TITLE: The kinematics and kinetics of riding a racehorse: A quantitative comparison of a training simulator and real horses

AUTHORS: A.M. Walker, C. Applegate, T. Pfau, E.L. Sparkes, A.M. Wilson, T.H. Witte

JOURNAL TITLE: Journal of Biomechanics

PUBLISHER: Elsevier

PUBLICATION DATE: 26 August 2016 (online)

DOI: 10.1016/j.jbiomech.2016.08.031

Original Article

The kinematics and kinetics of riding a racehorse: a quantitative comparison of a training simulator and real horses

*Walker, A.M., Applegate, C., Pfau, T., Sparkes, E.L., Wilson, A.M., Witte, T.H.

*Corresponding author: Structure and Motion Lab and Clinical Science and Services, Royal Veterinary College, Hawkshead Lane, Hatfield, Hertfordshire, United Kingdom.

amwalker@rvc.ac.uk

Word count: 2940 Summary: 238

Ethical Animal Research: Ethical approval from the Royal Veterinary College ethics committee. Ethics reference number 2013 0096H. Informed subject consent was obtained for all animals and jockeys used in the study.

Sources of funding: Horserace Betting Levy Board project number 759.
Conflict of interests: None.

Key words: Jockey, Kinematic, Kinetic, Simulator

Abstract

Movement of a racehorse simulator differs to that of a real horse, but the effects of these differences on jockey technique have not been evaluated. We quantified and compared the kinematics and kinetics of jockeys during gallop riding on a simulator and real horses. Inertial measurement units were attached mid-shaft to the long bones of six jockeys and the sacrum of the horse or simulator. Instrumented stirrups were used to measure force. Data were collected during galloping on a synthetic gallop or while riding a racehorse simulator. Jockey kinematics varied more on a real horse compared to the simulator. Greater than double the peak stirrup force was recorded during gallop on real horses compared to the simulator. On the simulator stirrup forces were symmetrical, whereas on a real horse peak forces were higher on the lead limb side. Asymmetric forces and lateral movement of the horse and jockey occurs towards the side of the lead leg, likely a result of horse trunk roll. Jockeys maintained a more upright trunk position on a real horse compared to simulator, with no change in pitch. The feet move in phase with the horse and simulator exhibiting similar magnitude displacements in all directions. In contrast the pelvis was in phase with the horse and simulator in the dorso-ventral and medio-lateral axes while a phase shift of 180 degrees was seen in the cranio-caudal direction indicating an inverted pendulum action of the jockey.

Introduction

The modern 'martini glass' jockey position was introduced in the 19th century and has been credited with a 5-7% reduction in race times (Pfau et al., 2009). In this position, 90% of the jockeys' mass is distributed over the withers (Fruehwirth et al., 2004), however, it has been proposed that jockeys are able to mitigate any deleterious effects by isolating their centre of mass (COM) movement from that of the horse (Pfau et al., 2009). Consequently, peak force under the saddle (Fruehwirth et al., 2004; Geser-von Peinen et al., 2013), mechanical work of the horse (De Cocq et al., 2013) and extension of the horse's back (De Cocq et al., 2010) are reduced compared to the classical seated trot and canter position, with a proposed reduction in injury risk and work of galloping.

Optimal stability in riding is traditionally ascribed to perfectly synchronous movement of horse and rider. This suggests that the traditional sitting trot and canter are the most stable scenarios (Wolframm et al., 2013; Viry et al., 2013) and the modern jockey position with its isolated centre of mass (COM)(Pfau et al., 2009) the least stable. Despite the apparent instability associated with this modern position, the reduced pressure under the saddle and mechanical work benefits of this position outweigh the reduced stability and increased risk of falls. More skilled riders are known to be at a lower risk of falling (Hitchens et al., 2012) with some studies reporting fewer fatal limb fractures in horses ridden by more skilled jockeys (Parkin et al., 2004). Skill comes with repeated training over time. With the financial burden of horse management and the ever-increasing campaign to improve horse and jockey welfare, the use of simulators to facilitate training and to aid in refining race jockey technique is increasingly common. In some cases racehorse simulators are used during assessment of jockey competency prior to licensing.

The physical effort and stress of riding a simulator have been compared to that of riding a real horse, and found to be significantly different with respect to the work carried out by the jockeys and stress levels associated with each scenario (Ille et al., 2015). Significant differences have also been found between the movement trajectory exhibited, with real horses showing significantly greater dorso-ventral and medio-lateral displacement amplitudes and smaller cranio-caudal displacement amplitudes (Walker et al., 2016). While it is commonly recognised by jockeys that the movement of the simulator is different from that of real horses, to date no studies have quantified the effect of these differences on jockey position and movement. If the position and movement of the jockey are comparable between a simulator and real horse this supports the efficacy of simulator use during training.

