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The effect that induced rider asymmetry has on equine locomotion and the range of motion of the thoracolumbar spine when ridden in rising trot.

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Summary

There is a paucity of evidence on the effect that rider asymmetry has on equine locomotion. The aim of this study was to evaluate the effect of rider asymmetry on equine locomotion by using a novel approach to induce rider asymmetry. Ten non-lame horses were recruited for this study. Joint centre markers were used to capture 2D kinematics (Quintic Biomechanics) of the horse and rider and horses were equipped with seven inertial sensors positioned at the fifth (T5) and eighteenth (T18) thoracic vertebrae, third lumbar (L3) vertebra, tubera sacrale (TS) and left and right tubera coxae. Rider asymmetry was induced by shortening the ventral aspect of one stirrup by 5cm. Kinematic data were compared between conditions using a mixed model with the horse defined as a random factor and stirrup condition (symmetrical stirrups and asymmetrical stirrups) and direction (inside and outside) defined as fixed factors. Data from riders where the right stirrup was shortened was mirrored to reflect a left stirrup being shortened. To determine differences between conditions a significance of $P \leq 0.05$ was set. On the rein with the shortened stirrup on the outside: an increase in lateral bending range of motion (ROM) at T5 ($P=0.003$), L3 ($P=0.04$) and TS ($P=0.02$), an increase in mediolateral displacement at T5 ($P=0.04$), T18 ($P=0.04$) and L3 (0.03) were found. An increase in maximum fetlock extension was apparent for both the front ($P=0.01$) and hindlimb ($P=0.04$) on the contralateral side to the shortened stirrup. For the asymmetrical stirrup condition on the rein with the shortened stirrup on the inside: an increase in flexion-extension ROM at T5 ($P=0.03$) and L3 ($P=0.04$), axial rotation at T5 ($P=0.05$) and lateral bending of T5 ($P=0.03$), L3 ($P=0.04$) and TS ($P=0.02$). Asymmetric rider position appears to have an effect on the kinematics of the thoracolumbar spine. These findings warrant further investigation to understand the long-term impact this may have on equine locomotor health.

1. Introduction

A rider needs to be able to withstand the propulsive forces generated by the horse during locomotion [1] and adjust to the temporal and spatial movement patterns of the horse's trunk [2]. The coupled system of the horse and rider produces coordinated patterns which can be used to determine gait and riding styles [3]. It is widely accepted that the rider's position is influential for enhancing equine locomotion and performance [4, 5]. Riders attempt to be positioned on the horse symmetrically, however, this is sometimes challenging due to the rider's skill level [2], functional asymmetries [6-8], perception [9] and pre-existing or historic injuries which the rider may have [6, 7, 10, 11]. Rider asymmetry has been quantified during ridden locomotion [7, 12, 13] and when unmounted [6, 8, 14]. There are multiple reasons why riders ride asymmetrically: potentially influenced by saddle design [10]; saddle position [15, 16]; or possibly due to the propulsive forces [1] being transmitted to the rider and the rider's physiological and technical ability to effectively absorb the forces; or as a result of the rider's own functional asymmetries [6, 8, 13, 14, 17].

The saddle is the interface between the horse and the rider. Recently it has been reported that a saddle, which had laterally displaced to one side, induced measurable amounts of rider asymmetry in both trot and canter. Furthermore, in trot, as a result of the laterally positioned saddle and asymmetric rider, a decrease in front fetlock extension on the ipsilateral side to where the saddle had displaced [16] was reported, suggesting that saddle + rider position has an effect on limb loading. Changes in ground reaction force and forelimb fetlock extension have been investigated with and without a rider [18]. With a rider in sitting trot, the forelimb fetlock joint extension increases during the second half of the stance phase when compared to a horse being trotted in hand [18], hence it seems likely that rider asymmetry will have an effect on limb loading. Recently it has been reported that rider asymmetry has an effect on the vertical displacement of the horse's pelvis and saddle forces [19].

Riding with a symmetrical seating style such as sitting trot and two-point seat has been reported to not influence the vertical displacement of the horse's pelvis or head [20]. In contrast, rising trot has been shown to induce changes in movement asymmetry of the horse, where there was a decreased pelvic rise when the rider was actively rising up in the stirrups, as a consequence creating downward momentum counteracting the horse's push off. This movement pattern mimics a hindlimb push off lameness, for the hindlimb that was in stance when the rider was seated during the trot cycle [20]. Furthermore, the uneven movement of the rider when in rising trot produces an uneven biphasic load on the horse's back affecting the motion symmetry of the horse's pelvis and lumbar spine [21]. When ridden in rising and sitting trot, the mean dorsoventral range of motion of the thoracolumbar spine is less when compared to being trotted in hand [22]. Therefore, it seems reasonable to assume that rider asymmetry will affect the kinematics of the thoracolumbar spine when a horse is ridden in rising trot.

To the authors' knowledge, no study has investigated the effect that induced rider asymmetry has on equine locomotion whilst in rising trot. The aim of this study was to investigate the effect that induced rider asymmetry has on the kinematics of the thoracolumbar spine and front and hindlimb locomotor patterns whilst in rising trot. The objectives of this study were to quantify the effect that raising the ventral aspect of the stirrup (from here on: shortened stirrup) by 5cm has on rising trot kinematics, in particular: 1) thoracolumbosacral vertebral kinematics; and 2) limb loading derived from fetlock extension [23]. It is hypothesised that the induction of rider asymmetry will result in: 1) an increase in lateral bending of the thoracolumbar spine; 2) reduced flexion-extension of the cranial region of the thoracolumbar vertebral segments; 3) increased axial rotation of the thoracolumbar spine; 4) increased limb loading (derived from fetlock extension) on the contralateral side to the shortened stirrup when in rising trot.

2. Materials and Methods

The study was approved by the Royal Veterinary College ethics and welfare committee, project number URN 20181785-2.

2.1 Horses

A convenience sample of ten adult sport horses was used in this study. Horses and riders were recruited via Facebook seeking riders to volunteer their participation. Inclusion criteria were the horse was 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 two disciplines (*n*= 8 dressage and *n* = 2 eventing). They ranged in height at the withers mean±standard deviation (mean±SD), (1.65-1.78m with a mean±SD of

1.70±0.02m), body mass (545-600kg with a mean±SD 570±36kg (weigh tape)) and age (9-15 years with a mean±SD 12±1 years). From a subjective assessment horses were of a similar sports horse type (warmblood) and posture, with well-defined epaxial musculature. Horses underwent a subjective veterinary assessment performed by an experienced orthopaedic veterinary surgeon, which included straight line visual observations in walk and trot from both the front/rear and lateral view. No overt signs of lameness were observed. In addition, the horses were trotted in a straight line while conducting quantitative gait analysis using a validated sensor system [24]. Horses were assessed by a veterinarian throughout the experiment, if any signs of lameness were observed the experiment was terminated. No overt signs of lameness were observed.

2.2 Riders

Ten female riders took part in the study. All riders were of an experienced level (competing in British Dressage, Medium or above and British Eventing 1*), (mean±SD) height 1.72 ± 0.05 m, body mass 71±11 kg. At the time of the study, all riders were free from any injuries. Informed consent was obtained, and riders could withdraw from the study at any point.

2.3 Saddles

An inclusion criterion was that all saddles had been checked by a Society of Master Saddlers (SMS) qualified saddle fitter one month preceding the study. On the day, saddles were checked independently by two SMS qualified saddle fitters who assessed the saddles following a static [25] and dynamic [26] saddle fitting assessment . No overt signs of incorrect saddle fit were observed. All saddles were dressage saddles with a seat size of 17.5”. All saddles were wool flocked.

