; and rider position being compromised by the rider leaning to the opposite side to the direction of saddle roll for the rider to align their center of mass closer to the midline of the horse thus optimizing balance. Using an SMSQSF and Prolite shims, this study has reported changes in locomotion, saddle pressures, and rider kinematics by correction of saddle position in this group of horses. Correct saddle fitting is hence essential to optimize the horse-rider system.

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Supplementary Data

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