The biomechanical interaction between horse and rider

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Summary

The forces exerted by a rider on a horse have a direct influence on the mechanical load experienced by the horse and consequently on its motion pattern. The aim of this thesis is to explore the biomechanical interaction between rider, saddle and horse in order to get insight in the loading of the horse and to identify potential opportunities to reduce load-related injuries.

The influence of man on the horse is mediated trough tack, which functions as an interface between the horse and the human being(s) using it. The tack is often connected to both horse and rider and is therefore well-positioned to incorporate measuring devices that can record the forces between horse and rider.

So-called saddle-pressure measuring devices have been used to evaluate saddle-fit and could also be a useful tool to study the interaction between horse and rider. However, not much was known thus far about the validity, reliability and usability of these devices for this purpose. Therefore, the first studies in this thesis focussed on this topic. The FSA system was only reliable in highly standardised circumstances. The Pliance system provided reliable and repeatable results and can be used indeed to study the interaction between horse and rider. In this thesis it was used to evaluate the effect of rider position on the force distribution beneath the saddle and to study the signals given by the rider to the horse performing lateral movements in dressage.

One of the important physical properties of the rider that influences the horse is the rider's weight. The effect of tack and weight on the movements of the horse was therefore studied. The introduction of a mass with considerable weight on the horse's back induced an overall extension that might contribute to back injuries.

During trot, the rider can either rise from the saddle during every stride (rising trot), or remain seated (sitting trot). The back movement during rising trot showed characteristics of both sitting trot and the unloaded condition, with a higher degree of extension during the sitting phase and less extension in the standing phase. In the standing phase peak force on the stirrups is higher, but the overall vertical peak force on the back of the horse is less. This supports the general assumption that rising trot is less demanding for the horse than sitting trot.

Three spring-(damper-)mass models were constructed to evaluate the biomechanical requirements the rider has to comply with during sitting trot, when using the modern riding technique adopted by jockeys during racing, and in rising trot. The models demonstrate which combinations of rider mass, spring stiffness and damping coefficient will result in these riding modes. Optimization to minimize the peak force of the rider and to minimize the work of the horse resulted in an "extreme" modern jockey

technique, which is not adopted by actual riders. The incorporation of an active spring system for the leg of the rider, was needed to simulate the rising trot.

The general discussion argues that the simultaneous use of a variety of approaches is required to further our understanding of the interaction between horse and rider. A combination of experimental research, which makes use of cutting-edge techniques to measure kinematics of horse and rider, forces acting between horse and rider and between horse and environment, and muscle activation patterns of both horse and rider, with mathematical modelling is the way forward. This combined approach could answer questions concerning the external and internal biomechanical loading of horse and rider of several horse riding and training techniques. Techniques that minimize risk of injury of both horse and rider could possibly be identified, reducing welfare problems of the equine athlete.

Contents

1. General Introduction

1.1 Biomechanical horse-rider interaction: clinical relevance, research approaches and aims of this thesis.

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Horse-rider interaction; possibilities to prevent injuries

Training in equine sports is largely empirically based, *i.e.* on experience and intuition. To optimize the training of equine athletes, there is a need for objective measurements of biomechanical, sport physiological and behavioural parameters. These parameters can be used by trainers to improve their training strategy. Performance of equine athletes is largely determined by the musculoskeletal apparatus of the horse. Thus far, studies on training have mainly focused on exercise physiology (Evans, 2007) or kinematics (Back et al., 1995; Clayton, 1993; Rogers et al., 2005). The incorporation of forces between rider and horse would provide essential information when comparing riding techniques, rider levels and training programs. This could lead to better training and increase the understanding of the horse-rider interaction.

Another important reason to develop objective measurement techniques for these parameters that are related to the use of the horse, is the high incidence of musculoskeletal disorders, which rank first among the causes of wastage in performance horses. These musculoskeletal injuries are almost invariably caused by single or repetitive biomechanical overload. Thirteen to 20% percent of all clinical problems in horses are related to lameness (Cole et al., 2005; Landman et al., 2004). About 12% of the Dutch horses have back problems (Landman et al., 2004). These injuries have a negative effect on the health and welfare status of the horses and also represent a significant economic cost. Important causes of mechanical overload are the rider and the exercise intensity. Riders have a crucial influence on the biomechanical load experienced by horses. Especially long-term overloading can originate from inappropriate riding techniques, saddle fitting, trimming, shoeing and ground characteristics. Unfortunately, studies on the interaction between rider and horse are limited. The reason for the scarcity of information probably arises from the complexity of the interaction between rider and horse.

Back pain and dysfunction in horses

Already in 1975, Jeffcott noticed an increased awareness of back problems. He pointed out that a number of factors may be responsible for the back problems, for example poor schooling and equitation. In a case series, examining 443 horses suspected of a back injury, Jeffcott (1980) found that 17% of the horses had more than one condition that could produce back problems. In 20% of the horses there was no evidence of a back problem. About two-third of these horses had a variety of hind limb lameness and in one-third of these horses no specific diagnosis could be made. Soft tissue injuries were diagnosed in 39% of the horses. In 3% of the horses a malformation of the spine was found and in 39% of the horses a vertebral lesion was found, mostly associated with crowding and overriding of the dorsal spinous processes (figure 1).

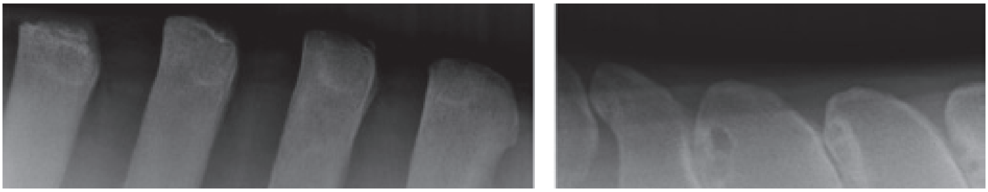

Figure 1
Left, x-ray of normal spinous processes of a horse, the vertebrae are evenly spaced. Right, x-ray of a horse with crowding and overriding of the dorsal spinous processes (Burlington Equine Veterinary Services, 2011; permission of use was granted).

Jeffcott (1999) points out that making a definitive diagnosis of many back problems is notoriously difficult. Research of Cousty et al. (2010), Erichsen et al. (2004), Gillen et al. (2009) and Meehan et al. (2009) points out that imaging techniques, such as radiography and scintigraphy, offer limited aid in the diagnosis of back problems, since ‘normal’ or ‘healthy’ horses often show a wide variety of abnormalities when using these imaging techniques. A thorough systematic examination is required and despite attention to detail and the use of sophisticated clinical aids, the diagnosis is often made by elimination of all other conditions. This has resulted in a plethora of therapies, from which it is evident that no superb, complete or ultimately satisfactory treatment exists. Jeffcott (1999) thinks that many cases of back pain recover in spite of various types of therapy and not because of them. He points out that basic knowledge on the functional anatomy of the equine spine and scientific studies on the causes of back problems are needed.

This PhD project focuses on the effect of the rider on the movements and the biomechanical loading of the equine back and provides basic knowledge on the influence a rider might have on these back problems.

Kinematics of the equine spine

As one of the most consistent features of a horse with chronic back pain is loss of performance, rather than overt back pain, quantification of the horse's gait and performance might be useful (Jeffcott et al., 1982). In an experimental study, back pain was induced by injecting lactic acid into the back muscles, causing a transient myositis. The changes in gait were quantified by using a computerised analytical system based on high speed cinematography (Jeffcott et al., 1982). This study detected no obvious gait disturbances. The main effects were stiffness of the spine and inability to perform at fast paces. From this work, it became clear that the ability to quantify back kinematics of the horse would be most useful, but knowledge of normal 3-dimensional motion characteristics of the equine spine would be required, which was still lacking in those days. Haussler et al. (2001) performed the first *in vivo* study on segmental vertebral kinematics. Relative movements of two adjacent vertebrae were recorded in 3 clinically sound horses. Liquid metal strain gauges were attached to Steinmann pins that had been implanted into the dorsal spinous processes of 3 vertebral regions: thoracic (T14 to T16), lumbar (L1 to L3) and lumbosacral (L6 to S2). The largest motion was detected in the lumbosacral junction.

In 1999, a further step was made when Faber et al. presented a convenient method to calculate the angles of rotation of a body segment during locomotion without defining the location of the centre of rotation, and without defining a local vertebral coordinate system. This method was used to determine the basic kinematic movements of the vertebral column at walk (Faber et al., 2000), trot (Faber et al., 2001a), and canter (Faber et al., 2001b). The use of this method has some restrictions: the average orientation of the anatomical axes of rotation of each spinal segment during a stride cycle must coincide with the three axes of the laboratory coordinate system, the rotations should be symmetrical with respect to both sides of the plane of symmetry of the spinal segment, and the subject must move parallel to one axis of the laboratory coordinate system. Faber et al. (1999) found maximal errors of 0.7° for a misalignment between the two coordinate systems of 10°. Based on this invasive method using bone-fixated markers, a non-invasive method using skin-fixated markers was developed and tested for validity (Faber et al., 2001c) and repeatability (Faber et al., 2002).

This new non-invasive method was used to study the effect of conformational aspects on back movements (Johnston et al., 2002), prompted by the fact that the relationship between structure and function is considered an important aspect in the judgement of horses. They found that taller and heavier horses have longer thoracic and lumbar back segments. During walking, horses with longer strides extended and flexed their backs more. The authors concluded that the relationship between back conformation and movement may be important to the orthopaedic health of the horse.

Signs of back problems and lameness are often found in the same horse. It has been assumed that back problems might cause lameness and vice versa. Gomez Alvarez et al. (2007, 2008a) studied the effect of a mild induced forelimb and hind limb lameness on back kinematics and ground reaction forces. They confirmed that lameness does indeed result in an altered movement of the back, especially at trot.

Kinematic studies have also been used to evaluate the effect of several therapies for back problems. Faber et al. (2003) applied their newly developed technique for the objective quantification of thoracolumbar motion to one dressage horse with a right-convex scoliosis from the 10th thoracic vertebra to the second lumbar vertebra. Measurements were performed before and after orthomanipulative treatments. They observed an improvement in the symmetry of movement. It was, however, recognized that the improvement in motion pattern was not necessarily equivalent to clinical improvement and that other measures than the treatment might be more decisive in terms of clinical efficacy. Gomez Alvarez (2008b) evaluated the effect of chiropractic manipulations in 10 horses. They found slight, but significant changes in thoracolumbar and pelvic kinematics after treatment. The main overall effect of the treatment was a less extended thoracic back and an improvement in symmetry of motion. Unfortunately, this was no long-term study and it would be interesting to see whether the effect is temporary or lasting and whether it is influenced by the rider.

Studies using back kinematics to evaluate the effect of the rider have focused on the head and neck position of the horse. Especially the more extreme head and neck positions, such as hyperflexion, are being criticized in equestrian sports. Rhodin et al. (2005) and Gomez Alvarez (2006) evaluated the effect of head and neck positions in horses without a rider. The head and neck positions were achieved by the use of side reins. It was observed that head and neck positions indeed influence back motion. The overall effect is an increase in extension in the situations where head and neck are carried high and an increase in thoracolumbar flexion in the lower head and neck positions. The effects were similar when the horses were ridden by their own rider (Rhodin et al., 2009). These observations did not provide any evidence that could support the critique on hyperflexion.

The rider might also influence the kinematics of the equine back by his or her body weight or by the riding technique that is used. In this PhD project, the effect of the rider’s weight and the effect of the riding techniques sitting and rising trot, on the movements of the horse’s back were studied.

The effect of tack on the horse

Several interfaces between horse and rider exist. Ridden horses are normally equipped with a bridle and a saddle, which serve as the main transmitters of signals from the rider. Other tools such as spurs and whips are also used to communicate with the horse. The tack often is connected to both horse and rider and therefore is suitable to incorporate measuring devices. The most commonly used tools in this respect are strain gauges. The electric resistance of strain gauges changes with the force exerted on them. Strain gauges can therefore be used to assess forces on bits, reins, and stirrups. Furthermore, flat pressure or normal force sensors can be incorporated in pads which can be placed underneath the saddle, underneath blankets or even simply between the horse and the rider's legs. Horse-rider combinations with instrumented tack are shown in figures 2 and 3. The instrumented tack can not only be used to study the effect of the tack itself, but also to study the interaction between rider and horse (figure 4). The following paragraphs focus on the effects of the saddle and saddle pads and on the influence of rein and bridle on the horse.

The effect of the saddle and saddle pads

Harman (1994) was the first researcher who used a computerized pressure measuring device (SaddleTech)[1] to evaluate the effect of a saddle and saddle pads on the horse. This first saddle pressure system was equipped with 256 sensors that used pressure-sensitive ink printed on a polyester film, which changed resistance when subjected to pressure. Harman studied several saddle pads: cotton-quilted pads, open-cell foam pads, gel pads and a balancing shim. The most common saddle fitting problem she identified was so-called bridging. In bridging, the front and the rear panels are contacting the horse, but there is no or reduced pressure in the central area in between. Only 35% of the tested saddle pads did improve the saddle fit, or at least did not change it in a negative way. The remainder in fact increased pressure, which was compared by Harman with the effect of a sock in a too tight shoe.

The study of Harman encouraged other researchers to take up the topic. Pullin et al. (1996) used a newer technique, Force Sensing Array (FSA)[2], for the evaluation of an equine athletic saddle pad and saddle liners. The FSA system consists of a matrix of piezo-resistive sensors that measure the force perpendicular to the surface. Although the system is referred to as a pressure-measuring system, the system in fact measures normal force and the distribution of this normal force (normal stress). Pullin et al. (1996) identified several potential sources of error within the system that could affect the objectivity of data collection and interpretation. They stressed the importance of numerical scoring based on specific measurements rather than relying on subjective impressions, the importance of the calibration procedure, the position of the sensor pad, and the position of both rider and horse. They further stated that measuring without a rider is not useful, as the weight of the rider is required to evaluate the weight distribution underneath the saddle.

Jeffcott et al. (1999) studied the validity of the FSA technology. In principle, according to Newtonian laws, the vertical force on the horse's back should be the sum of the weight of the saddle, the force exerted by a tightened girth and the weight of the rider. There should therefore be (approximately) a linear relationship between total weight and the normal stress measured underneath the saddle. They tested this hypothesis on both a wooden and a live horse in standing position. The correlation between weight and measured normal stress appeared to be high indeed. They also presented preliminary data on characteristic changes of the centre of pressure at walk, sitting trot, rising trot and canter.

The newest saddle force measurement technique uses capacitometric sensors (Pliance)[3]. This system also measures the forces perpendicular to the surface. As both the FSA and Pliance system only measure these normal forces, there are some limitations. Shear forces play a role too and for correct measurements these forces should be taken into account.

Figure 2
A horse-rider combination with force sensors incorporated in a blanket underneath the saddle and between the legs of the rider and the horse. To both rider and horse infrared light reflecting markers have been attached to measure kinematics.

Figure 3
A horse-rider combination with strain gauges incorporated between bit and reins and a saddle force device underneath the saddle. (Photo: Horse magazine Bit/ Lonneke Ruesink; permission of use was granted)

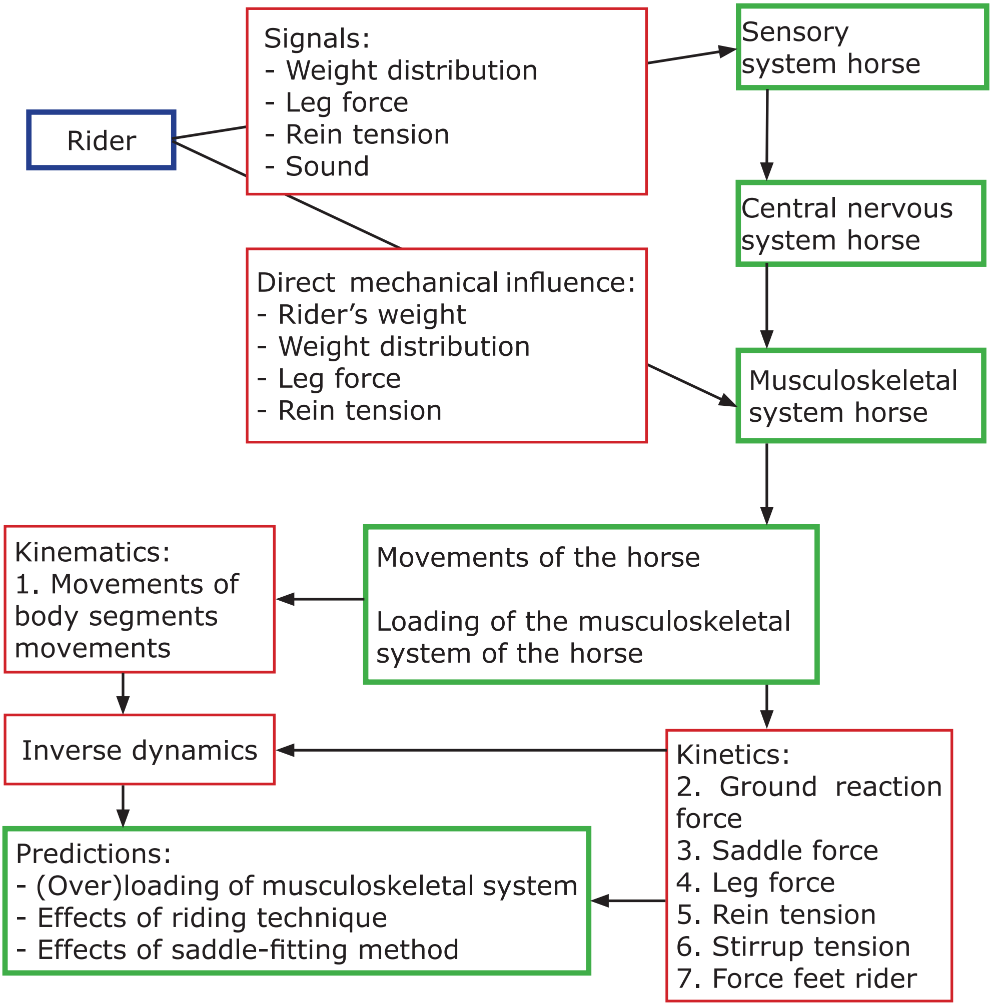

Figure 4
Diagram of the influence of the rider on the biomechanics of the horse and biomechanical approaches to study these influences.

Unfortunately, it is not possible to measure these non-perpendicular forces when the system is placed underneath the saddle. For the measurement of forces on the horse's back, the system is therefore limited to the summation of the magnitudes of the normal forces, hence carrying an inherent error. Since the back of the horse is curved, vertical forces exerted by the rider will be underestimated.

The Pliance system has been used in several studies on the effect of saddles and saddle pads. Werner et al. (2002) compared standard and custom-made saddles. They combined the saddle measurements with a clinical examination of the horses, which included back palpation. A correlation was found between high normal stress values (>3.5 N/cm^2) and both pain reactions and the occurrence of muscle atrophy. The following criteria for good saddle fit were identified: a wide, uniform contact area between saddle and horse, maximal normal stress values not exceeding 3.0 N/cm^2, and no stress peaks or bridging. In a study relating the magnitudes of the normal stress to clinical manifestations of saddle sores, significant differences were found between horses with "dry spots" (locally reduced sweat production), saddle laesions and a control group (von Peinen et al., 2010). Dry spots can be used as an early indicator of ill-fitting saddles. The values found in the three groups of horses provide important information on the magnitudes of normal stress that can still be considered acceptable in horse riding.

Several aspects of the construction of the saddle and saddle fit have been studied. Meschan et al. (2007) investigated the effect of the width of the tree on the forces and force distribution underneath the saddle. They demonstrated that the load under poorly fitting saddles is distributed over a smaller area than under properly fitting saddles, which can lead to potentially harmful pressure peaks. Mönkemöller et al. (2005) demonstrated that an adjustment of saddle fit can enlarge the contact surface underneath the saddle and hence, by reducing normal stress in the region of the caudal thoracic spine, reduce the number of horses with back pain. Nyikos et al. (2005) subdivided the contact area of the saddle into six regions. They found that the lumbar area was more sensitive to normal stress than the area of the withers. They concurred with Harman (1994) that 'bridging' was the worst problem related to saddle fit. Latif et al. (2010) compared a training saddle with a normal tree with a saddle with a flexible tree and a treeless saddle. In racehorses treeless saddles are often used because trainers and jockeys think that these saddles will interfere less with the back movements of the horse, thus enabling the horse to go faster. However, tree type did not influence the force distribution in the caudal third of the saddle at canter. In all saddles, high peak values were observed in this area at trot, which might influence the movements of the horse's back. Therefore, no advantage of a treeless saddle was found in this study. The placement of the girth strap and the panel flocking material might also influence saddle fit. Byström et al. (2010) developed a saddle in which both the girth strap placement and the panels could be altered. Both aspects of the construction of a saddle did indeed influence saddle forces. Wool seemed to be a better flocking material than foam and the traditional placement of the girth seemed to be equally good, if not better, than a v-system.

Where Harman (1994) had stated that saddle pads under fitting saddles can often be compared to the use of a sock in a too tight shoe, the use of a pad under a too wide saddle might theoretically be beneficial.

Kotschwar et al. (2009) investigated this situation and found that, although significant intra-horse effects were demonstrated, there was no significant general effect. The choice of a saddle pad to improve the fit of an excessively wide saddle, if such a saddle is to be used anyway, should therefore be based on highly individual criteria for each horse.

The effect of reins and the bridle

The research on the effect of the bridle has thus far been focused on the bit. The bit is in direct contact with the horse via the mouth and signals given by the hands of the rider are transmitted through the reins and the bit directly to the horse’s mouth.

As a large part of the bit is hidden from view, fluoroscopic techniques have been used to evaluate the position and action of several bits (Clayton and Lee, 1984; Clayton, 1985; figure 5). The first bit that was studied was a joined snaffle bit. In the resting position the mouthpiece was interposed between the tongue and hard palate, indenting the dorsum of the tongue. When applying an equal force to both reins simultaneously, the bit was moved caudally, deepening the indentation in the horse’s tongue. When applying asymmetrical force, the net effect depended on the relative forces applied to the active and opposing rein. It was not possible to produce an independent effect on one side of the mouth. The jointed mouthpiece was suspended in a more horizontal position when keepers were used to fix the position of the bit rings relative to the cheek pieces of the bit. The keepers also reduced the mobility of the bit within the oral cavity. Less intra-oral mobility was also observed in bits with a single mouthpiece. A bit that had two joints connected to an angled plate could be positioned in ways that the plate lay either parallel or perpendicular to the tongue and palate, which would make a marked difference with respect to the severity of the action of the bit.

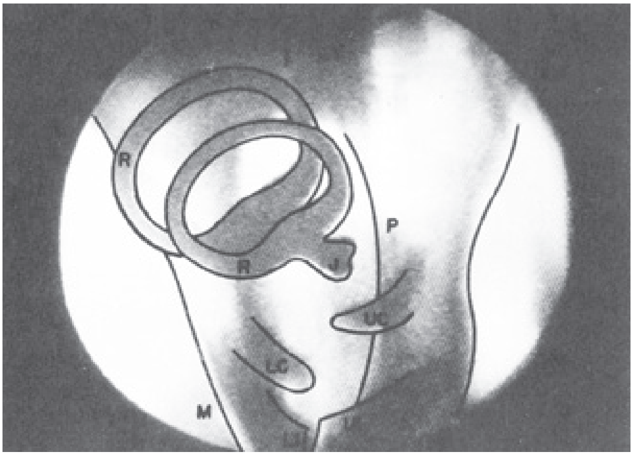

Figure 5
Fluoroscopic photograph of a correctly fitted and adjusted snaffle bit with relevant anatomical landmarks indicated (Clayton and Lee, 1984; permission of use was granted).
M. edge of mandible;
P. edge of hard palate;
UI. upper corner incisor;
LI. lower corner incisor;
UC. upper canine;
LC. lower canine;
J. joint of bit;
R. ring of bit.

The fluoroscopic studies demonstrated that the force exerted on the bit greatly influences the position and movement of the bit in the mouth of a horse. A next logical step therefore was to objectify the force that riders apply to the reins and which is transmitted to the bit (figure 6). In several studies force sensors have been attached in-between bit and reins to measure rein forces (Preuschoft et al., 1999; Clayton et al., 2005; Warren-Smith et al., 2005). Preuschoft et al. (1999) analysed the biomechanical effects of a number of head-gears. Most head-gears are designed to transmit tensile forces applied through reins or a lunge to the sensitive parts of the horse's mouth. The direction, duration and magnitude of these forces are essential factors in controlling the horse. Several head-gears and two major types of bits (with or without levers) were analysed using a device that could roughly quantify these forces. Rein forces were found to show regular patterns and to be dependent on the horse's gait. During competition, forces between 20-147 N were measured, in recreational use the range was 20-49 N. Clayton et al. (2005) used a more precise load cell and found similar rein force patterns consisting of a series of spikes with frequencies corresponding to two per stride in walk and trot and one in canter. They established a maximum force of 104 N in canter.

Warren-Smith et al. (2005) focused on developing a low-cost and practical sensor and recording system that could be used in everyday training. They tested two sensors on horses that were being led, lunged and ridden and measured forces in the range of 0-30 N for light rein contact. As other studies had reported considerably higher forces, they claimed that horses might be subject to unnecessarily high forces and that the education of horses and riders might be improved. In a follow-up study the same authors (Warren-Smith et al., 2007) focused on specific equitation exercises: left turn, right turn, going straight and coming to a halt, in both long-reining and riding. The rein force required for going straight was less than for any other activity. The force required to elicit the halt response was greater than for any other condition. The mean force exerted during long-reining was 10.7 ± 1.0 N and for riding this was 7.4 ± 0.7 N. These, again, were lower values than measured by others. Heleski et al. (2009) used a combination of behavioural observations and rein force measurements to study the effect of martingales and rein inserts. In practice, there is controversy about the use of these tools. Some claim that they can reduce discomfort caused by inexperienced and unsteady hands. Others consider them inappropriate 'crutches'. No differences in conflict behaviour were observed in horses with or without martingales or rein inserts. Mean rein forces were higher for martingales than for controls or rein inserts. The head of the horse was lower for horses ridden with martingales. It can be concluded that carefully fitted martingales might have a place in riding schools that teach novice riders.

Figure 6
Strain gauges that can be inserted between the rings of the bit and the reins.

From the forces that can be measured in-between horse and rider, this PhD project focuses on the interface between the saddle and the horse, as forces on the equine back are expected to be related to back problems. The first step was to find appropriate methods to measure these forces. Furthermore, the effect of saddle fit, rider position, specific equitation movements and riding technique on these forces was evaluated.

The effect of the rider on the horse

Riders have a direct and indirect biomechanical effect on the horse through their sheer mass and through the aids aiming at the horse's sensory system with which they actively try to influence locomotion (Meyer, 1999; Preuschoft et al., 1995), apart from visual and acoustic signals (figure 4). The main mechanical effect of riders on the horse is the gravitational force elicited by their mass. The distribution of this weight on the horse is also an important factor. Leg force is limited by the long lever arms of the reaction force. Therefore, spurs are used to create a relatively large local pressure. Studies on rein force have already been described in the previous paragraph. The effect of the rider on the horse is further influenced by the riding technique of the rider and, associated with this, the level of riding. This paragraph focuses on the direct effect of the rider's mass, the influence of riding technique and riding level.

The effect of the body mass of the rider

During horseback riding the horse has to carry the weight of the rider. This weight has a direct biomechanical effect on the musculoskeletal system of the horse, apart from the extra energy required due to the increase in total mass. According to Slijper's bow-and-string model (Slijper, 1946) a weight exerted on the horse's back will lead to an extension of the thoracolumbar vertebral column. The effect of the body mass of the rider can be simulated by the use of dead weight. Schamhardt et al. (1991) compared the effect of a rider and a sandbag of the same mass on ground reaction forces. Compared to the sand bags, the riders were able to shift part of the weight towards the hind limbs. Clayton et al. (1999) compared ground reaction forces between ridden and unridden horses. Although the absolute peak vertical ground reaction forces were higher with a rider, the mass-normalized peak vertical ground reaction forces were lower with a rider. There also was a change in timing of the peak ground reaction forces. A ridden horse seems therefore not equivalent to a proportionally larger horse with the same total mass. Sloet van Oldruitenborgh-Oosterbaan et al. (1995; 1997) compared the effect of a rider and a weighted saddle on limb kinematics. They did not find differences between these situations.

In certain equestrian disciplines, there are minimum requirements for the weight that the horse has to carry. When the rider is too light, weight is added to ensure a fair competition. The question is how this added weight (or an increase in body weight of the rider) affects the horse. During jumping, several kinematical differences can be observed in horses carrying a rider only compared to a rider with added weight. Two of these differences concern increases of the maximal extension of the fetlock and carpal joints (Clayton et al., 1997). When comparing trotting horses with or without rider, only small changes in fetlock kinematics are observed (Clayton et al., 1999). When the weight is added asymmetrically to a rider on a standing horse, this will lead to an asymmetrical force distribution underneath the saddle. This asymmetrical force distribution is likely to influence the musculoskeletal system of the horse. Rider asymmetry has anecdotally been associated with poor performance and injuries. This may be an important and as yet poorly studied item. Symes and Ellis (2009) demonstrated that asymmetries in the movements of the shoulders of riders are common indeed. The method for describing asymmetries presented in their paper could possibly also be used to evaluate the effect of an asymmetrical position of the rider on the loading and performance of the horse.

According to Newton's second law, the average vertical force on the horse's back must be equal to the weight of the rider, but during locomotion fluctuations around this average value can be expected because the rider accelerates and decelerates. This force on the horse's back can be estimated with the saddle force devices described earlier. Frühwirth et al. (2004) evaluated the force patterns at walk, trot and canter and indeed showed a fluctuating pattern. Von Peinen et al. (2009) related the saddle force pattern of a walking horse to the movements of both rider and horse.

The effect of rider experience

One factor that is likely to influence the performance of the horse is the experience of a rider. An experienced rider is able to maintain an upright body position, whereas a beginning rider is usually leaning more forward

(Schils et al., 1993). This change in body position may affect the force distribution underneath the saddle.

Terada (2000) found instability of the upper body of a novice rider in sitting trot that, as suggested by EMG data, provoked unbalance between the erector spinae and the rectus abdominis muscles. This effect was not observed in advanced riders. The stability of the rider might also affect the stability of equine gait. Peham et al. (2004) developed a method to evaluate horse motion pattern variability and demonstrated that the movement of the horse is more constant when ridden. On this same topic, Lagarde et al. (2005) found an increase in regularity of the oscillations of the trunk of the horse when comparing an experienced to a novice rider. The experienced rider was able to move in phase with the horse whereas the novice rider was not.

Even if it is clear that rider experience influences the movement of the horse, this does not mean that in all cases only an experienced rider will elicit good performance of the horse. Powers and Kavanagh (2005) studied the effect of novice and experienced riders on jumping kinematics of experienced jumping horses. Their results suggest that the rider's body position and body movement have no effect on the horse's jumping kinematics. However, it can be questioned whether the combinations were challenged enough by the 1.05 m fence that was used. In earlier work Powers and Harrison (2002) demonstrated that a rider can influence the jumping kinematics of a young horse when jumping a 1 m fence. It therefore seems that the individual jumping technique of a horse is less susceptible to rider influence in experienced horses. Lewczuk et al. (2006) studied the repeatability of horses' jumping parameters with or without a rider. The jumping parameters were more repeatable with a rider while jumping a 1.20 m fence. There were no differences when jumping lower fences. Both rider experience, horse experience and fence height therefore seem to influence jumping performance of a horse-rider combination.

The effect of riding technique

Taylor et al. (1980) hypothesized that it is the energetic cost of generating force to support body mass that determines the energetic cost of running, more than the mechanical work that has to be done. Several studies indicate that an elastic coupling between carrier and load reduces peak forces, thus reducing energetic cost (Foissac et al., 2009).

In trot, riders can choose between three different riding techniques: sitting trot, rising trot and two-point seat. Roepstorff et al. (2009) compared vertical ground reaction forces and kinematics of horses during the sitting and standing phases of rising trot. They found an increased ground reaction force and several changes in the kinematics of the horse during the sitting phase compared to the standing phase and concluded that the rider's movement in rising trot induces an uneven biphasic load that affects the back, pelvis and limbs of the horse. This biphasic load was confirmed by studies evaluating the loading of the horse's back with saddle force equipment (Peham et al., 2008; 2009). All these studies support the idea that rising trot is less challenging to the horse's back, making the technique useful for the training of young horses that have to be accustomed to the rider's weight and for the rehabilitation of horses with back problems.

The fact that the standing phase of rising trot is the least loading phase raises the question whether standing in the stirrups during the total stride cycle would even be less challenging to the back of the horse. Peham et al. (2009) also investigated this two-point seat and found that force peaks were indeed lowest in this riding technique. The two-point seat is a precursor of the rider position that is used during horse racing. The current riding technique of jockeys was developed in the late 19th century. During the same time, racing performance improved tremendously. It seems as if the jockey uncouples himself from the horse by moving relative to his mount. The jockey's body moves little in the vertical direction with respect to the world inertial frame, and therefore the horse supports the jockey's weight but accelerates and decelerates him relatively little compared to other horse riding techniques. This again leads to lower peak forces on the horse's back and might be the reason that the horses are able to gallop faster (Pfau et al., 2009).

Mechanisms to carry a load effectively

An important aspect of the horse-rider relationship is that the horse is carrying the weight of the rider. This load carriage has an energetic cost. When weight is added to an animal's trunk, the energy expenditure of carrying this load increases in direct proportion with that weight. For example, if a horse carries a load equal to 20% of body weight, the rate of energy consumption increases by 20% (Taylor et al.,1980). However, Pearson et al. (1998) found that, as the weight of the load increased, the unit energy cost of carrying it decreased. They suggested that it is more efficient in terms of energy expenditure to carry loads equivalent to 27 to 40 kg/100 kg of bodyweight than to carry lighter loads of less than 20 kg/100 kg bodyweight.

In studies of load carrying by humans, strategies to reduce this energy expenditure have been identified. African women seem to carry loads more efficiently by using their body as a pendulum during locomotion (Heglund et al., 1995). Nepalese porters are able to carry loads that are more than their own body weight up the mountains. The mechanism that enables them to do so is still unknown (Bastien et al., 2005). Abe et al. (2004; 2008) found an effect of both walking speed and load position on the energetics of load carriage. An energy-saving phenomenon was observed when the load was carried on the back at slower speeds.

Another mechanism to carry a load is by using springy poles. People throughout Asia use springy bamboo poles to carry loads in everyday life. The energy consumption rate using this technique was comparable with the consumption rate using backpacks. The pole suspension system does offer another advantage. It minimizes the peak shoulder forces and the peak vertical reaction force. This could be beneficial in the prevention of injuries (Kram, 1991).

The load itself can also influence energetic costs; the mechanical properties of a backpack (stiffness and damping coefficient) have been shown to affect the energetics of walking in a human carrying that backpack (Foissac et al., 2009). At an optimal stiffness of the connection between human and backpack the peak forces on the person decrease, which leads to lower oxygen consumption. It is even possible to use this elastic connection to generate electricity while walking. The application of this principle extends the possibilities of field scientists, explorers and disaster-relief workers to work in remote areas (Rome et al., 2005).

Similar strategies to reduce energy consumption or peak forces and thereby injuries might also be present in the interaction between horse and rider. In this PhD project we will use mathematical modelling to identify these strategies.

Thesis aim and outline

The forces exerted by a rider on a horse have a direct mechanical influence on the mechanical load on the horse and on its movement patterns (figure 4). The rider influences also the sensory system of the horse, by exerting forces, for example via reins and saddle (Meyer, 1999; Preuschoft et al., 1995), and by visual and acoustic signals. The main mechanical effect of a rider on the horse is the gravitational force of his or her mass. The distribution of the weight on the back of the horse is also an important factor. The saddle has been designed to distribute the weight of the rider over a large surface, while preventing peak stresses in sensitive areas. Permanent incorrect posture, a state of tension and lack of coordination between rider and/or horse may result in acute discomfort and permanent damage (Meyer, 1999). Injuries in horses may be prevented by avoiding biomechanical overloading of the horse by the rider. Adjustments in both riding technique and saddle use or design may reduce loading of the horse.

