Saddle and stirrup forces of equestrian riders in sitting trot, rising trot and trot without stirrups on a riding simulator

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Abstract

Studies into horse-saddle-rider interaction demonstrate that increased vertical forces on the horse's back are potentially damaging to the musculoskeletal system, and any practice that could lead to this warrants investigation. The contribution of the stirrups in stabilising the bodyweight of the rider, and the effect of riding without stirrups on force distribution to the horse, has yet to be fully described in the literature. The current study therefore aimed to compare saddle and stirrup forces in three conditions; sitting trot, rising trot, and sitting trot without stirrups on the riding simulator. Fourteen amateur female riders of mean age 34.6 ±10 years participated in the study and 20 seconds of data were collected for saddle and stirrup force across the three conditions. Mean and peak forces were extracted from the data for total force under the whole saddle, left and right sides of the saddle separately, left and right stirrups, and both stirrups combined. Peak vertical saddle forces were significantly higher in sitting trot without stirrups than with ($P=0.011$). Higher mean and peak saddle forces were seen on the right hand side in all conditions ($P<0.001$) and there was an overall tendency for higher left stirrup forces in both sitting and rising trot with this being significant for peak force in sitting trot ($P=0.039$). The higher forces recorded when trotting without stirrups indicate that the stirrups play an important role in controlling the vertical acceleration of the rider in relation to the horse, however further studies are needed on live horses before any specific recommendations can be made regarding training practices. Asymmetrical saddle forces have a potentially negative effect on the horse and future research should also aim to identify the underlying causes of these patterns of rider asymmetry to improve both horse welfare and performance.

Key words: equestrianism, dressage, horse-rider interactions, biomechanics, kinetics

The authors declare no conflict of interest

Introduction

The impact of the rider on equine locomotion has received increased interest over the last 15 years, with a growing body of research in this area (Clayton and Hobbs, 2017). This is partly due to the rise in popularity of equitation science, and the increasing availability of technologies developed to assess and measure the horse-rider relationship (Pierard *et al*., 2015). The equine sector as a whole is becoming more concerned with the welfare of the ridden horse (Hemsworth *et al*., 2015) and the biomechanical effects of the rider can be an influential factor in this (Clayton and Hobbs, 2017; Williams and Tabor, 2017).

The most significant area of force transmission between horse and rider is through the saddle (Clayton and Hobbs, 2017; Greve and Dyson, 2013) with peak vertical forces of up to two and a half times the rider's bodyweight being recorded in sitting trot (Bogisch *et al*., 2014). Patterns of force distribution through the saddle have been shown to follow a cyclical pattern in time with the horse's stride (de Cocq *et al*., 2010a; van Beek *et al*., 2012) with sitting trot showing two clear saddle force peaks (Bogisch *et al*., 2014; Freuhwirth *et al*., 2004) which are thought to be caused by vertical movement of the rider in response to the vertical oscillation of the horse's trunk within the trot (Bogisch et al., 2014).The addition of 75 kg of dead weight in the saddle has been found to increase the extension of the thoracolumbar spine (de Cocq *et al.,* 2004) and this can also be seen in both rising and sitting trot with a rider, although rising trot allows the spine to return to flexion when the saddle is unloaded in the standing phase of the stride (de Cocq *et al.,* 2010a). Rising trot can however lead to asymmetrical limb loading and pelvic movement between the weight bearing and non-weight bearing diagonals, which could be potentially damaging if the same diagonal is used for long periods of time or when combined with rider asymmetries (Roepstorff *et al*., 2009).

A number of recent studies into rider biomechanics have reported the presence of force asymmetry; riders have been shown to preferentially weight bear on the left ischial tuberosity (seat bone) when seated on a flat, static platform (Guire *et al*., 2017) and to weight bear asymmetrically whilst sitting astride a stationary saddle horse (Nevison and Timmis, 2013) and whilst riding their own horse at sitting trot (Hampson and Randle, 2015). This leads to uneven loads on the horse's back (de Cocq *et al*., 2009) which has implications for welfare and performance (Greve and Dyson, 2013).