Aim: Quantify and compare the kinematics and kinetics of jockeys during gallop riding on a simulator and on real horses.

Objectives: Quantify displacement of the jockey pelvis and feet and pitch of the trunk relative to movement of the horse/simulator.

Record forces exerted through the stirrups by the jockey on a simulator and real horse.

Compare the parameters recorded from each scenario.

Hypothesis: Jockeys exhibit larger and more varied force and displacement on real horses compared to simulator trials.

Materials and Methods

Data collection:

Six jockeys were assigned a category based on their experience (1 Expert, 4 Experienced and 1 Intermediate), according to the criteria in Table 1. All jockeys completed a consent form which had undergone review and approval by the Royal Veterinary College's Ethics Committee as part of the project application.

Each jockey was instrumented with MTw[1] inertial measurement units (IMU), attached using elasticated velcro straps laterally to the mid-segment of the fifth metatarsi, lumbosacral area of the pelvis (referred to simply as 'pelvis') and sternum of the jockey. An additional sacrum marker was attached to the sacrum of the simulator or horse. A custom-designed stirrup with an integrated force transducer[4] and global positioning system (GPS) and data logger were fitted to both sides of the saddle.

An MK9[2] racehorse simulator set at the highest speed level was used for all simulator testing. Five Thoroughbred racehorses in regular training at the British Racing School were used for the real horse trials. One horse was used twice with a different jockey on a different day. Inertial and force data were collected from all subjects during simulated gallop and during a real gallop, mean 12.12 ± 1.28m/s (27.11 ± 2.86 mph) on an all-weather seven furlong (0.88 mile) straight track. Valid trials were visually identified as horses galloping in a relaxed rhythm without any obvious trips or perturbations from the team driving alongside in the car. Stirrup force data were collected at 100Hz and inertial data at 30Hz. Stirrups were applied to the saddle at equal length, jockeys were able to alter the length of their stirrups after the warm up before the gallop but as far as practically possible none were known to be adjusted asymmetrically.

Data processing:

Acceleration data were calibrated and exported using commercial software (Xsens 'MT manager'). All data were high pass filtered (Butterworth 4th order 0.5Hz high pass) to remove drift. Accelerations in 3 axes were integrated to velocity and then again to displacement using numerical integration using custom written scripts in Matlab[3]. Displacement data were segmented into strides using minima in dorso-ventral displacement to represent mid-stance of the cycle. Stirrup data were synchronised to inertial data using a GPS time stamped trigger pulse produced when the inertial sensor data collection was initiated. Relative jockey displacements were calculated by subtracting the jockey values from the horse or simulator (sacrum) parameters. Directional stirrup force was calculated by subtracting the right amplitude from left amplitude while non-directional stirrup force was calculated by subtracting the smaller from the larger amplitude.

Data analysis:

Data were collected once for each jockey on the simulator and real horse. Data were collected for over a minute in each condition (e.g. simulator/real horse) providing in excess of 200 stride cycles for analysis. Mean and standard deviation displacement amplitudes in 3 axes, trunk pitch, trunk pitch amplitude and stirrup force amplitude were analysed using a linear mixed effects model in SPSS[7] with condition (simulator or horse), experience level (intermediate - elite) and side (left or right) as fixed factors and jockey as a random factor. The cut off for significance used was $P \leq 0.05$ and where applicable the post hoc test used was least squares difference.

Results

Jockey movement patterns during gallop on real horses were significantly different in many respects to those during simulator trials.

Jockey Stirrup force

Stirrup force amplitude on real horses were more than twice those recorded on the simulator for both the left and right stirrups ($P \leq 0.001$). Stirrup force on real horses were asymmetric with increased forces on the side of the lead leg (figure 1, table 2), whilst on the simulator they were not significantly different from symmetrical. Directional stirrup force symmetry (left minus right amplitude) did not differ significantly (P=0.420), however non-directional force symmetry (smaller amplitude subtracted from the larger amplitude) significantly increased in real horse trials (P=0.001) indicating a greater level of asymmetry.

Horse Sacrum

The horse exhibited significantly larger dorso-ventral (P=0.029) and medio-lateral (P=0.001) displacement amplitudes than those recorded on the simulator, a difference of 73 and 46 mm respectively (figures 2 and 6, table 2). In contrast the simulator had a significantly greater (58 mm) cranio-caudal displacement (P=0.010) than the real horse (figures 4 and 6, table 2). The combined cranio-caudal and dorso-ventral displacement trajectory of the real horse when being viewed from a left lateral angle was clockwise in direction while that of the simulator was in the opposite anticlockwise direction. During left lead the horse moves towards the left during the first half of the cycle and then towards the right during the second half of the cycle with the opposite occurring during right lead gallop.