The aim of this thesis is to explore the biomechanical interaction between rider, saddle and horse, in order to get insight into the loading of the horse and to identify potential opportunities to reduce injuries. Once this insight has been obtained, the possible beneficial effect of riding techniques can be evaluated.

The most important force between horse and rider is the force exerted on the horse's back. In recent years a large variety of force measurement devices for the evaluation of saddle fit has become available. In chapter 2: *Measuring forces between horse and rider*, the validity and repeatability of two saddle force measuring devices was tested. Furthermore, the use of a saddle force measuring device to objectify rider leg forces was introduced. The devices were tested under a variety of practical situations, amongst which saddle fitting, and investigations into the influence of rider position and lateral movements in dressage.

As the main mechanical effect of a rider on the horse is the gravitational force generated by his or her mass, the effect of the rider's weight on the horse's kinematics was evaluated in chapter 3: *The influence of the weight of the rider on movements of the horse.* In this chapter the effect of a girth, a saddle and 75 kg of lead on the limb and back kinematics of the horse walking, trotting and cantering on a treadmill was studied.

Two commonly used riding techniques in trot, rising trot and sitting trot, were studied in chapter 4: *The influence of sitting and rising trot on loading and movements of the horse.* First, the effect of these riding techniques on equine back kinematics and head and neck position were evaluated in horses trotting overground. Second, the force on the stirrups was measured in both riding techniques. Third, the forces of the rider on the horse were calculated from rider's kinematics and compared between rising and sitting trot. As the average vertical force of the rider on the horse's back is equal to the rider's weight, a beneficial effect of a riding technique is probably related to a reduction in vertical peak force. In chapter 4, it is confirmed that the peak force in rising trot is lower than the peak force in sitting trot.

In chapter 5: *Biomechanical modelling of the horse-rider interaction*, three simplified spring-(damper-)mass models were constructed to gain insight in the biomechanical requirements the rider has to comply with. The models demonstrate which combinations of rider mass, spring stiffness and damping coefficient will result in a sitting trot, rising trot, the modern riding technique used by jockeys or other cyclic and non-cyclic behaviours. Optimization of the spring-damper-mass model with respect to both minimal peak force of the rider and minimal work of the horse resulted in an "extreme" jockey technique, which resembles most the current technique used by jockeys. This therefore seems to be the preferred, or at any rate least challenging, technique for horse-rider interaction.

The final chapter, which is the *General Discussion*, explores possibilities to further our understanding of the interaction between horse and rider. Possibilities for both experimental research and mathematical modelling are discussed. A combination of these approaches could lead to new insights in peak force reduction in horse riding and could therefore lead to new approaches in injury reduction.

Manufacturers' addresses

[1] SaddleTech, EquiTech, Woodside, CA, USA
[2] FSA, Vistamedical, Winnipeg, Manitoba, Canada
[3] Pliance, Novel, Munich, Germany

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2. Measuring forces between horse and rider

2.1 Saddle pressure measuring: validity, reliability and power to discriminate between saddle-fits.

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Abstract

Saddle-fit is recognised as an important factor in the pathogenesis of back problems in horses and is empirically being evaluated by pressure measurement devices in clinical practice, although not much is known about the validity, reliability and usability of these devices in the equine field. This study was conducted to assess critically a pressure measurement device marketed for evaluating saddle fit. Validity was tested by calculating the correlation coefficient between total measured pressure and the weight of 28 different riders. Reliability and discriminative power with respect to different saddle fitting methods were evaluated in a highly standardised, paired measurement set-up in which saddle-fit was quantified by air pressure values inside the panels of the saddle.

Total pressures under the saddle correlated well with riders' weight. A large increase in over-day sensor variation was found. Within trial ICCs were excellent, but the between trial ICCs varied from poor to excellent and the variation in total pressure was high. In saddles in which the fit was adjusted to individual asymmetries of the horse, the pressure measurement device was able to detect correctly air-pressure differences between the two panels in the back area of the saddle, but not in the front area. The device yielded valid results, but was only reliable in highly standardised conditions. The results question the indiscriminate use of current saddle pressure measurement devices for the quantitative assessment of saddle-fit under practical conditions and suggest that further technical improvement may be necessary.

Keywords: horse; pressure; back; saddle; saddle-fit

1. Introduction

In recent years a large variety of pressure measurement devices for the objective evaluation of saddle-fit have become available. These systems have been used for the scientific evaluation of saddle pads (Harman, 1994, 1997; Pullin et al., 1996), different saddle brands (Werner et al.,2002) and saddles that were artificially made to be poor-fitting (Liswaniso, 2001). In equine practice and the saddlery industry, such devices are commonly used, as evaluation of saddle-fit using pressure measurement is thought to improve the quality of saddle-fit and provide a quantitative measure. Customers are prepared to pay for this, not least because bad saddle-fit is often incriminated as a cause of back problems (Harman, 1999). Moreover, there is scientific evidence that (weighted) saddles influence back and limb movements of the horse (De Cocq et al., 2004).

Nevertheless, the question remains as to whether saddle pressure systems really do contribute to better saddle-fit. The systems, which are derived from devices used in human research, are relatively new and have undergone little scientific scrutiny in the equine field. To date, the validity of only one pressure measurement device has been evaluated (Jeffcott et al., 1999). Other researchers using pressure measurement devices have reported no information about validity, variability and reliability (Harman, 1994, 1997; Liswaniso, 2001; Pullin et al., 1996), or have failed to explain the high variability found in their study (Werner et al., 2002). These data are in contrast to the human field, where pressure measurement devices specially developed to test wheelchair seats have been evaluated under standardised conditions for their hysteresis, creep, repeatability, response time and validity (Ferguson-Pell and Cardi, 1993; Ferguson-Pell et al., 2001; Nicholson et al., 2001). Recently, a pressure measurement device used to measure bicycle seat pressure was tested for reliability and validity under conditions that could be easily adapted to the equine field (Bressel and Cronin, 2005).

In the present study, a saddle pressure measurement device was tested for validity and reliability and for its effectiveness for the intended use, *i.e.* to discriminate objectively between different saddle-fits.

2. Materials and methods

2.1. Pressure measuring equipment

A commercially available saddle pressure measuring system was used (FSA, VERG Inc.). The system consisted of a four-way stretch Lycra fabric mat with an overall size of 79 x 106 cm and a sensing area of 66 x 96 cm. The mat contained 512 piezo-electric sensors with a size of 57 x 19 mm, arranged in a 32 x 16 pattern. The mat was 0.36 mm thick, had a maximal sample rate of 3072 sensors per second (6 Hz), and could be calibrated in the range of 0-40 kPa. The variation coefficient of the measurements was less than 10% according to the manufacturer.

The calibration process involved placing the pressure sensing mat in a pneumatic test rig, which sandwiched the mat together with an air-pressurised bag between two rigid surfaces. A series of readings from the mat was taken at different pressures, both in an inclining and a declining pressure range (steps of 4 kPa). The system's software uses the values that are generated to define for every individual sensor the exact pressure and establishes creep and hysteresis values, after which these errors are corrected for. In this study a variation coefficient of 5% (instead of the 10% recommended by the manufacturer) was deemed acceptable. The mat was calibrated at the beginning of every measurement day. The calibration set-up was also used for the over-day sensor variation measurements.

2.2. Procedure for validity testing

The validity of the pressure measurement device was tested before the saddle-fit experiment. Validity was tested in the same way as described by Jeffcott et al. (1999). Measurements were taken using one Warmblood horse (mare, 17 years, 654 kg, 1.65 m) and one standard 43 cm (17 in.) dressage saddle without stirrup and leathers, weighing 7 kg in total. The saddle was weighed with the girth, but without stirrup and leathers and placed directly on the pressure measuring device. A pressure measurement was taken with a loose girth and a tightened girth before and after the measurements with the riders. The measurements with the riders took place without removing the saddle or the pressure pad and without loosening the girth.

Twenty-eight different riders (21 females and 7 males, mean ± SD age 28 ± 9 years, mean ± SD weight 72 ± 13 kg, mean ± SD height 1.76 ± 0.09 m) were weighed and asked to mount the horse from a portable stepladder. Pressure measurements were performed for 5 s with a frequency of 2 Hz (10 readings in total) with the horse standing squarely. The total pressure for each of the 10 pressure readings was determined and the mean of these values calculated. Pearson's correlation coefficient between the riders' weight and the mean total pressure was calculated. A correction for the weight of the saddle and the pressure caused by tightening the girth was made by adding the weight of the saddle to the weight of the riders and subtracting the difference in total pressure between the measurements with a loose and a tightened girth from the total measured pressure. This was done to verify the assumption by Jeffcott et al. (1999) that the weight of the saddle and the tension of the girth caused the curve representing the correlation between pressure and weight not to pass through the origin.

2.3. Comparison of saddle-fitting methods

2.3.1. Horses

Twenty-five Dutch Warmblood horses were used (18 mares and 7 geldings, mean ± SD age 10.1 ± 4.7 years, weight 596.3 ± 52.5 kg). The horses were clinically sound and in daily use by students of the Veterinary Horse Riding School.

2.3.2. Saddle

A saddle with a flexible and adjustable tree was used (Jes Elite Dressage, Schleese Saddlery Service Ltd.). The tree could be adjusted with help of a specially developed tree-machine (Fig. 1), which changes tree size and angle by putting pressure on the inner side of the tree. The panels of the saddle were not filled with conventional filling material, but featured a special air system (Flair, First Thought Equine Ltd.) consisting of four air-bags that could be filled separately. These were a left and a right front air-bag, and a left and a right back air-bag.

2.3.3. Experimental design

Thirteen of the horses were first tested with a symmetrically fitted saddle (similar air pressure in the air bags in the panels), followed by testing with a saddle that was adjusted based on previously taken back conformation measurements. In the remaining 12 horses, the two conditions were tested in reverse order. Conditions were changed in-between measurements with the saddle on the horse and the girth tightened in order not to change the position of the saddle with respect to the pressure measurement device.

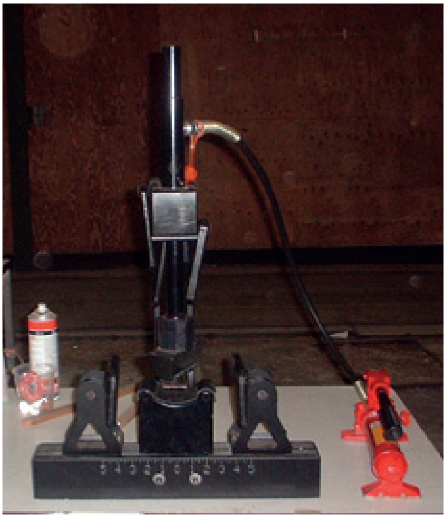
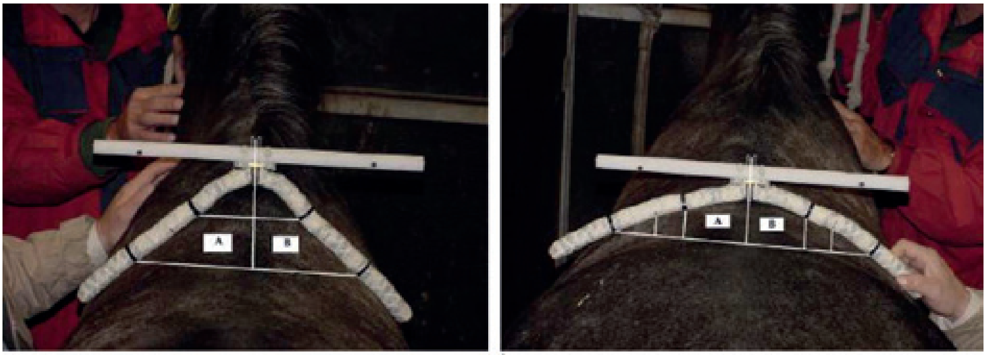


Figure 1 The tree machine used to adjust tree size and angle by putting pressure on the inner side of the tree.

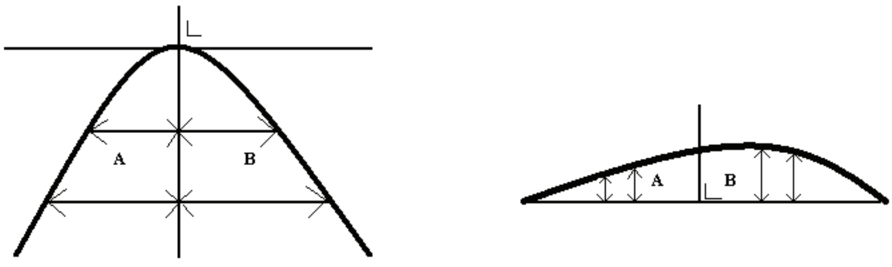
2.3.4. Saddle-fitting procedure

For each horse, measurements were taken with help of back gauges that were fitted on the back at the highest point of the withers and over the 18th thoracic vertebra (Figs. 2a, b). At both positions the gauge was adjusted to the shape of the back and the left-right differences were used to assess the asymmetry of the horse (Fig. 3). In addition to the gauge measurements, the saddle-fitter evaluated the conformation of the horse. Based both on gauge measurements and conformation the saddle-fitter determined the tree-size for each individual horse, which was not changed during the measurements. In the symmetrical condition the air chambers of the saddle were filled to a similar extent *i.e.* the same air-pressure at the right and left side. To adjust and actually fit the saddle, the saddle-fitter adapted the pressure in the chambers to correct for any asymmetries in the back of the individual horse



a b

Figure 2 Back gauge, used for taking measurements at the withers (a) and in the thoracolumbar area (b).



a b

Figure 3 Diagrammatic representation of back gauge measurements at the withers (a) and in the thoracolumbar area (b) that served for the individual adjustments of the saddle.

(The length of the ⟷ is measured at both right and left side. The side with the shortest ⟷ is the hollow/low/convex side).

Air-pressure in the saddle panels was measured with a sphygmomanometer (AMG, Century Medical Distributors Ltd.) by an independent assessor and in the standing horse without a rider. This information was not given to the saddle-fitter. Measurements with the saddle pressure measurement device were taken in the square standing horse mounted by one experienced rider (female, 23 years, 56 kg, 1.67 m). We tried to keep all environmental factors as stable as possible and so used an experienced rider who was presumed to have a more stable posture.

Each measurement took 5 s at a frequency of 2 Hz and was repeated three times. In this way three sets of 10 readings were obtained for each horse, before and after fitting the saddle.

2.3.5. Data analysis

The data was exported to Excel (Microsoft Corporation) and for each reading the mean, standard deviation, variation coefficient, number of active sensors and the individual reading of each sensor were recorded. The pressure readings were divided into four separate areas (left front, right front, left back, and right back). Left and right areas were separated by two rows of sensors not subjected to pressure (the gullet). The front areas consisted each of 12 rows and five columns of sensors. The back areas consisted each of 10 rows and five columns of sensors (Fig. 4). The total pressure was calculated as the sum of the four areas. To overcome the fact that some horses were hollow on the left side and others were hollow on the right side, data were grouped as 'high' (convex) and 'low' (hollow / concave) instead of right and left side.

2.3.6. Over-day sensor variation

Variation coefficients of the pressure measured by all sensors at 4 kPa pressure intervals in the calibration rig were calculated. The measurements took place directly after calibration and at the end of the measurement day. From these variation coefficients a mean variation coefficient was calculated. The mean variation coefficients at the beginning and at the end of a measurement day were compared using the Students' paired t-test. A P-value of < 0.05 was considered significant.

2.3.7. Within and between measurement intra-class correlation coefficients (ICCs)

Reliability within one measurement of 10 readings and between the three repeated measurements, in which the saddle and saddle pressure measurement device remained on the horse, was tested with the method proposed by Bressel and Cronin (2004). The within measurement ICCs were calculated using values collected at 1.5, 3.0 and 4.5 s from measurement 1. The between measurement ICCs were calculated using values at 1.5 s from measurement 1, 2 and 3. Reliability was designated as poor with ICCs < 0.700. ICCs between 0.700 and 0.800 were classified as fair and between 0.800 and 0.900, and 0.900 and 1.000 as good and excellent, respectively.

2.3.8. Evaluation of saddle-fitting

Measurements of the air-pressure in the four panels were compared before and after saddle fitting using a Students' paired t-test.

For the analysis of the measurements by the saddle pressure measurement device the number of active sensors, total pressures, pressures at the high and low sides at the front of the saddle and at the back of the saddle, the total high-to-low difference, and the high-to-low differences in front and back parts of the saddle were also compared between before and after saddle fitting using Students' paired t-test. For this comparison the mean values of the 30 readings from each horse in both the symmetrically fitted situation and the adjusted saddle situation were used. p-values < 0.05 were considered statistically significant.

3. Results

The correlation coefficient between the total measured pressure and the weight of the riders was 0.96 ($p < 0.001$) when uncorrected for the weight of the saddle and the pressure caused by the tightening of the girth (Fig. 5a). When corrected for these factors, the correlation coefficient was 0.97 ($p < 0.001$: see above) and the line of pressure against weight passed through the origin (Fig. 5b).

Over-day sensor variation increased from 3.9 to 15.4 ($p = 0.012$) and within trial ICCs ranged between 0.936 and 0.996. Between trial ICCs ranged between 0.687 and 0.971 (Table 1).

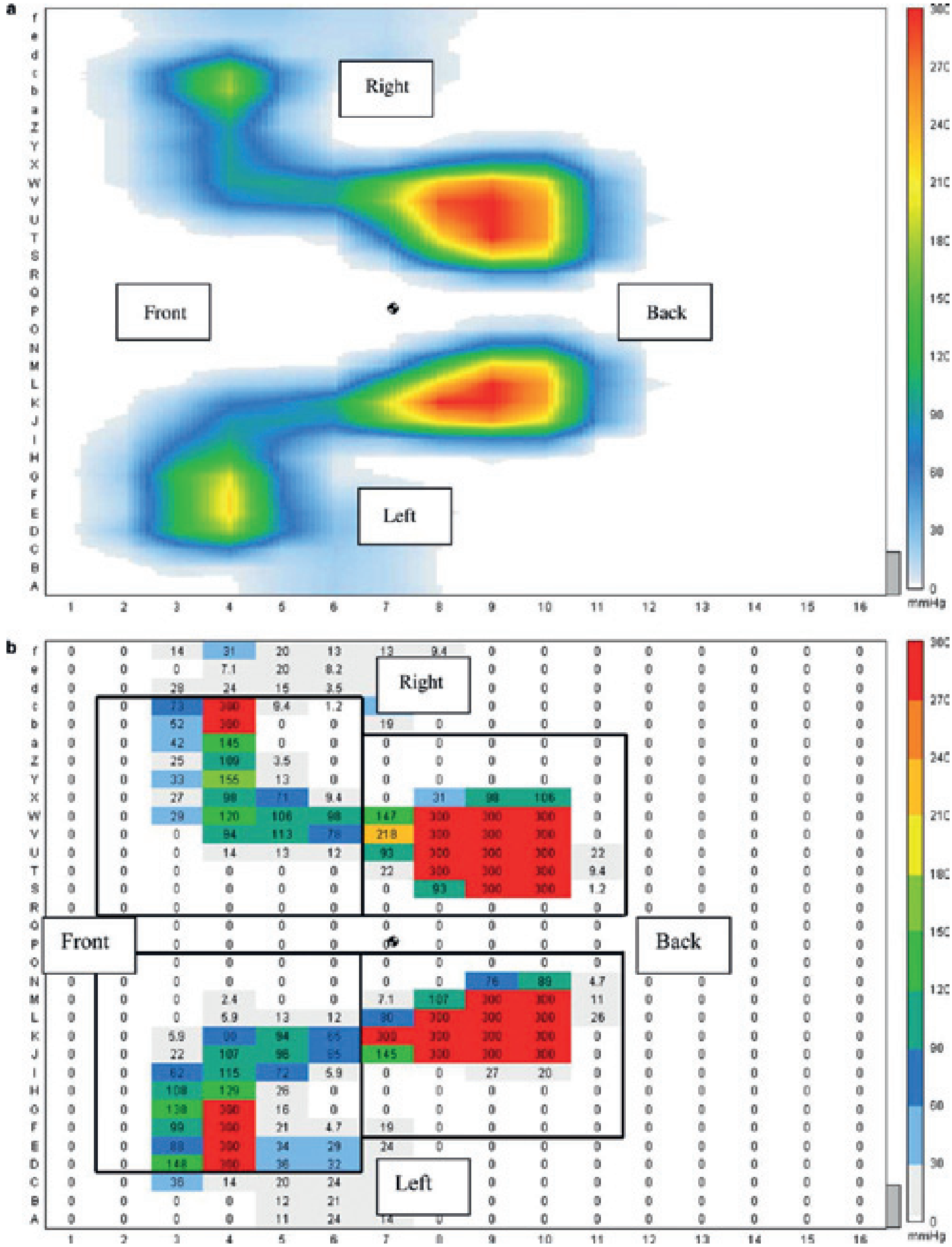


Figure 4 Pressure pictures.

a. typical example of a computer generated pressure picture. The first frame of the first measurement taken on one horse in the symmetrical saddle-fit situation.

b. pressure picture with model of the numbered values used for data analysis.

The same frame as used in figure 4, now with the individual sensors with the measured pressures in mmHg (1 mmHg = 0.1333 kPa).

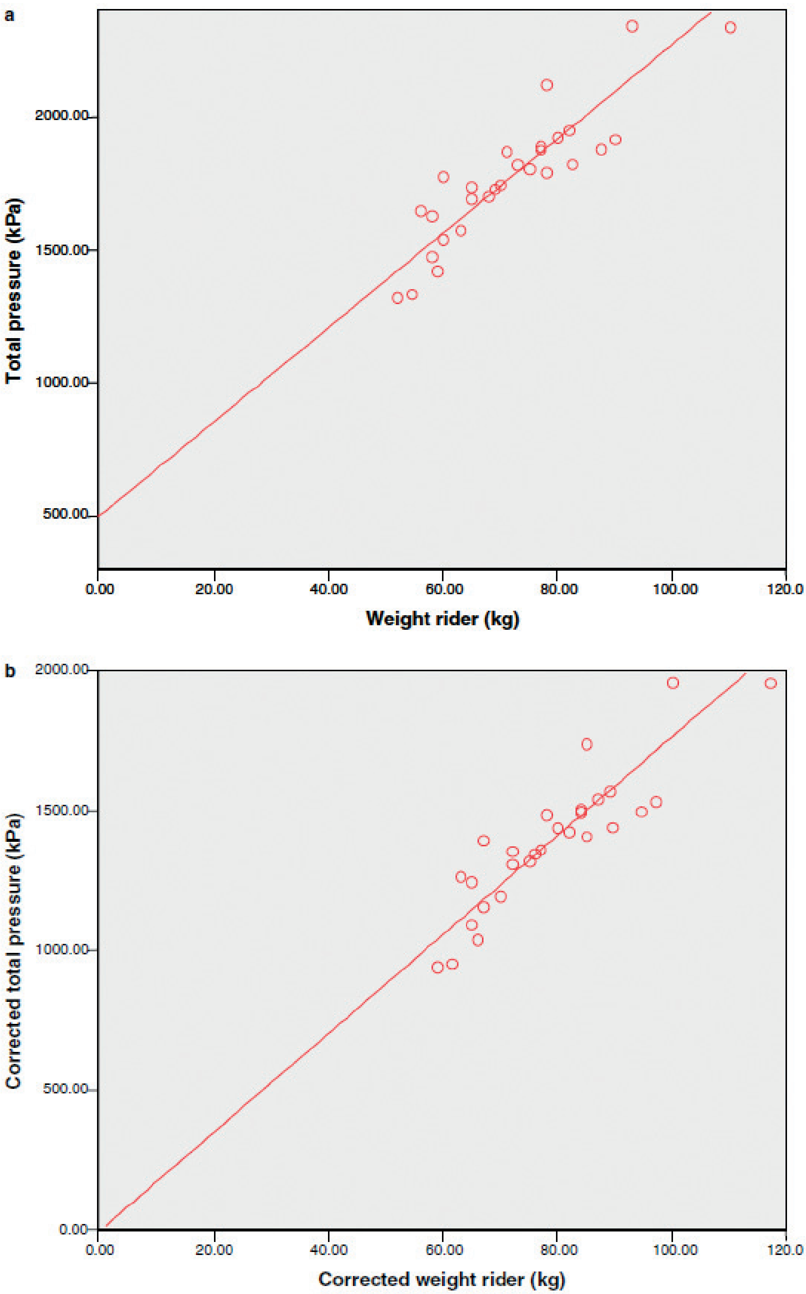


Figure 5 Correlation between rider weight and total pressure

a. without correction for saddle weight and pressure due to tightening of the girth.

b. with correction for saddle weight and pressure due to tightening of the girth.

Table 1 Within and between measurement intra-class correlation coefficients before and after saddle fitting.

Variables	ICC within before	ICC between before	ICC within after	ICC between after
Total number of sensors/surface	0.97	0.83	0.94	0.78
Total pressure	0.99	0.93	0.99	0.89
Pressure high side front	0.98	0.92	0.98	0.91
Pressure low side front	0.99	0.97	1.00	0.91
Pressure high side back	0.99	0.87	0.98	0.83
Pressure low side back	0.99	0.85	0.99	0.69
Δ pressure underneath saddle front	0.98	0.79	0.96	0.79
Δ pressure underneath saddle back	0.99	0.86	0.97	0.75
Δ pressure underneath saddle total	0.99	0.82	0.97	0.80

ICC: intra-class correlation coefficients
Δ: difference between high/concave and low/convex side
ICCs < 0.70 were designated as poor reliability, 0.70-0.80 as fair reliability, 0.80-0.90 as good reliability and 0.90-1.00 as excellent reliability.

The air pressure measurements showed that the adjustment process carried out by the saddle-fitter increased the air pressure at the low or hollow side. The air pressure in the right and left saddle panels was virtually equal in the symmetrically fitted saddle before and had a high-to-low difference of –2.3 kPa in the front part and of –3.2 kPa in the back part in the adjusted saddle after saddle fitting (Table 2).

Table 2 Differences in air-pressure inside the panels of the saddle between before and after saddle-fitting.

Variables	Before saddle-fitting	After saddle-fitting	p-value
Air-pressure high side front	6.6 ± 1.6	6.2 ± 1.4	0.257
Air-pressure low side front	6.5 ± 1.7	8.5 ± 3.1	0.002 *
Air-pressure high side back	5.4 ± 1.0	5.1 ±1.3	0.233
Air-pressure low side back	5.2 ± 0.9	8.2 ± 2.1	<0.001 *
Δ air-pressure front panels	0.1 ± 0.3	-2.3 ± 2.1	<0.001 *
Δ air-pressure back panels	0.2 ± 0.3	-3.2 ± 1.7	<0.001 *

All variables are expressed as mean ± sd in kPa.
Δ air: difference between high and low side.* : significantly different at p < 0.05

The measurements with the saddle pressure measurement device showed that the number of active sensors, total pressure, and pressure differences between the high and low side at the front of the saddle did not differ significantly between the symmetrical and adjusted saddle fittings. However, there was a significantly higher pressure at the hollow side at the back of the saddle after the saddle adjustment procedure (Table 3). Therefore, the pressure differences between the high and the low side at the back of the saddle differed significantly before and after saddle fitting.

Table 3 Differences in pressure measurements under the saddle between before and after saddle-fitting.

Variables	Before saddle-fitting	After saddle-fitting	p-value
Total number of sensors/surface	160 ± 17	159 ± 16	0.378
Total pressure	1720 ± 389	1760 ± 407	0.242
Pressure high side front	417 ± 152	425 ±174	0.536
Pressure low side front	391 ± 182	407 ±177	0.182
Pressure high side back	470 ± 137	445 ±165	0.143
Pressure low side back	442 ± 121	484 ±106	0.030 *
Δ pressure underneath saddle front	26 ± 94	18 ± 97	0.563
Δ pressure underneath saddle back	29 ±133	-39 ± 129	0.016 *

All variables are expressed as mean ± sd in kPa. Δ: difference between high and low side.
* : significantly different at $p < 0.05$

4. Discussion

The high correlation coefficient between total pressure and mass of the rider confirmed earlier work by Jeffcott et al*.* (1999), who found a correlation coefficient of 0.98 in a similar set-up. However, in our study total pressures were higher. This can be explained by a difference in technology. The sensors in the mat we used had a larger surface and the reading they gave was not an average over the sensor but the maximal pressure read by the sensor.

The increase in variation coefficient during one measurement day was not expected. The manufacturer recommends recalibration of a new mat after 50 uses and an older mat after 200 uses. Recalibration is advised because the sensitivity of the sensors changes over time during use, which would be especially true for new sensors (manufacturer's guide). The pressure mat used in our study was a mat that had been used before, and on one measurement day 36 measurements (6 horses times 6 measurements) were performed on average. As the manufacturer's guide gives a variation coefficient of less than 10% as acceptable, the pressure mat exceeded this limit within one measurement day. The high variation coefficient means that not all sensors will measure the same pressure when subjected to the same loading. A high variation in pressure patterns can be expected if the mat is slightly moved, in which case the same sensors measure different areas. In our study we avoided this problem by performing these measurements in both conditions (before and after saddle-fit) without removing the saddle and/or the pressure measurement device. This approach is, however, only possible in an experimental set-up with the horse standing squarely. Thus, for objective pressure measurement this device should preferably be calibrated between every measurement.

The intra-class correlation coefficients indicate that the reliability of the pressure measurement device was excellent within one measurement and ranged from excellent to poor between measurements. This decrease in reliability can only be caused by a change in the position of the horse or in the position of the rider, as all other factors remained the same in-between the measurements. These positions had been standardised as much as possible by only a horse standing squarely with one experienced rider, who sat in a similar position on all horses under both saddle-fitting conditions. Apparently, small changes in the horse's or the rider's position have a big impact on the pressure pattern measured. This emphasises the need of very standardised conditions, while using saddle pressure measurement devices.

The air pressure measurements indicated that the differences between the symmetrical fit and the adjusted fit mainly resulted from increasing the pressure (filling) of the panel on the hollow, concave side of the back of the horse. In the front part of the saddle the pressure on the hollow side was increased by 23%, but in the back part the pressure was increased by 58%. This would translate to considerable differences in filling if using conventional flocking material. This is a new observation adding to our understanding of saddle-fitting.

The saddle pressure measurement device could discriminate between the two fitting conditions in the back part of the saddle, but not in the front area, notwithstanding the significant air pressure difference in the front chambers. This lack of discriminative power may be related to the facts that the relative pressure increase in the back panels was more and that the inflatable panels accounted for the total contact surface in the back part of the saddle, whereas the contact surface in the front part consisted of both the inflatable panels and a part in which the pressure could not be altered (sweat flap). Therefore a difference in filling of the front panels would affect overall pressure distribution beneath the saddle less than a difference in filling of the back panels.

The variation in saddle pressure measurements was high. The overall variation coefficient was 23%. High variation coefficients have been found in other saddle pressure measuring studies too. In a study that also focused on a standing horse with a rider Werner et al*.* (2002) found a variation coefficient of 35%, using a different pressure measuring system. Total pressure should theoretically be identical in all horses, as one single rider with constant weight was used and because there is a linear relationship between mass of the rider and total force. Total force translates directly to total pressure if the total pressure-sensing area is constant. The high variation encountered in different studies is an indication of the sensitivity of the measurement system for slight changes in position of the pressure mat, thus emphasising the necessity for the use of standardised conditions.

Saddle pressure measurement devices used for the evaluation of equine saddle pressure are however derived from human saddle pressure devices. More criteria are necessary when measuring pressures in saddle fitting than are required in wheelchair or bicycle seat pressure measurement. For the evaluation of saddles for horses, measurements should be performed in a more dynamic way, *i.e.* during riding as well. For pressure changes caused by the back-movements in trot, a frequency of 4 Hz can be expected; so, according to current measurement protocols, a sample frequency of >8 Hz is necessary in order to establish a correct pattern. A higher frequency would further improve the data collection.

The sensors of the pressure measuring device used had an upper limit of 40 kPa. Even without weight with a tightened girth this maximal pressure of 40 kPa can be reached. This maximum pressure did not have a major influence in the validity experiment as it did not affect the linear relationship of weight against pressure, nor with the heavier riders. However, during movement this maximal pressure will become a greater problem and note should be taken that the pressure measurement device used in this study measured the maximal pressure on the sensors and not the average pressure. With the relatively large sensors (57 x 19 mm), the actual pressure can, therefore, be easily overestimated. Apart from raising the maximum pressure limit of the sensors, the use of sensors with a smaller surface would thus further improve performance of the pressure measuring device.

The problem with the maximal pressure was especially seen in the caudal thoracic region. In another study (Liswaniso, 2001) the principal pressure points were either side of the withers and not beneath the saddle panels in the caudal thoracic region. This difference can probably be explained by a difference in tree-fit. A general accepted way to fit a tree is parallel to the horse, but the saddle fitter in this study preferred a wider tree-fit at the top (heel) that becomes tighter towards the bottom (toe) of the tree. As the tree was fitted identical in both the symmetrical as the adjusted fit, this alternative tree fit did not influence our study. However, the difference in site of maximal pressure seen between our study and Liswaniso's demonstrated that tree-fit may indeed change the location of pressure points. To confirm this, a study in which different tree fits are compared, should be performed.

Another improvement of the pressure measurement device would be to shape the mat more according to the anatomy of the horse. The rectangular shape makes wrinkling unavoidable. As the mats are very sensitive to folding, this will probably cause a big part of the high variability seen in this study. Moreover, it would be easier to standardise the position of the mat if the mat was shaped like a saddle or saddle pad.

5. Conclusion

The saddle pressure measurement device tested in this study could be classified as a valid system for measuring total saddle pressures, but its reliability in practice and the power to discriminate between saddle fits remain questionable. Differences in pressures before and after fitting saddles could only be demonstrated in the back of the saddle under noticeably standardised conditions, which included the location of the mat beneath the saddle and the position of the horse and rider.

The future of saddle pressure evaluation lies in improving the technology. Ideally, both saddle fit adaptation devices and pressure measurement technology could be incorporated in a saddle, including perhaps a display on which the rider can see the measurements on line during performance. In this way, changes in saddle fit could be quantified in terms of saddle pressure and used in a practical way. The question as to which pressure patterns are optimal is of another order and will only be answered with help of studies integrating pressure measurements and kinetics and/or kinematics of the entire horse.

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2.2 Usability of normal force distribution measurements to evaluate asymmetrical loading of the back of the horse and different rider positions on a standing horse.

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Abstract

Pressure measurement devices in equine sports have primarily focused on tack (saddle pads and saddle fitting methods). However, saddle pressure devices may also be useful to evaluate the interaction and distribution of normal forces between horse and rider, including rider position and riding technique. This study examined the validity, reliability, repeatability and possibilities of using the device to evaluate rider position. All measurements were performed using a standing horse. Validity was tested by calculating the correlation coefficient between measured normal force and the weight of the rider. Repeatability was tested by calculating intra-class correlation coefficients. The possibilities to use the normal force measurements for evaluation of horse-rider interaction was tested by adding a known weight to saddle or rider and by taking measurements with the rider sitting in four different positions. The device was valid and reliable for force measurements in situations in which the measurement device was not replaced. The system could measure the expected differences with added weight and in the different rider positions. The normal force distribution measurements device proved to be a valid and reliable tool for studying static horse-rider interaction, provided it is positioned carefully and consistently relative to both the horse and the saddle.

Keywords: Equine; Saddle; Total force; Pressure; Equestrian

1. Introduction

Research using pressure measurement devices in equine sports is mainly focused on tack, such as saddle pads, saddle brands and saddle fitting methods (Harman, 1994, 1997; Werner et al., 2002; Liswaniso, 2001; de Cocq et al., 2006; Meschan et al., 2006). Another opportunity to use pressure measurement devices in equine sports lies in the evaluation of the interaction between horse and rider. Saddle pressure measurement devices consist of an array of sensors that measure forces acting normal (perpendicular) to their surface. These forces are potentially useful to evaluate rider position and riding technique.