It is a popular opinion amongst equestrian coaches that riding without stirrups is beneficial in stabilising a rider's seat (Print, 2011) and encourages them to sit more centrally (Loch, 2003). Yet there is no empirical evidence to support these ideas and the impact of working without stirrups on the forces distributed to the horse is not yet known. Van Beek *et al.* (2012) were the first to describe stirrup force patterns, demonstrating that the loading of the stirrups was temporally associated with loading of the saddle in both sitting and rising trot. The peaks in stirrup force occurred at the same point in the stride as the peaks in saddle force in the sitting trot (van Beek *et al*., 2012), indicating that the rider may be using the stirrups to control their downward acceleration. When stirrups are removed from the rider it is therefore possible that there would be increased forces directly on the horse's epaxial musculature as a result of less controlled downward acceleration of the rider. This could have potentially negative consequences for equine musculoskeletal health. As would be expected van Beek *et al*. (2012) also showed that the peaks in stirrup force within the rising trot were associated with a reduction in saddle force, and were significantly greater than the stirrup force peaks seen within the sitting trot, as the rider takes the whole bodyweight on the stirrups in the standing portion of the stride. Due to a sensor malfunction data were only collected from one stirrup during this study, meaning that the total proportion of bodyweight supported by the stirrups and information on the patterns of force distribution between left and right stirrups, including any possible asymmetries, could not be described (van Beek *et al*., 2012). Data collected from both left and right stirrups simultaneously has not been presented in the peer reviewed literature to date.

The current study firstly aimed to compare the total saddle and stirrup forces between rising trot, sitting trot, and trot without stirrups, testing the hypotheses that there would be a difference in saddle force between the three trot types and a difference in stirrup force between sitting and rising trot in line with the previous literature. Additional aims were; to describe the total force that riders place on the stirrups in relation to bodyweight, to describe the relationship between left and right stirrup force in both sitting and rising trot and to determine if force asymmetry was present for saddle and stirrup forces in this population.

Methods

Participants

A self-selecting convenience sample of 14 female riders of mean age 34.6 ±10 years (±SD), mean height 166.7 ±6.5cm, and mean weight 68.9 ±9.9kg took part in the study, of which 85.7% (n=12) were right handed and the remainder left handed. Participants were recruited via an advertisement on social media, detailing the aims, inclusion and exclusion criteria. Ethical approval for the study was granted by Hartpury University Centre Ethics Committee.

The inclusion criteria required all participants to be female, as spinopelvic anatomy, which may impact on the results of this study, differs between the sexes (Janssen *et al*., 2009; Rissech *et al*., 2003). Participants were aged between 18 and 60 years to reduce the potential impact of growth (Mac-Thiong *et al*., 2004) or age related joint changes (Johnson *et al*., 2004; Leunig *et al*., 2003) on the measured variables. Participants were also required to weigh less than 102kg, as this is the weight limit for the riding simulator. Riders at different levels have been shown to exhibit different pelvic movements (Munz *et al*., 2014), thus riders were required to be competent at British Dressage Preliminary or Novice level, with those above or below this standard being excluded. Exclusion criteria removed participants who were currently injured, or had previous injury to the pelvic region or hip joints as this can lead to development of compensatory movement patterns (Hammoud *et al*., 2014) which would impact the validity of the study.

Prior to commencement of data collection, informed consent was gained from each participant in line with the General Data Protection Regulations 2018 (GDPR). The anthropometric measurements were then taken; height (cm) was recorded without shoes using a Leicester Portable Height Measure and bodyweight (kg) was recorded using a Tanita Body Composition Analyser BF-350. Participants were required to wear a correctly fitted riding hat to current safety standard (PAS 015, ASTM F1163:04a or Snell E2001) and riding boots with a smooth sole and a small heel for the data collection on the riding simulator. A second bodyweight measurement was then taken, with riding hat and boots to use for calibration purposes.

Equipment and Protocol

Horses designated as sound by their owners have been shown to display movement asymmetry in some cases (Rhodin *et al*., 2017; Starke *et al*., 2012) which could affect the transfer of forces between horse and rider, therefore the data collection for the current study took place on a riding simulator (Racewood Ridemaster Pro) to remove these effects. This riding simulator model consists of a reinforced plastic horse form which sits on top of a motorised platform and moves to mimic the equine gaits of walk, trot and canter. This particular model has two speeds of the trot gait termed as ‘collected trot’ and ‘medium trot’. This simulator has leg sensors on both sides which allows it to detect the rider's leg aids and a sensor system built into the articulation between the head and the neck which allows it to respond to the rein aids, thus the rider can change between the gaits as they would on a live horse. There is also a manual control panel consisting of 'up' and 'down' buttons on the side of the simulator which allows the researcher to select the required gait. The simulator moves in a repeatable and symmetrical manner within all gaits, meaning that there is no indication on which 'diagonal' a rider should be rising on in the trot.