Jockey Sternum

Jockey sternum pitch was used to represents trunk position. When riding real horses jockeys maintained a 24 degree significantly (P=0.012) more upright trunk compared to that on the simulator. Despite the more upright position when riding real horses there was no significant difference in the pitch amplitude (P=0.712) despite a significantly (P=0.027) more variable position compared to that on the simulator (figure 3, table 2).

Jockey Feet

Jockey foot displacement was a similar magnitude and direction to that of the simulator or horse. On the simulator when viewed from the left lateral angle the feet moved in an anticlockwise direction while on the real horse they moved clockwise (figure 6) relative to the mean position.

Dorso-ventral foot displacement did not differ significantly between real horse and simulator trials (Table 2). Cranio-caudal foot displacement was significantly greater on the simulator with 63mm (P=0.012) in the right foot and 64mm (P=0.013) in the left foot (figure 5). Medio-lateral displacement of the feet was significantly greater on a real horse with 116mm in the right (P=0.001) and 105mm in the left (P=0.026) foot respectively. There was also greater variation in the medio-lateral displacement on the real horse (P=0.000), right foot and (P=0.001) left foot respectively when compared to values recorded on the simulator.

Relative displacement of the feet (foot minus horse) was significantly greater in the dorso-ventral direction (P=0.005 and P=0.008 for right and left foot respectively) during real horse trials compared to simulator trials. No significant differences were found in the relative foot movement between simulator and real horse riding in either the cranio-caudal or the medio-lateral directions.

Jockey Pelvis

Pelvic displacement of the jockey was in phase with the dorso-ventral (figure 2) and medio-lateral displacement of the simulator while being 180 degrees out of phase with the cranio-caudal displacement (figure 4). A slight delay in jockey pelvis dorso-ventral displacement was found on the real horse (figure 2). Medio-lateral displacement was in phase (figure 7) while similar to the simulator, cranio-caudal displacement was found to be 180 degrees out of phase. The jockeys pelvis had significantly greater dorso-ventral (40 mm P=0.015) and medio-lateral (25 mm P=0.006) displacement and variation (P=0.002 and P=0.009 for the dorso-ventral and medio-lateral variation) on the real horse. The relative dorso-ventral displacement (horse minus jockey) is also significantly (P=0.000) greater (44 mm) on the real horse. The combined dorso-ventral and cranio-caudal trajectory for the jockey pelvis when viewed from the left lateral side moves in the opposite direction to that of the horse/simulator namely clockwise on the simulator and anticlockwise on the real horse (figures 2, 4 and 6, table 2). Relative cranio-caudal displacement of the jockey pelvis was 68mm more, so significantly (P=0.001) greater, on the simulator than on the real horse.

Discussion

Jockey kinematics and kinetics differ significantly when riding in the modern martini glass position on a real horse and a racehorse simulator. Key differences are linked to the opposite direction of the simulator displacement trajectory (anticlockwise) compared to real horses (clockwise) when viewed from the left side, as well as the difference in the magnitude of the displacement amplitudes. The feet of the jockey move in the same direction and with similar phasing and magnitude to the horse or simulator. In contrast the jockey pelvis moves dorso-ventrally in phase, but with a smaller magnitude, while the cranio-caudal movement is 180 degrees out of phase with the movement of the horse or simulator. In essence the jockey moves forward as the horse moves backwards and vice versa. The authors believe this inverted pendulum action is a fundamental element of the martini glass technique and requires isolation of the jockey's centre of mass from that of the horse through work done by the jockeys legs as discussed by Pfau et al. (2009). This work carried out by the jockey helps reduce the additional energetic costs to the horse associated with load carrying. While dampened in the pelvis through limb compression, the dorso-ventral displacement of the feet and pelvis are in phase with the dorso-ventral displacement of the horse/simulator. It is also important to acknowledge that the sacrum displacement of the horse and simulator are being used to indicate movement of the horse or simulators trunk and therefore interaction with the jockey. While for the simulator this is representative due to its solid and fixed nature, the real horse is able to flex its spine along the lumbar region and through the lumbo-sacral junction in a dorso-ventral and medio-lateral direction. This flexion reduces the accuracy of the sacrum sensor to represent movement experienced by the jockey. While this is a limitation it is not considered to be sufficiently large to significantly affect the findings of this study.