Several devices are marketed for measuring the normal forces underneath the saddle but, as a prerequisite to their use in scientific studies, the accuracy and reliability should be evaluated. If there is a high correlation between the sum of the measured forces and the mass of the riders, the force measurement device might be useful to evaluate the force a rider applies to the horse. To date, only the FSA device (Vista Medical Ltd.) has been tested for validity and reliability in equine practice (Jeffcott et al., 1999; de Cocq et al., 2006). The Pliance system (Novel GmbH) has been used to evaluate different saddle brands (Werner et al., 2002), different saddle fits (Meschan et al., 2006), normal force distribution in movement, (Freuhwirth et al., 2004) and the effect of mounting from a mounting block (Geutjens et al., 2008).

Information about validity and reliability of the Pliance system from pressure bench tests (Hochman et al., 2002) indicates that it might be more reliable than the FSA, ClinSeat (Tekscan Inc.) and Xsensor (XSENSOR Technology Corporation) systems. A logical next step is to test the validity and reliability of the Pliance system *in situ* between the saddle and the horse's back, which is the focus of this study.

The objective of this study was to test the usability of the Pliance system for the evaluation of horse-rider interaction on a standing horse. As the expectations were that the Pliance system might be better to use in equine practise than previously tested devices, it was hypothesized that the validity and repeatability would be higher. Is was also hypothesized that the Pliance system would be able to distinguish between situations were different weight were added to saddle or rider and between different rider positions.

2. Materials and methods

The study was performed with approval of the All University Committee for Animal Use and Care and the University Committee on Research Involving Human Subjects at Michigan State University, and with full informed consent of the riders.

2.1. Normal force distribution measuring equipment

The electronic normal force distribution mat used in the study (Pliance Saddle System, Novel GmbH), consists of two separate mats for the left and right sides, each of which has 128 sensors arranged in 8 columns and 16 rows. Prior to the start of data collections, each mat was calibrated in a special device consisting of a rubber membrane, housed within a secure unit that is filled with air using a compressor. Pressure applied to the mat by the calibration device was measured using a manometer (GDH 13 AN, Greisinger electronic GmbH). The Pliance software then calibrates each sensor individually. The mat was calibrated each day prior to data collection and the results from these repeated calibrations were also used for the over-day sensor variation measurements. Placement of the force mat and saddle on the horse's back were identical with Geutjens et al., (2008). The mat was initialized to zero before placing the saddle on top of it. For each condition studied, data were recorded for 2 s at a frequency of 5 Hz (10 readings in total) with the horse standing squarely.

2.2. Procedures for evaluating normal force distribution beneath the saddle

2.2.1. Procedure for validity testing

Validity was tested in the same way as described by de Cocq et al. (2006) (based on method of Jeffcott et al. (1999) using one Dutch Warmblood horse (gelding, age 14 years, mass 462 kg, height 1.50 m) and one standard 44.5 cm dressage saddle (Schleese Saddlery Service Ltd.) without stirrups and leathers, that weighed 7.8 kg in total. Twenty-three riders (14 females and 9 males, age 31 ± 13 years, mass 74 ± 19 kg, height 1.72 ± 0.11 m) stepped onto the horse from a high mounting platform.

Data were recorded with a loose girth (no rider), with a tightened girth (no rider) and with the girth tightened and rider mounted. For each data recording, the magnitude of the forces measured by the individual sensors was summated to give the total force. The mean total force of the 10 readings of each rider was calculated. Pearson's correlation coefficient between the riders' weight and the mean total force per rider was calculated. A correction for the weight of the saddle was made by adding the weight of the saddle to the weight of the rider. A correction for the force caused by tightening of the girth was made by subtracting the difference in force measurements with a loose girth and a tightened girth from the mean total measured force per rider.

2.2.2.Over-day sensor variation

Over-day sensor variation was tested as described by de Cocq et al. (2006). Briefly, the mats were placed in the calibration device and the variation coefficient of the 128 sensors (sd/mean x 100%) was calculated at different air pressure levels: 0, 2, 4, 6, 10, 20, 40, 60, 40, 20, 10, 6, 4, 2 and 0 kPa. From these variation coefficients, a mean variation coefficient was calculated. The measurements took place directly after calibration and at the end of the measurement day. The mean variation coefficients at the beginning and at the end of a measurement day were compared using a Student's paired t-test. A p-value of < 0.05 was considered significant for all statistical tests used in this study.

2.2.3. Within and between measurement intra-class-correlation coefficients (ICC)

Measurements were taken using the same horse and saddle as during the validity testing to assess repeatability under three conditions with the method proposed by Bressel and Cronin (2005), in which intra-class-correlation coefficients (ICC) are calculated within one measurement and between different measurements. The three conditions were as follows:

Repeatability within one measurement of 10 readings was assessed using 23 riders (14 females and 9 males, age 31 ± 13 years, mass 74 ± 19 kg, height 1.72 ± 0.11 m). The within measurement ICCs were calculated using values recorded at 0.6, 1.2 and 1.8 s.

Repeatability between three repeated measurements that were taken without removing and replacing the force mat on the horse's back (ICC between_N; N: no replacement). The 22 riders (13 females and 9 males, age 31 ± 13 years, weight 75 ± 20 kg, height 1.72 ± 0.11 m) stepped on and off the saddle three times each and the between measurement ICCs were calculated using values at 0.6 s from the three measurements.

Repeatability between three measurements in which the force mat was removed and replaced between each of three recordings (ICC between_R; R: replacement) from 12 riders (8 females and 4 males, age 29 ± 13 years, weight 75 ± 18 kg, height 1.71 ± 0.08 m).

ICC were calculated separately for five different areas of the force mat (total, left front quadrant, right front quadrant, left back quadrant, right back quadrant). In these areas repeatability of total force and peak normal stress were tested. Repeatability was designated as poor (ICC < 0.7), fair (ICC 0.7-0.8), good (ICC 0.8-0.9), and excellent (ICC 0.9-1.0).

2.3. Asymmetrical loading

2.3.1. Horses and rider

Measurements were taken using six Arabian horses (6 geldings, age 13 ± 2 years, mass 451 ± 36 kg, height 1.50 ± 0.03 m) and one standard 44.5 cm (17.5 in.) dressage saddle with stirrups and leathers, weighing 8.7 kg in total. One experienced rider (female, age 26 years, weight 56 kg, height 1.67 m) was used.

2.3.2. Experimental design

Measurements were taken under three conditions in random order: no added weight, weight added to the left side and weight added to the right side. Measurements were taken in the situation with only the saddle and in the situation with saddle and rider. In the added weight conditions, 88 N was attached to the ring in front of the skirt of the saddle or around the rider's waist using a scuba diving belt. The force mat was initialized to zero before placing the saddle on the mat for measurements without a rider and after placing the saddle and tightening the girth for measurements with a rider.

2.3.3.Data analysis

The total force, force of the left mat and force of the right mat, for each of the 10 force readings was determined by summation of the magnitudes of the forces measured by the individual sensors in each measured area. The mean force-amplitudes for each horse in each situation were calculated. The forces in the situation without a rider were compared statistically in an ANOVA-repeated measurement test, followed by a *post hoc* Bonferroni test using SPSS software (SPSS Inc.). The forces in the situation with rider were compared using the same statistics.

2.4. Rider positions

2.4.1. Horse and riders

Measurements were taken using one Arabian horse (gelding, 14 years, 520 kg, 1.52 m), a standard 44.5 cm dressage saddle (G. Passier and Sohn, GmbH) with stirrups and leathers, weighing 8.7 kg in total, and 10 experienced, female riders (age 22 ± 6 years, mass 61 ± 10 kg, height 1.66 ± 0.39 m).

2.4.2. Experimental design

Measurements were taken in four different rider positions: neutral, 10° forward with hollow (extended) back, 10° backward with round (flexed) back, and 10° laterally to the right side. The position of the rider was based on measurements with a goniometer. The order of these measurements was randomized. The chosen angles were based on angles measured by Schils et al., (1993) indicating differences in rider trunk angles of about 20° when comparing novice and experienced riders. The force mat was initialized to zero after placing the saddle and tightening the girth.

2.4.3. Data analysis

Mean forces of the following areas were calculated: front half, back half, left half and right half. Data were analyzed statistically in an ANOVA-repeated measurement test, followed by a *post hoc* Bonferroni test using SPSS software.

3.Results

The Pearsons correlation coefficient between the weight of the riders and the measured total force of the riders was 0.936 ($p < 0.001$, Fig. 1). Over-day sensor variation increased from 4.4% to 5.0% ($p = 0.030$) and within ICCs ranged between 0.869 and 0.996. Between$_N$ ICCs ranged between 0.868 and 0.982 for total force data and between 0.562 and 0.872 for peak stress data. Between$_R$ ICCs ranged between 0.263 and 0.849 for total force data and between 0.020 and 0.776 for peak stress data (Table 1).

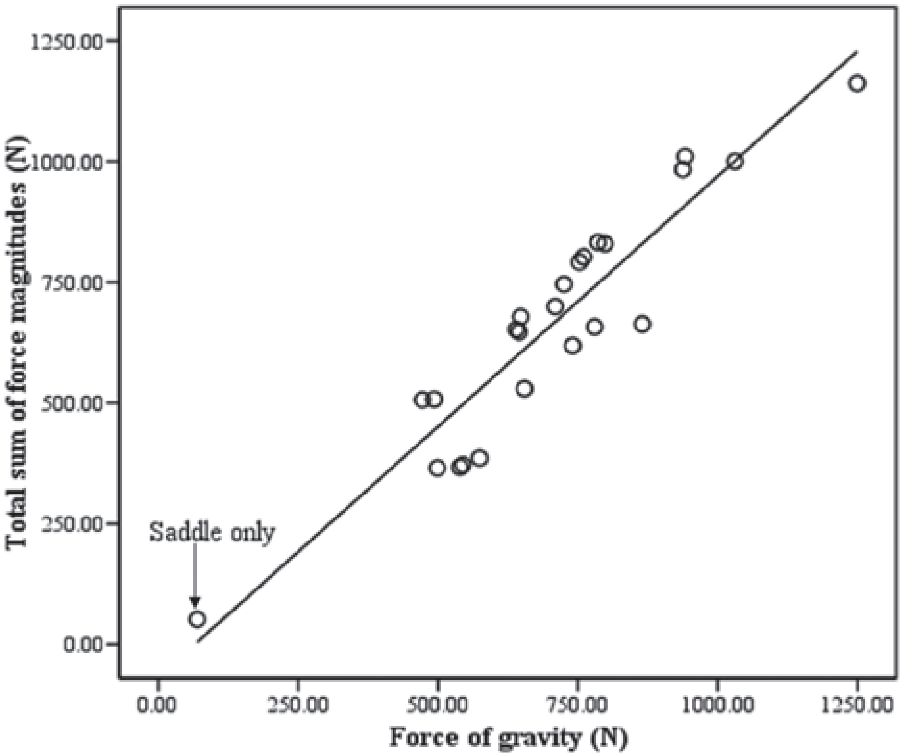

Figure 1
Correlation between measured force and weight of the riders with correction for saddle weight and force due to tightening of the girth.

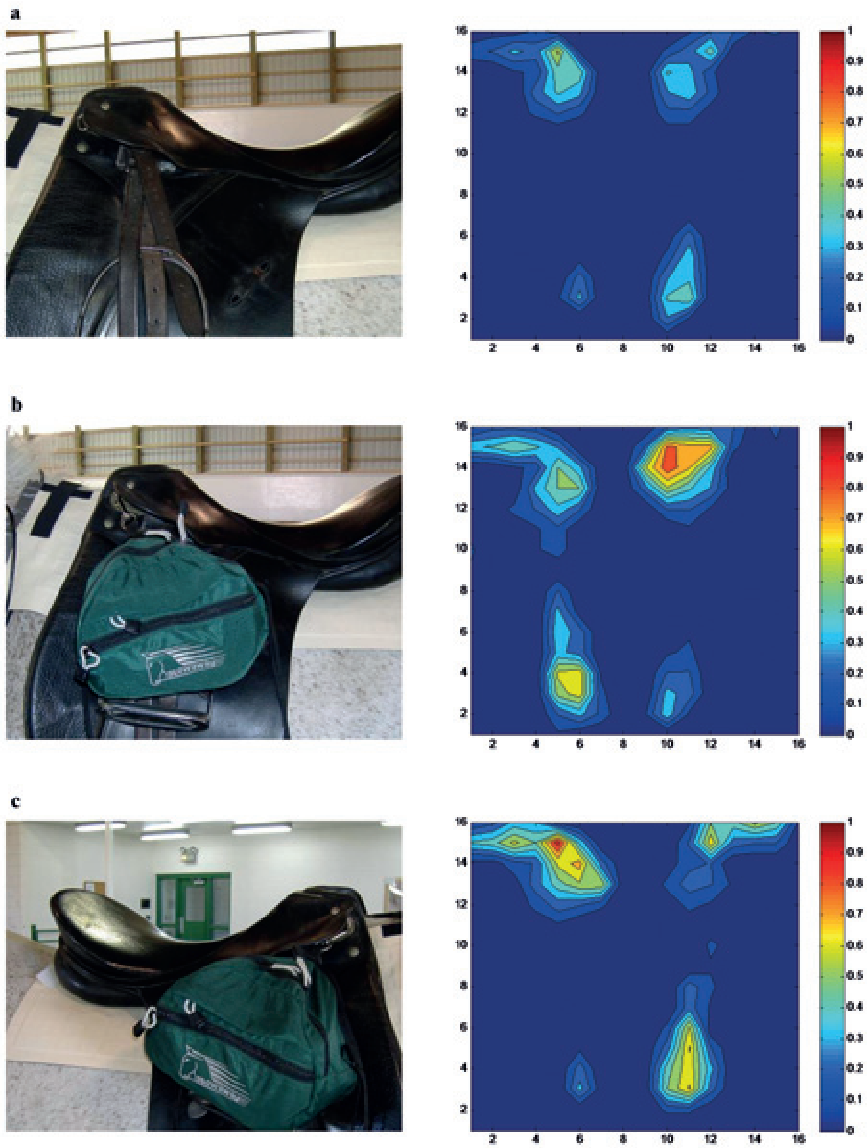

Figure 2 Measurements of the saddle without and with 88 N added weight.
Still photographs and the corresponding maps of normal force distribution under the saddle are shown (0-1 N/cm^2). The pommel is to the top, the left side is on the left.
a. no added weight
b. added weight to the left side
c. added weight to the right side

Table 1
Intra-class correlation coefficients of repeatability within one measurement of 10 readings (ICC), between three repeated measurements taken without removing and replacing the force mat from the horse's back (ICC between$_N$), and between three measurements in which the force mat was removed and replaced between each recording (ICC between$_R$).

Variables	ICC within	ICC between$_N$	ICC between$_R$
Force total	0.996*	0.982*	0.734***
Peak stress total	0.901*	0.562****	0.055**** NS
Force left front quadrant	0.983*	0.896**	0.263**** NS
Peak stress left front quadrant	0.918*	0.592****	0.020**** NS
Force right front quadrant	0.989*	0.868**	0.282**** NS
Peak stress right front quadrant	0.949*	0.616****	0.362****
Force left back quadrant	0.990*	0.884**	0.801**
Peak stress left back quadrant	0.990*	0.872**	0.769***
Force right back quadrant	0.970*	0.903*	0.849**
Peak stress right back quadrant	0.869*	0.702***	0.776***

ICC: intraclass correlation coefficients
NS: no significant correlation at $p < 0.05$
*: excellent
**: good
***: fair
****: poor

The measurements without a rider with asymmetrical added weight (88 N) showed an increase in total force of 71 N (added left side) and 61 N (added right side). The force on the side opposite to which extra weight was added also increased significantly (Table 2, Fig. 2).

Table 2
Differences in force measurements under the saddle in situations with 88 N weight added to the saddle

Variables	No extra weight	Weight left side	Weight right side	p-value
Force total	109 ± 27^{a}	180 ± 31^{b}	170 ± 27^{b}	< 0.001
Force left	50 ± 20^{a}	98 ± 24^{b}	80 ± 19^{b}	< 0.001
Force right	59 ± 12^{a}	82 ± 15^{b}	$90 \pm 24^{a,b}$	0.025

All values are in Newtons (N)
a,b values with the same superscript are not significantly different ($p < 0.05$, Bonferroni correction)

The measurements with a rider with asymmetrical added weight showed an increase in total force of about 120 N with the weight added to the left or right side. The force increased significantly on the side where the weight was added and showed a trend ($0.05 < p < 0.10$) on the side where no weight was added (Table 3, Fig. 3).

Table 3
Differences in force measurements under the saddle in situations with 88 N weight added to the rider

Variables	No extra weight	Weight left side	Weight right side	p-value
Force total	511 ± 59 ^{a}	634 ± 72 ^{b}	631 ± 86 ^{b}	< 0.001
Force left	250 ± 35 ^{a}	304 ± 46 ^{b}	286 ± 41 ^{a,b}	0.019
Force right	260 ± 31^{a}	330 ± 70 ^{a,b}	345 ± 50 ^{b}	0.003

All values are in Newtons (N)
a,b values with the same superscript are not significantly different ($p < 0.05$, Bonferroni correction)

The measurements with the four rider positions showed the following differences compared to a neutral position: in the forward position an increase of 88 N in the front part and a decrease of 88 N in the back part. In the backward position an increase of 59 N in the back part and a decrease of 57 in the front part. In the position to the right an increase of 24 N in the right part and a decrease (not significant) of 14 N in the left part (Table 4, Fig. 4).

Table 4
Differences in force measurements under the saddle in situations with different rider positions

Variables	Neutral	Forward	Backward	To the right side	p-value
Force front	210 ± 68 ^{a}	298 ± 73 ^{b}	153 ± 44 ^{c}	219 ± 60 ^{a}	< 0.001
Force back	342 ± 62 ^{a}	254 ± 52 ^{b}	401 ± 63 ^{c}	341 ± 59 ^{a}	< 0.001
Force left	237 ± 55	242 ± 57	237 ± 42	223 ± 59	0.055 NS
Force right	314 ± 64 ^{a}	309 ± 61^{a}	319 ± 56 ^{a}	338 ± 51 ^{b}	0.001

All values are in Newtons (N)
NS: not significantly different at $p < 0.05$
a,b values with the same superscript are not significantly different ($p < 0.05$, Bonferroni correction)

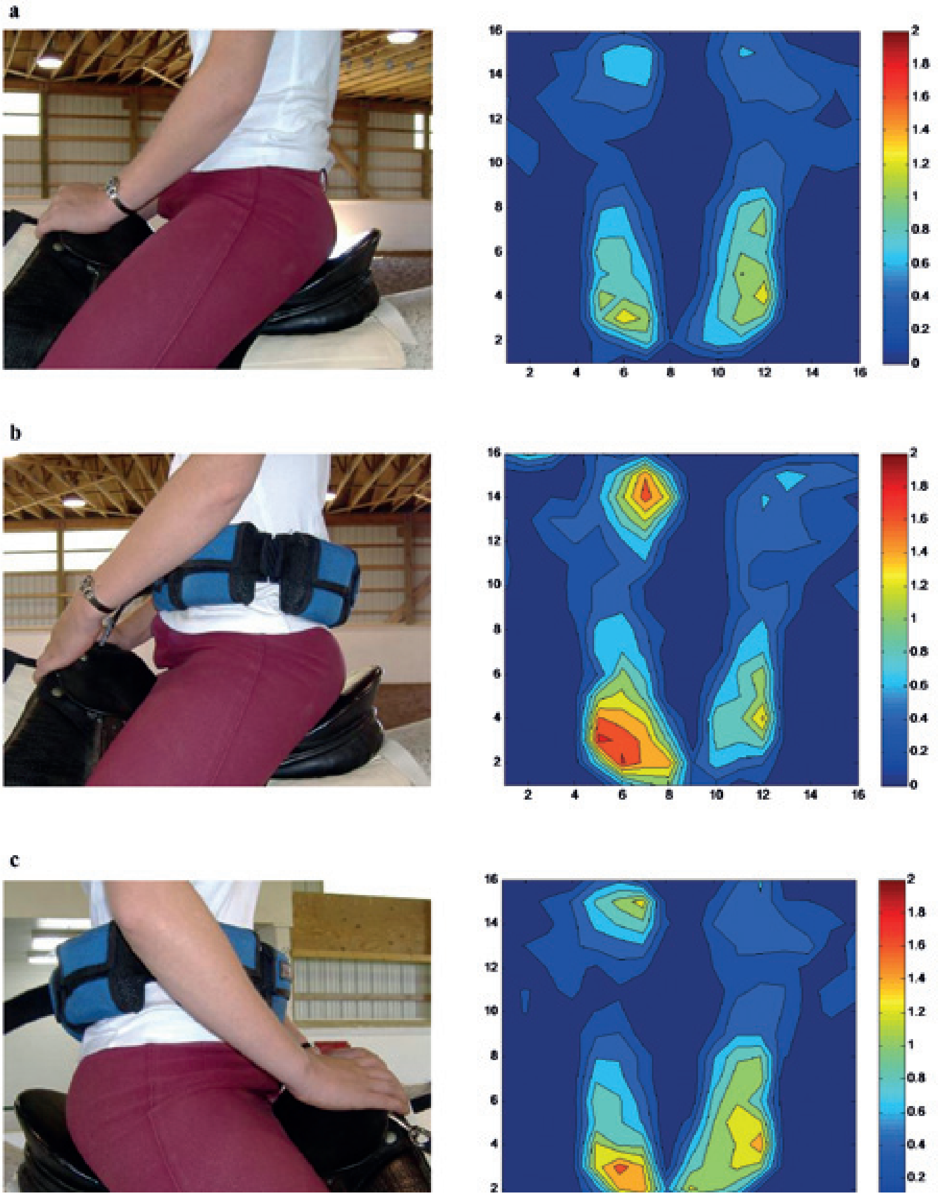

Figure 3 Measurements with a rider without and with 88 N added weight. Still photographs and the corresponding maps of normal force distribution under the saddle are shown (0-2 N/cm^2). The pommel is to the top, the left side is on the left.

a. no added weight
b. added weight to the left side
c. added weight to the right side

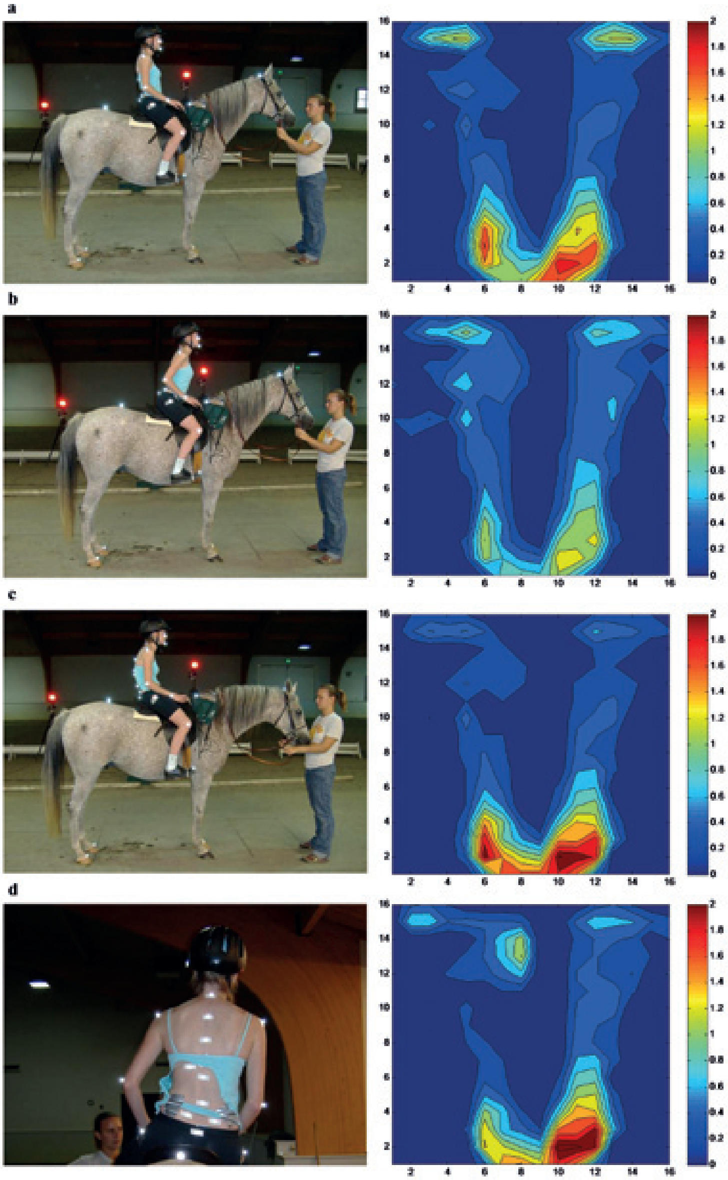

Figure 4 Measurements with four different rider positions.
Still photographs and the corresponding maps of normal force distribution under the saddle are shown (0-2 N/cm²). The pommel is to the top, the left side is on the left.
a. neutral position
b. 10° forward
c. 10° backward
d. 10° to the right side

Discussion

The high correlation coefficient between measured force and weight of the riders indicates that the Novel force mat is a valid device for measuring force passed through the saddle from the rider to the horse. Previous studies on validity of saddle normal force distribution measurement devices (Jeffcott et al., 1999; de Cocq et al., 2006) evaluated the summation of the measured pressures. In the study reported here, summation of the normal forces was preferred, since summation of the pressures, as measured by de Cocq et al., (2006), overestimates the force by a factor 2.1 (summed pressures: 172 N/cm^2 , correction girth: 50 N/cm^2, 160 sensors, 10.8 cm^2 per sensor, measured force = 1321 N; mass rider and saddle 63 kg, weight = 617 N (from de Cocq et al., 2006)).

The increase in variation coefficient during one measurement day indicates that the sensitivity of the sensors changes over time during use, but after one measurement day the variation coefficient is still within an acceptable value. This in comparison with the FSA system where the variation coefficient increased to an unacceptable value (>10%) after one measurement day (de Cocq et al., 2006). Based on these results, it would be adequate to recalibrate the Pliance mat daily, while the FSA system should be calibrated more frequently.

The intra-class correlation coefficients indicated that the repeatability of the Pliance mat was good to excellent within one measurement and between force measurements when the saddle and force mat stayed on the horse. Repeatability was poor to good between peak stress measurements, which might be a consequence of slight differences in the rider's position on the saddle between data collections. The ICCs indicate that the Pliance system is more repeatable than the FSA system (de Cocq et al., 2006). The striking difference between intra-class correlation coefficients in the front and back part of the saddle might be explained by a difference in normal force distribution in these sections of the mat. The front section showed a diverse normal force distribution with high peaks and the back section showed a more evenly distributed normal force. The difference between peak normal stress and force can be explained by the number of sensors that provide the value. The peak normal stress is measured by one sensor, the force is measured by 64 sensors per quadrant.

When the saddle and force mat were replaced, repeatability was fair to good for the total force and the summed forces on the back quadrants where the majority of the forces were applied but repeatability was poor for the less-loaded front quadrants and for the peak stress distribution. It is likely that small inconsistencies in placement of the mat relative to the horse's back, inconsistencies in placement of the saddle relative to the mat and the horse's back and changes in the rider's position relative to the saddle all contributed to the reduction in repeatability of the measurements when the mat and the saddle were removed and replaced. For example, the front and back quadrants are divided in the middle of the mat not in the middle of the weight-bearing area of the saddle. A small discrepancy in saddle position affects the number of sensors located beneath the front and back parts of the saddle, and this may explain some of the loss of repeatability when the saddle is removed and replaced. These findings suggest that greater repeatability can be expected in an evaluation of rider position when the saddle does not need to be removed but lack of repeatability may be a problem in practical saddle fitting situations. Another difference between the between_N ICCs and between_R ICCs is the number of riders used to determine the ICCs. This makes the outcome of the between_N ICCs more reliable. But as the variation between the riders is similar in both experimental set-ups, it is not expected that this will cause a difference in the outcome.

The measurements with the added weight show that the force mat is able to measure the difference of 88 N added gravitational force to the saddle/rider. In the situation without a rider the force was underestimated by roughly 20 N. In the situation with the rider the force was overestimated by roughly 30 N. An underestimation of the force can be explained by two different factors. The normal force sensors start measuring at normal stresses of 0.2 N/cm^2. In the lower normal force distribution ranges (situation without rider) there will be relatively more sensors loaded between 0 and 0.2 N/cm^2 that are not included in the force calculation. The second explanation for an underestimation of the force is the fact that only normal forces (perpendicular to mat) are measured, whereas some of the added weight, which was suspended from the side of the saddle, may have exerted a shear force. The overestimation of the force in the situation with the rider may be caused by contraction of the adductor muscles of the thighs of the rider to improve stability in the saddle when perturbed by the extra weight.

Measurements of the different positions of the rider demonstrate that a rider is able to change the force distribution underneath the saddle. As expected, force increases in the area toward which the rider is leaning and decreases in the opposite area. The total force remains the same. This indicates that the rider's position does influence the normal force distribution underneath the saddle, and that the saddle does not compensate for the different positions. However, the shape of the saddle and its relative rigidity may affect the pattern of force transmission to the horse's back as rider position changes.

Conclusions

The saddle normal force distribution measurement device tested in this study could be classified as a valid and reliable system for measuring total forces in a standardized set-up on a standing horse. The system is therefore suitable to evaluate rider-horse interaction in a paired set-up where the system remains underneath the saddle. Repeatability in a practical saddle fitting situation where the system has to be removed and replaced remains questionable. This study did not partition errors due to calibration of the mat changing, slight differences in positioning the mat and saddle relative to the horse's back, and inconsistencies in rider position on the saddle.

The results confirmed that rider position affects the normal force distribution underneath the saddle, but how this change affects the horse remains to be investigated. To achieve this, an integrated approach combining kinetics, kinematics and computer modelling is needed.

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2.3 Saddle forces and leg forces during lateral movements in dressage.

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Summary

Background: In the equestrian world it is assumed that riders use changes in weight distribution and leg forces as important instruments to give horses directions about speed and direction of movement. However, the changes of these forces have never been quantified.

Aims: The objective of this study was to investigate the distribution of normal forces (perpendicular to surface) underneath the saddle and of normal forces exerted by the rider's legs during lateral movements.

Materials and methods: Eleven riders performed three different exercises: riding straight ahead, shoulder-in and travers at trot. Three saddle force systems were used simultaneously. The magnitudes of the forces were summed for the total area, the inside and the outside half of the saddle, and inside and outside leg. Mean and maximum summed forces were statistically analysed.

Results: The saddle forces showed a rhythmic pattern, but leg forces were more irregular. Mean total saddle force was lower ($p = 0.006$) when riding straight ahead (671 ± 143 N) than when riding shoulder-in (707 ± 150 N) or travers (726 ± 165 N). Mean inside saddle force was higher ($p = 0.003$) when riding travers (468 ± 151 N) than when riding straight on (425 ± 121 N) or shoulder-in (413 ± 136 N). Maximum outside leg force was higher ($p = 0.013$) when riding travers (47.2 ± 33.9 N) than when riding straight on (31.6 ± 24.1 N) or shoulder-in (34.2 ± 27.3 N).

Conclusions: The study helps to give a biomechanical background to well-established, but intuitive horse riding techniques.

Keywords: equine, shoulder-in, travers, equitation, pressure measurements

Introduction

In equestrian sports, the communication between rider and horse is crucial. In case of miscommunication, unsafe situations may result and even accidents may happen. Further, unclear aids of the rider can lead to mental stress in the horse, thereby might negatively influence the welfare of the horse.

The rider has several options to give aids to the horse in order to change either speed or direction of movement. One of these is the use of reins and the bit. Measurement devices to measure rein force have been developed (Clayton et al., 2005; Warren-Smith et al., 2005) and have been used to quantify this force during specific equitation movements (Warren-Smith et al., 2007) and to evaluate the effect of martingales and elastic rein inserts on horse behaviour and rein tension (Heleski et al., 2009). Changes in weight distribution of the rider and application of forces by the rider's legs are traditionally considered the principal actors in correct horse riding (Decarpentry, 1971). De Cocq et al. (2009) showed that a change in body position of the rider indeed results in a changed normal force distribution underneath the saddle, but it is not clear to what extent this change in force distribution is indeed used to instruct the horse when performing dressage exercises.

In lateral movements in dressage, such as shoulder-in and travers, the horse is required to proceed in an orientation where the long axis of its body is not aligned with the direction of movement. According to the riding theory, this difference between body orientation and horizontal motion is affected and maintained through a series of aids that include a shift in weight distribution, a change in the position of the rider's leg and the asymmetrical exertion of leg forces (Hölzel et al., 1992). We aimed to test this theory quantitatively by measuring the distribution of normal (*i.e.* perpendicular to the surface) forces underneath the saddle and of normal forces exerted by the rider's legs during lateral movements of the horse.

Materials and Methods

Horses and riders

Eleven horse-rider combinations were used during this study. All riders rode on their own horse and one rider rode two additional horses. There were nine geldings, one mare and one stallion. Ten horses were Warmblood horses and one horse was a Fjord horse. The horses were 9.7 ± 2.5 years old, had a mass of 572.3 ± 53.0 kg and had a withers height of 1.70 ± 0.09 m. There were one male and eight female riders. The riders were 24.3 ± 5.8 years old, with a body mass of 66.7 ± 8.0 kg and a body length of 1.73 ± 0.08 m. The horses were clinically sound and fit to perform. The combinations had a competition level in dressage that was at least intermediate or higher. The horses were equipped with their own tack. Riders were not allowed to use spurs.

Measurement equipment

Normal forces underneath the saddle and the rider leg forces were measured with three saddle force systems (Pliance)[1]. Each saddle force systems consisted of 2 halves with 128 sensors each. The sensors had a size of 25 by 37.5 mm. One system was placed underneath the saddle, the other two were placed on the right and on the left side underneath the saddle flaps. The systems were connected to one another via a connection plug and measured synchronically with a frequency of 26 Hz. Before the measurements, all three saddle systems were calibrated using an air pressured calibration ridge. The calibration was tested after each measurement day. If the variation coefficient of the sensors was below 10%, measurements were considered reliable (de Cocq et al., 2006).

Data collection

After calibration, the three saddle force systems were placed in a custom made saddle pad. The saddle pad was placed on the back of the horse. When saddling the horse, it was checked whether the systems were placed symmetrically and whether the front of the saddle was on top of the first row of normal force sensors. After the girth was tightened, the saddle systems were set at zero.

Normal force measurements were performed at sitting trot in three conditions: proceeding along a straight line, shoulder-in and travers (Fig. 1). The order of the three conditions was randomised. Before the measurement the horses had a warming-up period of 10 to 15 minutes. The warming-up period included 5 minutes of walk and 5 to 10 minutes of trot on both leads. Riders were allowed to choose their preferred lead for the measurements. For all three conditions, the left side of the horse was the inside at the left lead and the outside at the right lead. The right side of the horse was the inside at the right lead and the outside at the left lead. Infrared gates connected to a time registration system were used to control the speed. The infrared gates stood 11 m apart and a variation in trial duration of maximally 0.4 s was accepted. A minimum of six trials per condition in this speed range was measured. Three digital video cameras were used to film the trials. One camera was facing the front of the horse, one the hind of the horse and one viewed the horse from the side. The video shots were used for the evaluation of the exercises by independent judges afterwards.

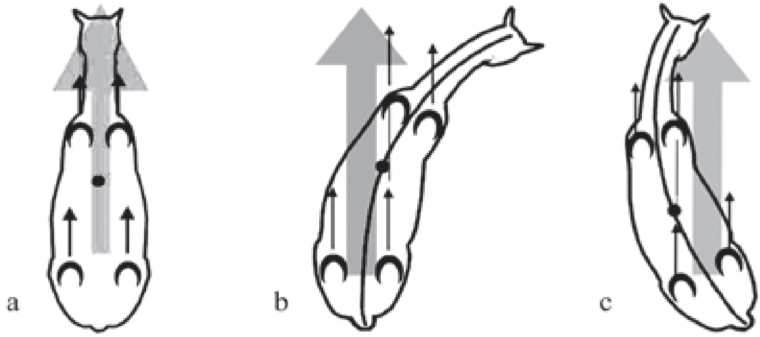

Figure 1
Body position of the horse and direction of movement during the 3 exercise conditions.
a. riding straight ahead;
b. shoulder-in;
c. travers.
The big arrows indicate the direction of movement of the horse;
The ∩ indicate the position of the horse's limbs and the small arrows indicate the direction of movement of the horse's limbs.
(http://www.sustainabledressage.com/collection/lateral.php)

Data analysis

The saddle force was calculated by summation of the magnitudes of the forces measured by the individual sensors of the saddle device that was placed underneath the saddle. Forces were calculated for the total surface and for the left and right half of the saddle device (de Cocq et al., 2009). The leg forces were calculated by summation of the magnitudes of the forces measured by specific areas of the saddle devices that had been placed on the left and the right side under the saddle flaps. These areas consisted of 11 rows by 8 columns of sensors (Fig. 2a).

