Original Article

Influence of functional rider and horse asymmetries on saddle force distribution during stance and in sitting trot

S. Gunst[1,*], M.T. Dittmann[1], S. Arpagaus[1], C. Roepstorff[1], S.N. Latif[1], B. Klaassen[2], C.A. Pauli[3], C.M. Bauer[3], M.A. Weishaupt[1]

[1] *Equine Department, Vetsuisse Faculty, University of Zurich, Zurich, Switzerland*

[2] *Faculty of Behavioural, Management and Social Science, University of Twente, Enschede, The Netherlands*

[3] *Department of Physiotherapy, Zurich University of Applied Sciences (ZHAW), Winterthur, Switzerland*

Animal welfare/Ethical statement: The experimental protocol was approved by the Animal Health and Welfare Commission and the Ethical Commission of the Canton of Zurich, Switzerland (TVB-Nr. ZH003/17-28698; BASEC-Nr. 2017-00188).

Conflict of interest statement: The authors declare no potential conflicts of interest. None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

* Corresponding author: Silja Gunst, Equine Department, Vetsuisse Faculty, University of Zurich, Winterthurerstrasse 260, Zurich CH-8057, Switzerland.

E-mail address: silja.gunst@bluewin.ch (S. Gunst).

Abstract

Asymmetric forces exerted on the horse's back during riding are assumed to have a negative effect on rider-horse interaction, athletic performance and health of the horse. Visualized on a saddle pressure mat they are initially blamed on a non-fitting saddle. The contribution of horse and rider to an asymmetric loading pattern, however, is not well understood. The aim of this study was to investigate the effects of horse and rider asymmetries during stance and in sitting trot on the force distribution on the horse's back using a saddle pressure mat and motion capture analysis simultaneously. Data of 80 horse-rider pairs (HRP) were collected and analyzed using linear (mixed) models to determine the influence of rider and horse variables on asymmetric force distribution. Results showed high variation between HRP. Both, rider and horse variables revealed significant relationships to asymmetric saddle force distribution ($P < 0.001$). During sitting trot, the collapse of the rider in one hip increased the force on the contralateral side and the tilt of the rider's upper body to one side led to more force on the same side of the pressure mat. Analyzing different subsets of data revealed that rider posture as well as horse movements and conformation can cause an asymmetric force distribution.

Since neither horse nor rider movement can be assessed independently during riding, the interpretation of an asymmetric force distribution on the saddle pressure mat remains challenging and all contributing factors (horse, rider, saddle) need to be considered.

Keywords: Horse-Rider Interaction; Collapse; Tilt; Saddle Pressure; Inertial Measurement Units

1. Introduction

The interpretation of an asymmetric saddle pressure pattern is challenging. The difficulty lies in determining whether an asymmetric loading is related to the saddle, the horse or the rider, and if an asymmetry of the horse or the rider is the causative or contributory factor in the complex horse-rider-saddle interaction.

Devices to measure saddle pressure have been validated and are used to visualize the forces exerted onto the horse's back [1]. One of their main applications is to assess saddle fit during riding. Therefore, an uneven saddle pressure distribution is initially blamed on a non-fitting saddle. Nevertheless, it is assumed that horse and rider can also cause an asymmetric saddle pressure pattern regardless of saddle fit [2].

Asymmetric forces are suspected of having negative effects on rider-horse interaction through weight aids, on athletic performance and health of the horse [2,3]. Therefore, the awareness in the research community for this topic is increasing. However, little is known about how the movement of the horse and the posture of the rider influence the dynamic force distribution under the saddle. Quantifying these interactions is more challenging than measuring the forces underneath the saddle.

Asymmetries related to the horse's back shape and movement have been shown to induce saddle slip [4]. In this study, observed saddle slip defined as a consistent slip to one side, was highly related to hindlimb lameness and associated with thoracolumbar shape and a crooked seat of the rider. The same study reported asymmetrical hair wear in horses with asymmetrical saddle movement, indicating asymmetric forces exerted on the horse's back. However, force distribution underneath the saddle was not measured and the crookedness of the rider was not quantified.

To objectively assess the lateral saddle movements in relation to the movements of horse and rider, a recently published study applied optical motion capture and a saddle pressure mat in non-lame horses ridden on a treadmill [5]. Their findings emphasized that the lateral displacement of the saddle is equally related to horse and rider movement asymmetries. Although they were using a saddle pressure mat they did not investigate the effect of saddle slip and rider position on the loading pattern.

Another recent study investigated the effects of saddle roll on rider kinematics, horse locomotion and saddle pressure distribution in sound horses over ground [6]. Results showed that while the saddle rolled to the outside the rider tended to lean inside with his trunk to maintain a straight position. After correction of the saddle's roll instability the rider's centre of mass became more aligned to the midline of the horse, indicating that an asymmetric saddle positioning influences rider kinematics significantly. Using a saddle pressure mat they could show that before correction of saddle roll, saddle pressure was higher in the thoracic region contralateral to the direction of saddle roll. However, the authors emphasised the need for further research to determine if rider asymmetry or horse movements induce saddle roll, or if the rider's posture is a function of saddle roll.

In a previous study, asymmetrical loading by the rider was shown to influence the force distribution underneath the saddle in the standing horse and the saddle could not compensate for different positions of the rider [1]. Compared to a centred position of the rider on the horse different rider postures such as leaning forward, backward and tilting to the right increased the force underneath the saddle in the area towards which the rider was leaning. However, how tilting of the rider's upper body to one side affects the force distribution underneath the saddle in motion has not been investigated.

Quantifying the rider's movement under field conditions is a challenging task, which has been attempted with different methods. Some studies have applied video analysis and have shown rider asymmetries in axial rotation and range of movement of the shoulders [3], while others have relied on inertial measurement techniques [7–11] to either quantify the dynamics of certain body segments (e.g. pelvis kinematics [7]), or, using full-body inertial measurement suits, to determine the movements of different body segments in relation to each other [10]. Therefore, rider asymmetries were quantified by a study as the left-right discrepancies in the angle of external rotation of the hip joint [11] and another study applying a full-body inertial measurement suit, found that the investigated riders' head, trunk, and pelvis showed a slight tilt to the right [10]. Results of all these studies confirmed anecdotal beliefs that most riders sit and move asymmetrically. This high prevalence of asymmetries in riders emphasises the importance of a better understanding of their effects on saddle pressure.

Based on anecdotal knowledge a widespread asymmetric riding posture seems to be the collapse in one hip (also referred to as sitting crookedly) and it was previously defined as a subjectively asymmetric position of the left and right shoulders and/or left and right tuber coxae of the rider [12]. While it is assumed to influence the force distribution underneath the saddle [2], it is unknown if this posture increases the force under the saddle either on the same or the opposite side of the collapsing hip [13].

Despite this considerable body of research many of the cited studies were limited by small sample sizes or subjective measurement techniques. The aim of the present study was to quantify functional asymmetries in riders and horses in motion and to investigate the corresponding loading pattern on the horse's back by combining an inertial measurement suit and saddle pressure testing under field conditions in a large number of horse-rider pairs (HRP). The objectives were to determine how saddle pressure is affected by riders collapsing in one hip or tilting with their upper body to one side, and how it is influenced by conformational and movement asymmetries of the horse.

It was hypothesised that (1) the rider collapsing in one hip increases the force underneath the saddle on the contralateral side of the saddle pressure mat (Fig. 1) and (2) sideways tilting of the rider's upper body increases the force underneath the saddle on the same side the rider is tilting to (Fig. 2).

2. Materials and Methods

This study has been approved by the Animal and Welfare Commission and the Ethical Commission of the Canton of Zurich, Switzerland. Written informed consent for data collection was obtained from the participants prior to the study.

2.1. Study design

HRP were recruited on a voluntary basis. The eligibility requirements were the following: minimal age of eighteen years for riders and five to eighteen years for horses as well as the absence of any medical condition (of rider and horse, rider's perspective) that would limit the current equestrian activity. Horses of any breed and withers height were eligible, but they had to be exercised at least twice a week by the respective rider and used as a leisure horse or in jumping, dressage, eventing or endurance discipline.

2.2. Horses, riders and saddles

Initially, 236 HRP were assessed. The present study comprised only non-gaited horses being ridden with an English saddle type. To prevent any gait-asymmetry associated bias horses were graded with a score from 0 to 3 (0=sound; 1=asymmetric; 2=irregular, but fit to compete; 3=lame, not fit to compete) based on a routine orthopaedic examination on a flat, hard surface. Eight horses were deemed sound, 45 horses showed grade 1 gait-asymmetries in one or more limbs, 41 horses showed irregularities (grade 2) in one or more legs. Horses with grade 3 were excluded. To prevent any saddle-asymmetry associated bias, only HRP with saddles that had subjectively been assessed as symmetrical were included (96 HRP were excluded due to asymmetric attachments of the panels and inhomogeneous flocking). Examination of the horses and manual assessments of the saddles were carried out by two professionals (M.W. and S.L.), both with many years of experience in such assessments. All of these criteria resulted in the inclusion of 80 HRP in this study.