2.4 Determining Static Distribution of Rider Weight

To determine static distribution of the rider’s weight, riders were asked to adopt a standing position with their left and right foot positioned on the centre of two glass digital scales (John Lewis), length 31cm x width 29cm x height 4cm with a maximum range of 150 kg which were positioned side by side on a level concrete surface. Standing position on the scales was assessed by a human physiotherapist throughout off-horse data collection. When stood on the scales, riders were asked to maintain a neutral head position. As an acclimatisation, all riders stood on the scales to become accustomed to the required standing position. After which, when the rider had adopted their standing position and confirmed verbally that they were standing equally on both their left and right feet, measurements were taken from the digital display on the respective scale. Riders were blinded to the data output from either of the scales. This process was repeated five times immediately before the exercise test. Only trials which were consistent were included in the final data i.e. if any riders lost balance the trial was repeated, only one rider lost balance resulting in one repeat. The limb which showed a reduction in weight support across the five trials was used to determine which stirrup was to be shortened.

2. 5 Inducing Rider Asymmetry - Shortening One Stirrup

To induce functional rider asymmetry during riding, one stirrup was shortened by 5cm (Figure1). The decision to raise the ventral aspect of the left or right stirrup was determined by the limb which the rider had reduced vertical loading during the off-horse measurements. Stirrup measurements and adjustments were made by the same technician using a tape measure (Stanley FMHT0-33854). The stirrup design/style remained the same throughout the testing. All stirrups were solid stainless-steel with solid sides which, in all cases, were fitted with a rubber tread which was uniformed in thickness from inside to outside.

Figure 1 – Altering stirrup length. One stirrup was shortened by 5cm. This alteration was performed by the same technician.

2.6 Study Protocol

Each horse underwent a fifteen-minute warm up period self-prescribed by the rider which included walk, trot and canter on both the left and right reins. This was followed by a prescribed trot protocol which included three passes on both the left and right rein, during which horse and rider kinematics were collected. Data were collected during straight line locomotion in both left and right rising trot, with the rider seated and then rising during the second half of the same stance phase of one diagonal pair (outside forelimb and inside hindlimb). All measurements were performed in a straight line in the same indoor school (60x 20 m), on the same surface, which was groomed prior to, and in between, each horse trial. Three repeats on the left and right reins were collected with each condition (symmetrical stirrups and asymmetrical stirrups). After the stirrup had been shortened (figure 2) the horse and rider had a further fifteen minutes self-prescribed acclimatization, at which point data were collected following the same exercise test as previously described. If the horse lost straightness, tripped or made an obvious alteration in gait pattern (e.g. shying) the trial was repeated.

Figure 2 – illustrating symmetrical stirrups (A) and the ventral aspect of the left stirrup being shortened by 5cm (B).

2.7 Kinematics - Two-Dimensional Motion Capture

Kinematic data were recorded with a high-speed video camera system, using twenty-four skin markers (30 mm) placed on each horse using double-sided tape. Marker locations were identified by manual palpation of anatomical landmarks identifying joint centres and segment ends. Once located, white skin paint was used to mark each reference point [27]. Markers were located:

Forelimb: (1) scapular spine; (2) greater tubercle of humerus (cranial); (3) lateral condyle of humerus; (4) lateral metacarpal condyle; (5) distal aspect of the metacarpus over the lateral collateral ligament of the metacarpophalangeal joint; (6) origin of the lateral collateral ligament (LCL) of the distal interphalangeal joint of the forelimb.

Hindlimb: (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 lateral collateral ligament of the metatarsophalangeal joint; (12) origin of the lateral collateral ligament (LCL) of the distal interphalangeal joint of the hindlimb, on both sides of the horse.

Two high-speed cameras (Quintic) were positioned at a ten-metre distance from the experiment track, simultaneously capturing left and right sides of the horse at 400 Hz (spatial resolution 1300x400, 400 fps at 10m distance), with a field of view capturing two complete strides in trot. A halogen light was used to illuminate the markers. High-speed video data were recorded and downloaded to a laptop (Lenovo) and processed using two-dimensional motion capture (Quintic Biomechanics). Automatic marker tracking was used to investigate:

- Maximum forelimb fetlock extension during stance for the forelimbs (palmar angle between (4) lateral metacarpal condyles, (5) distal aspect of the metacarpus over the lateral collateral ligament of the metacarpophalangeal joint and (6) origin of the lateral collateral ligament of the distal interphalangeal joint).
- Maximum hindlimb fetlock extension during stance for the hindlimbs (plantar angle between (10) talus, (11) distal aspect of the metatarsus over the lateral collateral ligament of the metatarsophalangeal joint and (12) origin of the lateral collateral ligament of the distal interphalangeal joint).
- Maximum carpal flexion during the swing phase (palmar angle between (3) lateral greater tubercle of humerus, (4) lateral metacarpal condyles and (5) distal aspect of the metacarpus over the lateral collateral ligament of the metacarpophalangeal joint).
- Maximum tarsal flexion during the swing phase (9) plantar angle between lateral condyle of the femur, (10) talus and (11) distal aspect of the metatarsus over the lateral collateral ligament of the metatarsophalangeal joint).
- Maximum hindlimb protraction (the angle between (8) the greater trochanter of the femur and (11) distal aspect of the metatarsus over the lateral collateral ligament of the metatarsophalangeal joint measured to the vertical).

All raw data were smoothed using a Butterworth low-pass filter, fourth order with a cut off frequency of 10 Hz [28].

2.8 Kinematics - Inertial Measurement Units

Horses were instrumented with seven MTw inertial measurement units (IMUs) (Xsens) using a validated sensor based system (7x Xsens MTw) [24, 29]. By manual palpation IMU sensors were attached over the poll, fifth thoracic vertebra (T5) (withers), eighteenth thoracic vertebra (T18), third lumbar vertebra (L3), tubera sacrale (TS) and left and right tuber coxae, using custom built pouches and double-sided tape. Sensors beneath the saddle (T5 and T18) were glued on to the skin using hair extension glue. The same technician applied each sensor throughout the study and sensor locations were referenced with white skin paint. To reduce variability, sensor pouches remained on the horse throughout. Sensor data were collected at 60 Hz per individual sensor channel and transmitted via proprietary wireless data transmission protocol (Xsens), to a receiver station (Awinda, Xsens) connected to a laptop computer running MTManager (Xsens) software. IMU specifications: internal sampling rate 1000 Hz; buffer time up to 30 seconds; dimensions, 47x30x13mm, mass 16 grams, operating temperature range 0°C - 50°C, dynamic accuracy 0.75 degrees, Root Mean Square (RMS) (roll/pitch) and 1.5 degrees RMS (heading).

IMU data were processed following published protocols [24]. In brief, tri-axial 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 [30], and median values for the following kinematic variables were calculated over all strides for both conditions.

Angular movement (a change in orientation) of T5, T18 and L3 was assessed in three planes, all data outcomes were measured in degrees.

- Flexion-extension range of motion (ROM) - body rotation around the transverse (lateral-lateral) axis.
- Axial rotation ROM - body rotation about the longitudinal (craniocaudal) axis.
- Lateral bending ROM - body rotation about the vertical (dorsoventral) axis.

Translational movement at T5, T18 and L3 were measured in millimetres in two directions:

- Vertical direction (up and down movement of the whole horse).
- Lateral-lateral direction (side to side movement of the whole horse, also referred to as lateral excursion).

2.9 Rider Kinematics

Rider kinematics in relation to the horse were quantified by applying 30mm spherical markers on anatomical landmarks. Markers were positioned: 1) occiput, 2) seventh cervical vertebra (C7), 3) medial border of the left and right spine of scapula, 4) seventh thoracic vertebra (T7), 5) fourth lumbar vertebra (L4), 6) left and right posterior superior iliac spine (PSIS) and 7) left and right calcaneus. Markers were fitted and checked between trials by the same qualified human physiotherapist. In order to limit the effect that clothing had on marker position, riders wore fitted base layers.

A high speed camera (400 Hz) was positioned on a tripod which remained in the same position caudal to the horse, capturing straight line rising trot locomotion on both reins with symmetrical and asymmetrical stirrups. With the camera zoom remaining the same from a caudal view, the riders' trunk and pelvic position were quantified. High-speed video data were recorded and downloaded to a laptop (Lenovo) and processed using two-dimensional motion capture (Quintic Biomechanics). Automatic marker tracking was used to investigate. All raw data were smoothed using a Butterworth low-pass filter, fourth order with a cut off frequency of 10 Hz.