As some riders performed the exercises on the left lead and others on the right lead, the measurements of the inside and the outside of the horse were grouped. The differences between inside and outside saddle and leg forces were determined by subtracting the inside forces from the outside force. Of each single trial the mean force was calculated. The force peaks of the data were identified by using a routine that marks a series of data points that are neighboured by at least eight points with lower values. From these force peaks the mean peak force was calculated. This mean peak force is called the maximum force. Furthermore, the data of the first trial of each horse rider combination of the total saddle surface, the inside and outside leg were imported into Matlab[2] and then power spectra of the signals were calculated using Fourier analysis. For the Fourier analyses all trials were sampled and a similar amount of time points (60) were used. The frequency with the highest power was called the main fundamental frequency.

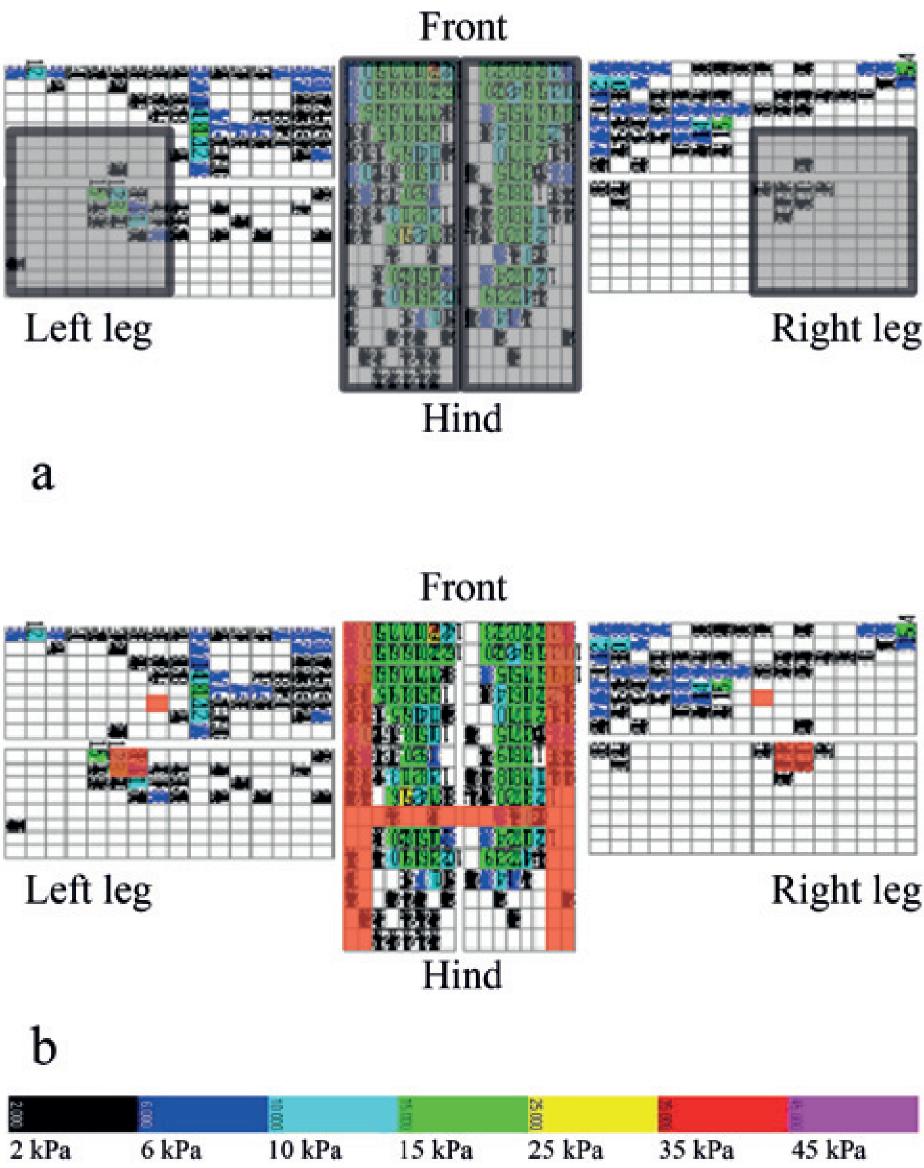

Figure 2
Specified areas for the saddle and leg force measurements.
a. the grey areas indicate the sensors that were used to measure leg and saddle force;
b. the red areas indicate malfunctioning sensors that were excluded from the analysis.

Statistics

Each trial consisted of five to six strides. All trials were judged by two independent national dressage judges on a scale from 0 to 10. The trails were judged on lateral bending, the number of tracks used, rhythm and the head and neck position. Trials with a mark above a 5.5 were considered correctly performed exercises. Mean ± sd were calculated from all six trials and for all correctly performed trials and all incorrectly performed trials for each horse rider combination at each condition. Data were checked for normality of distribution using a Kolmogorov-Smirnov test. Data were analyzed statistically in a GLM-repeated measures test followed by a *post hoc* Bonferroni test using SPSS software[3]. The condition (straight ahead, shoulder-in or travers) was the within-subject factor. The lead (right or left) was the between-subject factor. In case data were not distributed normally, the non-parametric Friedman test was used to test for differences between the conditions. If a significant difference was found with the Friedman test, a pairwise comparison was made using the Wilcoxon test. The differences between the left and right lead were tested using the Mann-Whitney test when data were not normally distributed. A p-value of < 0.05 was considered statistically significant.

Results

Calibration tests

The calibration results at the end of the first and second measurement day were within the accepted range (variation coefficient < 10%). The calibration results of the third day were, however, not acceptable. This problem was caused by malfunctioning sensors. These sensors were excluded from the data analysis for all horse-rider combinations (Fig. 2b).

Saddle force and leg force

Six riders rode on the right lead and five on the left lead. The pattern of the leg forces was irregular, while the pattern of the saddle forces had a rhythmic, regular appearance, as shown in the typical examples in Fig. 3. There were no significant differences, neither between riding on the right or left lead, nor between correctly and incorrectly performed exercises. Therefore, left and right, outside and inside data were pooled and the results of all trials are given.

Mean total saddle force was significantly lower (p = 0.006) when riding straight ahead (671 ± 143 N) than when riding shoulder-in (707 ± 150 N) or travers (726 ± 165 N). Mean inside saddle force was significantly higher (p = 0.003) when riding travers (468 ± 151 N) than when riding straight on (425 ± 121 N) or shoulder-in (413 ± 136 N). The difference in maximum saddle force between the outside and inside of the saddle was significantly higher (p = 0.038) when riding shoulder-in (75.0 ± 212.0)

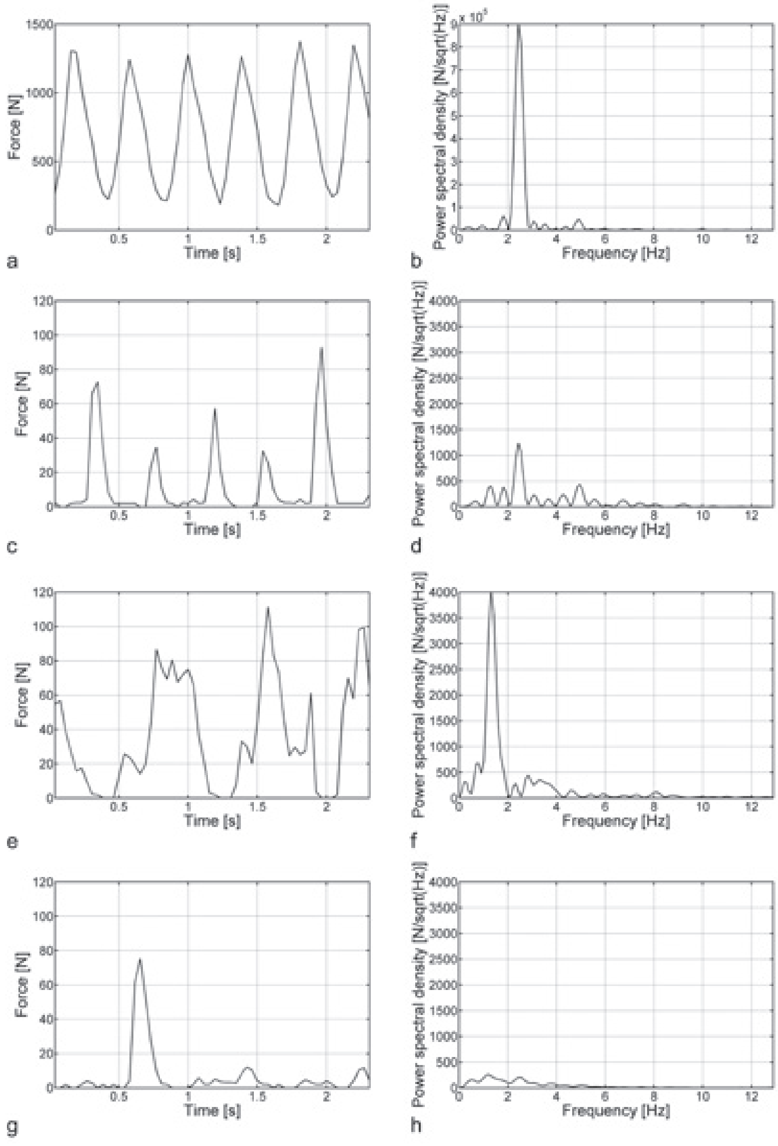

Figure 3 Typical examples of saddle and leg force patterns.

a. typical example saddle force pattern;
b. typical example power spectrum saddle force;
c. typical example leg force pattern, with one force peaks during each step;
d. typical example power spectrum leg force, with one force peaks during each step;
e. typical example leg force pattern, with one force peak during each stride;
f. typical example power spectrum leg force, with one force peak during each stride;
g. typical example leg force pattern, with low base value with irregular signals;
h. typical example power spectrum leg force, with low base values with irregular signals.

compared to riding straight on (38.3 ± 189.9) or travers (-3.4 ± 197.0). The main fundamental frequency of the total saddle force was 2.4-2.5 Hz and did not differ between the exercises (table 1). Maximum outside leg force was significantly higher ($p = 0.013$) when riding travers (47.2 ± 33.9 N) than when riding straight on (31.6 ± 24.1 N) or shoulder-in (34.2 ± 27.3 N). The main frequencies of the leg forces were lower and more variable compared to the saddle force (table 2).

Table 1 Saddle force while riding straight on, shoulder-in and travers (mean ± sd)

Variables	Straight on	Shoulder-in	Travers	p-value
Mean total saddle [N]	671± 143 [b]	707± 150 [a]	726 ± 165 [a]	0.006 *
Max total saddle [N]	1325± 247	1381 ± 336	1341 ± 251	0.913
Mean inside saddle [N]	425 ± 121 [a]	413 ± 136 [a]	468 ± 151 [b]	0.003 *
Max inside saddle [N]	817 ± 213	778 ± 213	833 ± 217	0.307
Mean outside saddle [N]	453 ± 102	469 ± 112	474 ± 115	0.761
Max outside saddle [N]	856 ± 142	853 ± 145	829 ± 154	0.913
Δ Mean saddle [N]	28.1 ± 116.0	55.6 ± 135.7	5.9 ± 134.2	0.103
Δ Maximum saddle [N]	38.3 ± 189.9 [a]	75.0 ± 212.0 [b]	-3.4 ± 197.0 [a]	0.038 *
Main fundamental frequency [Hz]	2.4 ± 0.1	2.5 ± 0.1	2.4 ± 0.2	0.337

Max is the mean peak force;
Δ is the difference between the outside and the inside force (outside minus inside);
* significantly different ($p < 0.05$, Bonferonni correction);
[ab] Values with different superscripts are significantly different.

Table 2 Rider leg force while riding straight on, shoulder-in and travers (mean ± sd)

Variables	Straight on	Shoulder-in	Travers	p-value
Mean inside leg [N]	17.6 ± 10.0	21.4 ± 12.6	20.7 ± 12.7	0.529
Max inside leg [N]	34.1 ± 20.3	42.1 ± 22.4	34.7 ± 18.2	0.529
Mean outside leg [N]	16.8 ± 23.6	21.0 ± 25.0	26.3 ± 28.7	0.060
Max outside leg [N]	31.6 ± 24.1 [a]	34.2 ± 27.3 [a]	47.2 ± 33.9 [b]	0.013 *
Δ Mean leg [N]	-0.8 ± 27.9	-0.4 ± 29.3	5.6 ± 31.4	0.178
Δ Maximum leg [N]	-2.4 ± 31.3	-7.9 ± 36.3	12.5 ± 38.0	0.078
Main fundamental frequency inside leg [Hz]	1.6 ± 0.8	1.8 ± 0.8	1.8 ± 0.7	0.697
Main fundamental frequency outside leg [Hz]	1.8 ± 0.6	2.0 ± 1.6	1.4 ± 0.8	0.723

Max is the mean peak force;
Δ is the difference between the outside and the inside force (outside minus inside);
* significantly different ($p < 0.05$, Bonferonni correction);
[ab] Values with the different superscripts are significantly different.

Discussion and Conclusion

This study showed that there were significant differences in force distribution over the saddle (measured indirectly as normal forces) in the different exercises performed, as is the force paradigm in the equestrian literature. For lateral movements in general, it has been postulated that the rider should always shift weight in the direction of movement of the horse (Stodulka, 2006). For the travers, in which the hind quarter is brought to the inside and the horse bents to the inside, this means that the weight shift should go towards the inside of the horse. This agrees indeed in the present study, as mean inside saddle force was significantly higher in the travers than in both other conditions and it was the only condition in which the mean difference between outside and inside force was negative. Shoulder-in is a more complicated topic. The riding literature states that it is the only exception to the rule, *i.e.* here more weight should be put on the inside where the opposite would be expected based on the general rule. It is said that an inward weight shift is necessary in this case to lower the inner hip, which would facilitate heavier loading of the inside hind limb (Stodulka, 2006). In the present study no such effect could be demonstrated. There was a slight tendency towards the opposite effect, as the outside-inside difference of the peak saddle force in the shoulder-in condition was significantly higher than in both other conditions.

There was a significant difference in mean total saddle force between riding straight and both the lateral gaits. This difference was unexpected as the mean vertical force of the rider remains the same in the three situations and there is no net vertical displacement of the riders. As the saddle system is curved on top of the horse's back, it does not only measure vertical forces, but also horizontal forces. It therefore seems that the riders are gripping onto the saddle using their thighs in both shoulder-in and travers. This would explain why the mean total saddle force was higher during these exercises.

The maximal outside leg force of the rider was higher in travers than during riding straight on or shoulder-in. During travers the hindquarters are set to the inside. Riders have to use their outside leg to support this position and to indicate the direction of movement (Hölzel et al., 1992). There were no other significant changes in leg forces. It should be noted that the variation in leg force magnitudes was high with standard deviations approaching the means in some cases. The leg force patterns as shown in Fig. 3 show that not only the force, but also the peak frequency of leg forces was highly variable. This figure demonstrates that the patterns of leg force are also very variable. This may well represent different strategies for using leg force by the individual riders. In general, the following patterns can be distinguished: a signal with each moving diagonal, a signal once during a stride cycle and very low base value with irregular signals. As the signals of the legs can be given independently of the movement of the horse, they may be better recognisable for the horse than signals emanating from changes in weight distribution. It would be interesting to investigate whether this type of patterns could be used for the assessment of rider quality.

During the experiment, problems occurred with malfunctioning sensors. These were identified during the calibration and henceforth removed from the analysis. Malfunctioning sensors is a common problem in saddle pressure analysis (Werner et al., 2002) and may in our case have been caused by a combination of sweat and folding of the saddle force system near the girth. It is therefore advisable to cover the saddle system with an extra water resistant cover and calibration tests seem imperative in this type of research to detect malfunctioning sensors. As removal of malfunctioning sensors results in lower force values, the malfunctioning sensors were removed from the whole data set in order to not influence the comparison between the three conditions.

It should be realised that the outcome of this study may have been influenced by the use of long-established horse-rider combinations that may have developed entirely or partly compensated asymmetries over time. Further, the riders were of a reasonable level, but not of international standard. Rider quality might also affect the outcome of saddle force measurements.

CONCLUSIONS: By applying state-of-the-art technology this study was able to measure, in terms of forces, weight and leg aids given in two lateral exercises as performed in dressage, compared to the standard situation of progression over a straight line with the longitudinal axis of the horse aligned to the line of progression. It appeared that leg aids were in line with expectations based on the equestrian literature, although inter-individual variation between riders was high. Shifts in weight distribution (as indicated by changes in normal saddle forces) were confirming the equestrian literature in travers too, but not when riding shoulder-in. Further and more detailed investigations into the exercise practiced in dressage are needed to confirm or falsify the empirically based theory behind this fascinating and heavily disputed equestrian discipline.

Acknowledgements

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Manufacturers' addresses

[1] Novel GmbH, Munich, Germany
[2] MathWorks, Natick, MA, USA
[3] SPSS Inc., Chicago, Illinois, USA

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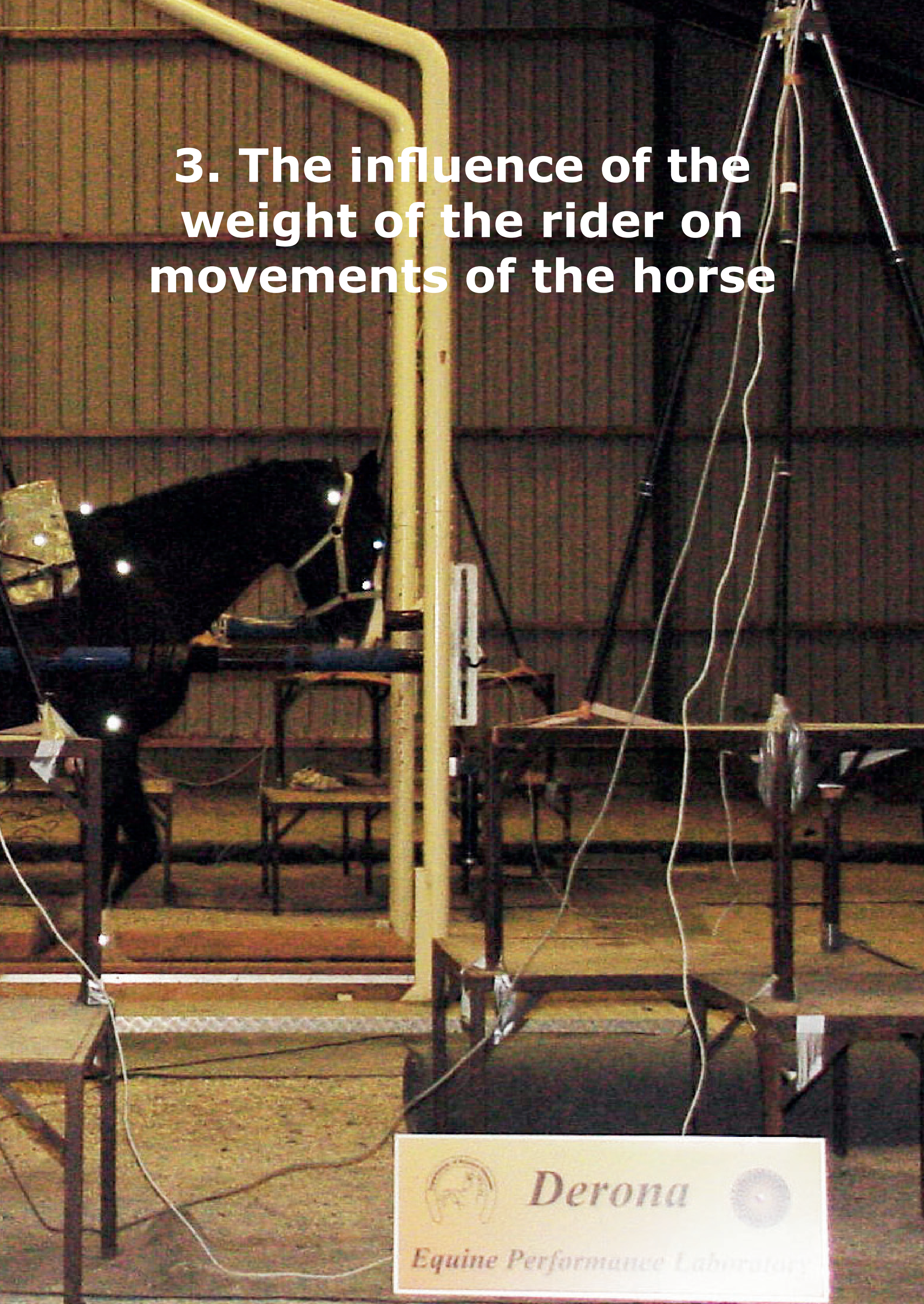
3. The influence of the weight of the rider on movements of the horse



3.1 The effect of girth, saddle and weight on movements of the horse.

Patricia de Cocq, P. René van Weeren and Willem Back

Equine Veterinary Journal, **36**, 758-763 (2004).

Summary

Reasons for performing study: Although the saddle is seen as one of the biggest causes of back pain, and weightbearing is seen as an important aetiological factor in 'kissing spine' syndrome (KSS), the effects of a saddle and weight on the back movements of the horse have never been studied.

Objective: To determine the effects of pressure on the back, exerted by tack and weight, on movements of the horse.

Hypothesis: Weight has an extending effect on the horse's back and, as a compensatory mechanism to this extension, an alteration in pro- and retraction angles was expected. A similar but smaller effect was expected from a saddle only and a lungeing girth.

Methods: Data were captured during treadmill locomotion at walk, trot and canter under 4 conditions: unloaded; with lungeing girth; saddle only; and saddle with 75 kg of weight. Data were expressed as maximal extension, maximal flexion angles, range of motion of L3 and L5 and maximal pro- and retraction angles of the limbs.

Results: At walk and trot, there was a significant influence on back kinematics in the 'saddle with weight' situation, but not in the other conditions. Overall extension of the back increased, but the range of movement remained the same. Limb kinematics changed in the sense that forelimb retraction increased. At canter, both the 'saddle with weight' and 'saddle only' conditions had a significant extending effect on the back, but there was no effect on limb kinematics.

Conclusions and potential relevance: Weight and a saddle induce an overall extension of the back. This may contribute to soft tissue injuries and the KSS. The data from this study may help in understanding the reaction of the equine back to the challenges imposed by man when using the animal for riding.

Keywords: equine; back; kinematics; load; tack; kissing spine

Introduction

Back pain is one of the most common and least understood clinical problems in horses. Causes are hard to identify but, as an important cause or aggregator, poorly fitting saddles are often mentioned (Harman, 1999).

'Cold back', a syndrome of persistent hypersensitivity with temporary stiffness and dipping of the spine on being saddled, is seen as a sign of saddle-fitting problems (Harman, 1999). Whether 'cold back' is actually painful, associated with some previous back pain or merely a matter of temperament is unclear (Jeffcott, 1999). It is a fact that soft tissue injuries are important causes of back pain. Muscle damage and ligamentous strain are seen in about 25% of horses with back pain and are often related to accidents during ridden exercise (Jeffcott, 1980). Chronic muscle or ligamentous pain could be caused or made worse by the pressure that a saddle with a rider puts on the muscles and ligaments.

Of the bony pathological conditions, crowding and overriding of the dorsal spinous processes or 'kissing spine' syndrome (KSS) is a common condition that may cause back problems. The lesions are detected most frequently in the saddlebearing area, between the 12^{th} and 18^{th} vertebrae (Jeffcott, 1980; Walmsley et al., 2002). It can be diagnosed in about 30% of the healthy horse population (Jeffcott, 1980) and it also occurred in the extinct horse *Equus occidentalis* (Klide, 1989). Clinically relevant KSS usually has a higher degree of severity in radiological findings (Jeffcott, 1980). The incidence of KSS is related to the type of work, probably to the amount of extension of the back required (Jeffcott, 1980). One of the causes of KSS is thought to be weightbearing and other stresses inflicted on horses by the rider.

The kinematics of the back have long been unexplored, because the subtle movements are difficult to capture with the human eye and the back is difficult to access with kinematic analysis techniques. The normal movement range of the equine back has been studied *in vitro* (Townsend et al., 1983; Townsend and Leach, 1984; Denoix, 1987). Recently, the normal back movements of the horse in stance and in motion have also been studied *in vivo* (Pourcelot et al., 1998; Licka and Peham, 1998; Audigié et al., 1999; Faber et al., 2000, 2001a,b; Haussler et al., 2001; Licka et al., 2001). The effects of high-speed trotting (Robert et al., 2001) and of conformational aspects on back movements (Johnston et al., 2002) have been studied. The effect of manual therapy has been evaluated in a case study (Faber et al., 2003).

The effects of a saddle and weight on the back-movements of the horse have never ben studied, we therefore focused on the analysis of the influence of tack (lungeing girth, saddle) and weight (saddle with 75 kg of lead) on back-movements and locomotion in general.

Materials and methods

Horses

Nine Dutch Warmblood horses were used (8 mares and 1 gelding, mean age 9.4 years, mean weight 568 kg). The horses were clinically sound, had no apparent back problems, had comparable conformation and athletic ability and were in daily use by the Veterinary Students' Riding Association. Four horses were fully accustomed to the treadmill[1] as a result of earlier kinematic research. These horses underwent at least 5 training sessions with saddle or saddle with weight before the measurements started. Five horses had no prior experience on the treadmill. These horses underwent at least 15 training sessions beforehand, from which at least 5 sessions were with saddle or saddle and weight. None of the horses showed signs of 'cold back'.

Tack

The same standard 17" (43 cm) dressage saddle (7 kg) and a standard lungeing girth were used on all horses. The same saddle was used in the situations with and without weight. In the latter condition, 2 bags each with 15 kg lead were attached to the stirrup bars of the saddle. Additionally, 2 lead flaps 22.5 kg were shaped similarly to the saddle and attached on top of it using safety belts and a lungeing girth (total additional weight 75 kg). To avoid any confounding effects of differences in tightening, the lungeing girth and saddle were always tightened by the same person and the saddle was tightened equally in both saddle only and saddle with weight situations.

Marker placement

The positions of the dorsal spinal processes of L1, L3, L5 and S3 were identified by palpation and used for marker placement (Faber et al., 2001c, 2002, Fig 1). Identical marker position in all conditions was ensured by shaving small areas. At these positions, spherical, reflective markers (19 mm diameter) were placed. As marker positions for determination of pro- and retraction angles, the proximal spina scapula, lateral collateral ligaments of the metacarpo- or metatarsophalangeal joints over the centre of rotation of the joint, and the cranial part of the trochanter major of the femur were used (Back et al., 1995a,b, Fig 1). For these marker positions, round, flat, reflective markers (18 mm diameter) were used and left on the horses between measurements.

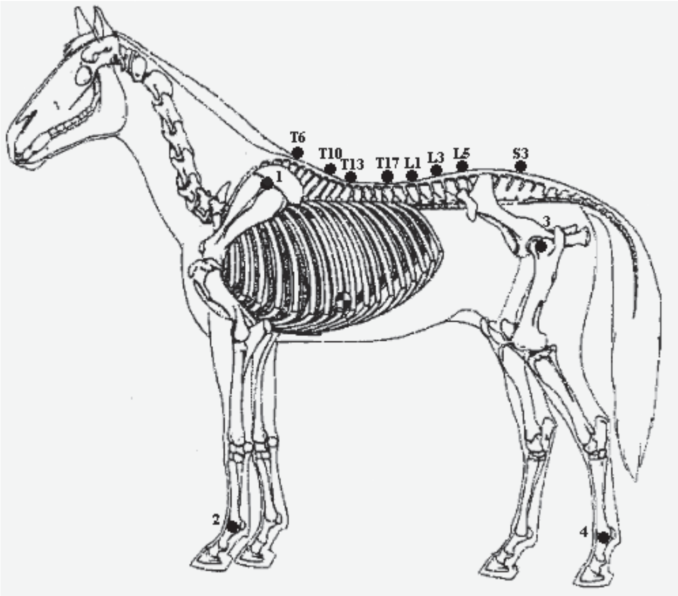


Figure 1
Marker placement on back and limbs.
Lumbar vertebrae 1, 3 and 5; Sacral vertebra 3
1 = Proximal spina scapula; 2 = Lateral collateral ligament of the metacarpophalangeal joint; 3 = Cranial part of the trochanter major of the femur; 4 = Lateral collateral ligament of the metatarsophalangeal joint

Data-collection

A modern, commercially available analysing system (ProReflex)[2] was used. The system consists of 6 cameras and is based on passive infrared reflective markers and infrared cameras. Calibration of the system is performed dynamically, using a calibration frame that defines the orientation of the coordinate system and a wand with a defined length. The positive y-axis was orientated in the line of progression, parallel to the treadmill. The positive z-axis was orientated upward and the positive x-axis was orientated perpendicular to the y- and z-axes. The cameras were placed around the treadmill to obtain a field of view of 1.3 x 4.0 x 2.5 m. The system's inaccuracy in identifying the location of markers in this set-up was less than 1.4%.

All horses had a 15 min warm-up period just before the measurements, which were performed under 4 conditions: unloaded; with lungeing girth; with saddle only; with saddle and weight (Fig 2). The order of the conditions was assigned randomly. For each horse under each condition, movement was captured in steady state locomotion at walk (1.6 m/sec) for 10 secs, and at trot (4.0 m/sec) and canter (7.0 m/sec) for 5 secs at a sample rate of 240 Hz.

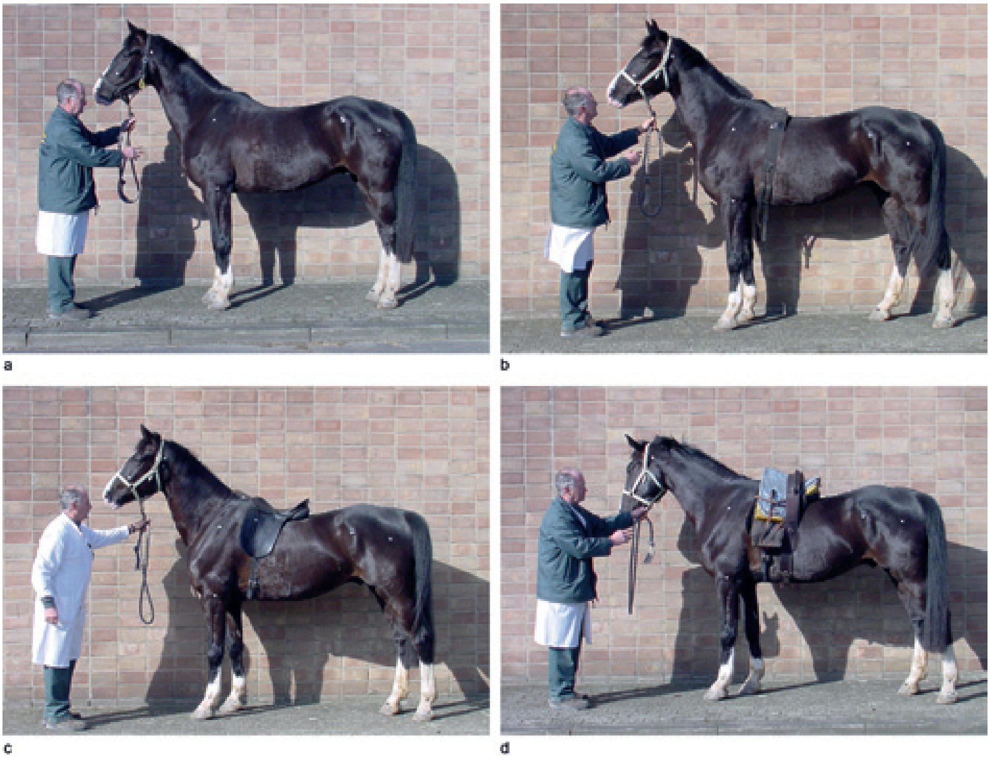


Figure 2
Pictures of all four situations:
a = Unloaded; b = Girth; c = Saddle; d = Saddle with 75 kg of lead

Data-analysis

The reconstruction of the 3D position of each marker is based on a direct linear transformation algorithm (Q Track)[2]. The raw coordinates were exported into Excel[3] for further data analysis.

Individual stride cycles were determined,with the beginning of each stride cycle defined as the moment of hoof contact of the left hindlimb in walk and trot, or the trailing hindlimb in canter. Detection of the moment of hoof contact was based on the horizontal velocity profile of the marker on the metatarsophalangeal joint (Peham et al., 1999).

The back movements and pro- and retraction angles of the legs were calculated using the y and z marker coordinates. The back movements were calculated using a method that was developed and tested for validity and repeatability by Faber et al. (2001c, 2002); briefly, the flexion-extension angular movement pattern (AMP) of a given vertebra (V2) is calculated from the position of the adjacent cranial (V1) and caudal (V3) markers. The AMP of V2 is represented by the orientation of the line

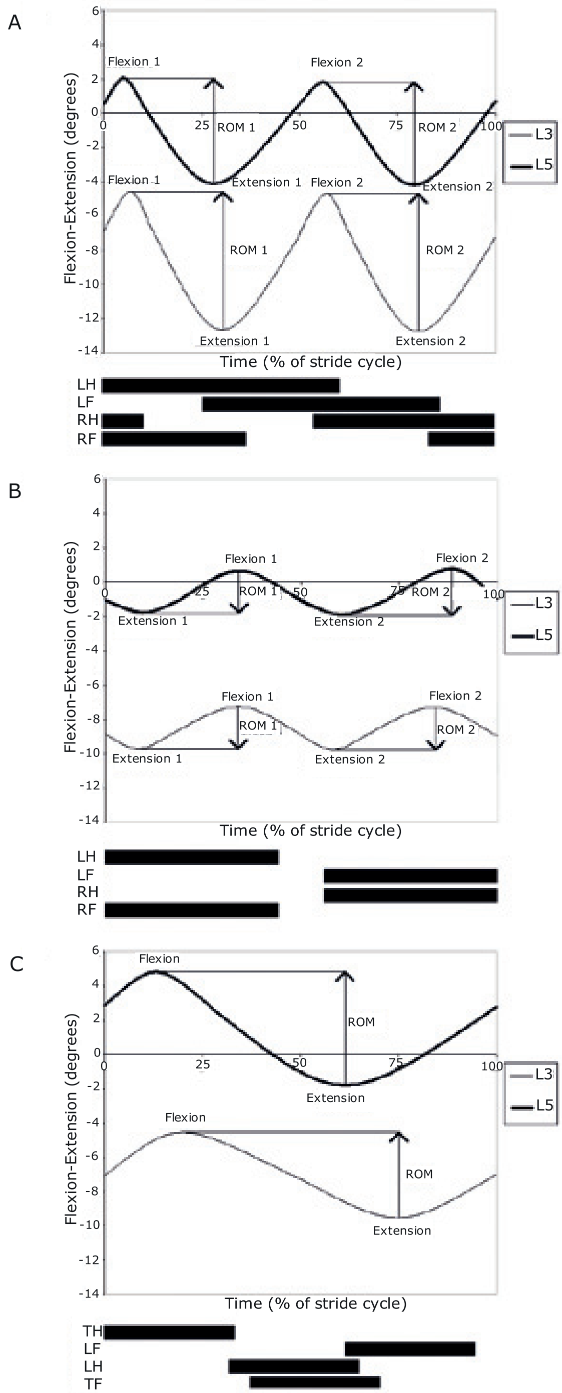


Figure 3 Process data analysis
Angular movement patterns of L3 and L5 in walk (A), trot (B) and canter (C)
L3: lumbar vertebrae 3; L5: lumbar vertebrae 5
max extension: maximal extension angle of the vertebrae; max flexion: maximal flexion angle of the vertebrae; ROM: range of motion of the vertebrae
1: first half of the stride cycle; 2: second half of the stride cycle
LH: left hind limb; LF: left fore limb; RH: right hind limb; RF: right fore limb
TH: trailing hind limb; LF: leading fore limb; LH: leading hind limb; TF: trailing fore limb.

through V1 and V3. The maximal flexion, maximal extension and range of motion (ROM) (difference between maximal flexion and maximal extension) of L3 and L5 were used as variables for further analysis (Fig 3). Pro- and retraction angles of the forelimbs were defined as the maximal angles between the line connecting the markers on the proximal spina scapula and on the metacarpophalangeal joint and a vertical line. Pro- and retraction angles of the hindlimbs were defined in a similar fashion using the markers on the cranial part of the trochanter major of the femur and on the metatarsophalangeal joint.