An under saddle pressure mat (Tekscan CONFORMat) was placed directly onto the back of the simulator and a dressage saddle weighing 7.5kg complete with stirrups was placed directly on top. The saddle was then attached to the girth buckles present on the sides of the simulator by two research assistants simultaneously from either side, ensuring neither the pressure mat nor saddle were pulled to one side. Ahead of data collection the saddle pressure mat was calibrated to the weight of the saddle using the Force Calibration function within the Tekscan CONFORMat version 7.6x software (Tekscan, 2013 pp139-150). This software was then used to view the under saddle force measurements within the Real Time viewing window, using the 'panes' tool to separate the 32 x 32 sensor array into two 32 x 16 sensor panes, corresponding to the left and right sides of the saddle. The left and right girth straps were then adjusted until the force difference between the left and right panes displayed in the Real Time window was no greater than one Newton. This process was repeated before each participant to ensure any saddle movement caused by one participant was corrected prior to the next rider mounting.

The Pliance stirrup force sensors (Novel gmbh), consisting of two 11cm x 5cm pressure mats, each housed within its own rubber protective sleeve, were fitted to the left and right stirrups. Prior to data collection the stirrup force sensors were calibrated using the weight of an 86kg adult using the Bipedal calibration function within the Loadsol app via an Android smartphone (Novel gmbh, 2017 pp26-7).

Riders were mounted onto the simulator from the left hand side, using a mounting block to minimise disruption to the sensors. Riders underwent a standardised four minute warm up, consisting of one minute in each 'walk', 'collected trot', 'medium trot' and 'canter' settings on the simulator. The simulator was then returned to halt. The saddle pressure mat was recalibrated at this stage for each rider, using the Force Calibration function as previously described, calibrating to the weight of the rider with hat and boots, plus the weight of the saddle. This ensured no drift in calibration throughout the data collection period (de Cocq *et al.*, 2009). The stirrup sensors were also unloaded and zeroed at this stage for each rider to eliminate the effects of any movement on the sensors and ensure accurate readings could be obtained (Novel gmbh, 2017 p29).

The simulator was set to 'medium trot' for the data collection element, and was controlled by the researcher using the control panel to ensure that riders' position was not disrupted by trying to locate the leg sensors. Once the rider had verbally confirmed that they were comfortable in the trot, 20 seconds of data were recorded from each the saddle and stirrup pressure sensors, for each the sitting trot, rising trot and the sitting trot without stirrups. Between each pace the simulator was returned to the 'walk' setting by the researcher, the participant was then briefed on the next condition to be measured, which included removal of stirrups for the without stirrups condition. The simulator was then returned to the 'medium trot' setting and the next 20 seconds of data collected. On completion of the trial participants were then given a one minute cool down period in walk before dismounting and being debriefed.

The medium trot setting on this model has a stride frequency of 0.93 seconds, in which time the plastic horse form raises and lowers twice to emulate the stance phases of each diagonal pair of limbs, each time followed by the short suspension phase as seen in the trot stride of the live horse (Barrey, 2001). The saddle force data were recorded at a frequency of 100Hz and the mat is accurate to 0.1N (Tekscan, 2013), the stirrup force data were also recorded a frequency of 100Hz and the stirrup sensors are accurate to the nearest 10N (Novel gmbh, 2017). Due to the two measurement systems being by different manufacturers, automatic synchronisation of data collection was not possible, the systems were manually synchronised in that data collection for both systems was started at the same time. Due to the potential for human error in this process, analysis was conducted on mean and peak values found over the 20 second data collection window and no analysis of the relationship between saddle and stirrup force at specific time points was included.

Data Analysis

Saddle pressure data were analysed within the Tekscan CONFORMat v7.6x software, total force (N) over the whole saddle pressure mat, and on the left and right sides of the saddle separately, was then extracted in Microsoft (MS) Excel. Left and right stirrup force data (N) were collected using the Novel Loadsol app via an Android smartphone and later downloaded into MS Excel, these were then combined within MS Excel to create a total stirrup force variable.