The stirrups are the main point of contact and weight support between the horse and jockey in the martini glass position. Forces in the jockey's stirrups therefore provide vital information about the balance and stability of the jockey and therefore the symmetry and peak forces distributed under the saddle. During simulator trials the peak forces, force amplitudes and impulses recorded in the left and right stirrups were not significantly different. Very little (8mm) lateral movement of the pelvis was recorded indicating there was even pressure under the saddle and the jockey was balanced with their centre of mass remaining close to the midline of the simulator. In contrast during real horse trials the peak stirrup forces and amplitudes were significantly different between left and right stirrups with a larger impulse asymmetry. Direction of this asymmetry is dictated by the horses lead leg. As discussed in Walker et al., (2016), the horses trunk displaces laterally and rolls down towards the side of the lead hind limb during stance of that leg. In conjunction with this, higher peak forces are recorded in the stirrup on the side of the lead leg with the jockey's pelvis displacing laterally towards the lead leg. This movement of the horse's trunk and pelvis towards the lead leg suggests the jockey is pushing away from the stirrup on the lead side in order to maintain the position of their centre of mass (COM) as close to the midline of the horse as possible and therefore keep their balance. This is further supported by the significantly smaller lateral displacement of the jockey's pelvis on the simulator as the simulator is unable to move laterally and is only able to roll slightly resulting in symmetrical stirrup forces.

The simulator has an anticlockwise trajectory which is the opposite direction to that recorded in the real horse. However, like the medio-lateral movement of the horse and pelvis being associated with increased stirrup forces to maintain a consistent position of the jockeys COM, cranio-caudal displacement of the pelvis was 180 degrees out of phase with the horse and simulator. Again this aids in maintaining a consistent position of the jockeys COM relative to that of the horse improving jockey balance and reducing the detrimental effect of load carrying. This method of improving stability and reducing the detrimental effect of load carrying both agrees and conflicts with previous findings by Viry et al., (2013) and Wolframm et al., (2013) in trot and canter. When stability is defined as jockey movement being in phase and synchronised with the movement of the horse, reducing the relative displacement between horse and rider, our findings indicate our jockeys are stable in a medio-lateral (figure 7) and dorso-ventral (figure 2) direction but are less stable in a cranio-caudal direction (figure 4). This cranio-caudal instability is likely a trade-off between stability and energetic cost of the horse and therefore performance. By moving out of phase with the horse the jockey is believed to reduce work done by the horse to accelerate and decelerate the jockey throughout each stride (Pfau et al., 2009). This is done to the detriment of jockey stability. However due to the cyclical nature of the horse's movement the additional support available to the jockey through tension on the reins and contact by the hands on the horse's neck aid this isolation of the jockey movement by the legs. The more upright position of the jockey's trunk when riding a real horse compared to the simulator may aid in maintaining their position in the cranio-caudal direction. Or, perhaps the reduced cranio-caudal displacement of the real horse compared to the simulator allows the jockey to maintain a more upright position, allowing the biological shock absorbing properties of the back and legs to be utilised. Despite this more upright position, the pitch amplitude on the horse does not differ significantly from that on the simulator despite more variation which can be attributed to the more varied movement of the horse compared to the consistent and cyclical movement of the simulator. We can further support the theory of the legs acting as a 'damper' to isolate the jockeys COM because although movement of the COM was in phase for dorso-ventral and lateral displacement the magnitude was significantly smaller in the pelvis.

Foot displacement was slightly out of phase but was of similar magnitude to that of the horse and slightly more than the simulator, resulting in a trajectory which goes in the same direction. i.e. anticlockwise for the simulator and clockwise for the real horse. This confirms that the damping of the pelvic movement is undertaken by the jockey's legs. Interestingly the relative (foot minus horse) movement on the simulator is greater in the cranio-caudal direction than that on a real horse, suggesting the greater simulator movement and lower ability to grip, reduces the ability of the jockey to balance on the simulator but the consistency of the movement allows the legs to effectively dampen the movement thus maintaining a consistent COM position similar to that on the real horse.

Conclusion

Jockeys use their legs to isolate their COM and dampen the movement of the horse to minimise their movement and maintain their position as close to the midline and COM of the horse as possible. A racehorse simulator exhibits smaller and more consistent dorso-ventral and medio-lateral but larger, although still consistent, cranio-caudal displacements when compared to those recorded in real horses. Training on a simulator likely improves the stability of the jockey in a cranio-caudal direction but is unlikely to have equal benefit on their lateral stability and fitness which is of increasing importance in real horses due to the asymmetric movement and loading of the limbs dependent on the lead leg used. Further the simulator exhibiting an anticlockwise trajectory when the horse has a clockwise trajectory may limit the benefits of simulator training in developing the ability to cope with large stride to stride variations found in real horses. The smaller dorso-ventral displacement and associated stirrup forces on the simulator fail to provide the opportunity for the jockeys to develop the ability to modulate the perturbations found in real horses increasing the risk of excess pressure on the horses back leading to increased tension, poor performance or injury. While simulators may be beneficial in developing basic technique in a safe and controlled environment they are limited in their ability to develop the technical skills required.

Acknowledgements

All data were collected in collaboration and with thanks to the British Racing School, Newmarket and all project funding was provided by the Horserace Betting Levy Board project number 759.