To account for conformational asymmetries each horse's shoulders were assessed independently by the abovementioned veterinarians, while the horses were standing still and square. If one shoulder was protruding more (laterally and/or dorsally) than the other, this was recorded as the subjectively more prominent shoulder.

The age of the included horses ranged from 5 to 18 years (7.8 ± 2.8 years; mean ± SD), height at the withers from 146 to 178 cm (166.7 ± 6.0 cm) and body weight estimated by a weight tape "Equimax" from Virbac (Virbac SA, Carros, France) from 407 to 731 kg (567.2 ± 54.5 kg). 32 horses were used for jumping, 19 for dressage, 9 for eventing, 2 in endurance and 18 as leisure horses. The study group comprised 47 geldings, 31 mares and two stallions. Breeds included Warmbloods (n = 66), Pure Spanish Horses (n = 6), one Franches-Montagne, one Thoroughbred, one pony, one Friesian and some mixed breed horses (n = 4).

The riders, 73 females and seven males, were of different skill levels from novice to expert and ranged in age from 18 to 72 years (37.3 ± 11.6 years), in height from 157.5 to 188.5 cm (171.5 ± 0.1 cm), and in body mass (including riding clothing and boots) from 48.7 to 102.1 kg (68.5 ± 11.6 kg). To assess for functional laterality in the rider, their handedness was recorded with a survey prior to the examination day. Additionally, to control for laterality in the lower body, a reactivity test was carried out by gently pushing them forwards with their eyes shut. The leg they protracted and landed on (further referred to as take-off-leg; TOL) was recorded. The distributions of these variables can be found in Table 1, line *Sitting Trot*.

The saddles included 35 dressage, 33 jumping and 12 eventing saddles. Depending on the preference of the rider, saddle force was measured without (n = 24) or with a saddle pad (n =

56: 51 lambskin, four foam rubber, one felt pad). The stirrup length was set by the riders choosing their normal preferred length.

2.3. Kinetic and kinematic data

A pressure measuring saddle mat was used simultaneously with inertial measurement units (IMU) to collect kinetic and kinematic data during a riding test.

The saddle force distribution was measured with the commercially available and previously validated Pliance Saddle System, Novel GmbH at a sampling frequency of 50 Hz [1]. The pressure mat consisted of two halves, each with 128 sensors. The halves were bridged in the middle, with a rostral and caudal gap along the spine with no sensors. Additionally, the mat halves were linked in the front and back with two Velcro strips to adjust the distance between halves individually to each horse's back. Care was taken to place the mat symmetrically on the horse's back. Before placing the saddle (with or without a pad) and tightening the girth, the mat was set to zero lying on the horse's back. The riders were instructed to mount from a raised platform while one of the researchers held the stirrup on the opposite side to prevent shifting of the saddle and pressure mat whilst the rider was mounting. Two saddle pressure mats were used to collect kinetic data during this project. Prior to and after every measurement series that comprised two to three consecutive measuring days (up to eight measurements per day) the saddle pressure mats were rechecked and recalibrated in a pressure calibration device.

Horses and riders were equipped with the Xsens™ MVN motion capture system (Xsens Technologies BV, Enschede, The Netherlands). IMUs combine gyroscopes, accelerometers and magnetometers from which orientation and translation of body segments were determined [14].

In total, twenty IMUs (MTw Awinda Wireless Motion Tracker) were attached to horse and rider. During riding, the rider wore a MVN full-body sensor setup as described by Eckardt *et al.* (2014), except no IMUs were placed on the hands [10]. Riders were equipped by people trained to this setup. The tight Xsens Awinda t-shirt included pockets for placement of sternum and shoulder inertial sensors, and the pelvis sensor was secured with a wide belt with Velcro straps to prevent slipping or rotation. The internal error check or Xsens gave a warning if sensors were not placed correctly (e.g. if sacrum and sternum sensor were swapped). Data were collected using the MVN Studio software with a measurement frequency of 60 Hz.
Rider variables were calculated using the sternum and pelvis sensor (Fig. 1& 2). On the horse, one sensor was adhered with double-sided adhesive tape to the horse’s sacrum, the others with custom-made Velcro attachments to the horse’s poll, sternum and right cannon bone, each sensor with a weight of 16g.
The calibration procedure (horse standing still and square and as recommended by Xsens™, N-Pose of the rider, standing on the ground and arms neutral beside the body) was performed prior to data collection. All kinematic data of the rider were measured in relation to the calibrated pose.

2.4. Data collection

The measurements took place in eight different indoor riding arenas, all with a sand-fibre surface and of a size of 20-by-60-meter. The track was groomed prior to every measuring day. To accustom to the facility and the equipment each HRP performed a five to ten minutes self-selected warm-up. The majority of HRP travelled to the locations, only a few horses were familiar with the arenas.
Data were collected during stance and while riding a given program consisting of walk and trot in a straight line and canter on a circle at the HRP’s preferred speed. For the stance

measurement, riders were instructed to sit straight (based on their own perception) and look ahead. Only stance measurements where the horses stood still and square were included in further analysis.

The riding program was first performed on the right rein and subsequently on the left rein. The riders wore their own riding trousers with a tight T-shirt, complemented by the Xsens Awinda Shirt. They used their standard tack consisting of the saddle (with or without saddle pad) and the bridle.

For this study only data of sitting trot were included due to the symmetrical gait pattern of trot and the presumably symmetric movement of the rider in the saddle (compared to rising trot; different movements between half-cycles of a stride). The symmetrical riding movements during sitting trot has been shown not to interfere with the horse's vertical movement [15]. Data were captured when the HRP was moving along the long side of the arena preventing the measurements from being affected by the turns at the end of the long side. The riding test was documented with a digital camcorder (Sony Europe Limited, Weybridge, United Kingdom) mounted on an automatic tracking robot (Pixio by Move'n See, Brest, France) following the radio emitter fixed to the horse's noseband.

2.5. Data processing

Kinetic raw data were exported from Pliance-X (Novel GmbH, Munich, Germany) and kinematic raw data from Xsens MVN Studio (Xsens Technologies BV, Enschede, The Netherland) into MATLAB (The Math Works Inc., Massachusetts, USA) for further processing.

Saddle pressure data were linearly up-sampled by a factor 4 to get higher spatial resolution. The region of interest underneath the saddle was bounded by creating a symmetric mask with respect to the medial plane. A 10% threshold of the 20 highest mean pressure values of the up-sampled data was used to exclude non-relevant cells outside the saddle area. The masks were created for each saddle pressure measurement individually. The pressure was multiplied by the loaded area to calculate mean forces for each half of the mat. For each stride the mean force of the left side was subtracted from the mean force of the right side. This variable was named as saddle force difference (SFD).

Kinematic data of the horses were double-integrated and filtered from acceleration to displacement according to calculations of a previous study [16].

The kinetic and kinematic data were synchronized analytically using cross correlation in MATLAB (xcorr). The IMU signal was cropped at the beginning and end by 16 % in order to assure a complete overlap with regards to the saddle pressure signal. To match sample frequency both raw signals were linearly interpolated (up-sampled) to 1000 Hz. Based on the stride peak acceleration and orientation signal of the right forelimb IMU, continuous kinetic and kinematic data were split with custom-written MATLAB scripts into individual strides starting with stance-on of the left forelimb and time-normalised to 100% stride.

As horse movement symmetry variables the minimal and maximal differences in vertical displacement between left and right stride half-cycles of the head (HDmin, HDmax), sternum (SDmin, SDmax) and pelvis (PDmin, PDmax) sensors were used and calculated as previously described for head and pelvis [17]. A positive value in HDmin or SDmin indicates less downwards movement of the head or sternum during stance of the right front limb (for the head would this be considered a horse with a right forelimb lameness in extreme cases), while a negative HDmin or SDmin would indicate less downwards movement during left front stance. For PDmin, positive values indicate less downwards movement of the tuber sacrale during stance of the right hindlimb (in extreme cases this would be considered a horse with a right hindlimb lameness), negative values indicate less downwards movement of the tuber sacrale during left hind stance.

Rider symmetry variables were calculated as following, using position and orientation of the sternum and pelvis sensor of the rider:

- The collapsing of the rider in one hip (termed collapse index; CI): difference of roll rotation (around the longitudinal axis [18]) between sternum and pelvis sensor of the rider (see Fig. 1)
- The sideways tilting of the rider's upper body to one side (termed tilt index; TI): angle between a virtual line from sternum sensor to pelvis sensor of the rider and the sagittal plane (regardless of the orientation of the sensors; see Fig. 2)

SFD, horse, and rider symmetry variables were calculated as stride mean values during sitting trot. For the stance measurement, SFD and rider symmetry variables were calculated as a mean value over the whole measurement (due to no movement the horse symmetry variables could not be calculated during stance).