Measured in degrees, automatic marker tracking was used to investigate:

- Angle between the left and right PSIS measured from the horizontal during the standing and seated phase of the trot.
- Angle between the medial border of the left and right spine of scapula measured from the horizontal during the standing and seated phase of the trot.
- Angle between C7 and L3 measured from the vertical during the standing and seated phase of the trot.

Values close to zero represent symmetry. Minus values (-) indicate left side asymmetry and positive values (+) indicate right side asymmetry.

2.10 Data Collection

From the in hand quantitative gait assessment, trot data were collected from 25±3 repeated strides in a straight line, outcome parameters were:

- minimum difference D (PDMin): difference between the two minima in vertical (z) displacement observed during the two diagonal stance phases in trot.
- maximum difference Head (HDMax) and Pelvis (PDMax): difference between the two maxima in vertical (z) displacement observed after the two diagonal stance phases in trot.

From the two-dimensional kinematic analysis, data were collected from two consecutive strides with three repeats, totalling six strides used for analysis in rising trot, both inside/outside directions for each horse for both conditions.

Outcome parameters for each condition were (equine):

- Maximum fetlock extension front and hindlimb during stance.
- Maximum carpal flexion during the maximum swing phase.
- Maximum tarsal flexion during the maximum swing phase.
- Maximum hindlimb protraction during the swing phase.

Outcome parameters for each condition were (rider) (figure 3):

- Scapula position relative to the horizontal during the standing and seated phase of the trot ($\text{Scapula}_{\text{Horz}}$) (A).
- Pelvic position relative to the horizontal during the standing and seated phase of the trot ($\text{Pelvic}_{\text{Horz}}$) (B).
- Trunk displacement relative to the vertical during the standing and seated phase of the trot ($\text{Trunk}_{\text{Tilt}}$) (C).

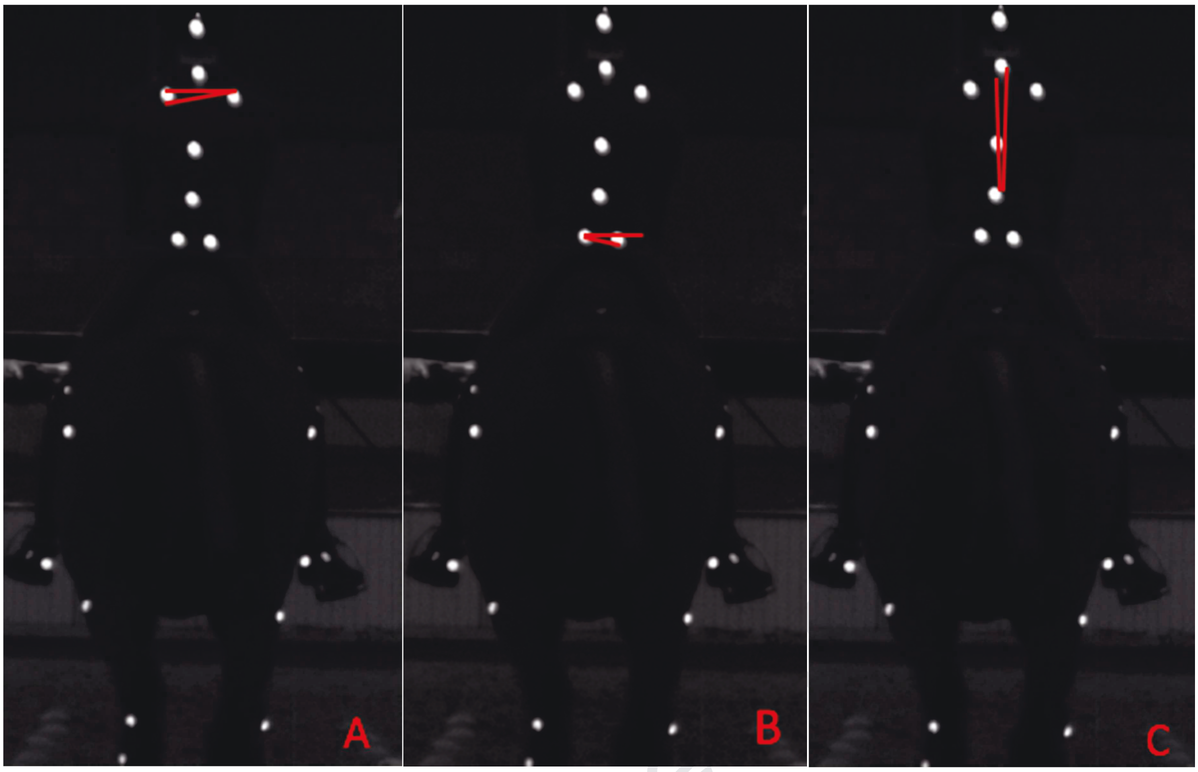


Figure 3 – illustrating the outcome parameters from the 2D rider kinematics, data collected in both the seated and standing phase of the trot. Image A - Scapula position relative to the horizontal ($Scapula_{Horz}$*), Image B - Pelvic position relative to the horizontal (*$Pelvic_{Horz}$*), Image C - Trunk displacement relative to the vertical (*$Trunk_{Tilt}$*).*

From the IMUs, data were collected from eleven consecutive strides from three repeats, totalling mean±SD 33±5 strides being used for analysis, in trot for both directions (left and right rein) for each condition.

Outcome parameters for the IMUs between symmetrical and asymmetrical conditions were as follows:

- minimum difference Head (HD_{Min}), Withers (W_{Min}) and Pelvis (PD_{Min}): difference between the two minima in vertical (z) displacement observed during the two diagonal stance phases in trot.
- maximum difference Head (HD_{Max}), Wither (W_{Max}) and Pelvis (PD_{Max}): difference between the two maxima in vertical (z) displacement observed after the two diagonal stance phases in trot.

- hip hike difference (HHD): difference between vertical upward movement amplitude of left and right tuber coxae during contra-lateral stance.
- Craniocaudal, vertical and mediolateral range of motion for T5, T13, T18, L3 TS.
- Axial rotation of T5, T13, T18, L3 TS
- Flexion and extension of T5, T13, T18, L3 TS
- Lateral bending of T5, T13, T18, L3 TS
- HHD (difference between the vertical upward movement amplitude of left and right tuber coxae)

2.11 Influence of Speed

Since many kinematic parameters are influenced by speed, we tested for differences in speed between the two conditions (symmetrical and asymmetrical stirrups). Due to the lack of direct speed measurements, stride time (extracted from IMU data during stride segmentation was used as a surrogate measure (of inverse speed) due to the negative relationship between speed and stride time within a gait [31]. No significant difference was found in stride time between the two conditions (pre left rein 891.00 ± 8.91 ms, post left rein 887.90 ± 12.05 ms, pre right rein 883 ± 13.76 ms, post right rein 885.78 ± 9.32 ms) hence stride time was not entered into the statistical model.

2.11 - Data Standardisation

To make optimal use of the sample size of *n=10* horses, all kinematic data were ‘standardised’ with respect to the side which the stirrup had been shortened. Data of horses where the right stirrup had been shortened (*n*=3) were combined with data of horses where the left stirrup had been shortened (*n*=7). This data standardisation process required (1) inverting IMU asymmetry data for horses where the right stirrup had been shortened, and (2) expressing movement conditions and limbs with respect to the side of the shortened stirrup as inside or outside rather than left or right. As a consequence, ‘rein with the shortened stirrup on the outside’ was used to express the direction of movement for a horse on the right rein and ‘rein with the shortened stirrup on the inside’ was used to express the direction of movement for a horse on the left rein. This process effectively assesses the three horses with a shortened right stirrup through a mirror.