Conflict of interest

There are no authors with any conflicts of interest relating to this manuscript.

References

1. De Cocq, P., Duncker, A.M., Clayton, H., Bonnert, M.F., Muller, M., Van Leeuwen, J.L. (2010) Vertical forces on the horses back in sitting and rising trot. *Journal of Biomechanics*.43:627-631.
2. De Cocq, P., Muller, M., Clayton, H., Van Leeuwen, J.L., 2013. Modelling biomechanical requirements of a rider for different horse-riding techniques at trot. *The Journal of Experimental Biology*. 216, 1850-1861.
3. Fruehwirth, B., Peham, C., Scheidl, M., Schobesberger, H., 2004. Evaluation of pressure distribution under an English saddle at walk, trot and canter. *Equine Veterinary Journal* 36,754–757.
4. Geser-von Peinen, K., Latif, S.N., Wiestner, T., Bitschnau, C. Renk, B., Weishaupt, M.A., 2013. Applied load on the horses back under racing conditions. *The Veterinary Journal* 198: 88-92.
5. Hitchens, P.L, Blizzard, C.L., Jones, G., Day, L.M., Fell, J., 2012. The association between jockey experience and race-day falls in flat racing in Australia. *Injury Prevention,* 18 (6) 385-391
6. Ille, N., Von Lewinski, M., Aurich, C., Erber, R., Wulf, M., Palme, R., Greenwood, B., Aurich, J., 2015. Riding simulator training induces lower sympathetic response in riders than training with horses. *Journal of Equine Veterinary Science*. 35: 668-672.
7. Parkin, T.D.H, Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M.,Morgan, K.L., 2004. Race and course level risk factors for fatal distal limb fracture in racing thoroughbreds. *Equine Veterinary Journal* 36:6:521-526.
8. Pfau, T., Spence, A., Starke, S., Ferrari, M., Wilson, A., 2009. Modern riding style improves horse racing times. *Science* 325(5938): 289.
9. Viry, S., Sleimen-Malkoun, R., Temprado, J. J., Frances, J. P., Berton, E., Laurent, M., Nicol, C., 2013. Patterns of Horse-Rider Coordination during Endurance Race: A Dynamical System Approach. *PLoS One* 8: e71804.
10. Walker, A., Martin, A., Pfau, T., Sparkes, E., Wilson, A., Witte, T., 2016. How realistic is a racehorse simulator. Submitted to Journal of Biomechanics.
11. Wolframm, I. A., Bosga, J., Meulenbroek, R. G., 2013. Coordination dynamics in horse-rider dyads. *Human Movement Science* 32 (1): 157-170

Figures and Tables

Figure 1: Mean stirrup forces (blue-left, red-right) during a single gallop cycle for a single jockey during left lead (solid line) and right lead (dashed line) during gallop on a real horse and on a racehorse simulator (dotted line). The solid black horizontal line at 266 N represents half the body weight of this jockey.

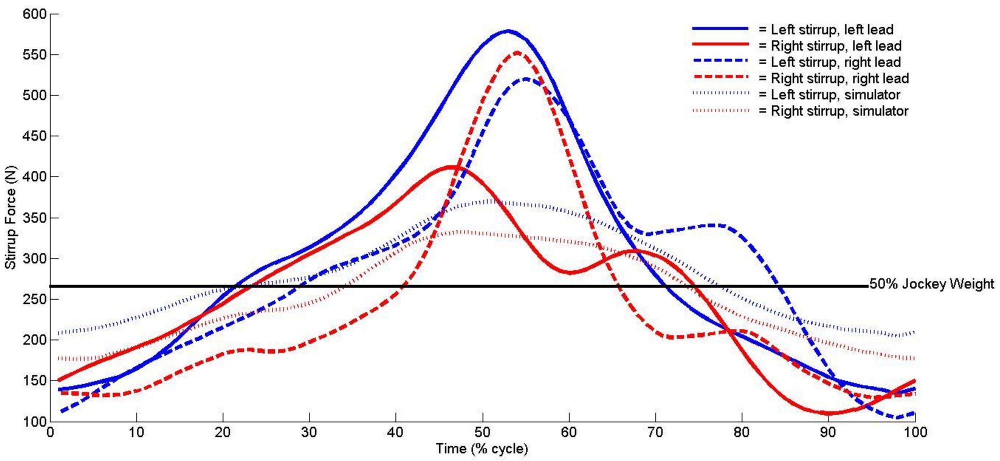


Figure 2: Mean dorso-ventral displacement of the horse (solid) and jockey pelvis (dotted) during a single gallop cycle for a single jockey on a real horse (red) and on a racehorse simulator (blue). Note the phase delay of the pelvis and smaller dorso-ventral pelvis displacement, which are more marked on the real horse.