For both saddle and stirrup data the mean value was calculated for left, right, and total force within each of the trot conditions over the entire 20 seconds of recorded data, with the obvious exception of stirrup force data for the 'without stirrups' condition. The data were then partitioned into strides, each stride lasting 0.93 seconds which was the average (mean, mode and median) time between high (standing) stirrup force peaks in the rising trot. A peak value for left, right, and total force was then extracted for each stride (0.93 second window) within the 20 seconds and a mean of these peak values taken. All data were then normalised to the bodyweight of the rider. Thus twelve variables were created; mean normalised saddle force (left, right, and total) mean normalised stirrup force (left, right, and total), peak normalised saddle force (left, right, and total) and peak normalised stirrup force (left, right, and total) and extracted into IBM SPSS Statistics v21for all remaining analyses.

Symmetry indices (SI) were calculated for mean normalised saddle and stirrup forces, using the formula;

$$SI(\%)= 100[(X_R-X_L)/0.5(X_R+X_L)]$$

Where X=measured parameter, R=right mean, L=left mean

(Alexander *et al*., 2015; Carpes *et al*., 2010; Robinson *et al.*, 1987).

Symmetry indices were produced as both directional and non-directional variates to allow comparison for both direction and overall degree of asymmetry between the conditions. For the directional SI a positive sign indicates higher force on the right and a negative sign indicates higher force on the left. Non-directional SI use only the value, with the sign removed, giving a percentage asymmetry for a variable but without direction of asymmetry.

Normality of all variables was confirmed using the Kolmogorov-Smirnov test. Differences in total mean and peak saddle force and saddle SI between the conditions were analysed using the repeated measures Analysis of Variance (RM ANOVA) with Bonferroni correction applied to the *post hoc* testing (α=0.017). Differences in total mean and peak stirrup force and stirrup SI between the sitting and rising conditions were analysed using the paired t-test (α=0.05) due to there being only two conditions in which this variable could be measured. Differences between left and right mean and peak values for both saddle and stirrup force were also analysed using the paired t-test (α=0.05). In order to further investigate the relationship between stirrup force and participant bodyweight the Pearson's product moment correlation was then used to test for association between non- normalised mean and peak stirrup force and bodyweight in both sitting and rising trot (α=0.05).

Results

Data shown are the averages for 14 participants of mean and peak saddle and stirrup force recorded at 100Hz for 20 seconds continuously, equivalent to 21 complete stride cycles, in each sitting trot, rising trot and trot without stirrups.

Saddle forces

Mean total saddle force did not significantly differ between the three conditions of rising trot, sitting trot and trot without stirrups (Table 1). There was a significant difference in peak total saddle force with pairwise comparisons showing the force in the without stirrups condition to be significantly higher than sitting trot with stirrups (P=0.011). There was a trend for peak total saddle force in rising trot to be higher than that in sitting trot, but the pairwise comparison was not significant (P=0.031) when the Bonferroni correction was applied (α=0.017).

Table 1: Results of RM ANOVA showing main effects for total normalised saddle force and saddle force symmetry index across the three conditions of sitting trot, rising trot and trot without stirrups on the riding simulator (n=14)

Variable	**Sitting Trot** (Mean ±SD)	**Rising Trot** (Mean ±SD)	**Without Stirrups** (Mean ±SD)	**F**	**P**
Mean Force (%bwt)	76.49 ± 4.7	76.43 ± 5.2	77.42 ± 4.9	0.384	0.685
Peak Force (%bwt)	187.79 ± 18.5^{a}	198.15± 26.6^{ab}	195.78± 28.7^{b}	4.437	**0.022***
Symmetry Index (%)	+41.21 ± 10.7	+39.87 ± 10.3	+40.54 ± 13.4	0.092	0.913

Directional SI; negative= higher force left, positive= higher force right
*=P<0.05 **=P<0.001; superscript letters reflect significant difference on pairwise comparison
bwt= bodyweight

When comparing saddle force between left and right hand sides of the saddle a significantly higher mean and peak force was recorded on the right hand side in all of the conditions (Table 2). There were no significant differences in SI between the three conditions (Table 1). As all saddle forces were higher on the right hand side of the saddle for all riders in the sample across all conditions directional and non-directional SI would yield the same results, therefore only one set were analysed.