2.12 Statistical Analysis

Statistical analysis was performed in SPSS (vers. 22, IBM, Armonk, USA). Kinetic and kinematic outcome parameters were assessed for normality using Shapiro-Wilk test of normality. Data were defined by movement condition and then analysed using a mixed model with the horse as random factor, and stirrup condition (symmetrical stirrups and asymmetrical stirrups) and direction (inside and outside) as fixed factors. To determine differences a significance value of $P \leq 0.05$ was set.

3. Results

3.1 Horse Inclusion

All horses (*n=10*) underwent a subjective lameness evaluation by an experienced veterinary surgeon. Horses were trotted in hand in a straight line on a firm level surface. All horses were deemed to be non-lame. From the objective movement asymmetry measures, horses had (mean ± SD) asymmetry values: HD_{min}, 5.0±1.8 and HD_{max} 6.5±2.3, PD_{min}-4.3±2.5 and PD_{max} -4.0±2.2, and HHD 2.4±2.6.

3.2 **Determining Static Distribution of Rider Weight**

Table 2 – mean ± standard deviation of vertical loading of the rider's left and right leg when using two scales with five repeats. The decision to raise the ventral aspect of the left or right stirrup was determined by the limb which the rider had reduced vertical loading.

Rider ID	Left Leg Weight Support mean ± SD kg	Right Leg Weight Support mean ± SD kg
1	33.5 ± 1.3	36.6 ± 0.9
2	35.2 ± 0.7	38.6 ± 0.9
3	30.6 ± 0.7	31.7 ± 0.3
4	39.2 ± 0.7	41.0 ± 2.0
5	31.6 ± 1.6	32.1 ± 1.8
6	39.4 ± 1.1	41.8 ± 1.5
7	38.7 ± 1.3	35.8 ± 1.7
8	38.5 ± 2.0	39.2 ± 2.2
9	32.3 ± 2.5	31.4 ± 2.3
10	34.1 ± 1.1	32.1 ± 0.6

3.3 **Kinematic data on the rein with shortened stirrup on the outside**

Data standardised resulting in data from riders with a shortened right stirrup (n=3) being mirrored to represent left stirrup shortened (Mean±SD).

3.3.1 Symmetry Parameters

Horse's (mean ± SD) asymmetry values;

- HD_{min}- Symmetrical stirrups, 11.3 ± 8.1 and asymmetrical stirrups 14.9 ± 9.3, P=0.31
- HD_{max} - Symmetrical stirrups 3.4 ± 4.2 and asymmetrical stirrups 6.7 ± 4.8, P=0.29
- W_{min} - Symmetrical stirrups 2.3 ± 5.8 and asymmetrical stirrups 5.7 ± 5.6, P=0.78
- W_{max} - Symmetrical stirrups 6.6 ± 6.6 and asymmetrical stirrups 6.7 ± 6.7, P=0.61
- PD_{min} - Symmetrical stirrups 2.9 ± 6.3 and asymmetrical stirrups 5.5 ± 6.4, P=0.09
- PD_{max} - Symmetrical stirrups 4.1 ± 3.5 and asymmetrical stirrups 8.7 ± 3.1, P=0.17
- HHD - Symmetrical stirrups 1.9 ± 5.3, asymmetrical stirrups 9.3 ± 4.3, P=0.04

3.3.2 Thoracolumbar Rotational Kinematics

T5

An increase in lateral bending was found for the asymmetrical stirrup condition, (symmetrical stirrups 7.0°±1.1°, asymmetrical stirrups 8.3°±2.0°, P=0.003).

L3

An increase in lateral bending (symmetrical stirrups 5.5°±2.0°, asymmetrical stirrups 6.2°±2.3°, P=0.04) and flexion extension was found for the asymmetrical stirrup condition (symmetrical stirrups 4.9°±2.0°, asymmetrical stirrups 5.0°±2.6°, P=0.04).

TS

An increase in lateral bending was found for the asymmetrical stirrup condition, (symmetrical stirrups 5.8°±1.4°, asymmetrical stirrups 6.0°±1.4°, P=0.02).

No significant differences (P>0.05) were found for the remaining rotational movement derived parameters.

3.3.3 Thoracolumbar Translational Kinematics

T5

An increase in mediolateral displacement was found for the asymmetrical stirrup condition, (symmetrical stirrups 27.0±6.0 mm, asymmetrical stirrups 31.2±6.4 mm, P=0.04).

T18

An increase in mediolateral displacement was found for the asymmetrical stirrup condition, (symmetrical stirrups 33.1±7.9 mm, asymmetrical stirrups 37.0±7.0 mm, P=0.04).

L3

An increase in mediolateral displacement was found for the asymmetrical stirrup condition, (symmetrical stirrups 31.0±9.2 mm, asymmetrical stirrups 35.5±7.5 mm, P=0.03.

No significant differences (P>0.05) were found for the remaining translational movement derived parameters.

3.3.4 Limb Kinematics

Forelimb Fetlock Extension

An increase in fetlock extension was found for the inside fetlock joint for the asymmetrical stirrup condition (symmetrical stirrups 242.9°±7.1°, asymmetrical stirrups 244.9°±6.5°, P=0.01) (Table 2**).**

Hindlimb Fetlock Extension

An increase in fetlock extension of the inside hindlimb was found for the asymmetrical stirrup condition, (symmetrical stirrups 236.8°±8.6°, asymmetrical stirrups 238.9°±7.4°, P=0.04) (Table 2).

Hindlimb Protraction

An increase in inside hindlimb protraction was found for the asymmetrical stirrup condition, (symmetrical stirrups 6.22°±1.4°, asymmetrical stirrups 6.76°±1.5°, P=0.03) (Table 2).

No significant differences (P>0.05) were found for the remaining limb kinematic derived parameters.

3.3.5 Rider Kinematics

During the standing phase in rising trot:

Pelvic$_{Horz}$ (symmetrical stirrups 2.7°±2.5°, asymmetrical stirrups 2.9°±3.1°, P=0.77)

Scapula$_{Horz}$ (symmetrical stirrups 1.5°±2.8°, asymmetrical stirrups -2.6°±4.9°, P=0.03)

Trunk$_{Tilt}$ (symmetrical stirrups -0.15°±2.3°, asymmetrical stirrups -1.59°±1.3°, P=0.03)

During the seated phase in rising trot:

Pelvic$_{Horz}$ (symmetrical stirrups 1.7°±2.9°, asymmetrical stirrups 2.7°±3.1°, P=0.34)

Scapula$_{Horz}$ (symmetrical stirrups 1.7°±2.1°, asymmetrical stirrups -1.4°±3.1°, P=0.03)

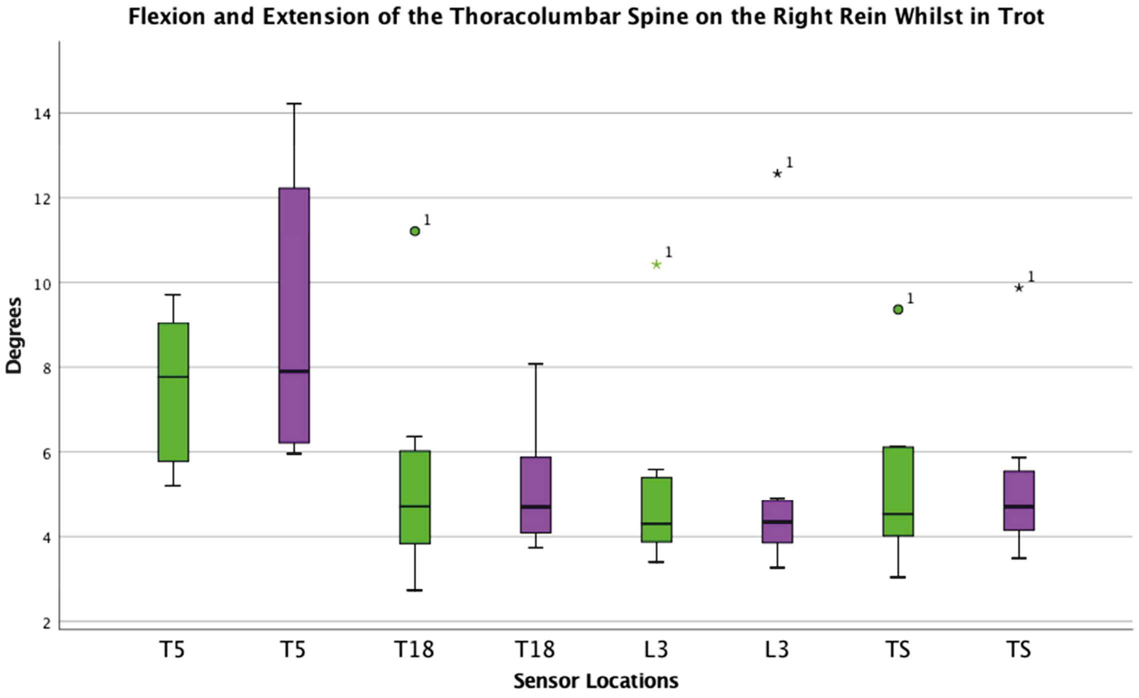
Trunk$_{Tilt}$ (symmetrical stirrups 0.31°±2.7°, asymmetrical stirrups -1.02°±2.1°, P=0.04)