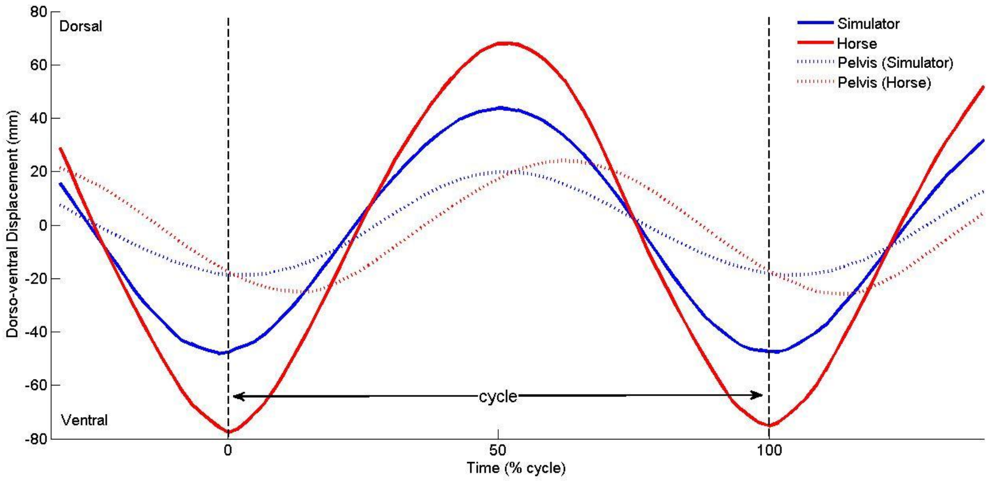


Figure 3: Mean (+/- SD) jockey trunk pitch during a single gallop cycle for a single jockey on a real horse (red) and on a racehorse simulator (blue). The difference in amplitude between real horse and simulator is not statistically significant but the difference in standard deviation is significant.

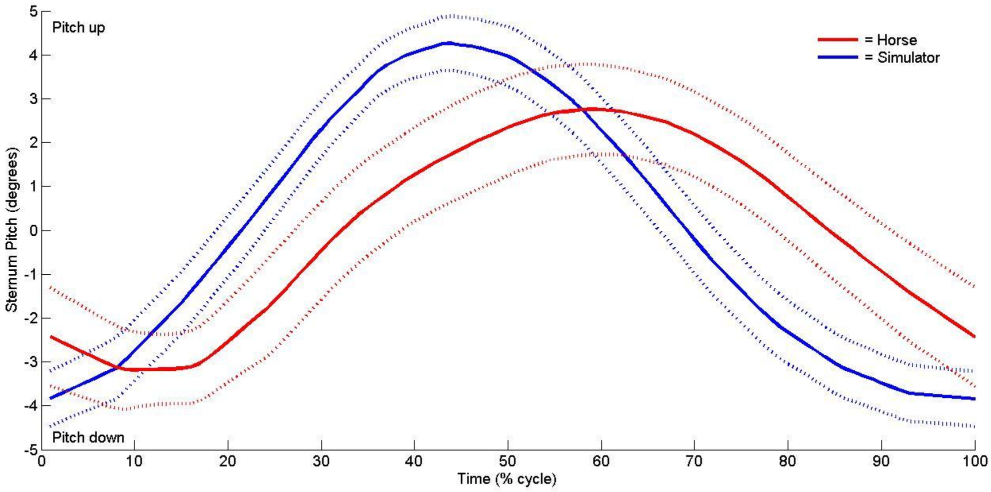


Figure 4: Mean cranio-caudal displacement of horse (solid) and jockey pelvis (dotted) during a single gallop cycle for a single jockey on a real horse (red) and on a racehorse simulator (blue). Note 180-degree phase shift of simulator compared to real horse and corresponding change in pattern of jockey pelvic displacement.