Stastistics

Means ± standard deviation (sd) were calculated from the first four usable strides. A stride was unusable when marker losses occurred during this stride. Data were excluded from further analysis if not enough usable strides were available. Data were analysed statistically in an ANOVA-repeated measurement test followed by a *post hoc* Bonferroni test using SPSS[4] software. A p-value of ≤ 0.05 was considered statistically significant.

Results

Data for maximal flexion, maximal extension and the resulting range of motion for L3 and L5 at walk, trot and canter are given in Tables 1, 2 and 3, along with pro- and retraction angles for front and hindlimbs. Significance of differences has been indicated.

While no influence on any of the variables measured at walk was seen in the situations with a lungeing girth or a saddle only, an overall extension of the back, represented by a decrease in the maximum flexion and extension angles of L3 and L5, was provoked by a saddle with weight, whereas the range of motion of the back appeared unaffected (Fig 4). An increase in the retraction angle of the forelimb was caused by the saddle with weight.

The situation was comparable at trot and canter, with an overall decrease in flexion and extension angles in the 'saddle with weight' condition and no effect on the range of motion. At trot, the increase in retraction angle of the forelimb was accompanied by (smaller) increases in retraction angle of the hindlimb and in protraction angle in the forelimb. At canter, a smaller decrease in maximal flexion angles of L3 and L5 could also be seen in the 'saddle only' situation, but there was no influence on pro- and retraction angles.

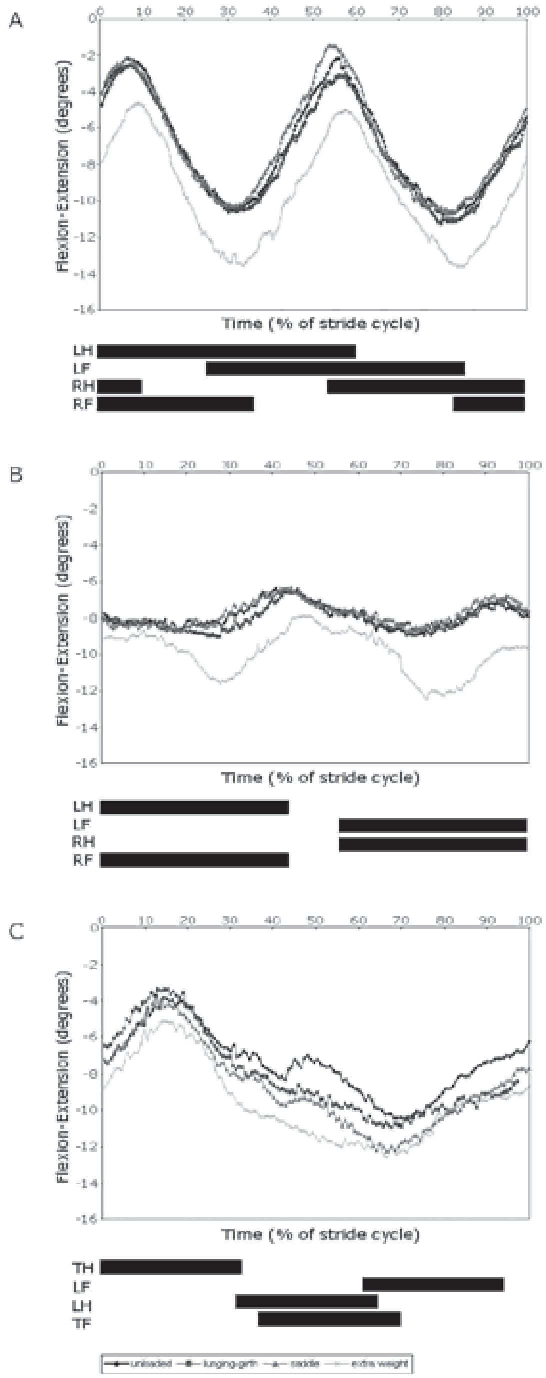


Figure 4 Typical example of the angular movement patterns of L3 in walk (A), trot (B) and canter (C), during one stride of one horse in all four situations. LH: left hind limb; LF: left fore limb; RH: right hind limb; RF: right fore limb
TH: trailing hind limb; LF: leading fore limb; LH: leading hind limb; TF: trailing fore limb

Tabel 1 Kinematical variables at the walk

Variables	Unloaded (º)	Girth (º)	Saddle (º)	Saddle + 75 kg (º)	p-value
L3 max extension 1	-11.2 ± 0.6 a	-11.3 ± 0.7 a	-11.5 ± 0.6 a	-13.9 ± 0.6 b	< 0.001
L3 max flexion 1	-4.0 ± 0.5 a	-4.1 ± 0.6 a	-4.2 ± 0.6 a	-6.5 ± 0.6 b	< 0.001
L3 ROM 1	7.2 ± 0.3	7.1 ± 0.3	7.2 ± 0.3	7.4 ± 0.4	0.885 NS
L5 max extension1	-4.5 ± 0.6 a	-4.4 ± 0.7 a	-4.6 ± 0.6 a	-6.3 ± 0.6 b	< 0.001
L5 max flexion 1	1.2 ± 0.7 a	1.4 ± 0.6 a	1.1 ± 0.6 a	-0.9 ± 0.7 b	< 0.001
L5 ROM 1	5.7 ± 0.4	5.7 ± 0.4	5.7 ± 0.5	5.5 ± 0.5	0.764 NS
Protraction fore	24.7 ± 0.7	24.4 ± 0.4	24.3 ± 0.4	24.2 ± 0.6	0.171 NS #
Retraction fore	18.5 ± 0.5 a	18.1 ± 0.7 a	18.4 ± 0.5 a	19.4 ± 0.6 b	0.002
Protraction hind	25.6 ± 0.6	25.1 ± 0.7	25.6 ± 0.5	26.2 ± 0.4	0.062 NS
Retraction hind	21.6 ± 0.6	20.9 ± 0.8	21.3 ± 0.7	21.2 ± 0.7	0.773 NS

Data are expressed as mean ± sd
L3: lumbar vertebrae 3; L5: lumbar vertebrae 5; max extension: maximal extension angle of the vertebrae; max flexion: maximal flexion angle of the vertebrae; ROM: range of motion of the vertebrae; 1: data of first half of the stride cycle, data of the second half of the stride cycle are similar; fore: forelimb; hind: hindlimb: data of the right hand side of the horse, data of the left hand side are similar; NS: no significant difference between groups ($p \leq 0.05$); ab : mean ± sd with same letter are not significantly different ($p \leq 0.05$, Bonferroni correction); # data of only 8 horses was used.

Tabel 2 Kinematical variables at the trot

Variables	Unloaded (º)	Girth (º)	Saddle (º)	Saddle + 75 kg (º)	p-value
L3 max extension1	-9.8 ± 0.6 a	-9.8 ± 0.6 a	-9.8 ± 0.7 a	-11.8 ± 0.9 b	0.050
L3 max flexion 1	-5.8 ± 0.6 a	-5.9 ± 0.6 a	-5.8 ± 0.6 a	-7.8 ± 0.7 b	0.002
L3 ROM 1	3.9 ± 0.5	4.0 ± 0.4	4.1 ± 0.6	4.0 ± 0.6	0.807 NS #
L5 max extension 1	-3.2 ± 0.8	-3.1 ± 0.9	-3.3 ± 0.8	-4.4 ± 0.9	0.080 NS
L5 max flexion 1	0.0 ± 0.8 a	0.1 ± 0.9 a	0.0 ± 0.8 a	-1.4 ± 0.8 b	0.008
L5 ROM 1	3.2 ± 0.4	3.3 ± 0.3	3.3 ± 0.5	3.1 ± 0.4	0.109 NS
Protraction fore	20.4 ± 0.6 a	20.7 ± 0.6 a	21.0 ± 0.7 a	21.8 ± 0.6 b	0.005
Retraction fore	18.4 ± 0.6 a	18.5 ± 0.6 a	18.6 ± 0.6 a	20.5 ± 0.6 b	0.002 #
Protraction hind	23.6 ± 0.4	23.7 ± 0.5	24.1 ± 0.5	24.6 ± 0.5	0.332 NS
Retraction hind	18.6 ± 0.4 a	18.7 ± 0.4 a	18.8 ± 0.4 ab	19.3 ± 0.4 b	0.003

Data are expressed as mean ± sd
L3: lumbar vertebrae 3; L5: lumbar vertebrae 5;max extension: maximal extension angle of the vertebrae; max flexion: maximal flexion angle of the vertebrae; ROM: range of motion of the vertebrae; 1: data of first half of the stride cycle, data of the second half of the stride cycle are similar; fore: forelimb; hind: hindlimb: data of the right hand side of the horse, data of the left hand side are similar; NS: no significant difference between groups ($p \leq 0.05$); ab : mean ± sd with same letter are not significantly different ($p \leq 0.05$, Bonferroni correction); # data of only 8 horses was used.

Tabel 3 Kinematical variables at the canter

Variables	Unloaded (º)	Girth (º)	Saddle (º)	Saddle + 75 kg (º)	p-value
L3 max extension	-9.3 ± 0.8 [a]	-9.4 ± 0.7 [a]	-10.4 ± 0.9 [a]	-12.2 ± 0.7 [b]	0.022
L3 max flexion	-3.7 ± 0.5 [a]	-4.0 ± 0.5 [ab]	-4.4 ± 0.6[b]	-5.0 ± 0.5 [b]	0.021
L3 ROM	5.6 ± 0.4	5.4 ± 0.4	6.0 ± 0.5	7.3 ± 0.6	0.065 NS
L5 max extension	-3.5 ± 1.0 [a]	-3.5 ± 0.9 [a]	-4.0 ± 1.0 [a]	-5.8 ± 0.8 [b]	0.031
L5 max flexion	4.8 ± 0.7 [a]	4.4 ± 0.8 [ab]	4.2 ± 0.8 [b]	3.8 ± 0.7 [b]	0.033
L5 ROM	8.3 ± 0.5	8.0 ± 0.4	8.2 ± 0.5	9.6 ± 0.4	0.207 NS
Protraction lf	20.4 ± 0.9	19.8 ± 0.7	19.4 ± 1.0	21.7 ± 1.2	0.177 NS #
Retraction lf	30.9 ± 1.1	31.2 ± 1.3	31.1 ± 1.3	31.8 ± 1.5	0.653 NS ##
Protraction th	33.8 ± 1.0	33.9 ± 1.1	33.4 ± 1.3	33.2 ± 2.0	0.945 NS ###
Retraction th	21.0 ± 1.2	20.6 ± 1.0	21.1 ± 1.1	21.4 ± 1.2	0.750 NS

Data are expressed as mean ± sd
L3: lumbar vertebrae 3; L5: lumbar vertebrae 5; max extension: maximal extension angle of the vertebrae; max flexion: maximal flexion angle of the vertebrae; ROM: range of motion of the vertebrae; lf: leading forelimb; th: trailing hindlimb; due to frequent marker losses data of the trailing forelimb and the leading hindlimb are not listed; NS: no significant difference between groups ($p \leq 0.05$); [ab] : mean ± sd with same letter are not significantly different ($p \leq 0.05$, Bonferroni correction); # Data of only 8 horses was used; ## Data of only 7 horses was used; ### Data of only 5 horses was used.

Discussion

No other studies on the changes in back movements caused by a saddle and weight exist, but there are models on back biomechanics. There is common agreement that the bow-and string concept as proposed by Slijper (1946) is the best biomechanical model for the back of the horse (Jeffcott, 1979). In this concept, the bow (thoracolumbar spine with adnexa) forms a functional entity with the string (abdominal muscles, *linea alba*). There are several factors that increase tension in the bow (*i.e.* flex the back), or decrease tension (*i.e.* extend the back), among which limb action is one of the most important. There is a tight connection between limb movements and excursions of the back, due to the continuity of soft tissue structures such as the common aponeurosis of the longissimus dorsi muscle (which is one of the most powerful muscles influencing back motion) and the middle gluteal muscle (which is instrumental for propulsion) (Dyce et al., 1996). Protraction of the forelimbs extends the back, as does retraction of the hindlimbs. Retraction of the forelimbs and protraction of the hindlimbs have the opposite effect (Jeffcott, 1979).

Another important factor in the bow-and-string concept not included in this study is the position of the head. The head acts as an attached beam supported at one end only. This beam receives additional support from the cervical muscles and the nuchal ligament. The tail represents a similar beam, but is of much less biomechanical importance (Jeffcott, 1979).

The weight used in this study (75 kg) is representative of the average rider. It may be argued that it is dead weight and not comparable to a rider. A study using a force-plate demonstrated that, compared with a sandbag, a rider was able to shift part of the weight towards the hindlimbs (Schamhardt et al., 1991). This may mean that, compared with a rider, the 'saddle with weight' situation will have more impact on the forelimbs. However, in kinematic studies on treadmill locomotion of horses with lead saddles and riders of the same weight, no significant differences could be demonstrated between the 2 conditions (Sloet van Oldruitenborgh-Oosterbaan et al., 1995, 1997). Therefore, we feel confident that the 'saddle with weight' condition sufficiently simulated a saddle with rider.

Saddling a horse influenced back movement at walk and trot only when at the same time the horse's back was challenged with a considerable weight. Although perhaps obvious at first sight, this observation means that tightening a girth around the horse's chest, thereby exerting pressure on the sternum and the withers, does not measurably influence back-movement. Girth tension has been related to reduced respiratory performance (Bowers and Slocombe, 1999), but there seems to be no biomechanical restriction to locomotion.

The reduction in maximal flexion of the angles of L3 and L5 seen in the canter in the condition with a saddle only, may be explained by the bigger and faster vertical movement of the back of the horse causing a larger acceleration of the saddle resulting in a higher impact on the back due to inertial forces, compared to walk and trot.

The influence of a saddle with weight can best be described as an overall extension or 'hollowing' of the back. Both maximal flexion and maximal extension angles decreased and ranges of motion remained unchanged. This suggests that loading a horse's back to the degree used in this study does not restrict the mobility of the back and hence will probably not significantly affect athletic potential. However, it should be understood that it slightly affects the conformation of the vertebral column and therefore the internal forces in this and adjacent anatomical structures. A slightly more extended back leads to a closer position of the spinous processes of the thoracolumbar vertebrae. This effect can be expected to be largest in the area where ventrodorsal flexion/extension excursions are largest, *i.e.* the last part of the thoracic vertebral column (Faber et al., 2000), which is the region where lesions associated with dorsal spinous processes of vertebral bodies are most frequently encountered (Jeffcott, 1980; Walmsley et al., 2002). Further, the altered anatomical situation when loaded with a saddle with weight also leads to other stresses and tensions in the many ligaments and muscles that make up the equine back. It is clear that these alterations will not invariably lead to clinical problems, but they may represent a predisposing factor, just as in the case of kissing spines.

For evaluation of the effect of a saddle with weight on locomotion (pro- and retraction), the back should be considered in the context of the entire animal. In order to counteract the extension of the back seen in the saddle with weight situation, an increased retraction of the forelimbs and protraction of the hindlimbs can be expected. In the present study, it seemed that the horses sought to counteract this influence by adapting the gait such that the retraction angle of the forelimbs increased. Apparently the forelimbs take the lead in this compensatory mechanism, which may be unsurprising as it is known that in the horse the forelimbs support 60% of bodyweight (Merkens et al., 1985). At trot there is also an increase in retraction angle of the forelimbs, but accompanied by lesser increases in retraction angle of the hindlimbs and protraction angle of the forelimbs. These latter changes seem contradictory, but become logical when considering that the trot is a gait where, unlike the situation at walk, there is a tight coupling between front and hindlimb movement and between the movements of the contralateral limb pairs. A significant increase in retraction angle of the forelimb at trot will lead to some increase of retraction angle of the contralateral hindlimb if the limbs are to remain in phase. Similarly, an increase in retraction angle of a forelimb, which results in a slight increase in retraction time if speed remains the same, may influence the simultaneous protraction of the contralateral forelimb. At canter, no effects on locomotion were noted. There may be methodological explanations for this asymmetrical gait, asymmetries in marker placement may have more effect and shifting of horses from the y-axis occurs earlier (Audigié et al., 1998). Further, because of frequent marker losses at this gait, not all horses could be used in the data analysis.

In conclusion, it seems intuitive that increased weight on the back might cause extension of the spine. This study confirms that loading of the dorsal back region with weights of the order experienced in competition does influence posture during exercise. An overall extending effect on the back, but no effect on mobility, was observed. Although no causal relationship can be concluded from this study, these changes in back motion are consistent with those allegedly implicated in the pathogenesis of kissing spines. It seems that the horse tries to compensate for the extending effect of the saddle by increasing retraction of the forelimbs.

Manufacturers' addresses

[1] Kagra AG, Fahrwangen, Switzerland
[2] Qualysis AB, Sävedalen, Sweden
[3] Microsoft Corporation, Redmond, WA, USA
[4] SPSS Inc., Chicago, Illinois, USA

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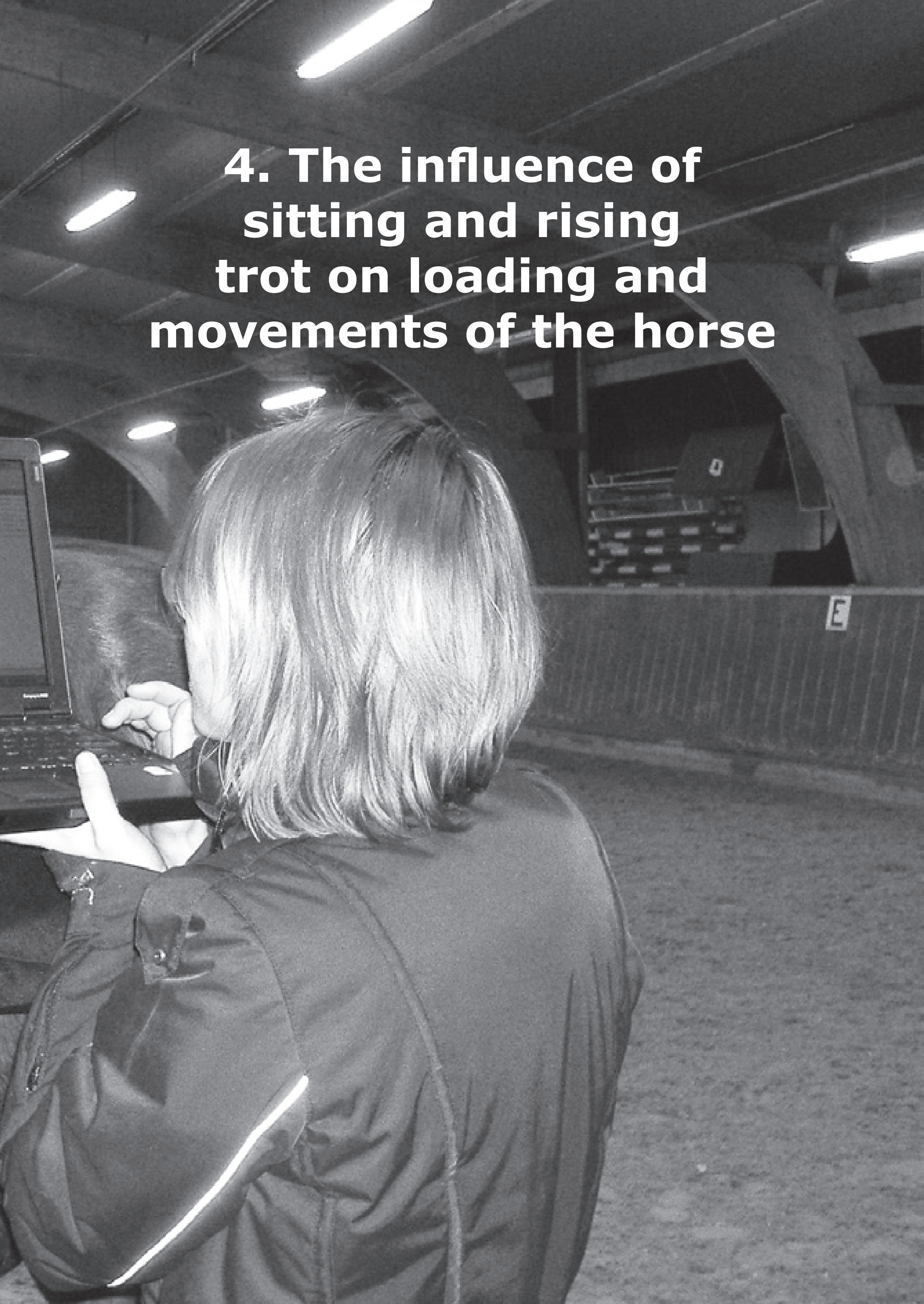
4. The influence of sitting and rising trot on loading and movements of the horse



4.1 The effect of rising and sitting trot on back movements and head-neck position of the horse.

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Summary

Reason for performing study: During trot, the rider can either rise from the saddle during every stride or remain seated. Rising trot is used frequently because it is widely assumed that it decreases the loading of the equine back. This has, however, not been demonstrated in an objective study.

Objective: To determine the effects of rising and sitting trot on the movements of the horse.

Hypothesis: Sitting trot has more extending effect on the horse's back than rising trot and also results in a higher head and neck position.

Methods: Twelve horses and one rider were used. Kinematic data were captured at trot during over ground locomotion under 3 conditions: unloaded, rising trot and sitting trot. Back movements were calculated using a previously described method with a correction for trunk position. Headneck position was expressed as extension and flexion of C1, C3 and C6, and vertical displacement of C1 and the bit.

Results: Sitting trot had an overall extending effect on the back of horses when compared to the unloaded situation. In rising trot: the maximal flexion of the back was similar to the unloaded situation, while the maximal extension was similar to sitting trot; lateral bending of the back was larger than during the unloaded situation and sitting trot; and the horses held their heads lower than in the other conditions. The angle of C6 was more flexed in rising than in sitting trot.

Conclusions and clinical relevance: The back movement during rising trot showed characteristics of both sitting trot and the unloaded condition. As the same maximal extension of the back is reached during rising and sitting trot, there is no reason to believe that rising trot was less challenging for the back.

Keywords: horse, back kinematics, rider, equitation

Introduction

Back problems are diagnosed more frequently nowadays in many equestrian sports, resulting in a growing interest in the study of back kinematics (Audigié et al., 1999; van Weeren, 2006). Next to an improper saddle fit, insufficient riding technique is often mentioned as a cause of back problems (Harman, 1999). At trot, the rider can choose between two different riding styles: rising trot and sitting trot. The difference between these riding styles is that the rider rises every stride cycle in rising trot and remains seated in the saddle in sitting trot. A general belief in the equestrian world is that rising trot loads the back of the horse less than sitting trot, as rising trot is believed to correspond more to the natural movements of the horse. It is therefore used to train young horses and in the warming-up period of a training session.

Since the development of a method to evaluate 3D back movements (Faber et al., 2001, 2002), several studies on factors that may affect back movements have been performed. These studies focused on the effect of different therapies (Faber et al., 2003; Haussler et al., 2007; Gómez Álvarez et al., 2008b), conformation (Johnston et al., 2002), saddle and weight (de Cocq et al., 2004), clinical back pain (Wennerstrand et al., 2004), head and neck position (Rhodin et al., 2005; Gómez Álvarez et al., 2006) and the relation between back problems and lameness (Gómez Álvarez et al., 2007, 2008a).

Unfortunately, studies on the interaction between rider and horse are limited. The existing studies include investigations of the influence of the rider on jumping performance of the horse (Merkens et al., 1991; Clayton, 1997; Powers and Harrison, 2002), the rider's weight (Schamhardt et al., 1991; Sloet van Oldruitenborgh-Oosterbaan et al., 1995, 1997; Clayton, 1997, Clayton et al., 1999; Nielsen et al., 2002; de Cocq et al., 2004; Peham and Schobesberger, 2004;), and of the effect of reins and bits (Cook, 1999; Biau et al., 2002; Roepstorff et al., 2002). Studies on riding style or riding techniques are relatively few (Summerley et al., 1998; Licka et al., 2004; Peham et al., 2004). Earlier studies on rising and sitting trot have focused on the kinematics of the rider, not of the horse (Schills et al., 1993, Lovett et al., 2005).

This study focuses on the effect of rising and sitting trot on kinematics of the equine back. It was hypothesised that overall extension of the back would be less in rising trot than in sitting trot, which would support the common belief that rising trot is less demanding for the equine back. Since the head-neck position has a direct effect on back kinematics (Rhodin et al., 2005; Gómez Álvarez et al., 2006), head-neck positions were measured together with 3D back movements.

Materials and methods

Horses and rider

Twelve Dutch Warmblood horses were used (3 mares and 9 geldings, age 11 ± 4 years, weight 563 ± 17 kg, height at the withers 1.65 ± 0.02 m). The horses were clinically sound, had no apparent back problems, were of comparable conformation and athletic ability and were in daily use by the Dutch Equestrian Centre.

One male rider weighing 84 kg was selected for the experiment. His riding level was intermediate.

Data collection

Measurements were performed using the infrared-based ProReflex automated gait analysis system[1], operating at 240 Hz.

For the evaluation of back movements, spherical infrared light reflective markers with a diameter of 30 mm were glued on to the skin over the spinous processes of the thoracic vertebra 6 (T6), lumbar vertebra 1, 3 and 5 (L1, L3, L5), and the spinous process of the 3rd sacral segment (S3). For the evaluation of the head-neck position, spherical markers with a diameter of 19 mm were glued on to the skin at the left side of bit, the left crista facialis (cranial edge) and the left side of cervical vertebra 1, 3 and 6 (C1, C3, C6) (Fig. 1). For determination of the stride cycle, flat markers with a diameter of 40 mm were glued on the lateral side of the left front and hind hooves and the medial side of the right front and hind hooves.

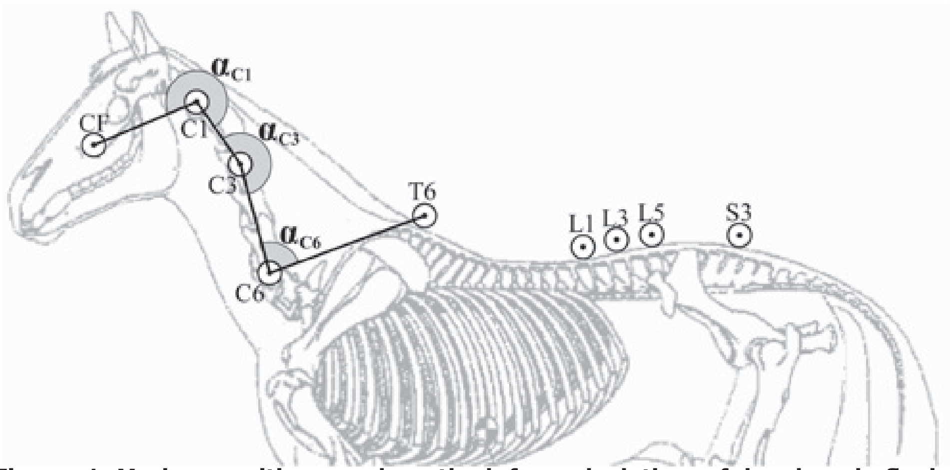

Figure 1 Marker positions and method for calculation of head-neck flexion-extension angles
An explanation of the calculation of the back angles is given in Fig. 2.
α_{C1}: angle between *crista facialis* (CF), C1 and C3; α_{C3}: angle between C1, C3 and C6; α_{C6}: angle between C3, C6 and T6; CF: *crista facialis*; C1: cervical vertebra 1;C3: cervical vertebra 3;C6: cervical vertebra 6; T6: thoracic vertebra 6; L1: lumbar vertebra 1, L3: lumbar vertebra 3; L5: lumbar vertebra 5; S3: sacral vertebra 3.

Six infrared cameras were positioned left of the measurement volume (6.4 m long x 1.5 m wide x 2.5 m high). A standard right-handed orthogonal Cartesian coordinate system was used. The positive y-axis was orientated in the line of progression of the horse. The positive z-axis was orientated upward and the positive x-axis was orientated perpendicular to the y- and z-axes. The marker locations were recorded while the horses were standing square and at trot in three conditions: unloaded (hand-led without rider) trot, rising trot and sitting trot. The order of the three conditions was randomised. Before the measurement the horses had a warming-up period of 10 to 15 minutes. The warming-up period included 5 minutes of walk and 5 to 10 minutes of trot on both reins. Infrared gates connected to a time registration system were used to control the speed. The infrared gates stood 6.7 m apart and a variation in trial duration of maximum 0.05 s was accepted. A minimum of six trials per condition in this speed range was measured.

Data analysis

The reconstruction of the 3D position of each marker is based on a direct linear transformation algorithm (Q Track)[1]. The raw coordinates were imported into Matlab[2] for further data analysis. Individual stride cycles were determined, with the beginning of each stride cycle defined as the moment of hoof contact of the left hindlimb. If the marker on the left hindlimb was missing, the marker on the right forelimb or the marker on the right hindlimb was used. This enabled the calculation of the angles during one complete stride. As only minimal and maximal values per strides were used, data was not further synchronised. Detection of the moment of hoof contact was based on the horizontal velocity profile of the marker on the hoof (Peham et al., 1999).

The back movement calculations were based on a method that was developed and tested for validity and repeatability by Faber et al. (2001, 2002) (Fig. 2a); briefly, the angular movement pattern (AMP) of a given vertebra (V2) is calculated from the position of the adjacent cranial (V1) and caudal (V3) markers. The AMP of V2 is represented by the orientation of the line through V1 and V3. This method provides an orientation of the vertebra independent of the position of the trunk of the horse. The following adaptation of this method was made in the present study: to take the trunk position into account the orientation of a line through T6 and L1 was used as a reference for the trunk position (Fig. 2b). For the calculation of flexion-extension of the back the Y and Z coordinates were used. For the calculation of lateral bending the X and Y coordinates were used. The minimal angles, maximal angles and ranges of motion (ROM) (difference between minimal angle and maximal extension) of L3 and L5 were used as variables for further analysis.

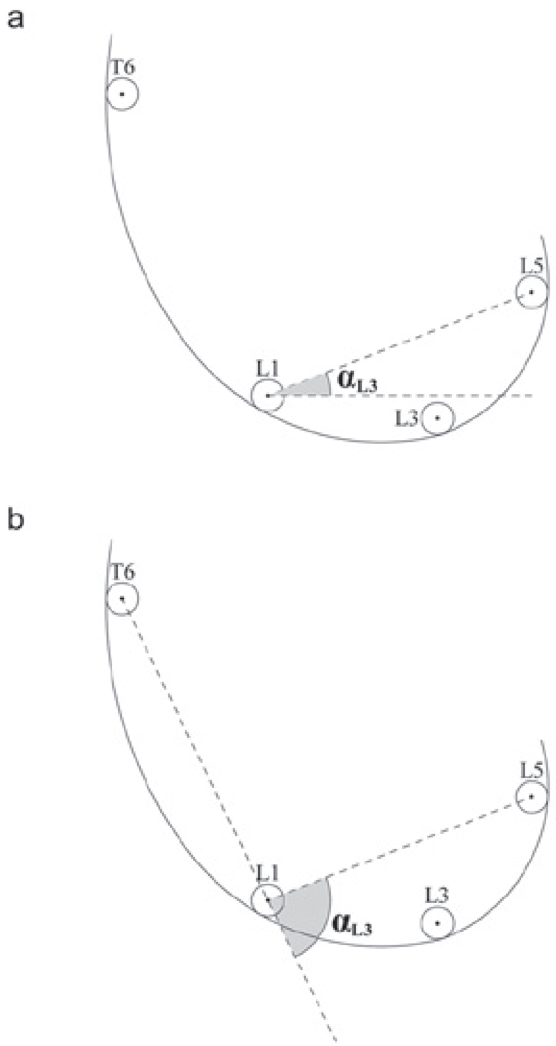

Figure 2 Comparison of methods used to calculate angular movement patterns of the back

The angles are not realistic for purposes of clear explanation of the different methods.

a. Method Faber et al. (2001, 2002): the angular movement pattern (AMP) of a given vertebra (L3) is calculated from the position of the adjacent cranial (L1) and caudal (L5) markers. The AMP of L3 is represented by the orientation of the line through L1 and L5. The AMP calculated using this method was validated using a marker device attached to the vertebra of interest (here L3). The rotation of the line was identical to the rotation of the vertebra of interest (here L3).
b. Method current study: The AMP of a given vertebra (L3) is calculated from the position of the adjacent cranial (L1) and caudal (L5) markers. The AMP of L3 is represented by the angle between the line through L1 and L5 and the orientation of the trunk (line trough T6 and L1).

The head-neck positions were calculated as flexion-extension angles (using Y and Z coordinates) between crista facialis, C1 and C3 (C1 angle), C1, C3 and C6 (C3 angle) and between C3, C6 and T6 (C6 angle). Higher values indicate flexion of the neck while lower values indicate extension of the neck (see Fig. 1). The minimal angles, maximal angles and ranges of motion (ROM) were used as variables for further analysis. Further, the vertical displacements (Z coordinates) of the bit and C1 were calculated.

Measurement accuracy (standard deviation caused by inaccuracy of kinematic measurement system) of the back movements was 0.8° for the L3 angles and 0.6° for the L5 angles. Measurement accuracy of the head and neck position was 0.9 mm for vertical displacement and 1.0°, 1.1°, 0.7° for respectively the C1 angle, C3 angle and the C6 angle. This measurement accuracy is based on the standard deviation for measuring a 3D distance. Spatial measurement accuracy was such that standard deviation when measuring a 750 mm long wand was ≤ 1.6 mm. For the estimation of the measurement errors, the assumption was made that the X, Y and Z distances contributed equally to the measurement error.

Statistics

Means ± s.d. were calculated from the first 4 usable strides. A stride was unusable when marker losses occurred during this stride. Data were excluded from further analysis if less than 4 usable strides were available. Data were analysed statistically in an ANOVA-repeated measurement test followed by a *post hoc* Bonferroni test using SPSS[3] software. A p-value of < 0.05 was considered statistically significant.

Results

Sitting trot had an overall extending effect on the back of horses when compared to the unloaded condition (-21.2° ± 1.7° and -17.0° ± 2.1° for maximal extension and -12.8° ± 2.3° and -11.0° ± 2.2° for maximal flexion of L3). In rising trot, the maximal flexion of the back was similar to the unloaded condition (-11.3° ± 2.1° and -11.0° ± 2.2°), while the maximal extension was similar to sitting trot (-21.2° ± 2.5° and -21.2° ± 1.7°) (Table 1, Fig. 3). The flexion-extension ROM was less in the unloaded condition compared to sitting and rising trot for L3. There was a trend (p = 0.059) towards a higher ROM in rising trot compared to sitting trot. For L5, the flexion-extension ROM was different in all conditions, with the lowest ROM in the unloaded condition and the highest ROM in rising trot. During rising trot, ROM of lateral bending of both L3 and L5 was increased compared with both the unloaded condition and sitting trot (Table 1, Fig. 4).

Table 1 Kinematic variables of back movements (mean ± s.d.)