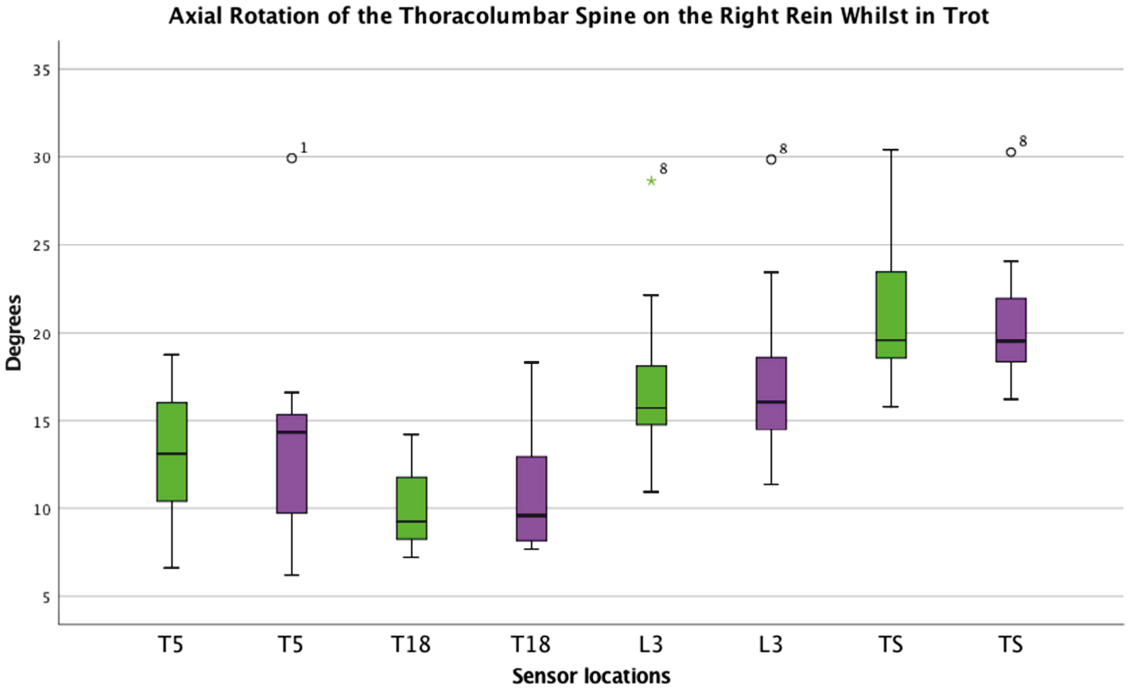
Table 2 - Mean and s.d. for two dimensional kinematic data for limb kinematics when in rising trot on a straight line for both the symmetrical and asymmetrical stirrups. Data mirrored to represent left stirrup shortened for n=10 horse. Significance level set at P<0.05.

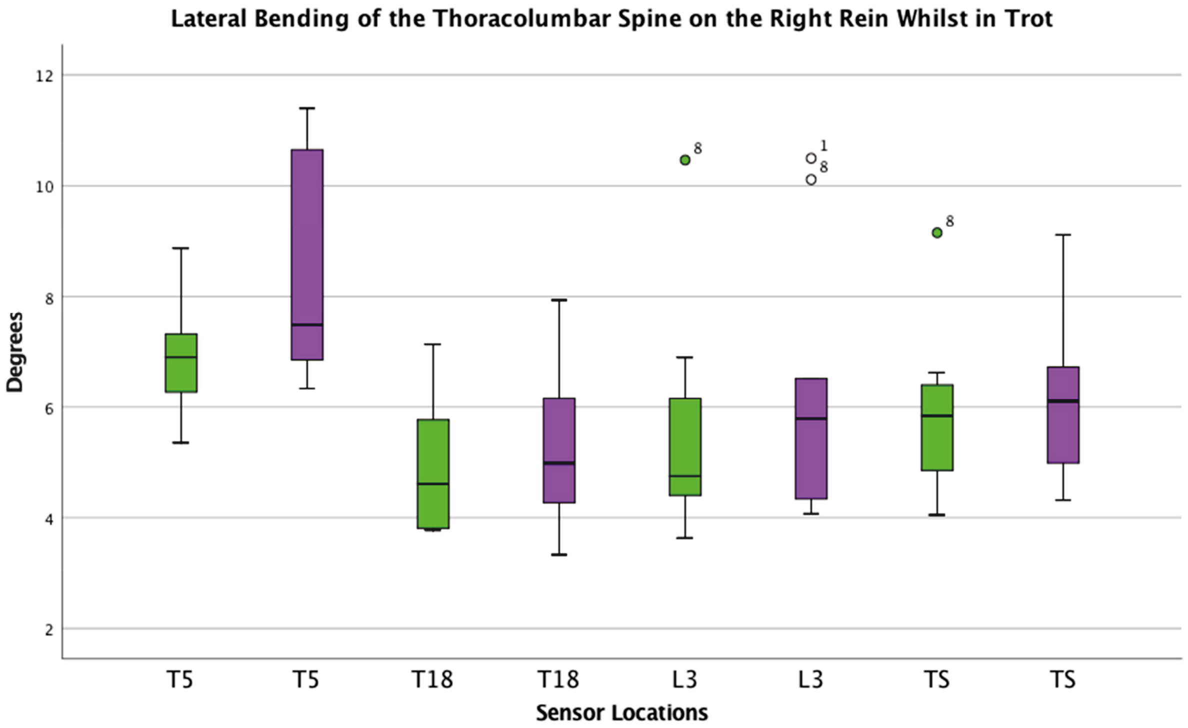
Rein with shortened stirrup (left stirrup) on the outside (Here: Right Rein)					
Condition	Front Fetlock Extension (Mean±SD) (°)	Carpal Flexion (Mean±SD) (°)	Hind Fetlock Extension (Mean±SD) (°)	Tarsal Flexion (Mean±SD) (°)	Hindlimb Protraction (Mean±SD) (°)
Symmetrical stirrups	242.9 ± 7.1	99.6 ± 7.7	236.8 ± 8.6	110.89 ± 6.21	6.22 ± 1.45

Asymmetrical stirrups	244.9 ± 6.5	100.1 ± 8.4	238.9 ± 7.4	110.62 ± 6.21	6.76 ± 1.55
P	0.01	0.08	0.04	0.56	0.03

*Figure 4, 5, 6 - Boxplots displaying IMU movement parameters for each sensor location when in rising trot on a straight line. a=flexion-extension, b=axial rotation and c=lateral bending; the symmetrical stirrups represented by the green boxes and the asymmetrical stirrups represented by the purple boxes. The central line represents the median; the box represents the 25th and 75th percentiles; and the whiskers represent the maxima and minima not considered to be outliers. ° represents outliers and * represents extreme outliers and the respective number is the horse for which the outlier relates to.*


Flexion and Extension of the Thoracolumbar Spine on the Right Rein Whilst in Trot
Degrees
14
12
10
8
6
4
2
1
1
1
1
1
1
T5
T5
T18
T18
L3
L3
TS
TS
Sensor Locations


Axial Rotation of the Thoracolumbar Spine on the Right Rein Whilst in Trot
Degrees
35
30
25
20
15
10
5
1
8
8
8
T5
T5
T18
T18
L3
L3
TS
TS
Sensor locations



3. 4 Kinematics data on the rein with shortened stirrup on the inside.