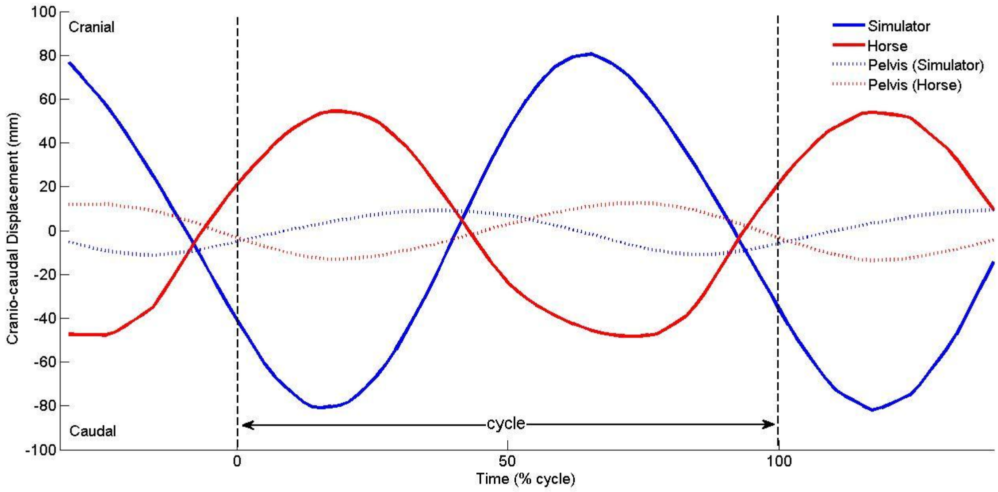


Figure 5: Mean cranio-caudal displacement of horse (solid), jockey left foot (dashed) and jockey right foot (dotted) during a single gallop cycle for a single jockey on a real horse (red) and on a racehorse simulator (blue). The relative magnitude of foot displacement varies between jockeys but the direction always follows that of the horse or simulator.

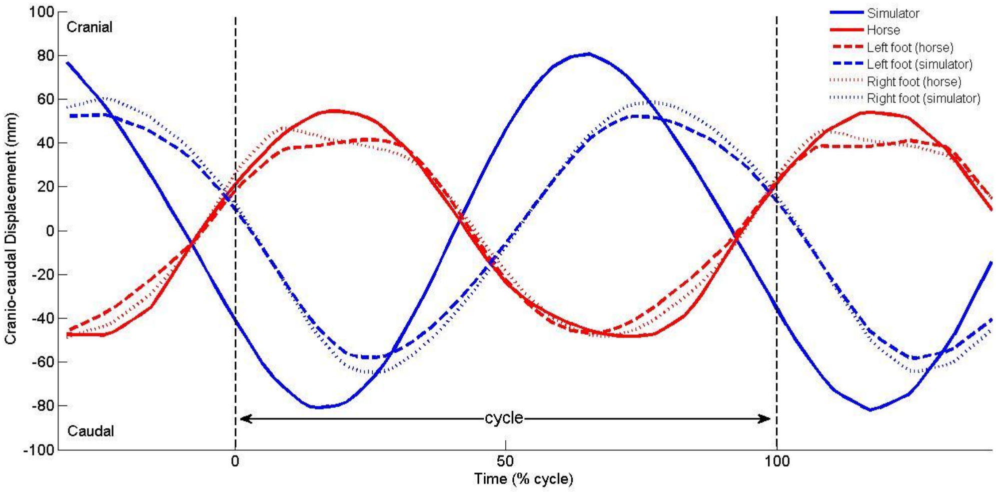


Figure 6: Mean cranio-caudal versus dorso-ventral displacement of horse (red), jockey left foot (dashed), jockey right foot (dotted), and jockey pelvis (black) during a single right lead gallop cycle for a single jockey on a real horse (red) and on a racehorse simulator (blue), i.e. as observed from a left lateral view. Note, simulator and associated jockey foot displacement trajectories are anti-clockwise and jockey pelvic displacement is clockwise. In contrast, real horse and associated jockey foot displacement trajectories are clockwise and jockey pelvic displacement is anticlockwise.

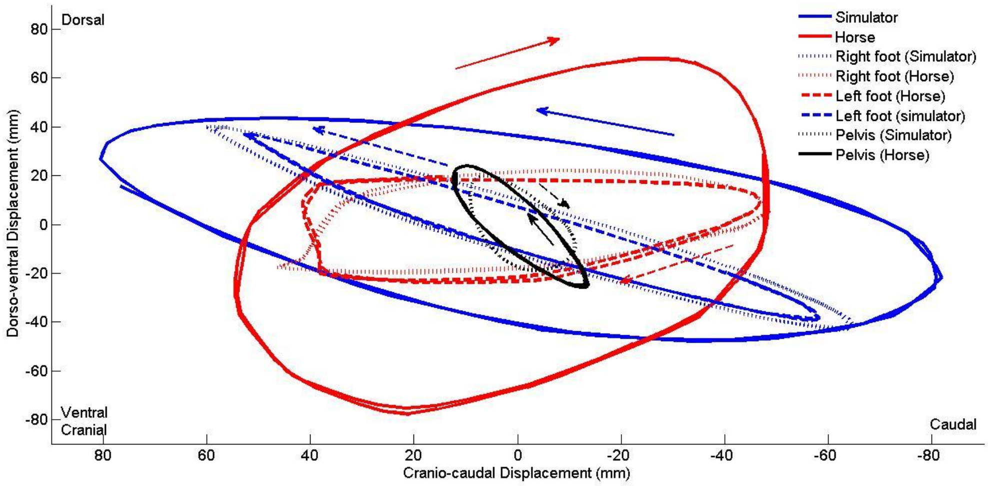
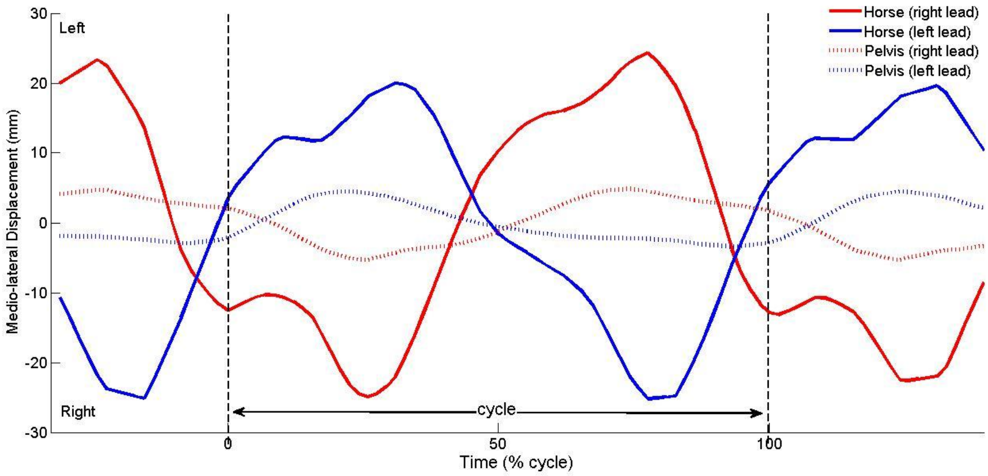