2.6. Data analysis and statistics

The influence of the following predictors on SFD were investigated with linear (mixed) models. Rider variables included CI, TI, TOL and handedness; horse variables included HDmin, HDmax, SDmin, SDmax, PDmin, PDmax (during sitting trot) and side of the more prominent shoulder. In all sitting trot datasets, where data were analysed on stride basis, HRP was included as a random factor to the mixed model. To determine the best fitting mixed model, stepwise exclusion of non-significant predictors was done based on Kuznetsova et al. (2017) [19]. The best fitting linear model was deemed as having the least number of predictors and the highest R^2. The initial model was fitted to different datasets, which were created as outlined below, and the best model was determined for each dataset. Residuals of all reported models were scrutinised for heteroscedasticity and normal distribution.

Significance levels were set to 0.05. All statistical analyses were carried out in R Studio (version 3.4.4, packages stats and lme4).

2.6.1. Stance

A total of 60 HRP were included in the stance analysis. The selection was based on horses standing still and square during the stance measurement. For each HRP, this dataset included only the mean values of CI and TI over the length of the stance measurement, TOL, handedness of the rider and the prominent shoulder of the horse. Relationships between SFD and predictors were investigated using a linear model.

2.6.2. Sitting trot

From all 80 HRP in this study the influence of the predictors mentioned above (including horse movement variables) on SFD was investigated by the aid of linear mixed models. This dataset included in total 2323 strides (on average 29.0 strides per HRP).

2.6.3. Most symmetric strides – horse

To minimise the influence of asymmetric movements of the horse, a dataset was created including 25% of the most symmetric strides based on the vector sum of the sternum (SDmin, SDmax) and pelvis (PDmin, PDmax) of the horse (n = 581 strides from 67 HRP, on average 8.7 strides per HRP). These parameters were chosen as it has been shown that saddle position is influenced by the protracting forelimb and the thoracolumbar movement of the back [20].

2.6.4. Most symmetric strides – rider

To minimise the influence of rider asymmetry, a dataset was created including 25% of the most symmetric strides based on the vector sum of CI and TI of the rider (n = 581 strides from 53 HRP, on average 11.1 strides per HRP).

2.6.5. Most symmetric SFD during stance – sitting trot data

A third dataset was created to investigate what induces an asymmetric saddle force distribution in sitting trot when the initial situation during stance is symmetrical (and not already biased by a left shift). For this purpose, we made a selection of the 25% of HRP (n=15) with the most symmetric saddle force measurements during stance, based on the lowest SFD values. We then created a dataset based on the sitting trot measurements of these 15 HRP (n = 473 strides, on average 31.5 strides per HRP).

3. Results

Arithmetic mean values and standard deviations of the investigated variables in the different datasets are shown in Table 1. Averages, stated in relation to main effects in the models, refer to least square means and standard deviations.

3.1. Stance

Overall, the mean force on the saddle pressure mat showed a slight shift to the left. On average SFD was -28.1 N, indicating more force on the left side of the saddle mat, which corresponds to a mean force difference of approximately 4.2% of the rider’s bodyweight. The best fitting model (R^2 = 0.16, P = 0.012) revealed two predictors:

- Horses with a prominent shoulder showed increased force underneath the saddle in the respective area (left shoulder: -82.7 ± 17.9 N, n = 27; no prominent shoulder: -44.2 18.9, n= 19; right shoulder: -27.7 ± 23.3 N, n = 14) (P = 0.018).

- A trend for a higher shift of force to the left side of the mat was shown in riders with a left TOL (-33.1 ± 25.8 N; n = 13) compared to riders with a right TOL (2.6 ± 18.6 N; n = 44) ($P = 0.10$)

3.2. Sitting trot

Overall, HRP was a significant random factor in all linear mixed models ($P < 0.001$), indicating a high level of variation in SFD between individual pairs.

Interestingly, SFD differed significantly between measurements on the left and on the right rein ($P < 0.001$), showing an even stronger shift to the left on the right rein, when compared to the left rein (right rein: -29.1 ± 46.5 N vs. left rein: -19.2 ± 51.8 N).

The rider symmetry value CI showed a significant negative correlation with SFD ($P < 0.001$; Fig. 3), indicating that riders collapsing in one hip showed more force on the opposite half of the saddle pressure mat (Fig. 1). Based on the model, per degree of collapsing in one hip saddle force increased by 1.5 N on the contralateral half.

TI was significantly positive correlated with SFD ($P < 0.001$; Fig. 4), indicating that riders tilting with their upper body to one side led to more force on the same half of the saddle pressure mat (Fig. 2). With every degree of tilting of the upper body to one side the saddle force increased by 1.4 N in the direction the rider was tilting to.

Further, SFD showed significant positive relationships with the head values of the horse HDmin and HDmax ($P < 0.01$). Significant negative relationships were found with SDmin ($P = 0.018$) (Fig. 5), SDmax, PDmin (Fig. 6) and PDmax (each $P < 0.001$). To illustrate, in a horse with 1 mm more vertical displacement of the sternum during right front stance (compared to left front stance), SFD would have been increased by 0.2 N on the left side underneath the saddle. Correspondingly, in a horse dropping its pelvis 1 mm less in right hind stance (compared to left hind stance), SFD would be 0.5 N higher on the left side.

SFD of riders with a left TOL showed increased force on the left side compared to riders with a right TOL (left: -36.7 ± 9.5 N, n = 23; right: -15.7 ± 6.2 N, n = 54; P = 0.067).

3.3. Most symmetric strides – horse

As observed previously, this dataset also showed an overall shift of SFD to the left (-16.0 ± 44.5 N). This shift was more pronounced on the right rein compared to the left rein (right rein: -21.2 ± 5.1 N, left rein: 14.1 ± 5.1 N; P < 0.001). In this dataset, SFD revealed a significant negative relationship with CI (P < 0.001). However, there was no significant relationship between SFD and TI.

Despite the selection of this dataset based on minimal pelvis and sternum movement asymmetry of the horse, SFD showed slight negative relationships with PDmin and PDmax (P = 0.024 and P = 0.015).

3.4. Most symmetric strides – rider

The overall SFD of this dataset was -34.4 ± 53.5 N, indicating a stronger shift of the force to the left compared to the complete dataset. In this dataset, no significant difference in SFD between left and right rein was found. SFD showed significant negative relationships with SDmax, PDmax (each P < 0.01) and PDmin (P < 0.001). This indicates, that after minimising the asymmetry of the rider's upper body, the horse as initiator of the movement influenced the saddle force pattern. As observed in the previous dataset, riders with a left TOL induced more force on the respective side of the saddle compared to riders with a right TOL (left: -37.3 ± 13.2 N; n= 12; right: -0.8 ± 12.1 N; n= 38; P =0.028). Horses with a left prominent shoulder showed a stronger shift of force to the left side of the saddle mat (-67.7 ± 10.9 N; n= 25) compared to horses without a prominent shoulder (37.2 ± 11.9 N; n= 14; P = 0.032).

Interestingly, there was no significant difference between horses with a left and those with a right prominent shoulder (-70.2 ± 13.6 N; n= 14; P = 0.86).

3.5. Most symmetric SFD during stance – sitting trot data

The initial SFD of these HRP in stance was 2.9 + 16.7 N. Despite starting out relatively symmetric, in sitting trot the SFD developed a shift to the left (-14.5 + 36.9 N). SFD showed a significant negative relationship with CI and a positive relationship with TI of the rider (P < 0.001), analogue to the outcome of the initial model of the complete sitting trot dataset. SFD also showed significant negative relationships with PDmax (P = 0.001), SDmin (P = 0.007), SDmax (P = 0.041) and strongest with PDmin (P <0.001), as well as a significant positive relationship with HDmax (P < 0.01).

4. Discussion

In general, the results confirmed our hypotheses: (1) a collapse of the rider in one hip increased the force on the contralateral side on the saddle pressure mat during sitting trot and (2) a tilt of the rider's upper body to one side increased the force on the same side of the saddle pressure mat. Nevertheless, our results also showed that the horse plays a role of a similar importance when investigating saddle pressure asymmetry in motion. Despite the high significance levels of the relationships between asymmetries, correlations were low and the variability of the data was high between individual pairs due to the variable population of HRP. Data analysis revealed that the saddle force pattern is influenced by various factors of functional and anatomical asymmetry of rider and horse.

In all datasets there was a shift of the force distribution to the left. This finding is in agreement with observations by Fruehwirth *et al.* (2004) [21], who found a trend for a higher loading on the left and suggested this could be caused by an uneven distribution of the rider's weight or by asymmetrical musculature of the horse. We assumed that the left shift in our data could also be an artefact of the riders mounting from the left side. However, special care was taken to prevent slipping of the pressure mat with careful symmetrical placement of the pad and saddle, and girthing was done from both sides. Riders then mounted into the saddle from a raised platform while someone was holding the stirrup on the opposite side. Results of a previous study showed that mounting from the ground or from a raised platform using the left stirrup led to a slip of the saddle towards the mounting side and to a consistent pressure profile with increased pressure on the left [22]. This pressure pattern persisted even after the rider tried to adjust the position of the saddle by stepping heavily into the right stirrup. This study proposed that asymmetrical development of the horse's musculature (as a result of mounting habitually from the left side) could contribute to higher pressure on the left. In accordance with another study [23], this indicates that human interaction with the horse, mainly from the left, may affect a left sidedness of the horse which could also be a possible cause of a left shift of the force. Further studies are required to confirm that mounting from the right side or without using the stirrups result in a more even loading pattern. Nevertheless, the results of this study are contributing evidence that the equestrian community should critically question the traditional habit of tacking up, leading and mounting a horse exclusively from the left.