Data standardised resulting in data from riders with a shortened right stirrup (n=3) being mirrored to represent left stirrup shortened (Mean±SD).

3.4.1 Symmetry Parameters

Horse's (mean ± SD) asymmetry values;

- HD_{min}- Symmetrical stirrups, 2.1 ± 9.0 and asymmetrical stirrups 9.0 ± 6.0, P=0.89
- HD_{max} - Symmetrical stirrups 2.1 ± 8.4 and asymmetrical stirrups 3.6 ± 8.07, P=0.77
- W_{min} - Symmetrical stirrups 3.6 ± 4.5 and asymmetrical stirrups 3.4 ± 4.2, P=0.90
- W_{max} - Symmetrical stirrups 1.3 ± 4.5 and asymmetrical stirrups 2.8 ± 8.5, P=0.78
- PD_{min} - Symmetrical stirrups 3.5 ± 5.2 and asymmetrical stirrups 6.3 ± 6.4, P=0.12
- PD_{max} - Symmetrical stirrups 3.6 ± 5.2 and asymmetrical stirrups 5.7 ± 4.8, P=0.98
- HHD - Symmetrical stirrups 4.2 ± 13.2 and asymmetrical stirrups 6.3 ± 14.9, P=0.78

3.4.2 Thoracolumbar Rotational Kinematics

T5

For the asymmetrical stirrup condition an increase was found in: flexion-extension, (symmetrical stirrups 7.3°±1.7°, asymmetrical stirrups 9.5°±4.4°, P=0.03); axial rotation (symmetrical stirrups 13.3°±4.2°, asymmetrical stirrups 14.2°±5.5°, P=0.05); and lateral bending (symmetrical stirrups 7.4°±1.0°, asymmetrical stirrups 8.9°±1.6°, P=0.003).

L3

An increase in flexion-extension was found for the asymmetrical stirrup condition, (symmetrical stirrups 5.2±4.9, asymmetrical stirrups 5.7°±2.6°, P=0.04). An increase in lateral bending was found for the asymmetrical stirrup condition (symmetrical stirrups 6.2°±1.9°, asymmetrical stirrups 6.9°±2.5°, P=0.04).

TS

An increase in axial rotation was found for the asymmetrical stirrup condition, (symmetrical stirrups 6.0°±1.4°, asymmetrical stirrups 6.6°±1.4°, P=0.02).

No significant differences (P>0.05) were found for the remaining rotational movement derived parameters.

3.4.3 Thoracolumbar Translational Kinematics

No significant differences (P>0.05) were found for any translational movement derived parameters.

3.4.4 Limb Kinematics

Carpal Flexion

A decrease in inside maximum carpal flexion during the swing phase was found for the asymmetrical stirrups condition, (symmetrical stirrups 99.6°±8.3°, asymmetrical stirrups 102.1°±7.7°, P=0.04) (Table 3).

No significant differences (P>0.05) were found for the remaining limb kinematic derived parameters.

3.4.5 Rider Kinematics

During the standing phase in rising trot:

$\text{Pelvic}_{\text{Horz}}$ (symmetrical stirrups 2.0°±1.2°, asymmetrical stirrups 3.1°±2.4°, P=0.09)

$\text{Scapula}_{\text{Horz}}$ (symmetrical stirrups 2.4°±2.2°, asymmetrical stirrups -2.7°±4.0°, P=0.01)

$\text{Trunk}_{\text{Tilt}}$ (symmetrical stirrups 1.0°±2.3°, asymmetrical stirrups -1.8°±2.1°, P=0.03)

During the seated phase in rising trot:

$\text{Pelvic}_{\text{Horz}}$ (symmetrical stirrups 2.1°±2.3°, asymmetrical stirrups 2.5°±2.3°, P=0.30)

$\text{Scapula}_{\text{Horz}}$ (symmetrical stirrups 3.0°±2.4°, asymmetrical stirrups -1.3°±3.7°, P=0.04)

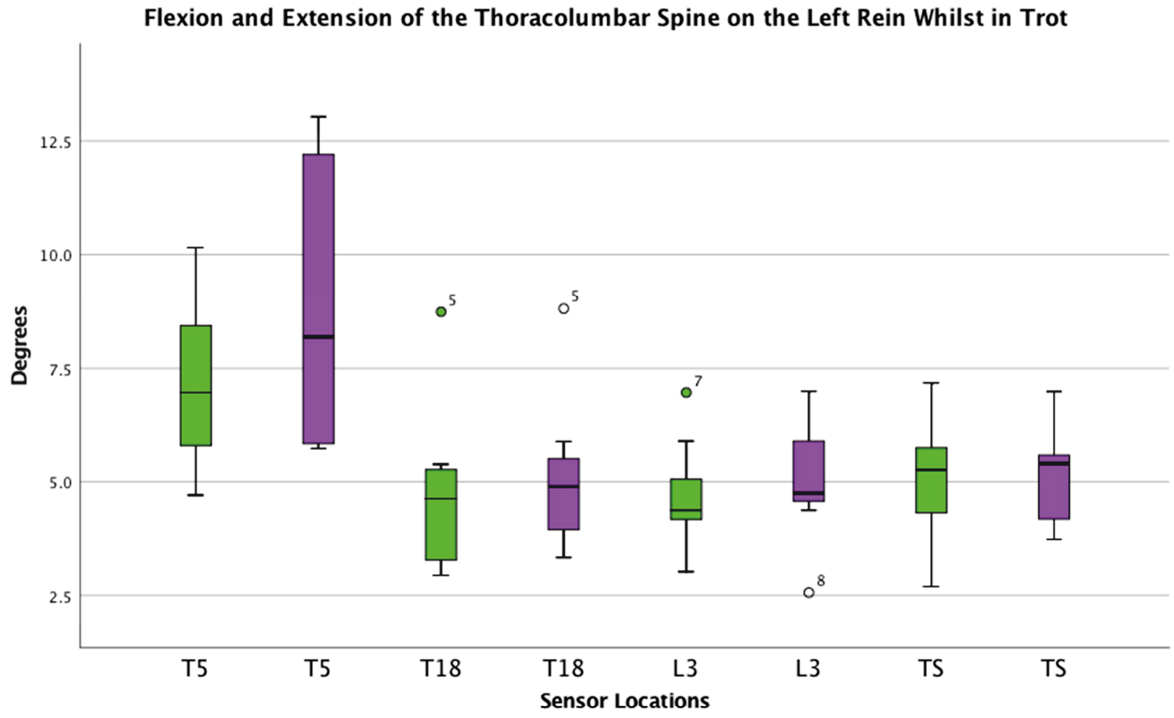
$\text{Trunk}_{\text{Tilt}}$ (symmetrical stirrups 0.5°±1.8°, asymmetrical stirrups -1.5°±2.8°, P=0.04)

Table 3 - Mean and s.d. for two dimensional kinematic data when in rising trot on a straight line for both the symmetrical and asymmetrical stirrups. Data mirrored to represent left stirrup shortened for n=10 horse. Significance level set at P<0.05.