Table 2: Results of paired t-test between left and right mean and peak normalised saddle forces across the three conditions of sitting trot, rising trot and trot without stirrups on the riding simulator (n=14)

Condition	Variable	Left (Mean ±SD)	Right (Mean ±SD)	t	P
Sitting Trot	Mean Force (%bwt)	30.37±2.8	46.12±3.3	-14.77	**<0.001*** **
	Peak Force (%bwt)	86.34±11.5	112.48±11.9	-9.05	**<0.001*** **
Rising Trot	Mean Force (%bwt)	30.64±3.3	45.79±3.1	-15.36	**<0.001*** **
	Peak Force (%bwt)	84.34±15.0	114.22±17.9	-5.73	**<0.001*** **
Without Stirrups	Mean Force (%bwt)	30.75±2.7	46.46±4.1	-11.50	**<0.001*** **
	Peak Force (%bwt)	93.14±15.9	118.48±15.9	-7.58	**<0.001*** **

*=P<0.05 **=P<0.001
bwt= bodyweight

Stirrup forces

Stirrup loading was seen to follow the cyclical pattern of the stride within both sitting trot (Figure 1) and rising trot (Figure 2) as described by van Beek *et al.* (2012), with the current study also allowing consideration of each left and right stirrup separately.

Within the sitting trot the group mean demonstrated a tendency for a higher left stirrup force (Figure 1C) and asymmetry in stirrup force could be seen in individual participants (Figure 1D). Within rising trot the left and right mean forces appear fairly similar at a group level (Figure 2C), however Figure 2D demonstrates a commonly seen movement pattern in individual participants in which the stirrup force is higher on one stirrup in the sitting phase of the stride (low peak) and then on the opposite stirrup when standing (high peak).

*Figure 1: Normalised stirrup force data in sitting trot for left stirrup (**A**) and right stirrup (**B**) showing mean (solid line) ± 1SD (dotted line) across all participants (n=14) and left and right stirrup composite graphs showing the mean of all participants (**C**) and an example of an individual participant (**D**) where solid line represents the left stirrup, dotted line represents the right. Please note the stirrup force measurement system used reports data to the nearest 10 Newtons, hence the staircase pattern in the individual participant data.*

*Figure 2: Normalised stirrup force data in rising trot for left stirrup (**A**) and right stirrup (**B**) showing mean (solid line) ± 1SD (dotted line) across all participants (n=14) and left and right stirrup composite graphs showing the mean of all participants (**C**) and an example of an individual participant (**D**) where solid line represents the left stirrup, dotted line represents the right. Note the high peak in the second half of the stride indicating the standing phase of the rising trot.*

Both mean and peak total normalised stirrup forces were significantly higher in rising trot than sitting trot (Table 3). Mean stirrup SI was calculated at -8.9% for both sitting and rising conditions, demonstrating a propensity within the group for a higher left stirrup force (Table 3), however this was only shown to be significant for peak forces within sitting trot (Table 4) where 71.4% of the sample showed a higher force on the left stirrup. There were no significant differences in stirrup SI between rising and sitting trot conditions. It was also noted that standard deviations for mean stirrup forces were more than double those for mean saddle force, demonstrating a greater inter-participant variability in this measure.

Table 3: Results of paired t-test for total normalised stirrup force and stirrup force symmetry index between sitting and rising trot on a riding simulator (n=14)

Variable	**Sitting Trot** (Mean ±SD)	**Rising Trot** (Mean ±SD)	**t**	**P**
Mean Force (%bwt)	22.33±6.8	37.06±8.4	-9.495	**<0.001****
Peak Force (%bwt)	39.70±9.6	123.75±13.4	-24.184	**<0.001****
Symmetry Index directional (%)	-8.92 ±22.2	-8.91 ±32.9	0	1.0
Symmetry Index non directional (%)	19.6 ±12.8	26.02±21.0	-1.035	0.320

Directional SI; negative= higher force left, positive= higher force right
*=P<0.05 **=P<0.001
bwt= bodyweight

Table 4: Results of paired t-test between left and right mean and peak normalised stirrup forces in both sitting and rising trot on a riding simulator (n=14)