Another explanation for the left shift could be anatomical asymmetries of the horse related to laterality. The abovementioned study investigated laterality in horses by observing different grazing positions and found that the majority of horses consistently protract the left front limb to graze [23]. Van Heel *et al.* (2006) could further show that the hoof that was protracted during grazing became the hoof with the lower hoof angle [24]. Future studies should investigate how different hoof angles affect the angulation of proximal limb joints and how this can induce further anatomical asymmetries and influencing the pressure pattern underneath the saddle (e.g. muscular development and angulation of the shoulders). Our data suggest that the left shift in saddle force was to some extent caused by movement. The HRP showing the most symmetric force distribution during stance still revealed a considerable shift to the left while trotting, indicating that the movement of horse and rider contribute to asymmetric forces beneath the saddle.

In some datasets the left shift was even stronger on the right rein compared to the left rein. This could be explained by the riders performing the riding test first on the right rein, including a circle in canter after sitting trot. Cantering on the right rein might have induced saddle roll to the left and thereby increased the force on the inside right panel of the saddle as observed in a recent published study [6]. Therefore, cantering on the right rein might have counteracted the existing left shift of forces (possibly caused by mounting from the left) underneath the saddle that was lower in the subsequent sitting trot on the left rein.

In our data, the force distribution was significantly related to several horse parameters. During stance, saddle force asymmetry could be explained with the more prominent shoulder as one influencing factor. In accordance to other studies [22,25] the majority of horses in the present study had a left prominent shoulder (Table 1). The relationship between SFD and the prominent shoulder is not surprising as an important issue to assess saddle fit is to account for free rotation of the scapulae. The saddle, especially jumping saddles with forward cut flaps interfere with the horse's scapula [25] as well as saddles positioned too far forward when lying over the dorso-caudal edge of the shoulder blade [26]. During movement it has been observed that the saddle tends to stop at the prominent shoulder and then slides towards the smaller shoulder if there is a large discrepancy in shoulder anatomy [26]. Interference of the front part of the saddle with the shoulder during the protraction phase of the leg has been shown to provoke localised high forces [21,27]. In the study of Fruehwirth *et al.* (2004) [21] the horses reacted with reducing the forward swing of the leg which resulted in shorter stride lengths. According to our results the prominent shoulder is therefore likely to cause increased force on the same side of the saddle pressure mat, as found during stance and in the dataset where rider asymmetry was minimised. Furthermore, the muscle around the scapula (*M. trapezius pars caudalis*), responsible for retraction and protraction of the forelimb, is assumed to be a potential cause of an asymmetric force distribution, because the force in the front of the saddle pressure mat is closely related with forelimb movements [27]. Unevenness of the back muscles in the shoulder region are a common asymmetry of the horse's back shape as recognized by Greve and Dyson (2014) [4]. Interestingly, the more prominent shoulder showed only significant influence on SFD during stance and in the dataset with minimised rider asymmetry. It can therefore be assumed that this anatomical asymmetry plays a little role compared to movement asymmetries of horse and rider.

Our data revealed a negative relationship between the difference in vertical displacement of the pelvis of the horse and saddle force asymmetry (Fig. 6). In a previous study, hindlimb lameness (or asymmetry) was shown to induce saddle slip: the saddle slipped visually towards the lame(r) hindlimb [28]. Saddle roll to one side appears to increase pressure in the cranial region of the opposite side of the saddle pressure mat [6]. These observations would explain the negative correlation between SFD and PDmin found in the present study, as in a horse asymmetric (or lame) in the left hindlimb, the saddle would slip to the left, causing increased pressures in the cranial region on the right side of the saddle pressure mat (due to the saddle being pulled against the withers).

A similar negative relationship between SFD and SDmin was found, but it was less pronounced (Fig. 5). We assume that the vertical movement of the sternum can be influenced by both, hind- and forelimbs. It has been shown that asymmetric movement of the pelvis translates to asymmetric movement of the wither on the contralateral side due to compensatory mechanisms [29]. On the other hand, SDmin could also reflect asymmetric vertical loading of the forelimbs. It has recently been shown that asymmetric vertical movements of the wither can be caused by different stride lengths of the forelimbs due to asymmetric pro- and retraction angles [30]. The resulting asymmetric caudal rotation of the scapula during protraction could induce asymmetric pressures under the cranial part of the saddle. Buchner *et al.* (1996) [31] already showed that the vertical displacement of the trunk adapts to forelimb lameness in order to reduce loading of the lame limb. Asymmetric vertical displacement of the sternum could therefore be the result of a variety of underlying causes: compensation of hindlimb asymmetry, asymmetric stride lengths or shoulder rotation. These causes could have influenced SFD in different ways, what would explain why the correlation with SDmin is low.

The present study quantified the crookedness of the rider as collapsing in one hip (Fig. 1) and tilting to one side (Fig. 2). The results were in agreement with our hypotheses regarding force distribution on the saddle pressure mat in relation to both riding postures. While collapsing in one hip remained the main influencing factor of the saddle force asymmetry when minimising asymmetry in the horse, the tilt of the rider's upper body lost its statistical significance ($P = 0.74$), despite the fact that the range of tilting was similar to the range measured in the complete sitting trot dataset. We therefore assume that the way the rider is tilting sideways with his upper body is influenced by the vertical and horizontal acceleration of the horse's trunk, which was shown to be responsible for kinematic, kinetic and muscular activation pattern of the rider [18]. Therefore, an asymmetric horse could directly influence the rider's way of tilting sideways. The ability of the rider is crucial to counteract or absorb these asymmetrical movements, especially in sitting trot. As shown in a previous study more experienced riders moved in closer phase relationship with the horse compared to novice riders [32] and another study showed that more experienced riders were able to maintain a straighter posture [4]. In the present study most riders were rather less experienced (only 6 out of 80 HRP competed on a high national level) and had therefore probably more difficulties to adjust to the horse's movements.

A previous kinematic study found that the movement of the rider during sitting trot occurs mainly in the head, lumbar back, the legs and feet and that the legs in sitting trot are used to control the vertical movement of the horse's trunk [20]. In accordance to this study, our results revealed that the TOL had an impact on saddle force asymmetry during stance and after minimising the asymmetry of the rider's upper body in sitting trot. During midstance in trot, the rider is pressed into the saddle and the leg joints have to flex, while during swing phase the rider is pushed out of the saddle and the legs extend. It seems likely that the left and right leg do not have the same capacity to absorb these impacts and thus lead to an asymmetric loading. As suggested by another study different knee angles could also contribute to rider asymmetry [10]. We can confirm that the rider's lower body, particularly the TOL, influences the saddle force distribution, potentially because it is the more reactive or stronger leg. A detailed examination of the rider's leg at different gaits and its effect on rider asymmetry and saddle force distribution is still required.

5. Conclusion

Collapsing of the rider in one hip and tilting of the rider's upper body to one side, as well as asymmetric movements of the horse were correlated with saddle force asymmetry. However, these correlations were weak due to the high variation between HRP, indicating that horse and rider compensate, react and rebalance individually to asymmetries of the counterpart.

After minimising the asymmetry of the horse or the rider the other remained the main influencing factor concerning saddle force asymmetry in sitting trot, showing that the relationship between horse, rider and saddle is complex since they inevitably influence each other. To assess functional rider asymmetry isolated during riding seems to be an impossible task as the horse dictates the rider's movements and it cannot be determined conclusively if the asymmetries of the horse influence the rider or vice versa.

The findings of the present study emphasise that the force distribution underneath the saddle needs a careful interpretation by considering all components before an asymmetric loading pattern is blamed on a non-fitting, asymmetric saddle.

Acknowledgements

The study was mainly funded by the Walter Haefner Foundation and by the Federal Food Safety and Veterinary Office. Further support was given by the Stiftung pro Pferd. The authors wish to thank all the participants of this project and Andrea Aegerter, Bettina Friedrich, Barbara Gubler and Kim Vetter from the Zurich University of Applied Sciences for examining the riders.

References

[1] de Cocq P, Clayton HM, Terada K, Muller M, van Leeuwen JL. Usability of normal force distribution measurements to evaluate asymmetrical loading of the back of the horse and different rider positions on a standing horse. Vet J 2009;181:266–73.

[2] Greve L, Dyson S. The horse–saddle–rider interaction. Vet J 2013;195:275–81.

[3] Symes D, Ellis R. A preliminary study into rider asymmetry within equitation. Vet J 2009;181:34–7.

[4] Greve L, Dyson SJ. The interrelationship of lameness, saddle slip and back shape in the general sports horse population. Equine Vet J 2014;46:687–94.

[5] Byström A, Roepstorff L, Rhodin M, Bragança FS, Engell MT, Hernlund E, et al. Lateral movement of the saddle relative to the equine spine in rising and sitting trot on a treadmill. PLoS One 2018;13:e0200534.