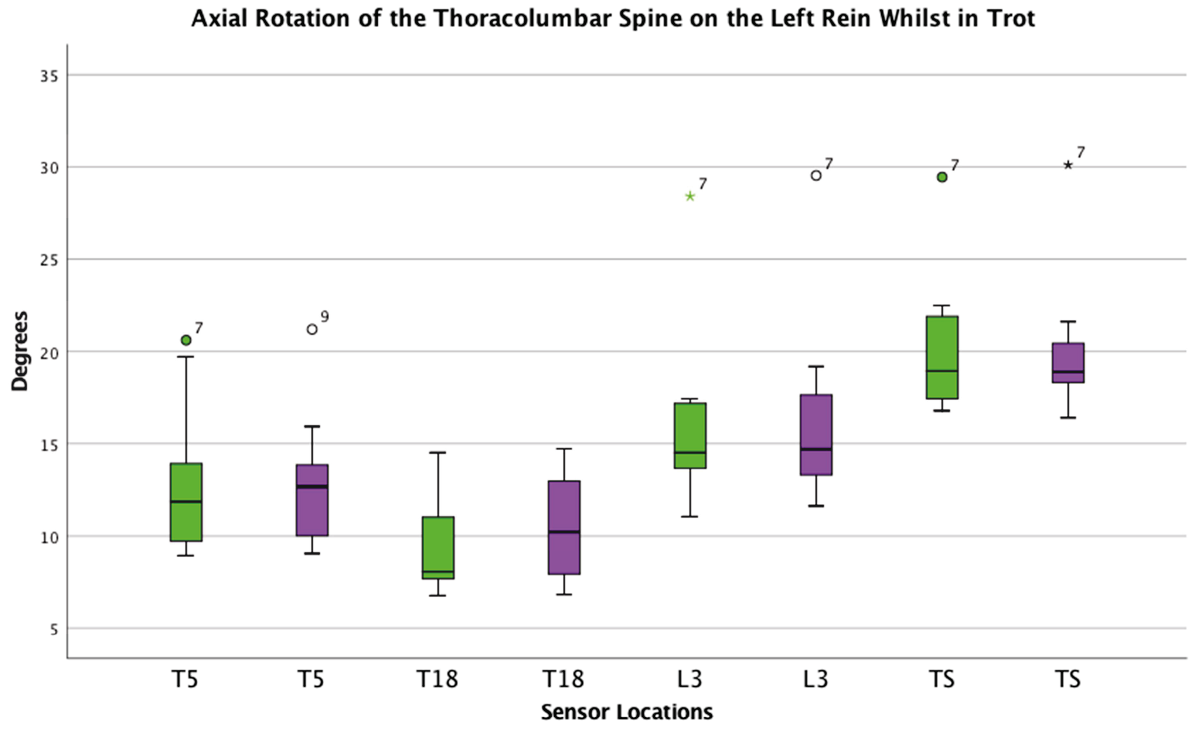
Rein with shortened stirrup (left stirrup) on the inside (Here: Left Rein)					
Condition	Front Fetlock Extension (Mean±SD) (°)	Carpal Flexion (Mean±SD) (°)	Hind Fetlock Extension (Mean±SD) (°)	Tarsal Flexion (Mean±SD) (°)	Hindlimb Protraction (Mean±SD) (°)
Symmetrical stirrups	240.1 ± 9.8	99.6 ± 8.3	233.6 ± 7.7	112.9 ± 7.6	7.5 ± 2.16
Asymmetrical stirrups	239.9 ± 11.2	102.2 ± 7.7	233.0 ± 8.7	112.8 ± 7.6	7.3 ± 2.4
P	0.09	0.40	0.47	0.65	0.67

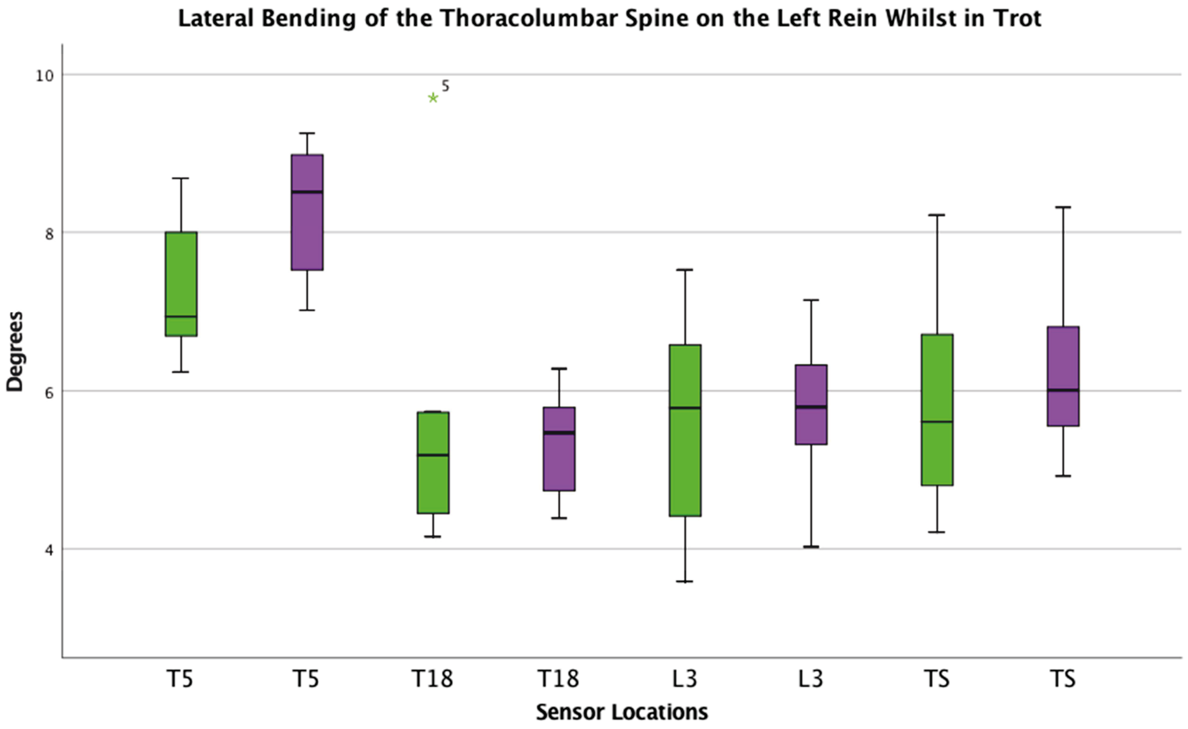
Figure 7, 8, 9 -

*Boxplots displaying IMU movement parameters for each sensor location when in rising trot on a straight line. a=flexion-extension, b=axial rotation and c=lateral bending; the symmetrical stirrups represented by the green boxes and the asymmetrical stirrups represented by the purple boxes. The central line represents the median; the box represents the 25th and 75th percentiles; and the whiskers represent the maxima and minima not considered to be outliers. ° represents outliers and * represents extreme outliers and the respective number is the horse for which the outlier relates to.*


Flexion and Extension of the Thoracolumbar Spine on the Left Rein Whilst in Trot
Degrees
12.5
10.0
7.5
5.0
2.5
5
5
7
8
T5
T5
T18
T18
L3
L3
TS
TS
Sensor Locations

8


Axial Rotation of the Thoracolumbar Spine on the Left Rein Whilst in Trot
Degrees
35
30
25
20
15
10
5
7
9
7
7
7
7
T5
T5
T18
T18
L3
L3
TS
TS
Sensor Locations



4. Discussion

This study induced rider asymmetry by shortening the ventral aspect of one stirrup by 5cm, in an attempt to quantify the effect that rider asymmetry may have on equine locomotion and the kinematics of the thoracolumbar spine. Although some differences have been reported, the authors appreciate that this study is limited by its sample size and the differences reported are small and could be as a result of biological variation. In order to make optimal use of the small sample size, data processing methods involved converting data from *n*=3 riders (right stirrup shortened) effectively resulting in left stirrup shortened for n=10 horses. In addition, data analysis was categorised with respect to whether the stirrup was shortened on the inside or outside irrespective of the actual side (left or right). From the data, horses 1 and 8 were found to be outliers on the rein with the shortened stirrup on the outside and horses 5 and 7 on the opposite rein *(figures 4-9)*. The authors have no explanation for this other than biomechanical adaptions as a result of biological variation in response to the induced asymmetry.