Condition	Variable	Left (Mean ±SD)	Right (Mean ±SD)	t	P
Sitting Trot	Mean Force (%bwt)	11.71±3.9	10.62±3.3	1.847	0.088
	Peak Force (%bwt)	21.90±5.6	19.21±5.2	2.299	**0.039***
Rising Trot	Mean Force (%bwt)	19.50±6.1	17.57±4.9	1.005	0.333
	Peak Force (%bwt)	62.55±9.7	61.71±16.5	0.135	0.895

*=P<0.05 **=P<0.001
bwt= bodyweight

For the non-normalised stirrup force data correlated with rider bodyweight (68.9 ±9.9kg); peak total force in rising trot showed a significant positive correlation (r=0.804, P=0.001), however peak total force in sitting trot did not (r=0.047, P0.873). Mean total stirrup force did not correlate with rider weight in either sitting trot (r=0.005, P=0.987) or rising trot (r=0.231, P=0.427).

Discussion

Saddle Forces

Significantly increased peak vertical saddle force was seen in the trot without stirrups condition compared to sitting trot with stirrups, supporting the original hypothesis. This is likely evident of the rider having less ability to control their downward acceleration relative to the saddle in this condition, this is in line with the findings of Lagarde *et al*. (2005) who demonstrated that an experienced rider uses flexion of the ankle to dampen the effects of vertical oscillations of the horse, which would be ineffective in the without stirrups condition. Whilst sitting trot is widely considered to be beneficial to rider posture (Loch, 2003; Print, 2011), there is growing interest within the literature on the negative effects of increased forces from the saddle on the horse (Clayton and Hobbs, 2017; Greve and Dyson, 2013). This finding demonstrates that future research is warranted to combine assessment of saddle force with three dimensional kinematic assessments of riders working without stirrups in order to gain a more complete picture of the potential impact of this common training activity on the horse.

Peak vertical saddle forces were higher in the rising trot than the sitting trot, although this was not significant. Previous studies have demonstrated the opposite with higher peak forces in the sitting trot when measured directly for one rider, riding multiple horses on a treadmill (Peham *et al*., 2010) and for multiple riders on two different horses overland (de Cocq *et al*., 2010b). It has however been seen that the equine spine flexes within the standing phase of the rising trot and extends within the sitting phase (de Cocq *et al*., 2010a; Roepstorff *et al*., 2009). The current study took place on a riding simulator which is rigid and cannot absorb or displace any of the vertical force from the movement of the rider, it may be that be that in extending the thoracolumbar spine at the moment of impact of the rider's seat with the saddle, the live horse attenuates some of this force, explaining why the forces described here are not consistent with those seen previously in the live horse (de Cocq *et al*., 2010b; Peham *et al*., 2010).

There was no difference in saddle force symmetry index between the three conditions. This is in agreement with Peham *et al*. (2010) who stated that the centre of pressure at the horse-saddle –rider interface did not differ in position or variability between rising and sitting trot. This lack of change also indicates that riders in this sample were able to stabilise their weight distribution easily without stirrups, which is perhaps a factor of experience level, with all participants being accustomed to working without stirrups. Novice riders may show a greater degree of variability. It is possible that the short time period for which this exercise was used, along with reduced biomechanical demands of the simulator (Ure *et al*., 2018) was not enough to require the rider to make postural adjustments to centralise their weight within the saddle for increased stability. Alternatively it could be the completion of exercises developed to improve the seat whilst working without stirrups that makes the difference to rider stability (Loch, 2003; Print, 2011) and not solely the removal of support for the legs.

All riders in the sample showed increased force on the right hand side of the saddle in all conditions, however this was a relatively small sample size and care should be taken not to over interpret the findings (Clayton and Hobbs, 2017). Great care was taken to ensure the saddle was positioned centrally on the pressure mat and total force under each side of the saddle was measured, which represents rider bodyweight distribution (de Cocq *et al.*, 2009), not pressure or contact area as these variables would be more affected by saddle fit. An under saddle pressure system cannot distinguish between vertical and shear forces (Janura *et al*., 2012) therefore the right hand force increase detected could have been due to shear forces associated with saddle roll to the left. Whilst no visible saddle roll was seen in the current study, Guetjens *et al.* (2008) found that mounting a live horse from the left side caused increased force under the right hand side of the saddle at the withers, even when using a high mounting block. It may be that this slight movement of the saddle is never completely reversed when on the simulator, as there is no movement of the back musculature which may naturally right the saddle, also the girth does not completely encircle the horse, instead the saddle is anchored on both sides, this may lead to a different pattern of saddle movement on the simulator as compared to the live horse. A small number of studies have described the differences in rider kinematics between the simulator and the live horse (Dumbell *et al*., 2015; Ure *et al*., 2018), but future studies could investigate the kinetic differences to build a more complete picture of the validity of the riding simulator as an alternative to the live horse within biomechanical studies. It would also be useful consider the impact of mounting from the opposite side on saddle force distribution, both on the simulator and the live horse.