[6] Mackechnie-Guire R, Mackechnie-Guire E, Fisher M, Mathie H, Bush R, Pfau T, et al. Relationship between saddle and rider kinematics, horse locomotion, and thoracolumbar pressures in sound horses. J Equine Vet Sci 2018;69:43–52.

[7] Münz A, Eckardt F, Heipertz-Hengst C, Peham C, Witte K. A preliminary study of an inertial sensor-based method for the assessment of human pelvis kinematics in dressage riding. J Equine Vet Sci 2013;33:950–5.

[8] Münz A, Eckardt F, Witte K. Horse–rider interaction in dressage riding. Hum Mov Sci 2014;33:227–37.

[9] Eckardt F, Witte K. Horse–Rider Interaction: A new method based on inertial measurement units. J Equine Vet Sci 2017;55:1–8.

[10] Eckardt F, Münz A, Witte K. Application of a full body inertial measurement system in dressage riding. J Equine Vet Sci 2014;34:1294–9.

[11] Gandy EA, Bondi A, Hogg R, Pigott TMC. A preliminary investigation of the use of inertial sensing technology for the measurement of hip rotation asymmetry in horse riders. Sport Technol 2014;7:79–88.

[12] Greve L, Dyson S. Saddle fit and management: An investigation of the association with equine thoracolumbar asymmetries, horse and rider health. Equine Vet J 2015;47:415–21.

[13] Hobbs SJ, Baxter J, Broom L, Rossell L-A, Sinclair J, Clayton HM. Posture, flexibility and grip strength in horse riders. J Hum Kinet 2014;42:113–25.

[14] Roetenberg D, Luinge H, Slycke P. Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. 2009.

[15] Persson-Sjodin E, Hernlund E, Pfau T, Andersen PH, Rhodin M. Influence of seating styles on head and pelvic vertical movement symmetry in horses ridden at trot. PLoS One 2018;13:e0195341.

[16] Pfau T, Witte TH, Wilson AM. A method for deriving displacement data during cyclical movement using an inertial sensor. J Exp Biol 2005;208:2503–14.

[17] Rhodin M, Egenvall A, Andersen PH, Pfau T. Head and pelvic movement asymmetries at trot in riding horses in training and perceived as free from lameness by the owner. PLoS One 2017;12:e0176253.

[18] Clayton HM, Hobbs S-J. The role of biomechanical analysis of horse and rider in equitation science. Appl Anim Behav Sci 2017;190:123–32.

[19] Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest package: tests in linear mixed effects models. J Stat Softw 2017;82.

[20] Byström A, Rhodin M, Peinen K von, Weishaupt MA, Roepstorff L. Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. Equine Vet J 2009;41:280–4.

[21] Fruehwirth B, Peham C, Scheidl M, Schobesberger H. Evaluation of pressure distribution under an English saddle at walk, trot and canter. Equine Vet J 2004;36:754–7.

[22] Geutjens CA, Clayton HM, Kaiser LJ. Forces and pressures beneath the saddle during mounting from the ground and from a raised mounting platform. Vet J 2008;175:332–7.

[23] McGreevy PD, Rogers LJ. Motor and sensory laterality in thoroughbred horses. Appl Anim Behav Sci 2005;92:337–52.

[24] Van Heel MC V, Kroekenstoel AM, Van Dierendonck MC, Van Weeren PR, Back W. Uneven feet in a foal may develop as a consequence of lateral grazing behaviour induced by conformational traits. Equine Vet J 2006;38:646–51.

[25] Clayton H. Assessing English Saddle Fit in Performance Horses. 2015. doi:10.1016/B978-1-4557-4555-5.00027-3.

[26] Harman J. Tack and saddle fit. Vet Clin North Am Equine Pract 1999;15:247–61.

[27] Von Peinen K, Wiestner T, Bogisch S, Roepstorff L, Van Weeren PR, Weishaupt MA. Relationship between the forces acting on the horse's back and the movements of rider and horse while walking on a treadmill. Equine Vet J 2009;41:285–91.

[28] Greve L, Dyson SJ. An investigation of the relationship between hindlimb lameness and saddle slip. Equine Vet J 2013;45:570–7.

[29] Rhodin M, Persson-Sjodin E, Egenvall A, Serra Bragança FM, Pfau T, Roepstorff L, et al. Vertical movement symmetry of the withers in horses with induced forelimb and hindlimb lameness at trot. Equine Vet J 2018;50:818–24.

[30] Byström A, Egenvall A, Roepstorff L, Rhodin M, Serra Bragança F, Hernlund E, et al. Forehand drop in walking dressage horses on treadmill. Comp Exerc Physiol 2018;14:S1–114. doi:10.3920/cep2018.s1.

[31] Buchner HHF, Savelberg H, Schamhardt HC, Barneveld A. Head and trunk movement adaptations in horses with experimentally induced fore-or hindlimb lameness. Equine Vet J 1996;28:71–6.

[32] Lagarde J, Peham C, Licka T, Kelso JAS. Coordination dynamics of the horse-rider system. J Mot Behav 2005;37:418–24.

Table 1
Mean ± standard deviation and frequency of the different predictors in the different datasets included in the statistical analysis.

Dataset	n HRP	n Strides	SFD (N)	SFD (% BW)	CI (°)	TI (°)	HDmin (mm)	HDmax (mm)	SDmin (mm)	SDmax (mm)	PDmin (mm)	PDmax (mm)	More prominent shoulder horse	TOL Rider	Handedness Rider
Stance	60	NA	-28.06 ± 73.67	-4.2 ± 9.8	1.50 ± 6.53	0.74 ± 2.68	NA	NA	NA	NA	NA	NA	L 27 R 14 Neither 19 *	L 13 R 44 NA 3 *	L 6 R 51 NA 3
Sitting Trot	80	2323	-24.12 ± 49.42	-3.6 ± 7.3	0.60 ± 6.56 ***	-0.31 ± 3.08 ***	2.94 ± 34.64 **	-2.91 ± 39.31 **	0.57 ± 9.50 *	2.36 ± 13.76 ***	1.44 ± 10.43 ***	-1.65 ± 13.48 ***	L 34 R 20 Neither 26	L 23 R 54 NA 3 **	L 11 R 66 NA 3
Most symmetric strides - horse	67	581	-16.0 ± 44.46	-2.6 ± 7.0	-0.52 ± 6.99 ***	-0.07 ± 2.82	-1.05 ± 33.81	-9.60 ± 35.12	0.06 ± 4.89	1.00 ± 5.35	0.81 ± 5.46 *	-0.76 ± 5.75 *	L 29 R 15 Neither 23	L 19 R 46 NA 2	L 10 R 55 NA 2
Most symmetric strides – rider	53	581	-34.43 ± 53.48	-5.0 ± 6.8	-0.23 ± 1.95	0.02 ± 1.68	2.51 ± 34.81	4.34 ± 43.93	1.39 ± 10.04	3.94 ± 12.83 **	1.82 ± 9.26 ***	-1.61 ± 13.58 **	L 25 R 14 Neither 14 *	L 12 R 38 NA 3 ***	L 6 R 55 NA 3
Sitting trot of most symmetric SFD during stance	15	Stance NA	-2.85 ± 16.70	-0.5 ± 2.8	1.48 ± 7.07	0.27 ± 1.84	NA	NA	NA	NA	NA	NA	L 6 R 5 Neither 4	L 3 R 12 NA 0	L 1 R 14 NA 0
		Moving 473	-14.54 ± 36.86	-3.4 ± 7.6	0.12 ± 8.30 ***	-0.26 ± 2.99 ***	5.12 ± 27.57	-4.45 ± 35.56 **	-1.30 ± 9.07 **	0.46 ± 12.86 *	3.77 ± 8.91 ***	-1.05 ± 13.01 **			

Abbreviations: HRP, horse-rider pair; SFD, saddle force difference; CI, collapse index; TI, tilt index; TOL, take-off leg rider;
SFD was calculated based on the mean force for each stride in newton (N) or % BW, percentage of the rider's bodyweight. Negative values indicate higher mean forces on the left side of the saddle pressure mat, positive values indicate higher mean forces on the right side.
TI, tilt of the rider's upper body: negative values indicate tilting to the left, positive values to the right; CI, rider collapsing in one hip: negative values indicate collapsing in the left hip, positive values in the right hip.
(H/S/P)Dmin/max: Difference in minimal/ maximal vertical displacement of the horse's head (H), sternum (S), or pelvis (P) between left and right stride half-cycles.
Predictors that showed a significant relationship with SFD in the best fitting model of the respective dataset are indicated *** ($P < 0.001$), ** ($P < 0.01$), or * ($P< 0.05$).