Variables	Unloaded	Rising trot	Sitting trot	p-value
$α_{L3}$ ME	-17.0 ± 2.1[a]	-21.2 ± 2.5[b]	-21.2 ± 1.7[b]	< 0.001
$α_{L3}$ MF	-11.0 ± 2.2[a]	-11.3 ± 2.1 [a]	-12.8 ± 2.3[b]	< 0.001
$α_{L3}$ ROM FE	6.0 ± 0.9[a]	9.9 ± 2.1[b]	8.4 ± 1.4[b]	< 0.001
$α_{L5}$ ME	-10.7 ± 2.0[a]	-13.8 ± 2.3[b]	-13.6 ± 2.2[b]	< 0.001
$α_{L5}$ MF	-4.2 ± 2.6[a]	-4.4 ± 2.6 [a]	-5.7 ± 2.7[b]	0.001
$α_{L5}$ ROM FE	6.5 ± 1.0[a]	9.5 ± 1.8[b]	7.8 ± 1.4[c]	< 0.001
$α_{L3}$ LB R	7.0 ± 2.8	8.3 ± 2.4	6.8 ± 1.7	0.120 NS ***
$α_{L3}$ LB L	-3.3 ± 1.8[a]	-5.3 ± 1.6[b]	-3.4 ± 2.2[ab]	0.021 **
$α_{L3}$ ROM LB	10.4 ± 3.0[a]	13.8 ± 2.6[b]	10.4 ± 2.2[a]	<0.001 **
$α_{L3}$ Δ LB	3.7 ± 3.9	3.2 ± 3.3	3.5 ± 3.4	0.900 NS **
$α_{L5}$ LB R	7.5 ± 1.9	9.5 ± 1.4	7.7 ± 1.6	0.155 NS ***
$α_{L5}$ LB L	-3.7 ± 2.4[ab]	-5.1 ± 1.4[a]	-3.5 ± 2.1[b]	0.045 **
$α_{L5}$ ROM LB	11.0 ± 2.0[a]	14.5 ± 2.2[b]	11.0 ± 2.2[a]	0.005 **
$α_{L5}$ Δ LB	3.6 ± 3.9	4.4 ± 1.9	4.1 ± 3.0	0.879 NS

All variables are expressed in degrees;
α = angle; L3 = lumbar vertebra 3; L5 = lumbar vertebra 5; ME = maximal extension angle of the vertebra; MF = maximal flexion angle of the vertebra; ROM = range of motion of the vertebra; FE = flexion-extension; LB = lateral bending; L = left side of the back is concave side; R = right side of the back is the concave side; Δ LB = difference lateral bending between maximal bending to the left and to the right side.
: data of only 7 horses were used; *: data of only 8 horses were used.
NS: not significantly different at $p < 0.05$; [ab] values with the same superscript are not significantly different ($p < 0.05$, Bonferroni correction).

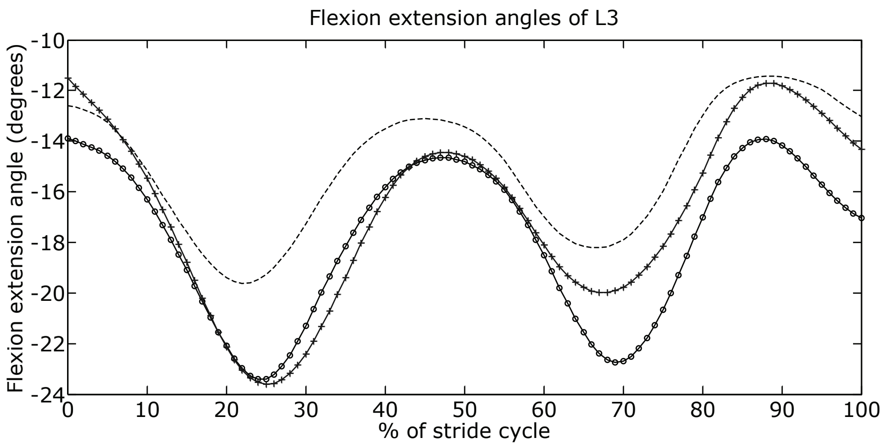

Figure 3 Typical example of the flexion extension angular movement pattern of L3
The stride cycle starts with hoof contact of the left hindlimb.
\- - - - - = unloaded condition; + = rising trot; O = sitting trot.

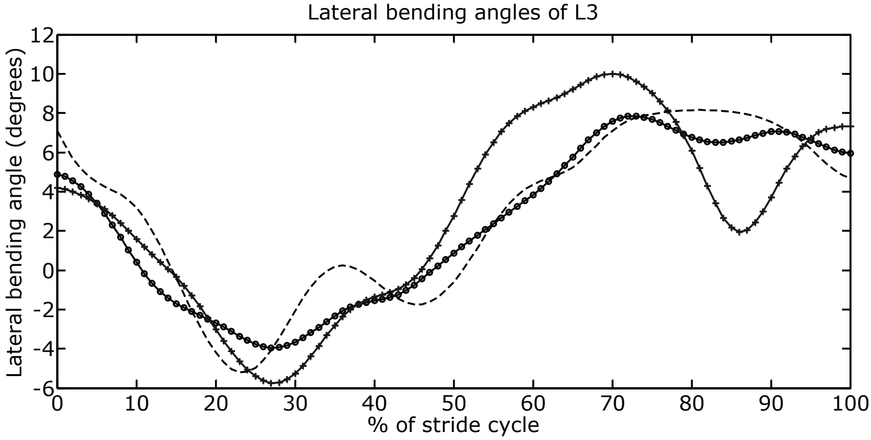

Figure 4 Typical example of the lateral bending angular movement pattern of L3
The stride cycle starts with hoof contact of the left hindlimb.
- - - - - = unloaded condition; + = rising trot; O = sitting trot.

During rising trot, the horses held their head lower than in the other two conditions (Table 2). The flexion-extension angles of C1 and C3 in the unloaded condition were smaller (indicating a more extended neck) than in the situations with the rider. The C6 angle was different between rising and sitting trot with the horses extending their necks more during sitting trot (Table 3).

Table 2 Vertical displacement of bit and wing of the atlas (mean ± s.d.)

Variables	Unloaded	Rising trot	Sitting trot	p-value
Bit min	1.29 ± 0.06[a]	1.18 ± 0.08[b]	1.24 ± 0.09[a]	0.003 ###
Bit max	1.40 ± 0.08[a]	1.29 ± 0.08[b]	1.35± 0.09[a]	0.006 ###
Bit ROM	0.11 ± 0.04	0.12 ± 0.04	0.11 ± 0.02	0.892 NS ###
C1 min	1.62 ± 0.09	1.59 ± 0.05	1.63 ± 0.07	0.228 NS ##
C1 max	1.72 ± 0.08[ab]	1.70 ± 0.05[a]	1.74 ± 0.06[b]	0.024 ##
C1 ROM	0.10 ± 0.02	0.11 ± 0.03	0.11 ± 0.01	0.372 NS ##

All variables are expressed in metres; Bit max is the maximum height of the bit marker; Bit min is the minimum height of the bit marker; Bit ROM is the range of motion of the height of the bit marker; C1 max is the maximum height of the wing of the atlas (C1); C1 min is the minimum height of the wing of the atlas; C1 ROM is the range of motion of the vertical displacement of the wing of the atlas.
##: data of only 9 horses were used; ###: data of only 10 horses were used.
NS: not significantly different at $p < 0.05$; [ab]Values with the same superscript are not significantly different ($p < 0.05$, Bonferonni correction).

Table 3 Kinematic variables of flexion extension movements of head and neck (mean ± s.d.)

Variables	Unloaded	Rising trot	Sitting trot	p-value
α_{C1} ME	138.8 ± 10.7^{a}	160.5 ± 8.5^{b}	162.4 ± 8.2^{b}	< 0.001 *
α_{C1} MF	150.9 ±10.4^{a}	168.4 ± 8.8^{b}	170.1 ± 7.3^{b}	< 0.001 *
α_{C1} ROM	12.1 ± 2.5^{a}	7.9 ± 1.2^{ab}	7.7 ± 2.0^{b}	0.005 *
α_{C3} ME	185.1 ± 10.1^{a}	194.7 ± 9.8^{b}	193.4 ± 9.4^{b}	< 0.001 ***
α_{C3} MF	194.7 ± 9.8^{a}	202.3 ± 9.7^{b}	202.3 ± 9.4^{b}	0.001 ***
α_{C3} ROM	9.6 ± 2.1^{ab}	7.6 ± 1.2^{a}	8.9 ± 1.6^{b}	0.037 ***
α_{C6} ME	98.7 ± 2.2^{ab}	101.3 ± 1.3^{a}	96.9 ± 1.3^{b}	0.002 ##
α_{C6} MF	110.0 ± 2.5	111.3 ± 1.8	108.9 ± 2.2	0.211 NS ##
α_{C6} ROM	11.3 ± 1.0^{ab}	10.6 ±1.1^{a}	13.5 ± 1.4^{b}	0.021 **

All variables are expressed in degrees;
α_{C1} is the angle between the marker on de *crista facialis*, C1 and C3; α_{C3} is the angle between C1, C3 and cervical vertebra 6 (C6); α_{C6} is the angle between C3, C6 and T6; ME is the maximal extension angle of the vertebra; MF is the maximal flexion angle of the vertebra; ROM is the range of motion of the vertebra.
*: data of only 6 horses were used; **: data of only 7 horses were used; ***: data of only 8 horses were used; ##: data of only 9 horses were used.
NS: not significantly different at $p < 0.05$; ^{ab}Values with the same superscript are not significantly different ($p < 0.05$, Bonferonni correction).

Discussion and conclusion

Although there are several studies on back movements using the method of Faber et al. (2001, 2002), comparison of these studies should be done with caution. In the original method of Faber et al. (2001, 2002) an orientation of the vertebra independent of the position of the trunk of the horse was used. In the case that the whole horse would change position (for example during bucking), the orientation of the line will change, even if the back shape does not change at all. However, under normal circumstances, using the original method of Faber et al. (2001, 2002) would lead to similar findings as the results showed in the present study. Although Gómez Álvarez et al. (2006, 2007, 2008a, 2008b) describe their method as a calculation of the angle between the three vertebrae, in fact they used the method of Faber et al. (2001, 2002) (personal communication Gómez Álvarez), but the interpretation of the data is confusing. Faber et al. (2001, 2002) defines flexion-extension as a rotation around the x-axis, lateral bending as a rotation around the z-axis and axial rotation as a rotation around the y-axis. The extension of the back is described as a clockwise rotation in the thoracic region and a counter clockwise rotation in the lumbosacral region. For flexion, a reverse situation applies. This means that an increase of the FE angles in the thoracic region indicates extension and an increase of the FE angles in the lumbar sacral region indicates flexion. Not all studies have taken this transition in interpretation into account.

The overall extension of the back seen in the sitting trot situation is in line with the findings of de Cocq et al. (2004). In that study, a dead weight had an overall extending effect on the back and it was suggested that a rider would have a similar effect. In the present study rising trot was hypothesised to have a less extending effect than sitting trot, because of the general belief in the equestrian world that sitting trot is less challenging and thus less prejudicial for the horse's back. However, it is demonstrated that this is only partially true. During one part of the stride cycle rising trot is similar to the unloaded condition, but when the rider is seated, it is similar to sitting trot.

As the same maximal extension of the back is reached during rising and sitting trot, there is no reason to believe that rising trot is less harmful. The clinical effect of the increased flexion and larger ROM in L3 and L5 in rising trot is not clear. It may be more challenging for the lumbar back on one hand (certainly when there is existing pathology in this area), on the other hand, it may help to create maximal suppleness of movement.

Rising trot also has an effect on lateral bending. As rising trot involves an asymmetrical movement of the rider, with the rider rising during half of the stride cycle and sitting during the other half, it was expected that rising trot might introduce an asymmetry in lateral bending. However, no differences in effect on lateral bending to the left and right could be demonstrated. It is possible that differences were too small to be demonstrated in this group of 12 horses, furthermore axial rotation was not measured in this study. As lateral bending and axial rotation are coupled movements, axial rotation might also influence the results. It was shown that rising trot increases the total ROM of lateral bending compared to the other two conditions. Again, this may be an advantage during the training of lateral movements (for instance in dressage horses), or possibly exacerbate existing pathology.

The difference seen in head-neck position between the unloaded (unridden) condition and the ridden conditions was expected, as a rider aims at a head-neck position asked for in competition, which is different from the natural head-neck position of the horse. The higher head-neck position in sitting trot compared to rising trot was not expected, because the rider had been instructed to ride the horse identically in both conditions. This higher head-neck position is probably caused by an increased extension of the neck in the caudal region (C6). It is hard to tell what is cause and what consequence of this increased extension of the neck. In theory, the head-neck position may change because of the difference in loading of the back in sitting trot, or because of (unconscious) changes in the actions of the rider. Gómez Álvarez et al. (2006) reported a decrease in lumbar FE angles in the situation with a wilfully achieved higher head-neck position. This finding is in line with the decrease of

FE angles in sitting trot found in this study. This would suggest that the changes in head-neck position are at least partly a cause of the changed back movements.

This study has demonstrated that a rider and the riding technique both affect back movements of the horse, and hence will have an influence on the loading of the back through the bow and string mechanism as proposed by Slijper (1946). How these changes in back movement and loading affect the horse in a more clinical sense is a topic of further investigation. An integrated approach of force measurements, kinematics and computer modelling will be the best way to improve the understanding of the interaction of horse and the effects of different riding techniques.

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4.2 Stirrup forces during horse riding: a comparison between sitting and rising trot.

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Abstract

Injuries of horses might be related to the force the rider exerts on the horse. To better understand the loading of the horse by a rider, a sensor was developed to measure the force exerted by the rider on the stirrups. In the study, five horses and 23 riders participated. Stirrup forces measured in sitting trot and rising trot were synchronised with rider movements measured from digital films and made dimensionless by dividing them by the body weight of the rider.

A Fourier transform of the stirrup force data showed that the signals of both sitting and rising trot contained 2.4 and 4.8 Hz frequencies. In addition, 1.1 and 3.7 Hz frequencies were also present at rising trot. Each stride cycle of trot showed two peaks in stirrup force. The height of these peaks was 1.17 ± 0.28 and 0.33 ± 0.14 in rising and 0.45 ± 0.24 and 0.38 ± 0.22 in sitting trot, with a significant difference between the higher peaks of sitting and rising trot ($p < 0.001$) and between the peaks within a single stride for both riding styles ($p < 0.001$). The higher peak in rising trot occurred during the standing phase of the stride cycle. Riders impose more force on the stirrups during rising trot than during sitting trot. A combination of stirrup and saddle force data can provide additional information on the total loading of the horse by a rider.

Keywords: Equine; Riding technique; Amplitude spectrum; Kinematics; Strain gauge

Introduction

Injuries due to excessively high mechanical loads occur frequently in ridden horses. Most commonly these injuries cause lameness and back problems (Landman et al., 2004). Incorrect training, incorrect distribution of load or ill-fitting saddles are often the source of these problems (Jeffcott, 1980; Harman, 1994), all of which are related to forces exerted by the rider on the horse.

The rider's movements affect the force transmitted to the horse. One factor that affects the rider's movements is the gait of the horse (Schills et al., 1993), so it is not surprising that the forces on the horse's back change according to gait (Fruewirth et al., 2004). During trot, a rider can choose between three different riding techniques: sitting trot, rising trot and the two-point seat. The most commonly used techniques are sitting and rising trot. It is generally accepted that rising trot imposes lower forces on the horse's back than sitting trot (De Cocq et al., 2009a). Young horses are therefore trained using rising trot before using sitting trot and, even with older horses, training sessions usually start with rising trot.

The rider exerts force on the horse through the reins, stirrups and saddle. The forces on some of these contact areas have been measured. Rein forces have been measured during walk, trot and canter (Clayton et al., 2005; Warren-Smith et al., 2007). Saddle force has been measured in standing horses (De Cocq et al., 2006; Geutjens et al., 2007; De Cocq et al., 2009b) and during stance and motion (Harman, 1994; Pullin et al., 1996; Harman, 1997; Jeffcott et al., 1999; Werner etal., 2002; Fruehwirth et al., 2004). All these studies showed differences between gaits but they did not address the effects of different riding techniques. Some studies have compared the effects of sitting and rising trot. De Cocq et al. (2006) showed that the maximal extension of the horse's back did not differ between sitting and rising trot. Roepstorff et al. (2009) evaluated loading of the left and right diagonals in rising trot by measuring the Vertical Ground Reaction Force (VGRF) and showed that VGRF was higher on the sitting diagonal than the standing diagonal. Asymmetry between rising on the left and right diagonals was also found with higher VGRF when sitting on the left diagonal compared with sitting on the right diagonal.

Peham et al. (2010) were the first to compare the force underneath the saddle during sitting and rising trot. They found no significant difference between sitting and rising trot. De Cocq et al. (2010) calculated the forces exerted on the horse using the kinematics of the rider and found a significant difference in vertical peak force between rising and sitting trot. The force peaks occurring during the standing and sitting positions of the rider were both lower in rising trot with the difference being most obvious in the standing phase. Pfau et al. (2009) proposed that the modern jockey's position enables the horse to go faster by uncoupling the movement of horse and rider. The jockeys stand in their stirrups and use the highly adjustable elastic properties of their legs, which might lead to lower forces on the horse's back. The effect of riding technique and rider position on the forces on the horse's back are largely unexplored. The techniques of sitting trot and rising trot offer an ideal opportunity to compare different riding techniques within the same gait.

Quantification of the complete horse-rider system could provide insights that allow improvement of current training and riding techniques. In this research, stirrup forces during sitting and rising trot are measured for the first time. These data will be a start in quantifying the forces on an unexplored contact point in the horse-rider system. The objective of this study was to compare the stirrup forces during sitting trot and rising trot. A higher force during the standing phase of the rising trot was expected.

Materials and methods

Horses and riders

In this study five horses, four Dutch Warmblood horses and one Hannoverian horse, three geldings and two mares, mean age ± s.d. 13.2 ± 2.8 years, height at the withers 1.66 ± 0.02 m, body mass (BM) 583 ± 27 kg and 23 riders (mean age ± s.d. 18.0 ± 1.7 years, height 1.70 ± 0.01 m, BM 61 ± 1 kg) participated. All riders were students at the Dutch Equestrian Vocational Centre (NHB Deurne). Year of study at NHB Deurne and competition level of the rider were noted. Each rider rode on one horse. The combination of horse and rider was assigned randomly.

Measuring equipment

The force exerted on the stirrups was measured using a strain gauge with a bridge-force sensor. A WMC-250 1112 N (250 lb_F) tension/compression sensor (Interface) was placed between the stirrup leathers and the stirrups (Fig. 1). The sensor was connected to an AD-converter with 32 inputs at 16 bits up to 250 kS/s (NI USB 6218, National Instruments), which was connected to a laptop (HP Compaq). The sensor was powered by a 9 V battery. A continuous power supply was secured by a voltage stabilizer. The AD-converter and laptop were put in a saddle bag behind the saddle of the horse. Data recording was managed by custom software written in MatLab 2007 (Mathworks Inc.), that ran on the laptop during data collection. The measuring frequency was 250 Hz. The sensors were calibrated before and after the experiment by hanging a preset mass of 10, 20, 30, 40, 50, 60 and 78 kg on them. The correlation coefficient (r^2) of the correlation between force and voltage was 0.999.

Data were collected continuously during the complete test of each rider and time was recorded simultaneously by starting a stopwatch every time a new testbegan. Infrared gates (Barten Electro) were positioned at the start and end of the measurement track to determine the time taken between the gates from which the average speed of the horse was calculated. Stopwatch lap measurements were used to identify thestart of each trial within the data string. The infrared measurements were used to establish the exact times the horse spent in the measurement track.

Video recordings (25 Hz) were made during every trial (GZ-MG505E Everio Harddisk; JVC) to record horse and rider as they moved along the measurement track. These recordings were used to synchronize the movements of the rider and horse with the stirrup force measurements as a function of time.

Figure 1 The stirrup force sensor
A strain gauge in housing (indicated with Δ) is placed between the stirrup leather (to be inserted in a connection on top) and the stirrup (below). The numbers indicate the size of the stirrup and sensor in cm.

Track

All riders were asked to perform different gaits in this order: walk, rising trot, sitting trot, rising trot and canter on both leads. All riders received the same instructions on which route to take. The measurement track was located along the long side of the riding arena. Measurements were made during the whole session, but only the data recorded within the measurement track were used for analysis.

Data analysis

In total, 23 trials of sitting trot and 23 trials of rising trot were analyzed. In general, one trial consisted of four complete stride cycles. Data were recorded in voltage (V) and transformed into force (N) using the calibration data. Only the data from sitting trot and rising trot were analyzed, the rest of the data will be used in a separate project. Forces (N) were normalised by dividing them by the weight (N) of the rider and are therefore dimensionless. These normalised forces will be referred to as Body Weight (BW).

A Matlab program was written to analyze the data. An amplitude spectrum analysis calculated by Fourier transformation of the signal was performed for every trial. This shifts the signal from the time-domain to the frequency domain (Brigham, 1988) to show which frequencies are present in the signal. A cosine window was used to avoid spectral leakage. A Butterworth data filter was selected that filtered only those signals higher than the highest frequency present in the signal (8 Hz). The position of the peaks in the amplitude spectrum analysis were determined using a peak routine to mark a series of data points that are both above a chosen line and are neighboured by points with lower values. Data points meeting both conditions were considered peaks in the amplitude spectrum analysis.

The filtered data were also analysed using the peak routine. Since trot is a two-beat gait, every complete stride cycle was hypothesized to show two peaks. Video recordings were used to test this assumption and to determine the moment the rider was in an extreme position (completely standing or sitting) during rising trot. The stirrup force signal was divided into separate stride cycles, each starting with a valley in stirrup force. These separate stride cycles were stride-normalised to 100%.

Preliminary data synchronization of stirrup and saddle force

After the experiment, synchronized measurements of stirrup force and saddle force (Pliance®-s system, Novel, variation coefficient calibration > 5%, measurement frequency 50 Hz) were performed in one horse (gelding, 5 years, height at withers 1.70 m, mass 595 kg) and one rider (female, 29 years, height 1.68 m, mass 61 kg). Before starting the measurements, a signal was recorded by both measurement devices to synchronize the stirrup and saddle force data as an extra control on the synchronisation of rider movement and stirrup forces.

Statistics

Means ± s.d. were calculated from all strides of each rider in sitting and rising trot. Normality of distribution was tested with a Kolmogorov-Smirnov test. The trial of rising trot closest in speed to the sitting trot trial was used for analysis. Peak force data were analysed statistically in a GLM-repeated measures test followed by a *post hoc* Bonferroni test using SPSS software (SPSS Inc.). Data were corrected for speed of the horse by adding speed as a covariant. The within factor analysis tested for differences between sitting trot and rising trot. The between factors analysis tested for effects of the horse used, year of study of the rider and competition level of the rider. A p-value of < 0.05 was considered statistically significant.

Results

Forces are given in Newton (N) and as a ratio of body weight (BW: force divided by body weight of the rider). All results are forces measured on one stirrup as the other sensor malfunctioned during the measurements. In the force pattern, two force peaks are present in every stride cycle. Typical examples of a force patterns showing raw data for rising trot and sitting trot during one pass along the measurement track are shown in Fig. 2.

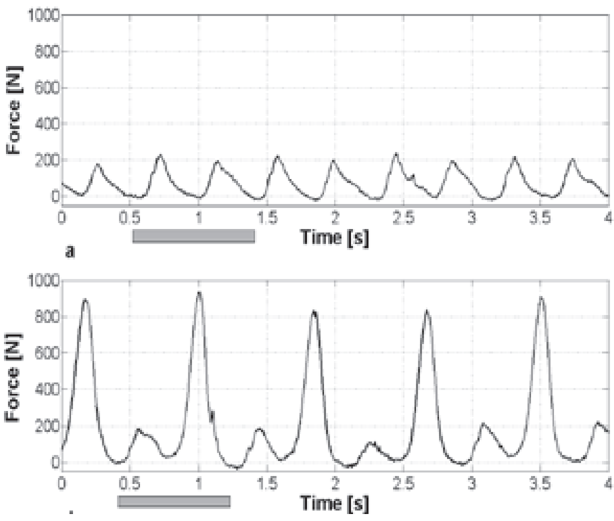

Figure 2 Typical example of raw stirrup force data measured during one trial at sitting trot and one trial at rising trot.
a. sitting trot
b. rising trot
▬: one complete stride cycle
Every stride cycle shows two peaks in stirrup force. Note the difference in amplitude (N) between sitting trot and rising trot and the regular pattern of the signal in both riding techniques.

Amplitude spectrum

Analysis of the amplitude spectra showed that the signal contained no energy above the frequency of 8 Hz, so data were filtered using an 8 Hz Butterworth filter. Amplitude spectrum analysis of both sitting trot and rising trot (Fig. 3) showed two peaks standing out between the neighbouring peaks in the sitting trot data, at 2.6 and 5.2 Hz. In the data of the rising trot, four peaks stood out at 1.3, 2.6, 3.9 and 5.2 Hz. The height of these peaks is expressed as a percentage of the total height of all peaks. An overview of these data and the height differences between the peaks is given in Table 1.

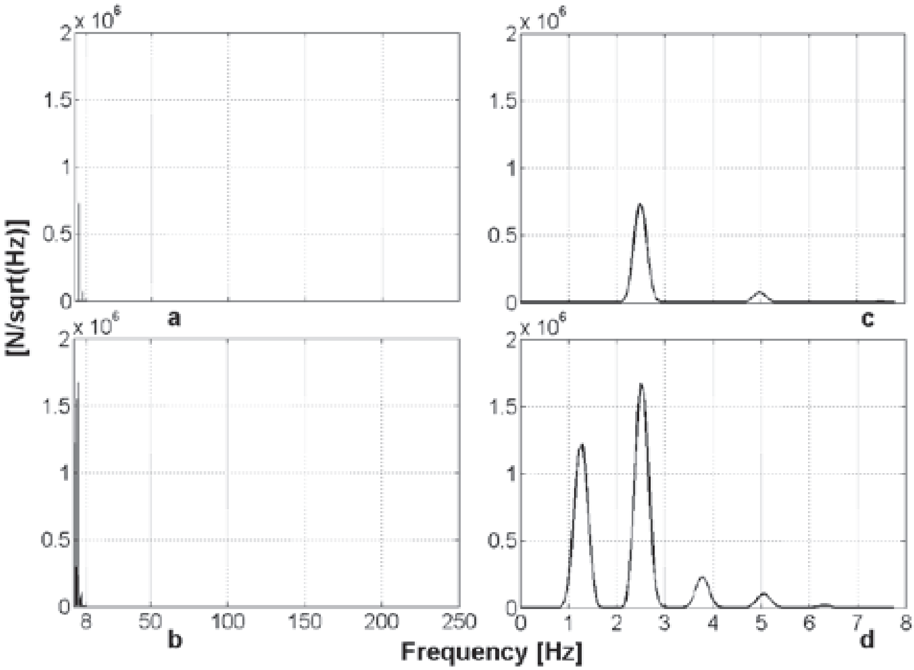

Figure 3 Amplitude spectral density of stirrup force data during sitting trot and rising trot.
a. sitting trot, complete spectrum from 0-250 Hz
b. rising trot, complete spectrum from 0-250 Hz
c. sitting trot, zoom from 0-8 Hz
d. rising trot, zoom from 0-8 Hz
a and b: the signal of sitting and rising trot contains no energy above the frequency of 8 Hz (indicated by the first vertical gridline).
c and d: during sitting trot, 2 frequencies (visible as peaks in the spectrum) stand out in the signal. During rising trot, two extra frequencies appear.

Table 1 Frequency peaks in stirrup force data of sitting trot and rising trot according to amplitude spectral density

Riding style	Peak number	Frequency [Hz]	Percentage (%)
Sitting trot	1	2.6±0.2	89.0±6.1
	2	5.2±0.4	11.1±6.1
Rising trot	1	2.6±0.1	50.4±11.1
	2	1.3±0.1*	39.8±10.0
	3	3.9±0.2	7.3±2.0
	4	5.2±0.3	3.2±1.5

Both sitting and rising trot contain the frequencies 2.6 and 5.2 Hz. In rising trot, two extra frequencies are present.
* Frequencies that appear in data for the rising trot but not for the sitting trot.

Forces

The force pattern showed two force peaks, one high peak and one low peak, per riding technique per stride cycle, which represented the two-beat rhythm of the trot. For rising trot, peak values were (mean peak force ± standard deviation) 1.17 ± 0.06 and 0.33 ± 0.03. For sitting trot, peak values were 0.45 ± 0.05 and 0.39 ± 0.05. Forces in N are given in Table 2. The high peak of rising trot differed significantly from the peaks of sitting trot. The two peaks within one stride cycle differed significantly for both riding techniques. In rising trot, the low peak in stirrup force coincided with the sitting phase of the rider and the high peak coincided with the standing phase (Table 2, Fig. 4).

Table 2 Stirrup forces at the two force peaks of the stride cycle, during sitting trot and rising trot, in N and BW (mean ± standard deviation) for 23 trials.

	Sitting trot		Rising trot		p-value [a]	
	N	BW	N	BW	N	BW
High peak	286 ± 160	0.450 ± 0.237	739 ± 212	1.17 ± 0.284	<0.001*	<0.001*
Low peak	244 ± 151	0.383 ± 0.224	208 ± 98	0.329 ± 0.139	0.249	0.108
p-value [b]	<0.001*	<0.001*	<0.001*	<0.001*		

The two peaks within one stride cycle are significantly different for both sitting trot and rising trot. The high peaks in the stride cycles of sitting trot and rising trot differ significantly, the low peaks do not.
N = Force in Newtons
BW = Force in dimensionless units (bodyweight = ratio of force/body weight of the rider).
a = p-value of comparison of same peak between riding style;
b = p-value of comparison of the two peaks within a riding style;
* = Significant difference.

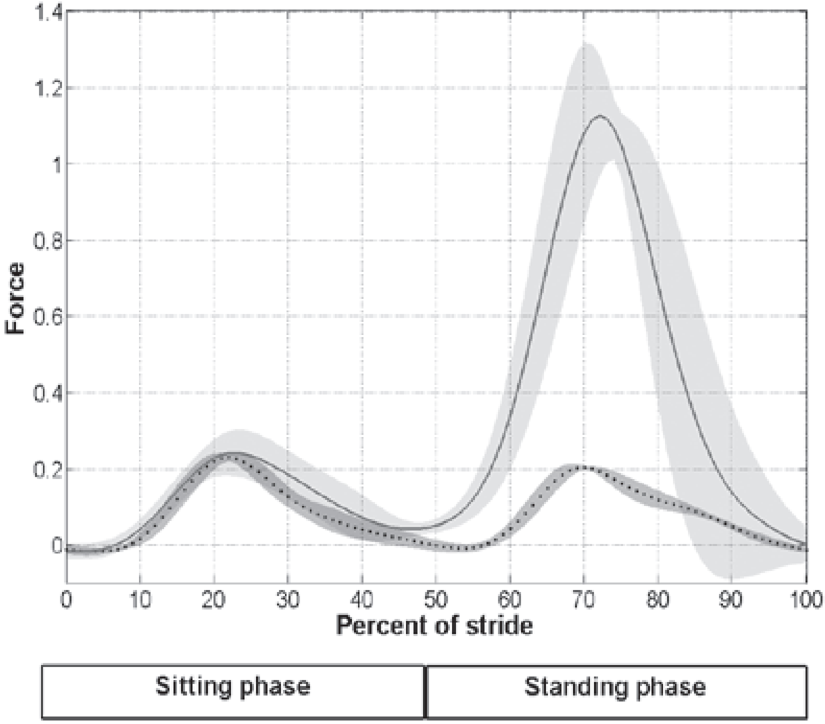

Figure 4 Stirrup force (BW) and rider position during sitting trot and rising trot, averaged for one rider.
---: rising trot;
•••: sitting trot.
Solid lines represent mean forces in dimensionless units (BW = ratio of force/bodyweight of the rider). Shaded areas represent standard deviation. The amplitude of the high peak in rising trot is larger than the amplitude of the high peak in sitting trot. The amplitude of the low peaks does not differ between sitting and rising trot. The amplitudes of the two peaks within one stride cycle do differ significantly within both riding techniques.

The height of the force peaks was not influenced by horse, year of study of the rider, competition level of the rider or years of riding experience of the rider. P-values for this between-subjects analysis were 0.446, 0.861, 0.763 and 0.678, respectively.

Synchronization of stirrup and saddle forces

Synchronization of preliminary recordings of saddle and stirrup force (Fig. 5) showed that peaks in stirrup and saddle force coincide. In rising trot, the saddle force shows alternating low and a high peaks comparable to the stirrup force pattern in rising trot. However, a low peak in saddle force coincides with a high peak in stirrup force and vice versa.

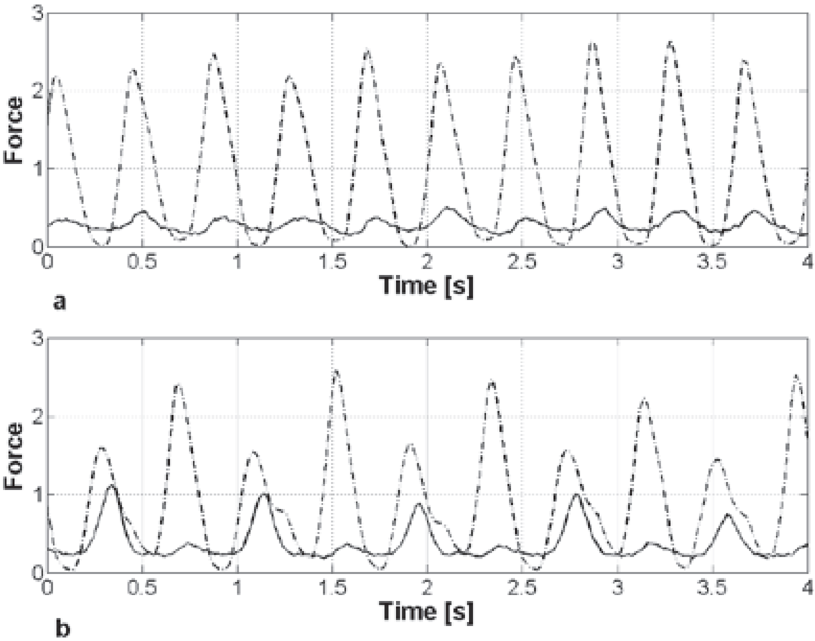

Figure 5 Typical example of preliminary data of the synchronized stirrup force and saddle force, measured during one trial using sitting trot and one trial using rising trot.
a. sitting trot
b. rising trot
_____: Stirrup force
-.-.-.-: Saddle force
Forces are expressed in dimensionless units (BW = ratio of force/body weight of the rider). Note the division of force between saddle and stirrup during rising trot: a higher peak in saddle force coincides with a lower peak in stirrup force.

Discussion

Since this is the first time stirrup forces have been measured and analysed, both the general features of the stirrup force signal and differences in the forces between sitting and rising trot will be discussed.

The amplitude spectrum of both sitting trot and rising trot showed the largest peak at 2.6 Hz, which is the normal step frequency of the alternating diagonal leg pairs of a trotting horse (Barrey, 1999). A peak around 5.2 Hz was also visible in both signals, which is twice the 2.6 Hz frequency, the first overlapping frequency. The latter is probably the fundamental frequency and 5.2 Hz its first harmonic. Harmonics are multiplications of the fundamental frequency, in which the system vibrates easily (Elemans et al., 2008). Harmonics are often present in complicated mass spring systems, where multiple masses and springs are connected, as in the horse–rider system. Higher harmonics are also visible in Fig. 3, showing small peaks at higher multiplications of the fundamental frequency. However at rising trot, two extra frequencies appear: 1.3 and 3.9 Hz. The first frequency, 1.3 Hz, is the frequency of a complete stride cycle in trot. This could represent the standing up of the rider, as this happens once every stride cycle. The frequency 3.9 Hz is probably the third harmonic of this frequency. The second harmonic of this frequency is invisible, as the frequency 2.6 is already present in the signal.

Analysis of the peak forces showed significant differences between and within riding technique. The difference between riding techniques shows that the peak stirrup force in rising trot is higher than in sitting trot. The difference within riding technique shows an alternation between high and low peaks within each stride cycle in rising trot, which is caused by the movement of the rider standing in the stirrups. Sitting trot also shows an alternating force pattern. Probably, a high force on the left stirrup coincides with a lower force on the right stirrup and vice versa. This could be caused by the effect on the rider of the horse's alternating diagonal limb movements. This alternation of force between the right and the left sides of the horse is also seen in the trajectory of the centre of pressure measured by saddle force systems (Fruewirth et al., 2004). Byström et al. (2009) showed that the saddle of a horse ridden in sitting trot on a treadmill rotates around the vertical axis (yaw movement) away from the supporting hindlimb. At the next footfall, the saddle moves away in yaw from the 'new' supporting hindlimb. This movement could contribute to the alternation of stirrup force found in our study. However, it is also possible that this effect is caused by the laterality of the horse and/or the rider. This hypothesis could be tested in a setup with working stirrup force sensors on both sides.