Figure 7: Mean medio-lateral displacement of the horse sacrum (solid line) and jockey pelvis (dotted line) during a single left lead (blue) and right lead (red) gallop cycle. Positive values are movement to the left therefore negative values represent movement to the right. The jockey's pelvis moves in the same direction as the horse.



Tables

Table 1 Jockey experience categories.

Experience Level	Description
Intermediate	Working full time for over 1 year, holds a licence but less than 20 rides – recently got licence e.g. done Apprentice licence course in last yr.
Experienced	Riding over 3 years, has held licence for more than one year, had over 20 rides and ridden up to 20 winners corresponding to Apprentice Continuation Course.
Elite	Has held a licence for over 3 years, ridden over 20 winners and riding races on a daily basis.

Table 2 Mean amplitude (+/- SD) horse kinematics and jockey kinematics and kinetics during gallop on a racehorse simulator or on a real horse. Horse refers to kinematic data from the horse. All other data refers to the jockey. RF and LF refer to jockey right and left foot respectively. Relative data are jockey values subtracted from the horse or simulator (sacrum) parameters.

Variable	Simulator	Horse	P-value
Horse Dorso-ventral (mm)	95 (6)	168 (15)	0.029
Horse Cranio-caudal (mm)	166 (12)	108 (19)	0.010
Horse Medio-lateral (mm)	15 (4)	61 (14)	0.001
Pelvis Dorso-ventral (mm)	46 (6)	86 (13)	0.015
Pelvis Cranio-caudal (mm)	35 (6)	61 (17)	0.139
Pelvis Medio-lateral (mm)	9 (4)	34 (11)	0.006
RF Dorso-ventral (mm)	50 (8)	77 (14)	0.066
RF Cranio-caudal (mm)	167 (14)	104 (17)	0.012
RF Medio-lateral (mm)	54 (5)	116 (17)	0.001
LF Dorso-ventral (mm)	55 (8)	70 (13)	0.220
LF Cranio-caudal (mm)	161 (13)	97 (23)	0.013
LF Medio-lateral (mm)	55 (6)	105 (14)	0.026
Left Stirrup Amplitude (N)	197 (45)	507 (74)	0.000
Right Stirrup Amplitude (N)	195 (23)	548 (117)	0.001
Non-directional force amplitude symmetry (N)	29 (13)	148 (56)	0.001
Trunk Pitch (degrees)	-22 (12)	-46 (16)	0.012
Trunk Pitch Amplitude (degrees)	9 (1)	10 (2)	0.712
Relative Pelvis Dorso-ventral (mm)	53 (6)	97 (21)	0.000
Relative Pelvis Cranio-caudal (mm)	129 (14)	61 (29)	0.001
Relative Pelvis Medio-lateral (mm)	8 (5)	42 (22)	0.002
Relative RF Dorso-ventral (mm)	42 (8)	107 (22)	0.005
Relative RF Cranio-caudal (mm)	30 (12)	18 (35)	0.334
Relative RF Medio-lateral (mm)	45 (7)	48 (28)	0.878
Relative LF Dorso-ventral (mm)	38 (8)	107 (21)	0.008
Relative LF Cranio-caudal (mm)	33 (13)	14 (30)	0.182
Relative LF Medio-lateral (mm)	43 (7)	47 (24)	0.829