Figures

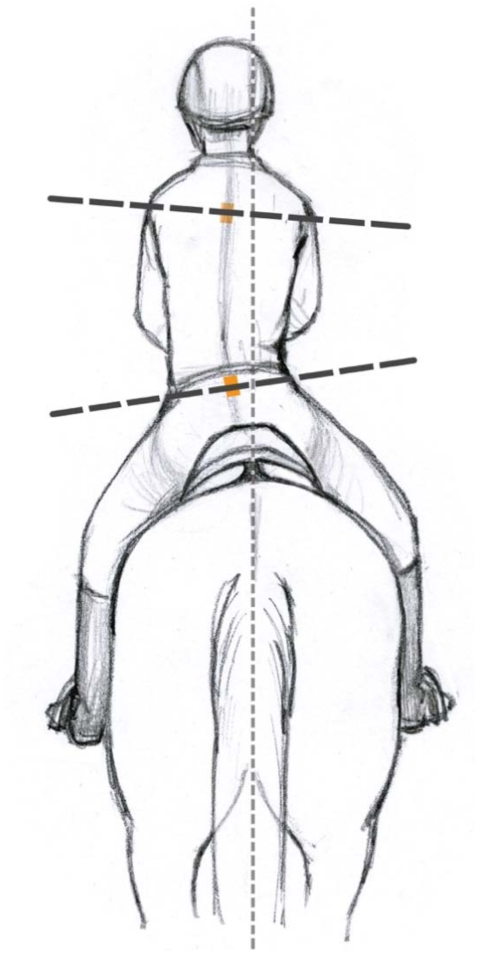


Fig. 1. Illustration of a rider collapsing in the right hip. Sternum and pelvis sensors are highlighted orange, bold dashed lines indicate the lines that were used to define the angle of pelvis to sternum for the rider variable collapse index (CI).

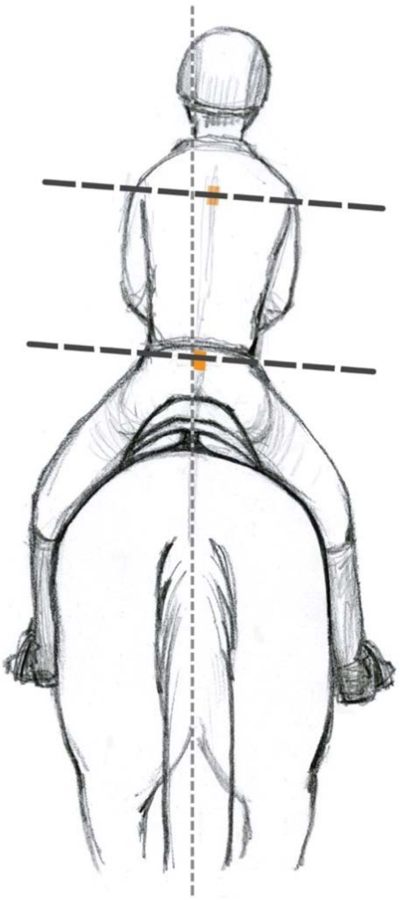


Fig. 2. Illustration of a rider tilting with his upper body to the right (without collapsing in one hip). Highlighted in orange are sternum and pelvis sensors. Tilt index (TI) was defined as the angle between the vertical dashed line and a straight line connecting sternum and pelvis sensor.

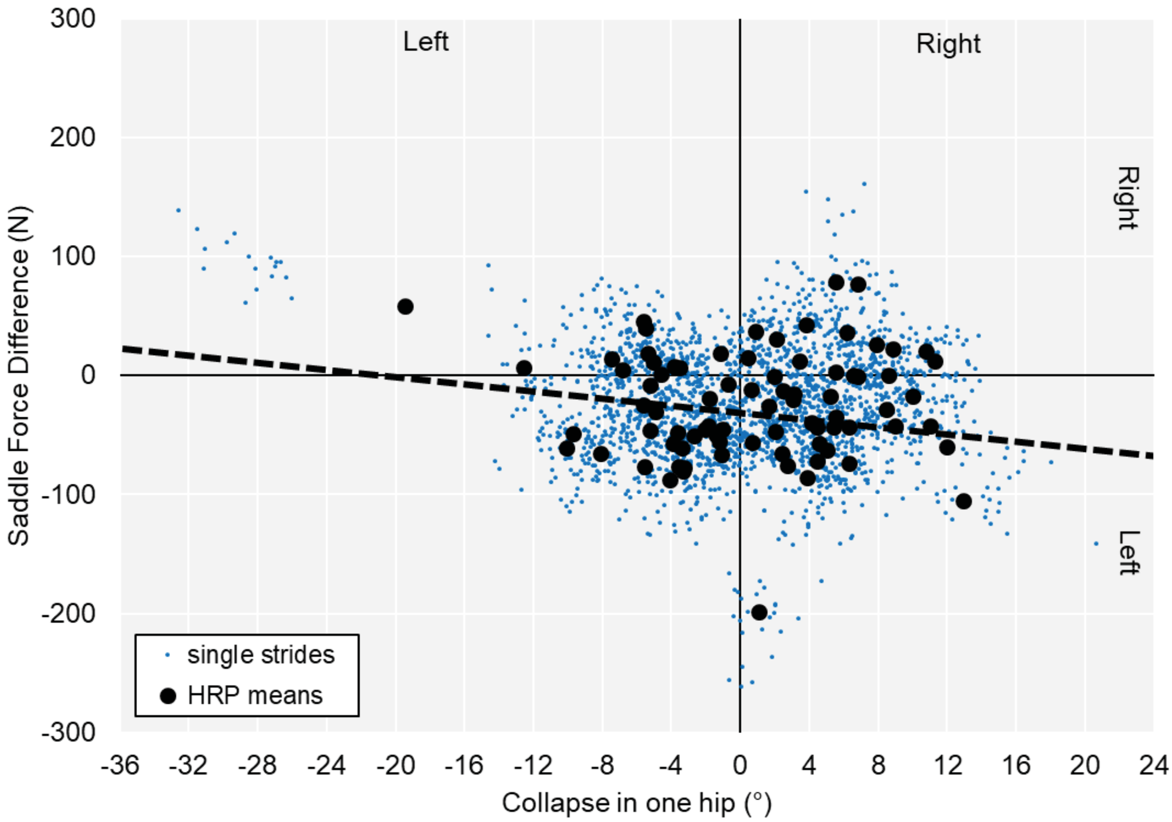


Fig. 3. Relation between SFD and rider variable collapse index (CI) in the sitting trot dataset (n=80). Blue dots indicate values of single strides and black dots indicate mean values of a horse-rider pair (HRP). Regression line showing negative relationship between CI and SFD based on the best fitting mixed model.

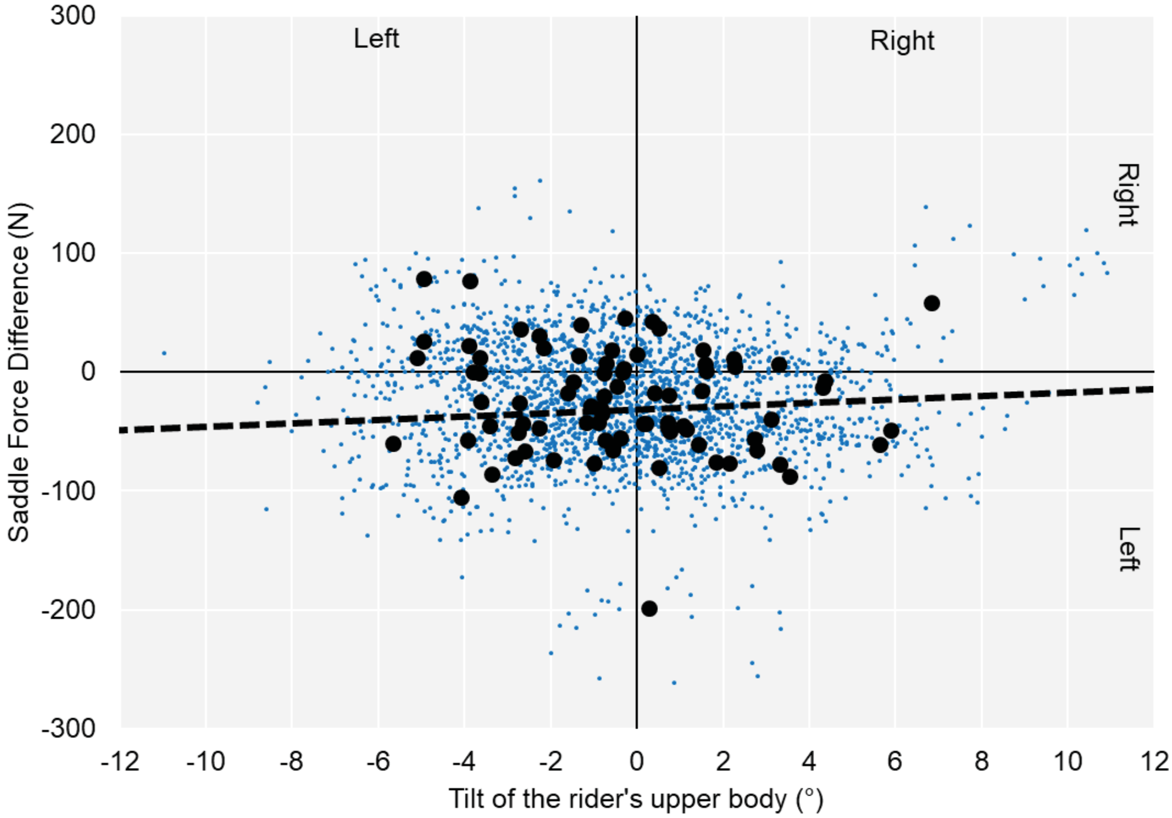


Fig. 4. Relation between SFD and rider variable tilt index (TI) in the sitting trot dataset (n=80). Blue dots indicate values of single strides and black dots indicate mean values of a horse-rider pair (HRP). Regression line showing negative relationship between TI and SFD based on the best fitting mixed model.