In accordance with our hypothesis, in straight line locomotion after shortening one stirrup by 5cm, changes in the kinematics of thoracolumbar spine whilst trotting (rising) were observed. This study found that the kinematics of the thoracolumbar spine differ when the shortened stirrup was on the inside compared to the outside. On the rein with the shortened stirrup on the inside, this study found an increase in flexion-extension and lateral bending of the cranial thoracic (T5) and lumbar spine (L3) when ridden with asymmetric stirrups. On the rein with the shortened stirrup on the outside, an increase in flexion-extension at T5 and an increase in lateral bending at T5 and L3 was found when ridden with asymmetric stirrups. On both reins, there was no significant differences in rotational movement at the eighteenth thoracic vertebra (T18) when ridden with asymmetric stirrups.

On the rein with the shortened stirrup on the outside, mediolateral displacement of the thoracolumbar spine at T5, T18, L3 increased with the asymmetric rider. On the contralateral rein, nearly all sensor locations (T5, T13, T18), showed an increase in mediolateral displacement however, this was not statistically significant. In trot, reduced mediolateral displacement and rotational movement of the thoracolumbar region has been proposed as an indicator of increased dynamic stability of the thoracolumbar region [31]. In the current study, it is speculated that rider asymmetry decreases the dynamic stability of the thoracolumbar spine hence resulting in an increase in rotational and translational movement with an asymmetric rider. Furthermore, it is speculated that these differences are likely as a result of the asymmetric forces created by the rider in the stirrups resulting in an asymmetric push off from the stirrup when the rider rises.

Although rotational and translational changes were found at T5, T18 and L3 this study cannot quantify the effect that rider asymmetry has on the mid-thoracic region. The region of T10-T13 has been shown to be a region where the *m. longissimus* is most active [32, 33] and an area where areas of high pressures from the saddle can alter locomotion [27, 34], and where the epaxial musculature can alter its dimensions after thirty minutes of exercise [35]. Therefore, it is speculated that T13 is an area that may show measurable changes with an asymmetric rider. The use of small IMUs positioned on the midline of the back [36] (under the saddle) without causing hindrance to the saddle or horse would be beneficial and warrants further investigation.

With respect to the rider kinematics, as a result of the shortened stirrup, the riders altered their position likely in an attempt to rebalance and maintain their position. From our 2D kinematics, riders lowered their shoulder (towards the side of the shortened stirrup) and tilted their trunk towards the shortened stirrup. In sitting trot, a recent study found that per degree a rider collapsed their hip, a 1.5 Newton's (N) increase in saddle force was identified beneath the contralateral panel of the saddle towards the collapsed hip. In the current study, shortening one stirrup did not have a significant effect on pelvic position however, when riders tilt their trunk, it has been reported that for every degree of trunk tilt, a 1.4 N increase in saddle forces was found beneath the saddle on the same side that the rider was tilting towards. The shortening of one stirrup resulted in riders tilting their trunk towards the side of the shortened stirrup. Therefore, it is speculated that this would have increased the saddle forces beneath the panel that they were leaning towards. Advances in technology where IMUs along with a pressure mat could be integrated would be advantageous in advancing our knowledge of saddle-horse interaction. Including pressure data on top and beneath the saddle would add to the study, it is speculated that the induced rider asymmetry would result in asymmetric saddle and seat pressures. [13, 19].

Further support that rider asymmetry has an effect on equine locomotion arises from our kinematic data. A linear relationship between fetlock extension and peak vertical force has been demonstrated [23]. This study used fetlock extension as an indicator of differences in force production. On the rein with the shortened stirrup on the outside, an increase in inside front and inside hind maximal fetlock extension was found. In sitting trot, the effect that the rider has on fetlock extension has previously been quantified [18], where the addition of the rider altered fetlock extension during the caudal part of the stance phase. When performing rising trot on the rein with the shortened stirrup on the outside, the rider is seated during the diagonal stance phase of the inside hind limb and outside front limb. As the rider rises, the maximum standing position coincides with the diagonal stance phase of the outside hind and inside front limb, the reverse pattern is seen when on the opposite rein. In the current study, increased force, derived from increased fetlock extension, was found for both the inside hind limb and inside front limb. The increase in inside hind limb fetlock extension (and force) could be due to the sitting diagonal which would be in accordance with previous studies where the vertical ground reaction forces have been reported to be higher for the sitting diagonal [21] (here: inside hind). However, in the current study, rider asymmetry when the shortened stirrup was on the outside affected fetlock extension of the inside forelimb. This coincides with the standing position of the rider. The increased fetlock extension could be due to the rider exerting greater force on the shortened stirrup resulting in the rider rising asymmetrically. This study can only report the immediate effect that rider asymmetry has on equine locomotion. It is however, proposed that riders who ride asymmetrically may create asymmetric forces leading to increased displacement of the thoracolumbar region and asymmetric fetlock extension resulting in increased tension of the palmar soft tissues which support the fetlock joint, increasing the risk of injury [18] or locomotor asymmetries.

Finally, in further support that induced rider asymmetry has an effect on equine locomotion arises from our movement symmetry derived parameters. The difference between the vertical upward movement amplitude of left and right tuber coxae during contra-lateral stance (HHD) was significantly greater on the rein with the shortened stirrup on the outside. For the remaining symmetry parameters, although no significant changes were found between the different stirrup conditions, the highest asymmetry values were found for the condition with the shortened stirrup. The horses in the current study had higher asymmetry values than published thresholds attributed to non-lame horses [37] however, they are in accordance with additional thresholds obtained using the same quantitative gait system used in this study [38]. Furthermore, studies have shown horses in routine training exceeding the lameness identification threshold values [39]. Thresholds are designed for lameness investigations, hence for the identification of the affected limb(s) in horses that have been identified as having an ‘issue’. Applying these thresholds to horses without identified performance issues will lead to high false positive ‘lameness’ rates.

Caution should be taken not to over interpret the results presented. This study recruited experienced riders in order to reduce the potential effect that shortening one stirrup had on rider balance, stability and coordination. It is speculated that the effects of shortening one stirrup may have a greater effect on the rider’s pelvis position and trunk stability, however, no supporting data are presented here. This study quantified immediate changes in equine locomotion after the induction of rider asymmetry whilst in rising trot. The results presented here may not be transferable to other seating positions such as sitting trot or two-point seat, where it has been reported that both these positions did not overtly affect equine movement symmetry [20]. A longitudinal study quantifying the effect that rider asymmetry has on whole horse locomotion in all gaits with multiple seating positions along with quantifying rider asymmetry movement patterns is warranted. Furthermore, this study only shortened the stirrup on the limb where the rider showed a reduction in weight support when standing on a set of scales, future studies could randomly assign which stirrup should be shortened. This study used horses of a similar posture, identified subjectively. The use of a more objective muscle grading system would be advantageous in an attempt to quantify equine posture. Lastly, quantifying each rider's position off horse using an objective screening process to determine functional asymmetries would be useful.

5. Conclusion

This study has attempted to quantify the effect of induced rider asymmetry on equine locomotion and thoracolumbar kinematics. Using our method of inducing asymmetry, changes in thoracolumbar kinematics and increase in fetlock extension on the contralateral side where the ventral aspect of the stirrup had been shortened have been found. As a result, it is speculated that rider asymmetry has the potential to create asymmetrical loading, and hence force production, between the left and right sides of the horse. Whilst the measured changes are generally of small magnitudes, the repetitive nature – repeating similar movements with each stride cycle – suggests that riders and coaches should not underestimate the effects of their functional asymmetries on the locomotor apparatus of the horse.

6. Acknowledgements

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Highlights

1. Rider asymmetry affects range of motion of the thoracolumbar spine
2. Rider asymmetry affects front and hind limb loading
3. Riders need to be aware of the effect that their position has on equine locomotion

The study was approved by the ethics and welfare committee of the first author’s institution.

Conflict of Interest Statements

None of the authors on this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of this paper.