Whilst the effect of mounting on the saddle may impact force distribution, consistent patterns of rider asymmetry have also been reported in other studies. Riders have been shown to display a marked pelvic tilt, most usually to the right with a corresponding left trunk tilt (Alexander et al., 2015) and to axially rotate to the left whilst showing a greater right shoulder displacement (Symes and Ellis, 2009). Asymmetrical rider posture is known to have an impact on saddle force asymmetry (de Cocq *et al*., 2009) and patterns such as those described could have contributed to the tendency of this group to have a higher force on the right hand side of the saddle. Several potential causes of rider asymmetry have been proposed including innate laterality, musculoskeletal pain, and training effects (Clayton and Hobbs, 2017; Hobbs *et al*., 2014) and whilst there have been a number of studies which attempt to remedy rider asymmetry using a variety of techniques (Alexander *et al*., 2015; Hampson and Randle, 2015; Nevison and Timmis, 2013) there has been little investigation into the various potential causes in order to assess their relative contribution and the ultimate effect of this on forces transferred to the horse.

Stirrup Forces

It was noted that there was a tendency for one stirrup to bear more weight throughout the sitting trot, in the case of this sample population a greater proportion of riders (71.4%) placed more weight in the left stirrup. This could indicate a potential effect of pelvic limb laterality (footedness) on the stirrup force data, as this value closely agrees with the proportion of the population thought to have a left 'stabilising' limb, which is the limb naturally better conditioned to supporting the body weight, whilst the opposite 'mobilising' limb carries out a movement task (Previc, 1991; Sadeghi *et al*., 2000). Future studies of rider laterality could focus on footedness rather than handedness, which may help to better understand some of the common asymmetries seen in the literature.

Van Beek *et al*. (2012) hypothesised that the right and left stirrups would be alternately loaded in the sitting trot with a high peak on the right being associated with a low peak on the left and vice versa. This exact pattern was not seen in the current study, with one stirrup showing higher force in both peaks (Figure 1D), however when considering the group as a whole it was seen that the force peaks did appear to increase and decrease in opposition to each other, without actually overlapping (Figure 1C). It could be that the resolution of the stirrup force sensors (10N) made this subtle difference difficult to discern for individual participants. Van Beek *et al*. (2012) did suggest that the expected pattern of alternating left and right stirrup force could be due to the rotation of the saddle about the vertical axis (yaw) as a result of the alternating stance phases of the horse's hind limbs. The current study was conducted on a simulator, which whilst trying to approximate equine locomotion as closely as possible, is not capable of producing the rotational motion of the saddle, therefore the pattern proposed by van Beek *et al.* (2012) may be more clearly evident on the live horse.

Alternating higher and low peaks were however clearly seen in the rising trot with individual riders demonstrating more force on one stirrup in the seated phase of the stride, and then the opposite stirrup in the standing phase (Figure 2D). This could be linked to the muscle movement pattern associated with rising on a particular 'diagonal' (Print, 2011) with the rider unconsciously maintaining their centre of gravity more towards the side of the supporting hind limb (that which is in stance) when in rising trot on a live horse. If this alternating pattern is generated by rider movement and not the specific motion of the horse itself, this would explain why it persists on the simulator. Individual asymmetries in stirrup force seen within the participants in rising trot showed no significant differences when considered at the sample level. This may partly have been due to the necessity to consider 'left' and 'right' as the main groupings, rather than 'inside' and 'outside' as there is no limb movement, and therefore no difference between a left and right diagonal stance phase. This means that it cannot be determined if rider asymmetries in the rising trot are true asymmetries, or if they are associated with unconsciously rising on specific diagonal.