Fig. 5. Relation between SFD and horse variable SDmin in the sitting trot dataset (n=80). Blue dots indicate values of single strides and black dots indicate mean values of a horse-rider pair (HRP). Regression line showing negative relationship between SDmin and SFD based on the best fitting mixed model.

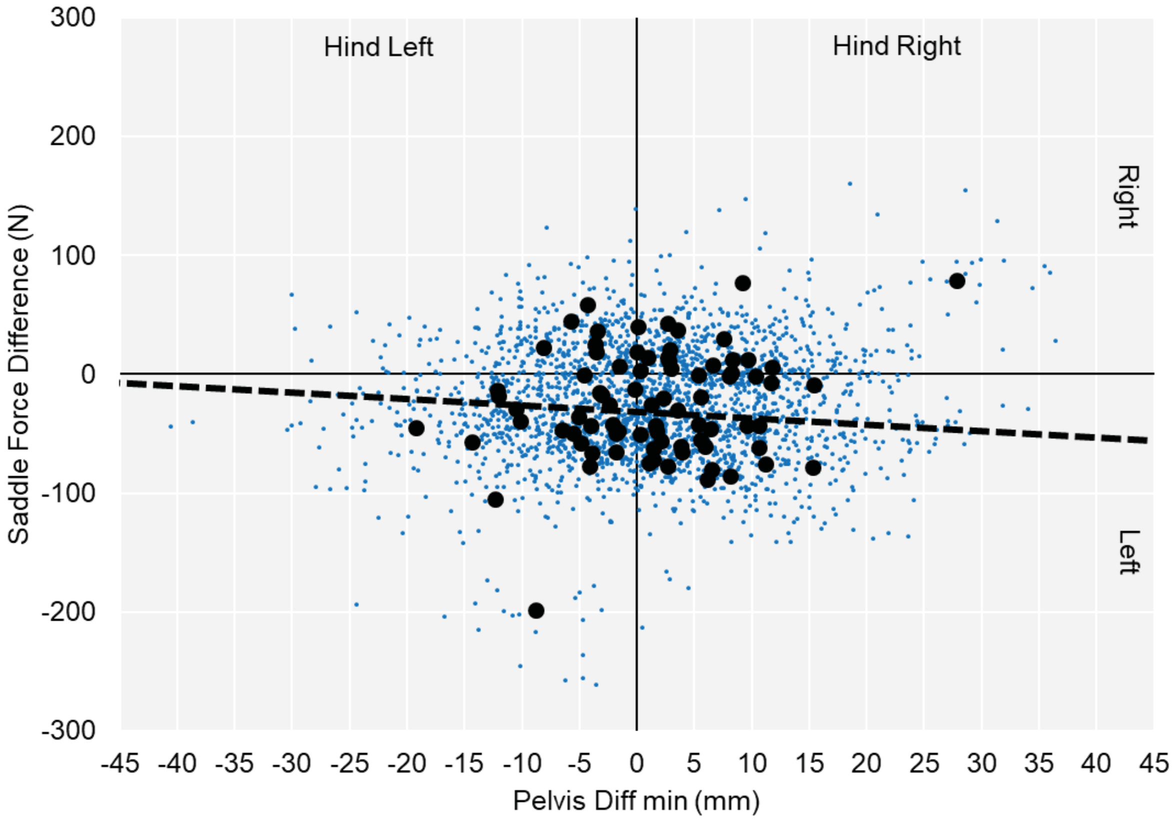


Fig. 6. Relation between SFD and horse variable PDmin in the sitting trot dataset (n=80). Blue dots indicate values of single strides and black dots indicate mean values of a horse-rider pair (HRP). Regression line showing negative relationship between PDmin and SFD based on the best fitting mixed model.

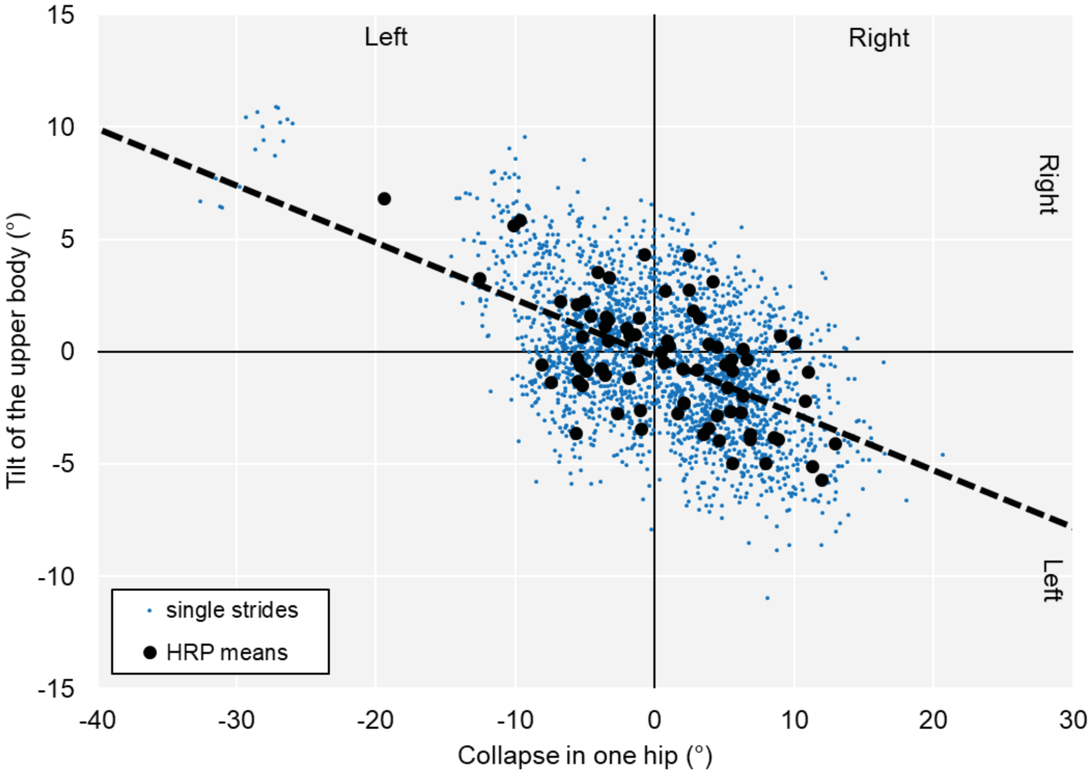
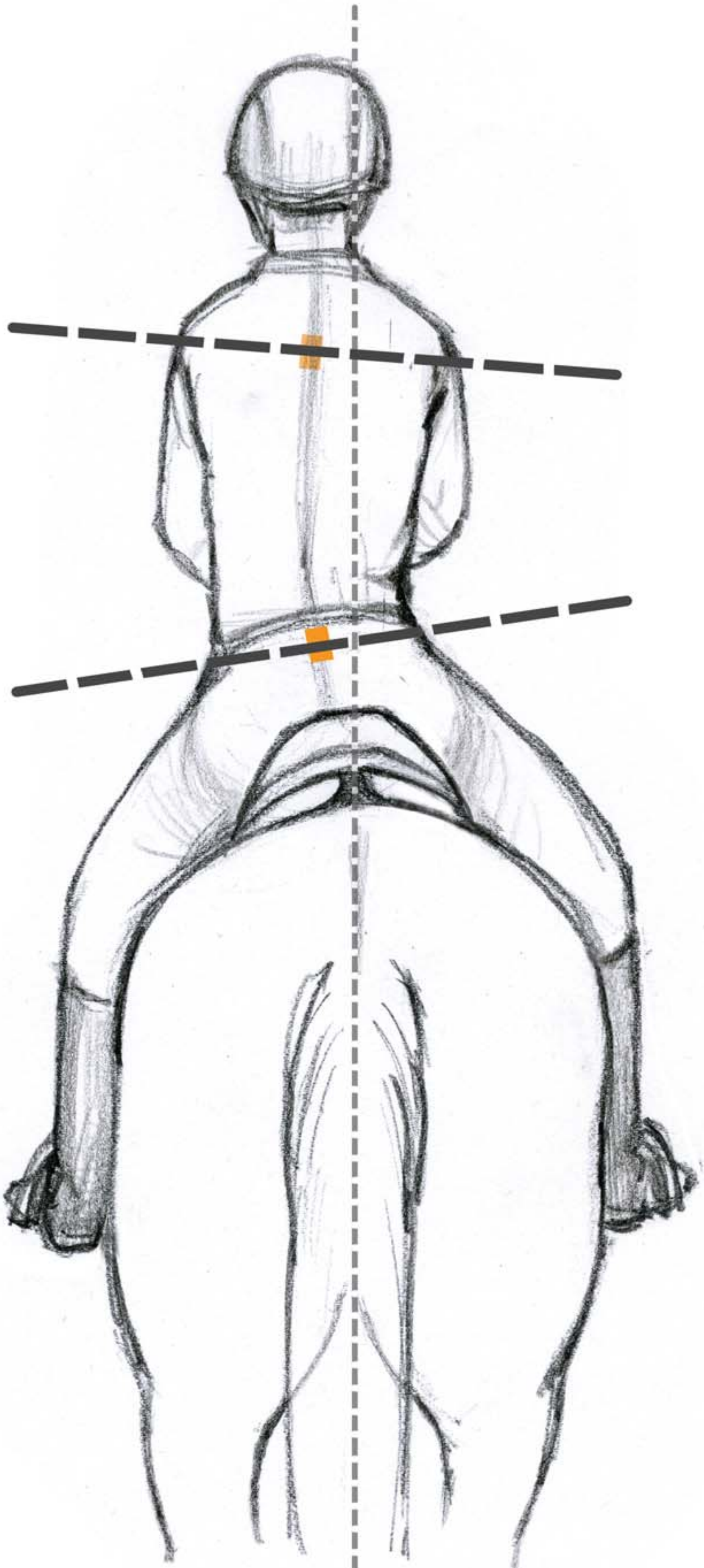