The stirrups are attached to the saddle. Most of the force applied to the stirrups will result in a similar force underneath the saddle. Peham et al. (2010) found no significant difference in the maximum force underneath the saddle between sitting trot and rising trot butthey did indicate that there might be a difference between the highest peak in rising trot and the highest peak in sitting trot. De Cocq et al. (2010) confirmed that the highest vertical force peak is indeed lower when the rider performs rising trot. During this peak, the rider is standing in the stirrups causing the high peak in stirrup force that is also reflected in the synchronized saddle and stirrup force pattern: when the saddle force decreases, the stirrup force increases as the rider stands in his stirrups. In order to understand the mechanism that reduces the peak force on the horse's back, it would be interesting to know whether all vertical force is shifted to the stirrups during the standing phase or whether the rider also uses friction at other contact surfaces with the horse (*e.g.* contact with the rider's knees). De Cocq et al. (2010) found a peak vertical force ratio of 1.95 (BW) during the standing phase. The peak stirrup force found in this study was 1.17 for one stirrup, which is larger than the passive weight of the rider. Assuming that forces on the left and right stirrups are approximately equal, total stirrup force would be 2.34. This is higher than the vertical force measured by de Cocq et al. (2010). The preliminary results of the synchronized stirrup force and saddle force measurements in this study also indicate that total stirrup force might be higher than the force on the horse's back. The question remains as to how the rider is able to reduce the total vertical force. The use of the rider's ankle as a spring, as observed by Lagarde et al. (2005), might play a key role in the reduction of peak force on the horse's back.

Conclusions

Two frequencies stood out in the stirrup force signal a sitting trot. At rising trot, the same two frequencies and two additional frequencies stood out. Stirrup forces indicated two peaks in every stride cycle at both sitting and rising trot. These stirrup forces appeared similar during half of the stride cycle at sitting and rising trot, but in the other half of the stride cycle, the force peak that coincided with the standing phase of the rider at rising trot was significantly higher than the peak at sitting trot. The total stirrup force appeared higher than the net vertical force on the rider (*i.e.* passive rider BW). Combining stirrup force measurements with measurements of the force on the horse's back will increase our understanding of the mechanisms used by the rider to reduce the peak force on the horse's back.

Conflict of interest statement

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

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4.3 Vertical forces on the horse's back in sitting and rising trot.

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Abstract

In equestrian sports, it is generally assumed that rising and sitting trot load the horse's back differently. The objective of this study was to quantify the load on the horse's back in these riding techniques. Kinematic data of 13 riders were collected in rising and sitting trot. The time-history of the position of the rider's centre of mass (CoM) was calculated, and differentiated twice to obtain the acceleration of the CoM. The reaction force between the rider and the horse's back was calculated from the acceleration. Forces were divided by the body weight of the rider to obtain dimensionless forces. As expected, the computed average vertical force did not differ between riding techniques and was not significantly different from the body weight of the riders. At trot, two force peaks were present during one stride cycle. Both peaks in rising trot were significantly lower compared to sitting trot (peak 1: 2.54 ± 0.30 versus 2.92 ± 0.29; $p < 0.001$; peak 2: 1.95 ± 0.34 versus 3.03 ± 0.32; $p < 0.001$). This supports the general assumption that rising trot is less demanding for the horse than sitting trot.

Keywords: *Equus caballus*; Locomotion; Riding technique; Rising trot; Sitting trot

1. Introduction

In equestrian sports, it is generally assumed that riding technique influences the loading of the horse's back. An example of these riding techniques are sitting and rising trot. In sitting trot, the rider remains seated in the saddle. In rising trot, the rider sits in the saddle during half of the stride and rises from the saddle during the other half of the stride in coordination with the horse's limb movements. The common opinion in the equestrian world is that rising trot is less demanding for the horse than sitting trot. It is therefore used to train younger horses that have not yet developed sufficient muscle strength for ridden exercise and to relax older horses in the warming-up and cooling down phases of a training session.

Studies investigating the influence of the rider on the horse, have evaluated the effect of weight (Clayton et al., 1999; De Cocq et al., 2004; Sloet van Oldruitenborgh-Oosterbaan et al., 1995) and riding technique (De Cocq et al., 2009a; Roepstorff et al., 2009) by comparing limb and back movements of the horse. Although these studies provide useful information on the effects of loading, a direct method to evaluate the loading of the horse by a rider would be preferable. Forces exerted on the horse by the rider can be used to evaluate the loading of the horse by a rider. Since on average the net vertical force on the back of the horse is equal to the body weight of the rider, possible differences between rider techniques are to be found in the variation of force patterns around the average value on the horse's back.

The forces between rider and horse have been measured with electronic force measuring devices that have been shown to provide valid and reliable measurements of normal forces between the saddle and the horse's back in the standing position (De Cocq et al., 2009b). Such devices have been used to study the influence of the rider on a standing horse (De Cocq et al., 2009b) and to compare forces on the horse's back during sitting trot and rising trot (Peham et al., 2008, 2010). Although the latter studies did not find significant differences in peak forces, the second peak force in rising trot, i.e. the peak that occurs at the moment the rider is standing, was lower than in sitting trot.

An alternative method of obtaining the forces exerted on the horse by the rider, is to use rider kinematics to calculate the horse reaction force on the rider. This force will be equal but opposite in direction to the force of the rider on the horse's back. This method has, to our knowledge, not been applied in equestrian sports but does give the opportunity to compare net forces of the rider on the horse's back between different riding techniques. We expected to find the main differences between the riding techniques in the vertical force and expected that the forces in forward-backward and sideward direction are relatively small.

The objective of this study was to quantify the force on the horse's back in sitting and rising trot by using kinematic data of the rider.

2. Materials and Methods

The study was performed with approval of the All University Committee for Animal Use and Care and the University Committee on Research Involving Human Subjects at Michigan State University, and with full informed consent of the riders.

2.1 Riders, horses and saddles

In this study 13 female riders (mean age ± SD 31 ± 14.3 years, height 1.67 ± 0.1 m, mass 62 ± 5.6 kg) and two horses participated. One horse, eight years old, 1.53 m in height at the withers and 451 kg, was ridden by 6 riders. The other horse, 24 years old, 1.63 m in height at the withers and 667 kg, was ridden by 7 riders. Riders were weighed using a scale before the measurements. Both horses were clinically sound and were ridden with their own saddle.

2.2 Data collection

Kinematic data were collected using a Motion Analysis System (Santa Rosa, CA, USA) with eight infrared cameras operating at 120 Hz. The cameras were positioned in a riding arena around a calibrated volume measuring 8 m long × 2 m wide × 2.5 m high. A dynamic calibration procedure was performed using a wand with a width of 0.5 m between two markers; the maximal standard deviation of the measured width was 0.0015 m. Horse and rider were prepared by placing spherical (20 mm diameter) and cubic (6 mm length) infrared light retroreflective markers. The markers of the rider were placed on the skin above the approximate joint centres of the shoulder, elbow, wrist, hip and knee, as well as on the head and back (chin, spinous processes of vertebrae C7 and T12). The markers over the joint centres of the ankle and on the toe were attached to the shoe of the rider. The riders wore special clothes to enable placement of the markers directly on the skin. On the back of the rider the spherical markers were used, to ensure that they were visible by the cameras. On the horse, markers were placed on the hoofs. The markers were attached to the skin with double-sided adhesive tape and glued to the hooves.

Rider and horse warmed up for 5-10 minutes prior to data collection. Data were collected while the horse trotted in a straight line at its preferred speed (average 3.11 m/s) with a rider performing sitting trot or rising trot in random order. The trials within one rider had a maximal speed range of ± 0.05 m/s. Six trials at both sitting and rising trot were collected within the allowed speed range. During each trial, one full stride was collected. Four full strides at both sitting and rising trot were analyzed for each horse/rider combination.

2.3 Data analysis

The reconstruction of the 3D position of each marker was based on a direct linear transformation algorithm. The raw coordinates were imported into Matlab (MathWorks Inc, Natick, MA, USA). The raw kinematic data were filtered using a zero-lag 8 Hz second order (effectively fourth order) low pass Butterworth filter before calculating derivatives. During rising trot, not all riders rose on the same diagonal. Individual stride cycles were therefore extracted, with the beginning of each stride cycle defined as the moment of hoof contact of the hindlimb that was grounded when the rider was sitting in the saddle during rising trot. Consequently, all riders sat in the saddle during the first half of the stride cycle and rose from the saddle during the second half of the stride cycle in rising trot. Data of riders that rose during ground contact of the left hind limb were mirrored in order to be able to compare the sideward forces. The same hoof sequence was used to define the stride cycle in sitting trot. Detection of the moment of hoof contact was based on the horizontal velocity profile of the marker on the hoof (Peham *et al.*, 1999).

The amount of vertical force on the rider depends on the mass and acceleration of the rider, in accordance with Newton's second law:

$$F_{z\_rider} = m_B\,(\ddot{z}_{MCB} - g)\,, \qquad (1)$$

where F_{z_rider} is the vertical component of the reaction force vector, m_B is body mass, g is the acceleration due to gravity (9.81 m/s^2), and $\ddot{z}_{MCB}$ is the vertical component of the acceleration of the body's mass centre. If the body is subdivided into 4 rigid segments, equation (1) can be written as:

$$F_{z\_rider} = \sum_{i=1}^{4} m_i\,(\ddot{z}_{CM,i} - g)\,, \qquad (2)$$

where m_i is the mass of the ith segment and $\ddot{z}_{CM,i}$ is the vertical acceleration of the centre of mass of the ith segment. Four body segments were defined; foot, lower leg, upper leg, and the upper body including the arms, the hands and the head. Data on the segmental masses (percentages of body mass) and positions of segmental mass centres (percentages of segment lengths) in female athletes were used (Zatsiorsky, 2002). The filtered positional data of the segmental mass centres were differentiated twice using the five point method to obtain accelerations. The vertical force contributions of the segments, $m_i(\ddot{z}_i - g)$, were determined from these accelerations. Forces were normalized by dividing them by the body weight of the rider and are therefore dimensionless. Strides were interpolated to 100% of the stride cycle.

The same approach was used for the horizontal forces. The equation for the forward-backward forces becomes:

$$F_{x\_rider} = \sum_{i=1}^{4} m_i(\ddot{x}_{CM,i}) , \qquad (3)$$

where F_{x_rider} is the forward-backward component of the reaction force vector and $\ddot{x}_{CM,i}$ is the forward-backward acceleration of the centre of mass of the *i*th segment. The equation of the sideward forces becomes:

$$F_{y\_rider} = \sum_{i=1}^{4} m_i(\ddot{y}_{CM,i}) , \qquad (4)$$

where F_{y_rider} is the sideward component of the reaction force vector and $\ddot{y}_{CM,i}$ is the sideward acceleration of the centre of mass of the *i*th segment.

2.4 Statistics

Means ± s.d. were calculated from 4 strides of each rider at each situation. Data were checked for normality of distribution using a Kolmogorov-Smirnov test. Data were analysed statistically in a GLM-repeated measures test followed by a *post hoc* Bonferroni test using SPSS software (SPSS Inc., Chicago, Illinois, USA). Riding technique (sitting or rising) was the within-subject factor. The horse was included as a between subject factor. For the average force, the rider's weight measured using a scale was also included in the analysis. A p-value of < 0.05 was considered statistically significant.

3. Results

Data of one rider of horse 1 were not used because markers were frequently lost from view. Normalized force values are presented in Table 1 and 2. Normalized force patterns are shown in Fig. 1.

Table 1 Normalised forces (mean± SD) in rising trot and sitting trot

Variables	Rising trot	Sitting trot	p-value
Average vertical force	0.96 ± 0.09	0.96 ± 0.09	> 0.999
Peak vertical force 1	2.54 ± 0.30	2.92 ± 0.29	< 0.001 **
Peak vertical force 2	1.95 ± 0.34	3.11 ± 0.39	< 0.001 **
Average forward-backward force	-0.02 ± 0.01	0.01 ± 0.02	< 0.001 **
Peak forward force 1	0.48 ± 0.17	0.50 ± 0.25	0.068
Peak forward force 2	0.46 ± 0.16	0.67 ± 0.20	<0.001 **
Peak backward force 1	-0.24 ± 0.13	-0.54 ± 0.20	<0.001 **
Peak backward force 2	-0.68 ± 0.20	-0.49 ± 0.22	0.633
Average sideward force	-0.00 ± 0.01	-0.00 ± 0.01	0.301
Max sideward force	0.21 ± 0.07	0.27 ± 0.09	0.007 **
Min sideward force	-0.24 ± 0.07	-0.30 ± 0.08	0.009 **

Forces are expressed in dimensionless units (force/body weight of the rider);
** Values are significantly different ($p < 0.05$, Bonferroni correction);
A positive sideward force is directed towards the side of the hindlimb which lands at the beginning of the stride cycle; a negative sideward force is directed to the opposite site.

In rising trot, the average vertical force was 0.96 ± 0.09. In sitting trot, the average force was 0.96 ± 0.09. Rising trot and sitting trot did not differ significantly. There was no significant difference between the average vertical force of either riding technique and the body weight of the rider. The two horses did not differ in average vertical force.

At trot, two force peaks were present during one stride cycle. For the first force peak, values for rising trot were lower than those for sitting trot (2.54 ± 0.30 versus 2.92 ± 0.29). The second force peak was also lower at rising trot (1.95 ± 0.34 versus 3.11 ± 0.39). Both peaks of horse 2 were significantly higher than the peaks of horse 1.

The forward-backward force had two forward peaks and two backward peaks. The forward peak in the second half of the stride cycle was significantly lower in rising trot compared to sitting trot (0.46 ± 0.16 versus 0.67 ± 0.20). The magnitude of the backward peak in the first half of the stride cycle was significantly smaller in rising trot (0.24 ± 0.13 versus 0.54 ± 0.20). The peak forward-backward forces were higher in horse 2 compared to horse 1. The pattern of the sideward force was more variable between riders. The maximum forces to the left and to the right were higher during sitting trot compared to rising trot. There was no difference in sideward force between the horses.

Table 2 Normalised forces (mean± SD) of horse 1 and horse 2

Variables	Horse 1	Horse 2	p-value
Peak vertical force 1 rising trot	2.32 ± 0.16	2.69 ± 0.28	} 0.008 **
Peak vertical force 1 sitting trot	2.69 ± 0.13	3.09 ± 0.26	
Peak vertical force 2 rising trot	1.62 ± 0.24	2.19 ± 0.13	} < 0.001 **
Peak vertical force 2 sitting trot	2.73 ± 0.06	3.38 ± 0.26	
Peak forward force 1 rising trot	0.35 ± 0.13	0.58 ± 0.12	} 0.080
Peak forward force 1 sitting trot	0.27 ± 0.12	0.68 ± 0.16	
Peak forward force 2 rising trot	0.31 ± 0.05	0.57 ± 0.11	} 0.001 **
Peak forward force 2 sitting trot	0.51 ± 0.13	0.79 ± 0.14	
Peak backward force 1 rising trot	-0.13 ± 0.09	-0.32 ± 0.09	} 0.009 **
Peak backward force 1 sitting trot	-0.39 ± 0.14	0.65 ± 0.16	
Peak backward force 2 rising trot	-0.55 ± 0.04	-0.78 ± 0.21	} 0.001 **
Peak backward force 2 sitting trot	-0.49 ± 0.22	-0.67 ± 0.24	

Forces are expressed in dimensionless units (force/body weight of the rider);
** Values are significantly different ($p < 0.05$, Bonferroni correction).

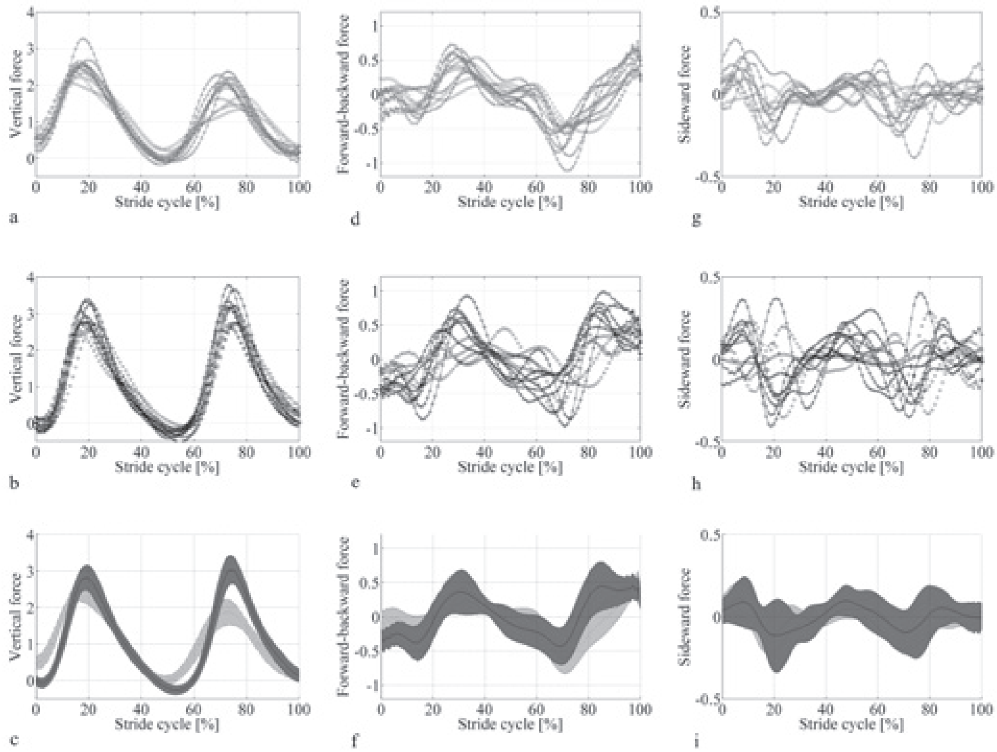

Figure 1 Normalised forces of the horses on the riders in rising and sitting trot

a. individual patterns of vertical reaction force of the horses on the riders in rising trot;
b. individual patterns of vertical reaction force of the horses on the riders in sitting trot;
c. mean ± sd patterns of vertical reaction force of the horses on the riders in rising and sitting trot;
d. individual patterns of forward-backward force of the horses on the riders in rising trot;
e. individual patterns of forward-backward force of the horses on the riders in sitting trot;
f. mean ± sd patterns of forward-backward force of the horses on the riders in rising and sitting trot;
g. individual patterns of sideward force of the horses on the riders in rising trot;
h. individual patterns of sideward force of the horses on the riders in sitting trot;
i. mean ± sd patterns of sideward force of the horses on the riders in rising and sitting trot;

Force patterns for each rider-horse combination were calculated using four strides. Mean ± sd patterns were calculated using data of four strides of 12 rider-horse combinations;

••••: rising trot;
-----: sitting trot;
oooo : riders on horse 1 (n=5);
+ - +: riders on horse 2 (n=7);
Forces are expressed in dimensionless units (force/body weight of the rider);
Note that the horizontal forces have been plotted on a different scale than the vertical forces.

4. Discussion

Peak vertical forces on the horse’s back were smaller in rising trot than in sitting trot, especially in the part of the stride where the rider is standing in the stirrups, which agrees with Peham et al. (2008, 2010). In our study we also found a significantly lower first peak in rising trot compared to sitting trot, which Peham et al. (2008) indicated might not be significant in their study due to the large variance in the saddle force data. This large variance in Peham’s study may be a result of transferring the saddle pad between horses, which tends to increase the variability (De Cocq et al., 2009b). Furthermore the variance in back shape of the horses will also influence the results of saddle force measurements as the saddle force devices measure normal forces and the pressure mat is arched over the back of the horse in the frontal plane.

Another difference between vertical force calculations from rider kinematics and saddle force measurements is that in the former the saddle was not included while it is included in the saddle force measurements. Fruehwirth et al. (2004) found a maximal vertical force of 302.4 N ± 33.9 underneath the saddle of an unridden horse at trot. But because the saddle moves with the horse and the saddle’s mass is relatively low compared to a rider, this is unlikely to affect the difference in forces between riding techniques.

The peak forward-backward and sideward forces were also lower in rising trot compared to sitting trot. Peham et al. (2008, 2009) found decreased movement of the centre of force in the forward-backward direction in rising trot compared to sitting trot. In the sideward direction, they did not find a difference in the movement of the centre of force. Less movement of the centre of mass of the rider explains the lower forces in rising trot found in this study.

There was a significant difference in peak vertical and forward-backward force between the two horses, which had been trained for different types of riding and were of a different age. Vertical ground reaction forces during trotting vary between breeds of horses that are used for different occupations (Back et al., 2007) as a consequence of differences in vertical displacement of the body during the stride. In this study there was indeed a significant difference in vertical displacement between the two horses (horse 1: 0.055 ± 0.008 m; horse 2: 0.088 ± 0.004 m; $p < 0.001$) while the horses were moving in approximately the same stride frequency. This could also explain the observed differences in the peak vertical forces in our study as a consequence of larger vertical oscillations of the rider. Furthermore age influences back kinematics. Johnston et al. (2004) found that age was negatively correlated to extension and flexion of the thoracolumbar junction. This could also influence the rider’s kinematics.

When calculating forces from kinematics of the rider, several causes for errors exist. One important cause for errors is skin displacement. The markers are attached to the skin and can move relative to the segmental mass centres. We used 4 segments and assumed that these segments were rigid. However, there was a variance in segment length. The standard deviation of the upper body length was 0.008 m, of the upper leg was 0.004 m, of the lower leg was 0.002 m and of the foot was 0.0003 m. This variance is a result of skin displacement and the measurement error of the cameras (0.0015 m for 0.5 m wand). Other sources of error are filtering and differentiating the data. We estimated this error by using different cutoff frequencies. Cutoff frequencies of 16, 30 and 50 Hz produced similar results to those presented here. Using a cutoff frequency of 4 Hz resulted in an underestimation of the accelerations. Therefore, it seems that these errors are of minor importance.

The question remains whether the decrease of peak forces seen in rising trot is indeed more comfortable for the horse. A study on back kinematics of the horse showed no difference in peak extension of the back between rising and sitting trot (De Cocq 2009a): in rising trot peak extension occurred during the first (higher) force peak; during the second (lower) force peak extension of the back was less than in sitting trot. This indicates that the reduction in peak force when the rider rises out of the saddle in the second part of the stride cycle is of practical relevance regarding the loading of the back of the horse, while the reduction in the first part of the stride cycle when the rider sits in the saddle is of less importance. Another study by Roepstorff et al. (2009) demonstrates that the vertical ground reaction force of the horse is increased during the sitting phase of the rising trot compared to the rising phase. But because the difference was minor in absolute terms, they think it is unlikely to have a direct impact on the occurrence of locomotor injuries.

In addition to reducing peak forces, standing up by the rider might also reduce the energy expenditure of the horse. Standing up is also used by jockeys during horse racing (Pfau et al., 2009). Jockeys adopt a posture in which the quasi-elastic capacities of their legs can be used. With this posture they are able to reduce the peak loading on the horse’s back enabling the horse to go faster. The same method for reducing peak forces can be used by making an elastic interface between the backpack and the body (Rome et al. 2005; Foissac et al., 2009) and by using springy poles in carrying loads (Kram, 1991). As load carrying also has energetic costs, the question remains whether the use of elastic coupling also influences the energy expenditure of the carrier. If this is the case, elastic coupling can be used to reduce the energy expenditure of load carrying. Taylor et al., (1980) hypothesized that it is the cost of generating force to support body mass that determines the cost of running, and not the mechanical work that has to be done. If this is true, elastic coupling does not influence the energetics. Foissac et al. (2009), however, found that the mechanical properties of a backpack (stiffness and damping coefficient) did indeed affect the energetics of walking in humans carrying backpacks. With respect to equestrian sports, by using the rider's legs as an elastic coupling during rising trot, the rider may not only reduce peak forces but may also reduce the energetic cost of carrying the rider.

In conclusion, the peak forces in rising trot were lower than the peak forces in sitting trot. This supports the assumption that rising trot is less demanding to the horse than sitting trot. Rising trot can therefore be used to prevent injuries in the horse. The legs of the rider act as a quasi-elastic coupling between rider and horse. Whether this coupling also reduces the energetic costs of load carriage could be tested by comparing the energetics of horses ridden at the same speed in rising trot and sitting trot.

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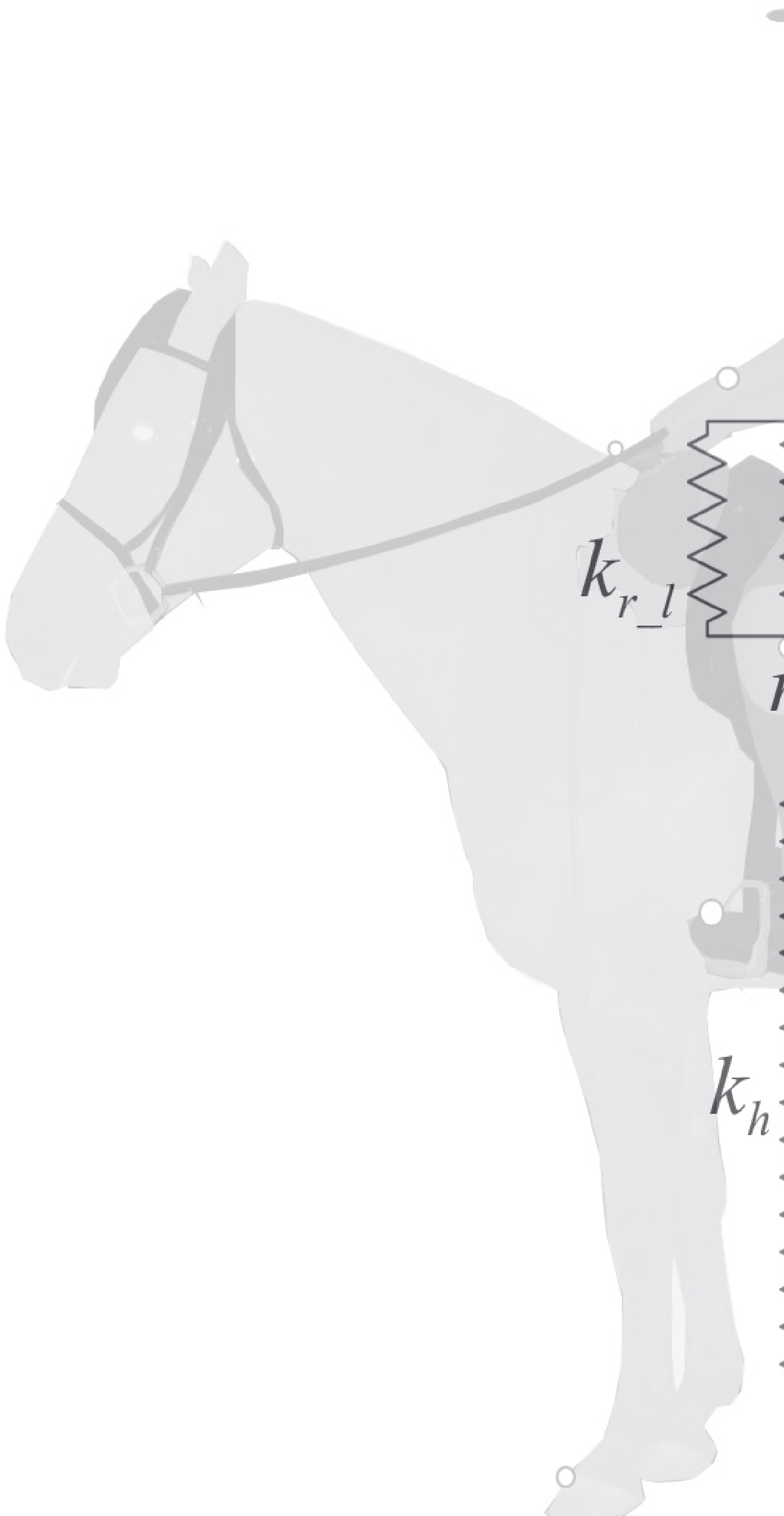

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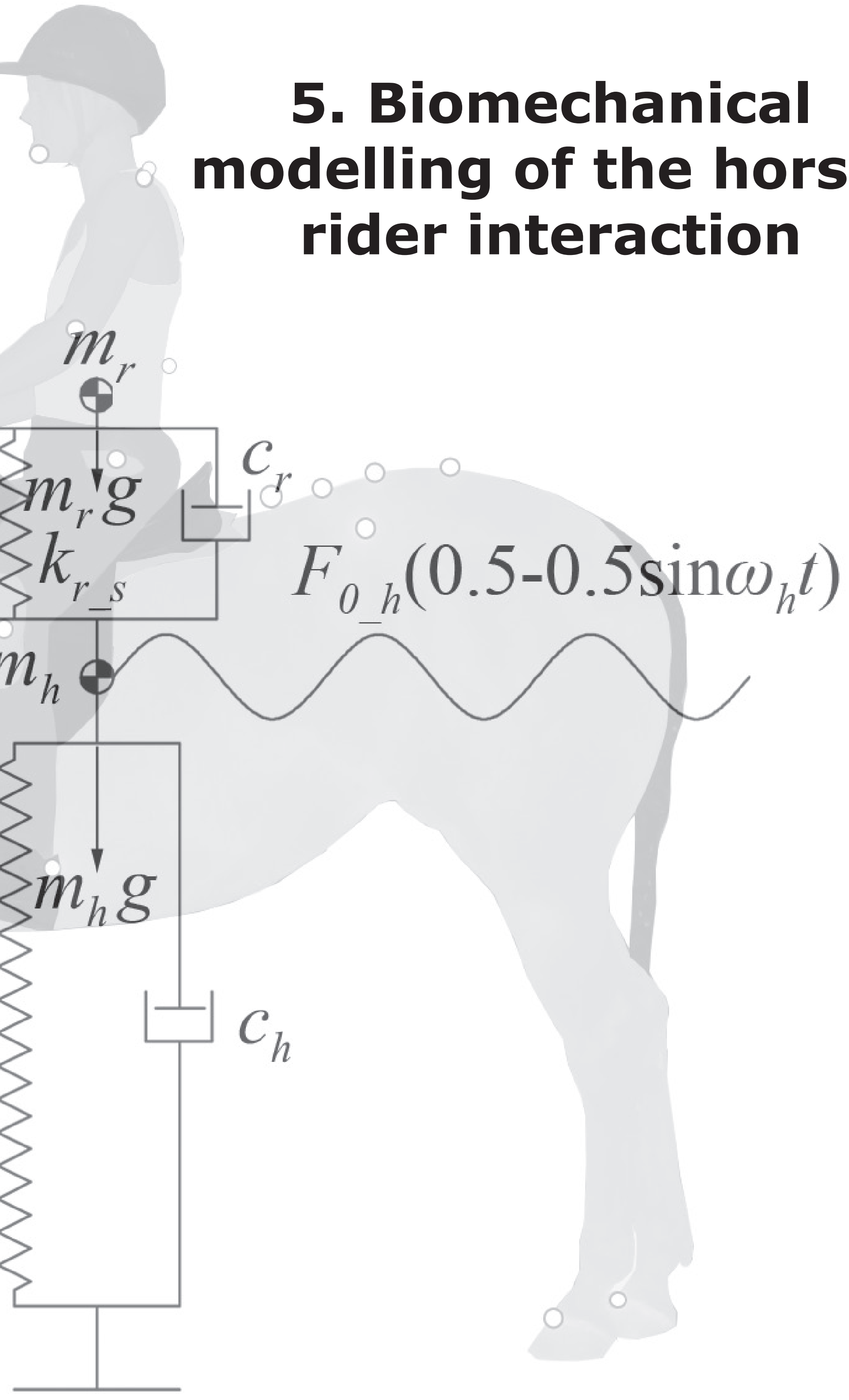
5. Biomechanical modelling of the horse-rider interaction



5.1 Modelling biomechanical requirements of a rider for different horse-riding techniques at trot

Patricia de Cocq, Mees Muller, Hilary M. Clayton and Johan L. van Leeuwen

Submitted

Summary

The simplest model possible for bouncing systems consists of a point mass bouncing passively on a mass-less spring without viscous losses. This type of spring-mass model has been used to describe the stance period of symmetric running gaits.

In this study, we investigate the interaction between horse and rider at trot using three models of force driven spring-(damper-)mass systems consisting of a spring (and damper) representing the body of the horse and the mass of the horse and a second spring (and damper) representing the body of the rider and the mass of the rider. In the second spring-damper-mass model, a free fall and a forcing function for the rider were incorporated. In the third spring-damper-mass model, an active spring system for the leg of the rider was introduced. The output of the models was compared with experimental data of sitting and rising trot and with the modern riding technique used by jockeys in racing.

The models demonstrate which combinations of rider mass, spring stiffness and damping coefficient will result in a different riding technique or other behaviours. Optimization to minimize the peak force of the rider and the work of the horse resulted in an "extreme" modern jockey technique. The incorporation of an active spring system for the leg of the rider, was needed to simulate the rising trot.

Thus, the models provide insight into the biomechanical requirements a rider has to comply with to respond effectively to the movements of a horse.

Keywords: Equus caballus; Spring-Mass model; Sitting trot; Rising trot; Jockey

Introduction

Since the domestication of the horse, load carriage has been an important task of these animals, both for work horses and sport horses. Load carrying has an energetic cost. When mass is added to the horse's trunk, the energy expenditure increases (approximately) in direct proportion to the mass of the load. For example, if a horse carries a load equal to 20% of body weight, the rate of energy consumption increases by 20% (Taylor et al., 1980). In studies of load carrying by humans, strategies to reduce this energy consumption have been identified. African women seem to carry loads more efficiently by using their body as a pendulum during locomotion (Heglund et al., 1995). The load itself can also influence energetic costs; the mechanical properties of a backpack have been shown to affect the energetics of walking in the human carrying the backpack (Foissac et al., 2009). There is an optimal stiffness for the connection between backpack and human that is associated with the lowest energy consumption.

Horses may be required to carry an inanimate load (dead weight) or an animate load (rider). In the case of a rider, both the rider's skill level and the style of riding may affect the interaction between rider and horse. In horse racing, Pfau et al. (2009) found that horse racing times decreased after jockeys started to use short stirrups and adopted a position in which they were standing in the stirrups. The authors hypothesized that the horses were able to gallop faster because the jockey uncoupled himself from the horse, which lowered the vertical peak forces and enabled the horse to go faster. The trot is a symmetrical gait in which the movements of the horse's limbs are diagonally synchronized; alternating diagonal pairs of limbs support the body as it descends and then raise the body into an aerial phase. Thus, the body ascends and descends twice during each stride. The rider has a choice of accommodating the bouncing motion of the horse's back using a sitting or standing (two-point seat) style or a combination of these styles (rising trot). In sitting trot, the rider remains seated in the saddle. In the two-point seat, the rider is standing in the stirrups. The modern jockey position is an extreme variety of the two-point seat, with extremely short stirrups. This technique is most frequently used during gallop races, but it is also possible to use the technique at trot. In rising trot, the rider alternately sits in the saddle and rises from the saddle during the two successive diagonal stance phases. Therefore, the rider rises during one half of each complete stride. The common belief in the equestrian world is that the two-point seat and rising trot are less demanding than sitting trot for both horse and rider. On this basis, rising trot is recommended for training young horses and for all horses during the warming-up and cooling down phases of a training session. This belief is supported by a study on back movements of the horse which showed an overall extension of the thoracolumbar spine when the rider performed sitting trot compared to an unloaded situation. At rising trot, thoracolumbar extension is similar to sitting trot in the phase when the rider is seated, but resembles the unloaded situation when the rider rises from the saddle (de Cocq et al., 2009). Studies using saddle force measurements (Peham et al., 2009) or rider's kinematics (de Cocq et al., 2010) to compare the loading of the horse's back by a rider using the sitting and rising techniques confirmed this. Peham et al. (2009) found a significant reduction in peak force in two-point seat compared to both sitting and rising trot. They did not find significant differences in peak loading between rising trot and sitting trot, but in the phase of rising trot when the rider rose from the saddle peak force was lower than at sitting trot. De Cocq et al. (2010) found a significant reduction in vertical peak force in rising trot compared to sitting trot.