The only stirrup force variable which showed a significant positive correlation with rider weight was peak force in the rising trot condition. This indicates that downward force on the stirrups in the standing phase of rising trot is mostly a function of the rider's body mass combined with the downward acceleration of the limb into the stirrup required to push the body out of the saddle. Mean forces in rising trot, which describe the whole stride cycle, and both mean and peak forces in sitting trot were not significantly correlated with body weight. This, coupled with the high degree of variability in the proportion of body weight supported by the stirrups indicates a large degree of individual difference in riders' load bearing patterns when seated in the saddle. These differences could be related to riding level, with more experienced riders being shown to have a more open hip angle and a straighter leg alignment in line with classical riding guidelines (Kang *et al*. 2010; Schils *et al*., 1993) and more effectively use the ankle to dampen the acceleration caused by vertical movement of the horse's trunk (Lagarde *et al*., 2005), both factors which could impact on stirrup force. Whilst rider competence was controlled within the sample, this was self-reported and the number of years' riding experience was very variable, therefore this could have been a confounding factor. There are several commonly observed rider faults, such bracing into the stirrup, or having an unstable lower leg (Loch, 2003), which could potentially influence mean stirrup force and have not yet been investigated. Terada (2000) also found that riders with poor core muscle activation showed an increase in activation of the adductor magus muscle, which would lead to the movement of gripping with the knees. This is highly likely to reduce stirrup force and increase force variability. Further research in this area could consider the relationship between stirrup forces and rider kinematics to determine the how asymmetrical or variable stirrup loading relates to the rider's posture and performance.

Limitations

This study did not include any male riders, in an attempt to control as many potential confounding variables as possible at this early stage in the research. Males show different spinopelvic anatomy to females (Janssen *et al*., 2009; Rissech *et al*., 2003) which may impact on movement patterns at the rider-saddle interface. Female athletes in other sports have been shown to have a greater propensity for internal hip rotation and a higher asymmetry in hip abductor muscle strength when compared to males (Brophy *et al*., 2009). These factors have the potential to influence the force distribution across the saddle and stirrups when riding, therefore the findings of the current study may not be as applicable to a sample of male riders.

This is the first peer reviewed study using this particular model of stirrup force sensor, thus the protocol in terms of calibration, fitting and usage may require further development. Within this trial the sensors were only calibrated once, prior to commencement of data collection, future validation studies may be necessary to determine how much these single sensors are subject to drift in calibration. Also this technology outputs the results to the nearest 10N, which may mean that subtle differences in stirrup force are missed, especially in the lighter weight riders. As the research area progresses more sensitive technologies may be required, however this provides some useful preliminary data to support the development of future studies. The fact that the saddle and stirrup force sensors could not be synchronised within this study also limits the potential applications of this work and would be a valuable addition to future research to fully describe the temporal relationships between these variables.

Some potential limitations and unknown factors with relation to the use of the simulator to emulate the movement of a live horse have already been highlighted. It is also worth noting that the trot stride duration of the simulator (0.93 seconds) is markedly longer than commonly seen on the live horse, with 0.8 seconds being reported for collected trot and 0.7 for medium trot (Walker *et al*., 2017). This difference in the stride duration could potentially give riders longer to react to the movement of the horse and to stabilise themselves. The movement is also very predictable from stride to stride. These factors together could make it easier for the rider to co-ordinate their movement pattern and this may help to explain why the peak forces shown here are consistently lower than those seen in similar studies using live horses (Bogisch *et al*., 2014; de Cocq *et al*., 2010a).

Conclusion

Sitting trot without stirrups is a common practice in rider training, however this study demonstrates that this could lead to increased peak vertical forces on the horse's back, the effects of this force increase on the horse are not yet known and this highlights an important area for future study. Predictable patterns of stirrup loading in time with the stride can be seen, however the variability of stirrup force and the lack of relationship between this and rider bodyweight, points to a great degree of variation between riders in how much weight they place in the stirrups. Marked asymmetries in saddle and stirrup force across the population add to the number of studies reporting significant asymmetry in equestrian riders. There are several potential causes for rider asymmetry discussed in the literature including laterality, musculoskeletal pain, and training effects. Future research should focus on characterising common rider asymmetry patterns within a larger sample population and investigating the underlying causes, so as to better support riders and minimise the potential for damage to the horse from uneven force distribution.

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