Fig. 7. Relation between the tilt index (TI, tilt of the upper body to one side in °) and the collapse index (CI, collapse in one hip in °) of the rider in the sitting trot dataset (n=80). Blue dots indicate values of single strides and black dots indicate mean values of a horse-rider pair (HRP). Regression line showing negative relationship between TI and CI, based on a linear correlation.



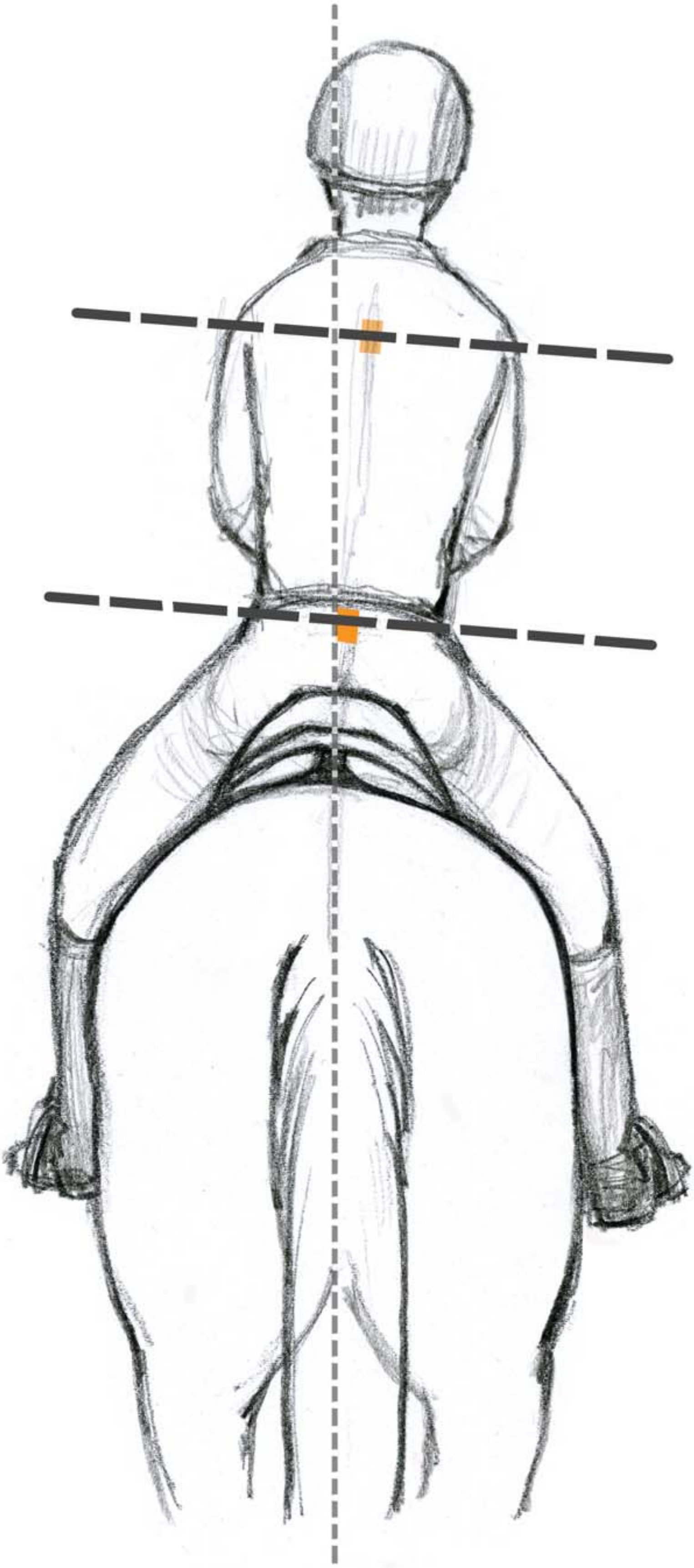


Table 1
Mean ± standard deviation and frequency of the different predictors in the different datasets included in the statistical analysis.

Dataset	n HRP	n Strides	SFD (N)	SFD (% BW)	CI (°)	TI (°)	HDmin (mm)	HDmax (mm)	SDmin (mm)	SDmax (mm)	PDmin (mm)	PDmax (mm)	More prominent shoulder horse	TOL Rider	Handedness Rider
Stance	60	NA	-28.06 ± 73.67	-4.2 ± 9.8	1.50 ± 6.53	0.74 ± 2.68	NA	NA	NA	NA	NA	NA	L 27 R 14 Neither 19 *	L 13 R 44 NA 3 *	L 6 R 51 NA 3
Sitting Trot	80	2323	-24.12 ± 49.42	-3.6 ± 7.3	0.60 ± 6.56 ***	-0.31 ± 3.08 ***	2.94 ± 34.64 **	-2.91 ± 39.31 **	0.57 ± 9.50 *	2.36 ± 13.76 ***	1.44 ± 10.43 ***	-1.65 ± 13.48 ***	L 34 R 20 Neither 26	L 23 R 54 NA 3 **	L 11 R 66 NA 3
Most symmetric strides - horse	67	581	-16.0 ± 44.46	-2.6 ± 7.0	-0.52 ± 6.99 ***	-0.07 ± 2.82	-1.05 ± 33.81	-9.60 ± 35.12	0.06 ± 4.89	1.00 ± 5.35	0.81 ± 5.46 *	-0.76 ± 5.75 *	L 29 R 15 Neither 23	L 19 R 46 NA 2	L 10 R 55 NA 2
Most symmetric strides – rider	53	581	-34.43 ± 53.48	-5.0 ± 6.8	-0.23 ± 1.95	0.02 ± 1.68	2.51 ± 34.81	4.34 ± 43.93	1.39 ± 10.04	3.94 ± 12.83 **	1.82 ± 9.26 ***	-1.61 ± 13.58 **	L 25 R 14 Neither 14 *	L 12 R 38 NA 3 ***	L 6 R 55 NA 3
Sitting trot of most symmetric SFD during stance	15	Stance NA	-2.85 ± 16.70	-0.5 ± 2.8	1.48 ± 7.07	0.27 ± 1.84	NA	NA	NA	NA	NA	NA	L 6 R 5 Neither 4	L 3 R 12 NA 0	L 1 R 14 NA 0
		Moving 473	-14.54 ± 36.86	-3.4 ± 7.6	0.12 ± 8.30 ***	-0.26 ± 2.99 ***	5.12 ± 27.57	-4.45 ± 35.56 **	-1.30 ± 9.07 **	0.46 ± 12.86 *	3.77 ± 8.91 ***	-1.05 ± 13.01 **			

Abbreviations: HRP, horse-rider pair; SFD, saddle force difference; CI, collapse index; TI, tilt index; TOL, take-off leg rider;
SFD was calculated based on the mean force for each stride in newton (N) or % BW, percentage of the rider's bodyweight. Negative values indicate higher mean forces on the left side of the saddle pressure mat, positive values indicate higher mean forces on the right side.
TI, tilt of the rider's upper body: negative values indicate tilting to the left, positive values to the right; CI, rider collapsing in one hip: negative values indicate collapsing in the left hip, positive values in the right hip.
(H/S/P)Dmin/max: Difference in minimal/ maximal vertical displacement of the horse's head (H), sternum (S), or pelvis (P) between left and right stride half-cycles.
Predictors that showed a significant relationship with SFD in the best fitting model of the respective dataset are indicated *** ($P < 0.001$), ** ($P < 0.01$), or * ($P< 0.05$).

Conflict of interest statement:
The authors declare no potential conflicts of interest. None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

Animal welfare/Ethical statement:

The experimental protocol was approved by the Animal Health and Welfare Commission and the Ethical Commission of the Canton of Zurich, Switzerland (TVB-Nr. ZH003/17-28698; BASEC-Nr. 2017-00188).