The biomechanical requirements riders have to comply with to perform these different riding techniques are not clear. Riders generally use a limited set of preferred modes (or riding styles), which have a cyclic behaviour and can be considered as the equilibrium states of a biomechanical model. A shift in input parameters of the model will change the behaviour of the model, which will result in different modes. This will provide insight into the requirements needed to adopt the different modes. In addition, it is interesting to evaluate the effects of different sets of input values on the outcome of the model and to explore how the rider should adapt his biomechanical properties to avoid instability, minimize the peak force between horse and rider and/or minimize the energy requirements for horse and rider.

Therefore, three spring-(damper-)mass models were developed to provide insight into the mechanism of these riding techniques. The first approach involved constructing a simple spring-mass model in which both the musculoskeletal system of the horse and of the rider are considered mechanically as linear spring mass systems. The spring mass system of the horse is actively driven. Each system is assumed to behave like a point mass bouncing on a mass-less spring without viscous losses, which is the simplest model possible for any bouncing system.

Although such a simple model may provide useful information on the strategies a rider can use to respond to the movement of the horse, it has limitations. In the simple spring-mass model the horse maintains contact with the ground during locomotion; this is not true for trotting in which there are two phases in each stride when none of the feet is in contact with the ground (the suspension phases). Although the rider maintains contact with the horse, the rider and the horse are not attached to each other. The laxity of this contact can be modelled by combining a mass-spring model and a free fall. Furthermore, since the legs of both horse and rider have damper-like functions and since there is a phase shift between horse and rider (Lagarde et al., 2005) dampers for both horse and rider should be introduced to the model. During rising trot, the rider is actively standing up. Two approaches were used to simulate this muscle activation of the rider. The second spring-damper-mass model incorporates a free fall, dampers for both horse and rider and a forcing function for the rider. The third spring-damper-mass model incorporates a free fall, dampers for both horse and rider and an active spring system for the leg of the rider with a varying stiffness and rest length.

Materials and Methods

The study was performed with approval of the All University Committee for Animal Use and Care and the University Committee on Research Involving Human Subjects at Michigan State University, and with full informed consent of the riders.

Experimental setup

Horses and riders

Measurements were taken using one horse (gelding, age 24 years, mass 667 kg, height 1.63 m) and seven experienced female riders with mean ± SD age 34 ± 15 years, height 1.69 ± 0.07 m, mass 61.4 ± 5.0 kg.

Data collection

Three-dimensional kinematic data were collected using eight Eagle infrared cameras recording at 120 Hz using real-time 5.0.4 software (Motion Analysis Corporation, Santa Rosa, CA, USA). A standard right-handed orthogonal Cartesian coordinate system was used. The positive x-axis was oriented in the line of progression of the horse. The positive z-axis was oriented upward and the positive y-axis was oriented perpendicular to the y- and z-axes. The measurement accuracy was estimated by measuring the length of a 500 mm wand that was moved through the field of view; a residual error of 0.55 ± 0.98 mm was found.

To evaluate the vertical movement of rider and horse, infrared light reflective markers were attached to the skin over palpable anatomical locations. The markers on the rider were placed on the skin over-lying the approximate joint centres of the shoulder, elbow, wrist, hip and knee, as well as on the head (chin) and back (spinous processes of the 7th cervical (C7) and 12th thoracic (T12) vertebrae). Markers were also attached to the shoe of the rider over the joint centre of the ankle and on the toe. The riders wore special clothes to enable placement of the markers directly onto the skin. On the back of the rider larger spherical markers were used to ensure that they were visible for the cameras. On the horse two spherical markers were attached dorsal to the spinous processes of the 6th thoracic (T6) and the 1st lumbar (L1) vertebrae. For determination of stride time, markers were glued to the lateral sides of the hind hooves.

Measurements were taken at trot under two conditions performed in random order: rising trot and sitting trot. The average speed of a trial was calculated using the position of the marker on L1. Trials within a speed range of 0.05 m/s were collected, with a minimum of six trials within this speed range being recorded for each condition and each rider. During each trial, one full stride was collected. Four full strides at both sitting and rising trot were analysed for each horse/rider combination.

Data processing

Reconstruction of the 3D position of each marker is based on a direct linear transformation algorithm. The raw coordinates were imported into Matlab (The Mathworks Inc., Natick, MA, USA) for further data analysis. Individual stride cycles were determined, with the beginning of each stride cycle defined as the moment of contact of the hind hoof that was grounded when the rider was sitting in the saddle during rising trot. Consequently, all riders sat in the saddle during the first half of the stride cycle and rose from the saddle during the second half of the stride cycle. The same hoof sequence was used to define the stride cycle in sitting trot. Detection of the moment of hoof contact was based on the horizontal velocity profile of the marker on the hoof (Peham et al., 1999).

Vertical displacement of the horse was calculated by averaging the z-coordinates of the T6 and L1 markers on the horse. For calculation of the vertical displacement of the centre of mass of the rider, four body segments were defined; foot, lower leg, upper leg, and the upper body including the trunk, arms, hands and head. Data on the segmental masses (percentages of body mass) and positions of segmental mass centres (percentages of segment lengths) in female athletes were used Zatsiorsky (2002). Vertical displacement of the rider’s centre of mass can be defined by:

$$z_r = \sum_{i=1}^{4} z_{COM,i} m_i / m_r \qquad (1)$$

where z_r is the vertical displacement of the centre of mass of the rider, m_i is the mass of the ith segment, $z_{COM,i}$ is the vertical displacement of the centre of mass of the ith segment and m_r is the mass of the rider. As an equilibrium position is used for the spring-mass model, the average height of horse or rider was subtracted from marker heights at all time points. The vertical displacement time histories were normalized to a 100% stride cycle. Average displacements of the trials were calculated per rider and for the entire group. Standard deviations were calculated from the average displacement patterns of all riders. Vertical displacements of horse and rider were plotted against time and against each other.

The simple spring-mass model

The seemingly artificial situation of hopping in place, i.e. at zero speed, can be taken as a model for bouncing gaits in animals (Farley et al., 1985). Assuming a linear spring, the following equation of motion during ground contact can be formulated:

$$\sum F = -m_h g - k_h(\delta_{st} + z_h) = m_h \ddot{z}_h \tag{2}$$

Where ΣF is the sum of the vertical forces on the horse, m_h is the mass of the horse, z_h is the vertical displacement of the horse, g is the magnitude of the gravitational acceleration, k_h is the stiffness of the spring of the horse and δ_{st} is the static deflection due to the weight of the mass acting on the spring. If the static equilibrium position is chosen as a reference for z_h, the weight factor can be eliminated and the equation of motion becomes:

$$\sum F = -k_h z_h = m_h \ddot{z}_h \tag{3}$$

During motion, the horse's body moves up and down rhythmically. Since the standing horse does not oscillate in a vertical sense with the force of gravity as the energy source, it is apparent that vertical oscillations have to be excited by a motor system. In the model, the vertical oscillations are caused by a forcing function which is described as a sine wave function (Rooney, 1986). The equation of motion therefore becomes:

$$\sum F = m_h \ddot{z}_h = -k_h z_h + F_{0\_h} \sin \omega_h t \tag{4}$$

Where F_{0_h} is the amplitude of the forcing function of the horse, ω_h is the angular frequency ($2\pi f_h$, where f_h is the bouncing frequency of the horse) of the forcing function of the horse and t is time. The rider-horse interaction can be simulated by adding a second one-dimensional spring-mass system for the rider. Again we assumed a linear spring and contact between rider and horse. The coupled differential equations for this combined system are:

$$m_h \ddot{z}_h = -k_h z_h - k_r(z_h - z_r) + F_{0\_h} \sin \omega_h t \tag{5}$$

$$m_r \ddot{z}_r = -k_r(z_r - z_h) \tag{6}$$

Where m_r is the mass of the rider, z_r is the vertical displacement of the rider and kr is the stiffness of the spring of the rider (Fig. 1A). These coupled differential equations can be solved analytically, resulting in the following solutions:

$$z_h = -\frac{F_{0\_h}\,(k_r - m_r\omega_h^{\,2})}{m_h m_r \omega_h^{\,4} - (m_h k_r + m_r k_r + m_r k_h)\omega_h^{\,2} + k_h k_r}\sin \omega_h\, t \tag{7}$$

$$z_r = -\frac{F_{0\_h} k_r}{m_h m_r \omega_h^{\,4} - (m_h k_r + m_r k_r + m_r k_h)\omega_h^{\,2} + k_h k_r}\sin \omega_h\, t \tag{8}$$

During cyclic behaviour, the masses of horse and rider can move either in phase or 180° out of phase, other phase relationships are not possible. This basic model was used to evaluate the effect of differences in rider mass and rider spring stiffness on the vertical displacement and force of both horse and rider.

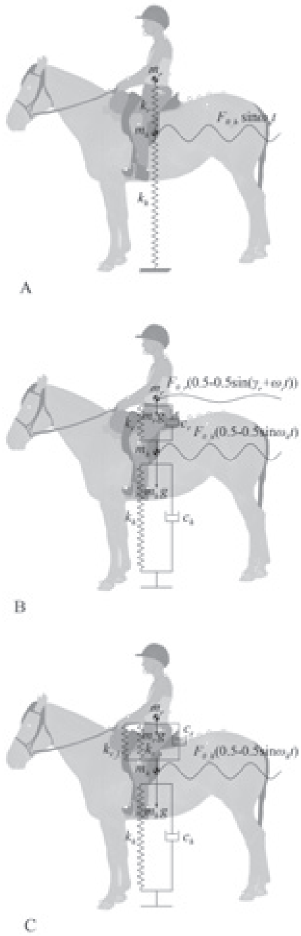


Figure 1
Mechanical models of horse-rider interaction

A. simple spring-mass model;
B. spring-damper-mass model with forcing function of the rider;
C. spring-damper-mass model with active spring system of leg of the rider.

m_h is the mass of the horse, m_r is mass of the rider, k_h is the spring of the horse, k_r is spring of the rider, k_{r_s} saddle spring of the rider, k_{r_l} active spring system of the leg of the rider, c_h is the damping coefficient of the horse, c_r is the damping coefficient of the rider, F_{0_h} is the amplitude of the forcing function of the horse, ω_h is the angular frequency of the forcing function of the horse and t is time. F_{0_r} is the amplitude of the forcing function of the rider, γ_r is the phase difference and ω_r is the angular frequency of the forcing function of the rider.

The spring-damper-mass model with forcing function of the rider

The second spring-damper-mass model incorporated a free fall for both horse and rider, dampers for both horse and rider and a forcing function for the rider (Fig. 1B). A numerical approach was used, simulating 50 stride cycles with time steps of 0.005 s. Since the equations of the model are quite stiff, an appropriate ODE solver (ode15s of Matlab) was used. The extended spring-mass-damper model can be described by the following equations:

$$m_h\ddot{z}_h = -\eta_h c_h \dot{z}_h - \eta_r c_r(\dot{z}_h - \dot{z}_r) - \eta_h k_h \varepsilon_h + \eta_r k_r \varepsilon_r - m_h g + \eta_h F_{0\_h}(0.5 - 0.5\sin\omega_h t) \qquad (9)$$

$$m_r\ddot{z}_r = -\eta_r c_r(\dot{z}_r - \dot{z}_h) - \eta_r k_r \varepsilon_r - m_r g + \eta_r F_{0\_r}(0.5 - 0.5\sin(\gamma_r + \omega_r t)) \qquad (10)$$

$$\varepsilon_h = (z_h - z_{h\_\eta}) / z_{h\_\eta} \qquad (11)$$

$$\varepsilon_r = ((z_r - z_h) - z_{r\_\eta}) / z_{r\_\eta} \qquad (12)$$

$$\eta_h = 0.5 + 0.5\tanh -10^4\,\varepsilon_h \qquad (13)$$

$$\eta_r = 0.5 + 0.5\tanh -10^4\,\varepsilon_r \qquad (14)$$

Where η_h is the force contact factor of the horse (varying from 0 in suspension phase to 1 in contact phase), η_r is the force contact factor of the rider (varying from 0 in suspension phase to 1 in contact phase). c_h is the damping coefficient of the horse and c_r is the damping coefficient of the rider. F_{0_r} is the amplitude of the forcing function of the rider, γ_r is the phase difference and ω_r is the angular frequency ($2\pi f_r$, where f_r is the bouncing frequency of the rider) of the rider. ε_h is the strain of the horse and ε_r is the strain of the rider. z_{h_η} is the height of the horse at the moment just before the suspension phase, z_{r_η} is the height of the rider minus the height of the horse just before the rider loses contact with the horse. This model was used to calculate vertical displacement, forces, power and work of both horse and rider.

The spring-damper-mass model with active spring system of leg of the rider

During the sitting phase of the rising trot, the biomechanical properties of the rider are determined by the upper body, the legs and the saddle. During the standing phase, there is no contact between upper body and saddle. This phase will therefore be determined by the leg of the rider only. When the rider is standing up, muscle activation and changes of geometry will change both the effective stiffness of the leg and the effective rest length of the leg. Therefore, an active spring system for the leg was introduced in the third spring-damper-mass model, instead of the forcing function of the rider (Fig. 1C). The rider has two springs; a saddle spring with a fixed stiffness and rest length and a leg spring with a varying stiffness and rest length. The third spring-mass-damper model can be described by the following equations:

$$\begin{aligned} m_h \ddot{z}_h = & -\eta_h c_h \dot{z}_h - \eta_{r\_c} c_r (\dot{z}_h - \dot{z}_r) - \eta_h k_h \varepsilon_h + \eta_{r\_s} k_{r\_s} \varepsilon_{r\_s} \\ & + \eta_{r\_s} k_{r\_l} \varepsilon_{r\_l} - m_h g + \eta_h F_{0\_h} (0.5 - 0.5 \sin \omega_h t) \end{aligned} \tag{15}$$

$$m_r \ddot{z}_r = -\eta_{r\_c} c_r (\dot{z}_r - \dot{z}_h) - \eta_{r\_s} k_{r\_s} \varepsilon_{r\_s} - \eta_{r\_s} k_{r\_l} \varepsilon_{r\_l} - m_r g \tag{16}$$

$$k_{r\_l} = k_{r\_l\_base} + k_{r\_l\_amp} (0.5 - 0.5 \sin(\gamma_r + \omega_r t)) \tag{17}$$

$$z_{r\_\eta l} = z_{r\_\eta l\_base} - z_{r\_\eta l\_amp} \sin(\gamma_r + \omega_r t) \tag{18}$$

$$\varepsilon_h = (z_h - z_{h\_\eta}) / z_{h\_\eta} \tag{19}$$

$$\varepsilon_{r\_s} = ((z_r - z_h) - z_{r\_\eta s}) / z_{r\_\eta s} \tag{20}$$

$$\varepsilon_{r\_l} = ((z_r - z_h) - z_{r\_\eta l}) / z_{r\_\eta l} \tag{21}$$

$$\eta_h = 0.5 + 0.5 \tanh - 10^4 \varepsilon_h \tag{22}$$

$$\eta_{r\_s} = 0.5 + 0.5 \tanh - 10^4 \varepsilon_{r\_s} \tag{23}$$

$$\eta_{r\_l} = 0.5 + 0.5 \tanh - 10^4 \varepsilon_{r\_l} \tag{24}$$

$$\eta_{r\_c} = \eta_{r\_s} \quad \text{if } \eta_{r\_s} \geq \eta_{r\_l} \qquad \eta_{r\_c} = \eta_{r\_l} \quad \text{if } \eta_{r\_s} < \eta_{r\_l} \tag{25}$$

Where η_{r_s} is the force contact factor of the saddle spring of the rider, η_{r_l} is the force contact factor of the active spring system of leg of the rider, η_{r_c} is the force contact factor of the damper of the rider. Furthermore, k_{r_s} is the spring stiffness of the saddle spring of the rider, k_{r_l} is the spring stiffness of the active spring system of leg of the rider, $k_{r\_l\_base}$ is the base value of the spring stiffness of the active spring system of leg of the rider,

$k_{r\_l\_amp}$ is the increase of the spring stiffness of the active spring system of leg of the rider. $z_{r\_\eta s}$ is the length of the saddle spring just before the rider loses contact with the horse, $z_{r\_\eta l}$ is the length of the active spring system of leg of the rider just before the rider loses contact with the horse (rest length), $z_{r\_\eta l\_base}$ is the base value of the rest length of the active spring system of leg of the rider, $z_{r\_\eta l\_amp}$ is the amplitude of the rest length of the active spring system of leg of the rider. ε_{r_s} is the strain saddle spring of the rider ε_{r_l} of the active spring system of leg of the rider. This model was used to calculate vertical displacement, forces, power and work of both horse and rider at the rising trot.

Parameter estimation

The input parameters of the spring-(damper)-mass models are presented in table 1. The range of input values is based on values found in the literature (Blum et al., 2009; Bobbert and Casius, 2011; Farley et al., 1991; Farley et al., 1993; Zadpoor and Nikooyan, 2010). Furthermore, the value of the spring stiffness of the horse was estimated experimentally by measuring the vertical displacement of the horse with and without a rider of 75 kg. This resulted in approximately the same value as that found in the literature (Farley et al., 1993). For the simple mass-spring model, contour plots were used to determine which combination of input values would provide realistic output values (displacement of both horse and rider). For the extended spring-damper-mass models, the Downhill Simplex method (Nelder and Mead, 1965) was used to optimize with regard to vertical displacement of horse and rider, peak force between horse and rider and work of horse and rider. The Downhill Simplex method is a technique for minimizing an objective function in a many-dimensional space. The method uses the concept of a simplex, with a special polytope of N + 1 vertices in *N* dimensions. The algorithm extrapolates the behaviour of the object function measured at each test point arranged as a simplex and chooses to replace one of the test points with the new test point and so the technique progresses. For the optimization of vertical displacements the sum of the squared differences between the measured vertical displacement and calculated vertical displacement of both horse and rider were calculated. Phase plots of the last two stride cycles were used to give a graphical overview of the parameter space.

Table 1 Input parameters of mass-spring-damper models

Input parameter model	Value input parameter model	Literature
Mass rider simple model [kg]	30-150	Range of rider masses evaluated
Mass rider extended model [kg]	60	Average rider
Mass horse [kg]	600	Average warmblood horse
Spring constant rider [kN/m]	0-80	Range of rider spring constants evaluated Running: 11-19 kN/m (Blum et al., 2009) Hopping (60 kg rider): 9 – 45 kN/m (Bobbert and Casius, 2011; Farley et al., 1991)
Spring constant horse [kN/m]	52	Overall leg stiffness was calculated according to Farley et al. (1993)
Amplitude forcing function horse simple model [N]	3900 (0.1-6000)*	
Amplitude forcing function horse extended models [N]	9900	Gravity was added
Frequency forcing function horse [Hz]	2.4	Step frequency horse at trot: 2.4 Hz (this study)
Damping coefficient rider [kg/s]	0-3000	Range of rider damping coefficients evaluated Leg human: 300-1900 kg/s (Zadpoor and Nikooyan, 2010)
Damping coefficient horse	5000 (0-10000)**	
Rest length rider [m]	0.60	
Rest length saddle spring rider [m]	0.60	
Rest length leg spring rider [m]	0.60 ± 0.03	
Rest length horse [m]	1.24	
Amplitude forcing function rider [N]	0-1200	
Frequency rider [Hz]	1.2	Frequency standing phase rider
Phase difference rider	0-2π	

*This range of input values was tested using a contour map of the amplitude and the frequency of the forcing function. The combination of the (known) frequency of 2.4 Hz and an amplitude of 3900 N, resulted in a vertical displacement of the horse that was comparable with the experimental data.
**This range of input values was tested using the Downhill Simplex method. This damping coefficient resulted in the best match with the experimental data of horse and rider.

Results and discussion

Measured vertical displacement of rider and horse

The experimentally measured vertical displacements (Fig. 2 A, B) show a sine wave pattern for the horse and rider during sitting trot with the rider moving almost in phase with the horse. The phase difference between horse and rider shows that the movement of the rider is delayed compared to the movement of the horse. During rising trot, however, the pattern of the rider seems to consist of a cosine wave with a long period and a large amplitude (sitting phase) and a cosine wave with a short period and a small amplitude (standing phase). In the figure the rider appears to move further downward than the horse, but this is merely the effect of plotting the movements around the average position of either horse or rider. In fact, the rider is moving more upward than the horse. Phase plots of the measured vertical displacements are shown in figure 2 C, D.

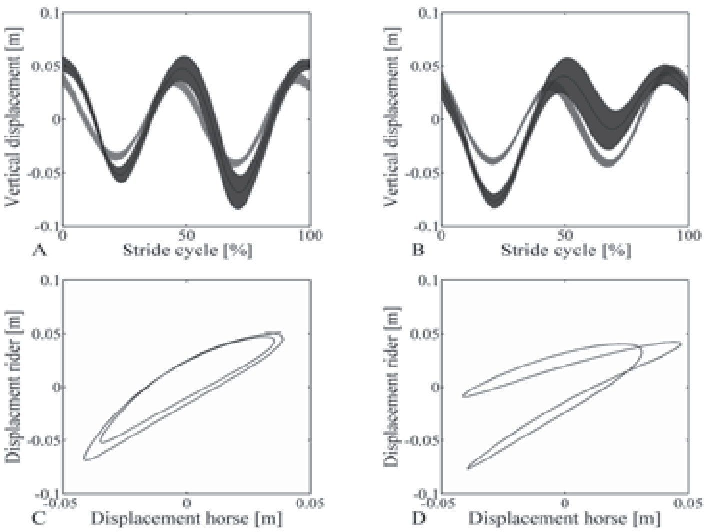


Figure 2
Vertical displacement of horse and rider during sitting and rising trot
A. vertical displacement during sitting trot;
B. vertical displacement during rising trot;
C. phase plot of vertical displacement of horse and rider at sitting trot;
D. phase plot of vertical displacement of horse and rider at rising trot.
••••: displacement of horse relative to the static equilibrium position of the horse (± sd: shaded area);
——: displacement of rider relative to the static equilibrium position of the rider (± sd: shaded area).
Time zero represents contact of the hind limb on which the rider sits in the saddle at rising trot. Movements of the horse and rider are plotted around the average positions of horse and rider, respectively.

Simulating sitting trot and jockey technique with a simple spring-mass model

With the basic model it is possible to simulate a sitting trot (Fig. 3A). With a relatively high stiffness of the spring the rider moves in phase with the horse with an amplitude comparable to the experimental data. The movement in counter phase resembles the movement of a rider in jockey technique as described by Pfau et al. (2009). The jockey technique can be simulated by the model by using a relatively low stiffness for the rider spring (Fig. 3B). Note that the vertical displacement of the horse is larger and the vertical displacement of the rider is smaller during the jockey technique. The effects of combinations of rider mass and spring stiffness on rider displacement are shown in figure 4. Specific combinations of rider mass and rider stiffness will lead to a vertical displacement of the rider that is in phase with the horse. These combinations can be found in the right half of the figure and represent the sitting trot. Other specific combinations of rider mass and rider stiffness will lead to a vertical displacement of the rider that is in counter phase with the horse. These combinations can be found in the left half of the figure and represent the jockey technique.

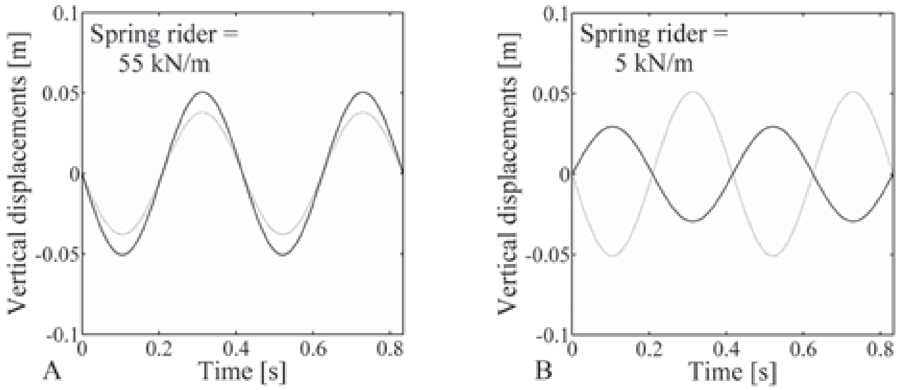


Figure 3
Displacement of both horse and rider calculated using the basic spring-mass model
A. simulation sitting trot (high rider spring stiffness);
B. out of phase movement of horse and rider; comparable to vertical movements of horse and rider in the jockey position of the rider (Pfau et al, 2009) (low rider spring stiffness);
- - - : displacement of horse relative to the static equilibrium position of the horse;
——: displacement of rider relative to the static equilibrium position of the rider.

In sitting trot, the rider stays seated in the saddle. The movement of the rider is influenced by the saddle, the skin, the muscles and the flexion of the lower back of the rider. The influence of the legs of the rider is limited. Therefore, it is likely that the lower back of the rider is the dominant factor for the mechanical properties of the rider during sitting trot. In this range of high spring stiffness of the rider, the vertical displacement and force of the rider are not very sensitive to a change in spring stiffness (Fig. 4B, D).

When the rider stands in the stirrups in the jockey position, the legs of the rider determine the mechanical properties of the rider. In this range of low spring stiffness of the rider, vertical displacement of the rider is very sensitive to a change in spring stiffness (Fig. 4B). This could mean that control of leg stiffness in this position is critical. Between these two ranges of spring stiffness there is a resonance zone with very high and unrealistic displacements and forces (Fig. 4C, D).

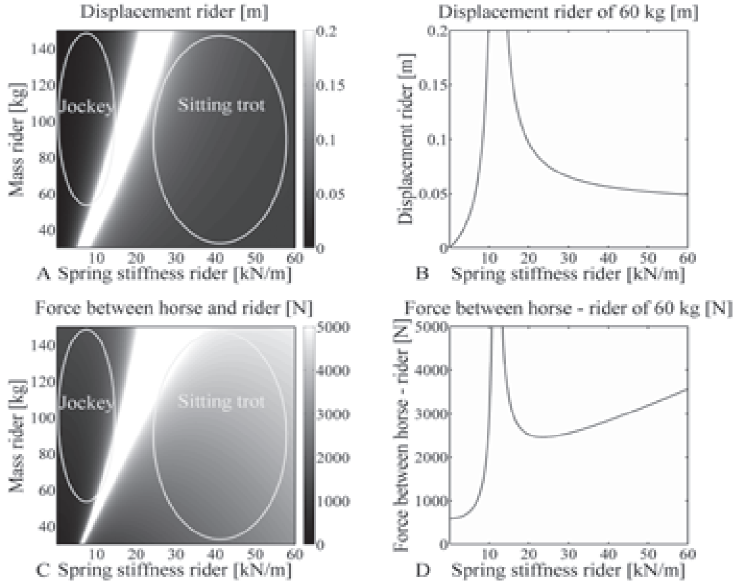


Figure 4:
Effect of combinations of rider mass and rider spring stiffness on vertical displacement and force of the rider

A. effect of combinations of rider mass and rider spring stiffness on vertical displacement of rider;
B. effect of spring stiffness on vertical displacement of rider of 60 kg (peak value: 10.60 m);
C. effect of combinations of rider mass and rider spring stiffness on force of rider;
D. effect of spring stiffness on force of rider of 60 kg (peak value: $1.25*10^5$ N).

Rider mass and rider spring stiffness combinations for sitting trot and the jockey technique are indicated. Between these two regions of spring stiffness there is a resonance zone with very high and unrealistic displacements and forces.

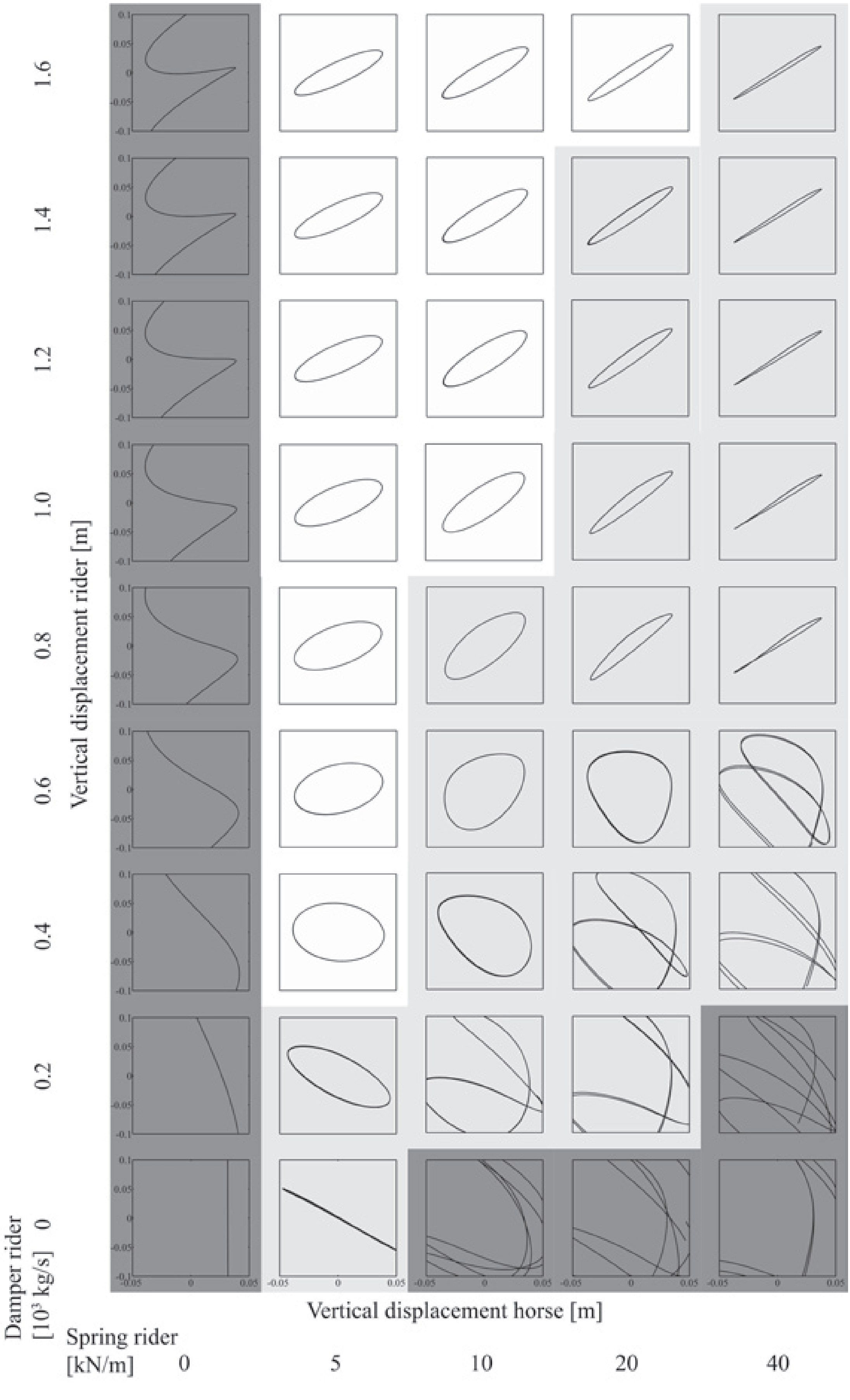
Simulating sitting, rising trot and jockey technique with the extended spring-damper-mass models

In the extended spring-damper-mass models, a free fall was introduced. This free fall changes the requirements for the stability of the horse-rider system. It is no longer possible that the springs of the model are loaded under tension. Damping is needed to provide stability. Figure 5 gives an overview of the effects of the spring stiffness and damping coefficient of the rider. It indicates where the movements of horse and rider are no longer cyclic, where the movements are cyclic but the rider loses contact with the horse, and where the movements are cyclic and the rider remains in contact with the horse. Combinations of a low damping coefficient and low spring stiffness will result in a phase relationship that resembles the modern jockey technique. An increase in damping coefficient will result in the sitting trot. When the spring stiffness is also increased, a lower damping coefficient is needed for a sitting trot. It is striking that for the two riding modes, sitting trot and modern jockey technique, it is possible to have a stable cyclic simulation with a suspension phase. This raises the question whether the rider does in fact have a suspension phase. In fact, both the total vertical force on the rider and the stirrup force do reach zero during sitting trot (de Cocq et al., 2010; van Beek et al., 2011). This supports the idea that there is a suspension phase at sitting trot, although this might not be visible to the eye.

There is a wide range of combinations of rider's spring stiffness and damping coefficients, that will result in a sitting trot. An increase in damping coefficient will increase the work required of the horse and an increase of spring stiffness will increase the peak forces on the rider and therefore on the horse' back. This indicates that there is an optimal combination of damping coefficient and spring stiffness of the rider.

The Downhill Simplex method was used to optimize for the measured vertical displacements of horse and rider in sitting and rising trot, peak force of the rider and work of the horse. The combination of spring stiffness and damping coefficient of the rider that resembles the experimentally measured displacements of sitting trot most closely are 23.6 kN/m and 1056 kg/s (Fig. 6A, E, I, M). In the modern jockey technique, the rider has an average displacement of 0.06 m and the rider moves in counter phase with the horse (Pfau et al., 2009). The combination of spring stiffness and damping coefficient of the rider that resembles this situation the most are 3.3 kN/m and 10 kg/s (Fig. 6B, F, J, N). This riding technique has high peaks in the power of the rider and is therefore the most demanding technique for the rider.

Rising trot cannot be simulated based on changes in the spring stiffness and damping coefficient of the rider. When a forcing function is incorporated in the model, it is possible to simulate a rising trot (Fig. 6C, G, K, O), although the agreement with the experimental data is not optimal. The spring stiffness and damping coefficient needed to simulate a rising trot are relatively low (4.8 kN/m) and high (2779 kg/s) respectively. With the third spring-damper-mass model, the simulation of the rising trot has a far better agreement with the experimental data. During the sitting phase, the forces on the rider are indeed dominated by the saddle


Vertical displacement rider [m]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Damper rider
[10³ kg/s]
Vertical displacement horse [m]
Spring rider
[kN/m]
0
5
10
20
40

spring. During the standing phase, the saddle spring loses contact with the horse and the active spring system of the leg of the rider takes over (Fig. 7). The force patterns of the total force on the saddle resemble the measured forces of de Cocq et al. (2010). The spring leg forces resemble the measured stirrup forces of van Beek et al. (2011) which have a small force peak in the sitting phase and a large force peak in the standing phase. However, the timing of the first small peak of the spring leg force is relatively early compared to the measured stirrup forces. In the model, the timing of the change in spring stiffness and rest length of the active spring system of the leg is the same. In real life, there probably is a timing difference between the change in spring stiffness and rest length. This could explain the observed difference between the simulated spring leg force and measured stirrup forces.

The lowest work of the horse and lowest peak force of the rider are both a result of relatively low spring stiffness and low damping of the rider. This combination goes even further than the modern jockey technique (Fig. 6D, H, L, P). This mode, seems, therefore, to be the preferred mode for horse-rider interaction.

Conclusion

The models provide insight into the biomechanical requirements a rider has to comply with in different riding techniques. At sitting trot, the rider is able to follow the movement of the horse by using a relatively high spring stiffness and a high damping coefficient. The modern jockey technique results from of a relatively low spring stiffness and a low damping coefficient. The rising trot requires an active spring system for the leg of the rider, which changes both in stiffness and rest length. The model confirms the hypothesis that the biomechanical properties of the rider are an important factor in strategies that could reduce the vertical peak force exerted by the rider on the horse’s back and the mechanical work of the horse. An “extreme” modern jockey technique is the optimal mode for the minimization of both vertical peak force of the rider and mechanical work of the horse.

A topic for further research is how the rider actually changes his biomechanical properties. These biomechanical properties result from the complex interplay between muscle stimulation-time histories, muscle properties and geometry. Research on riding techniques, measuring kinematics, forces between horse and rider and electromyography of the leg muscles of the rider is needed to tackle this problem.

Figure 5:
Phase plots of the displacement of the horse versus the displacement of the rider for different values of spring stiffness and damper coefficient of the rider.
Note that a combination of a low rider spring stiffness and a low rider damper coefficient results in a phase relationship that resembles the jockey position and that a combination of a high rider spring stiffness and a high rider damper coefficient results in a phase relationship that resembles the sitting trot.
Some combinations lead to phase relationships that do not seem to occur in horse riding. This might result in a fall of the rider from the horse:
Dark grey: no cyclic behavior;
Light grey: cyclic behavior, but rider loses contact with horse.

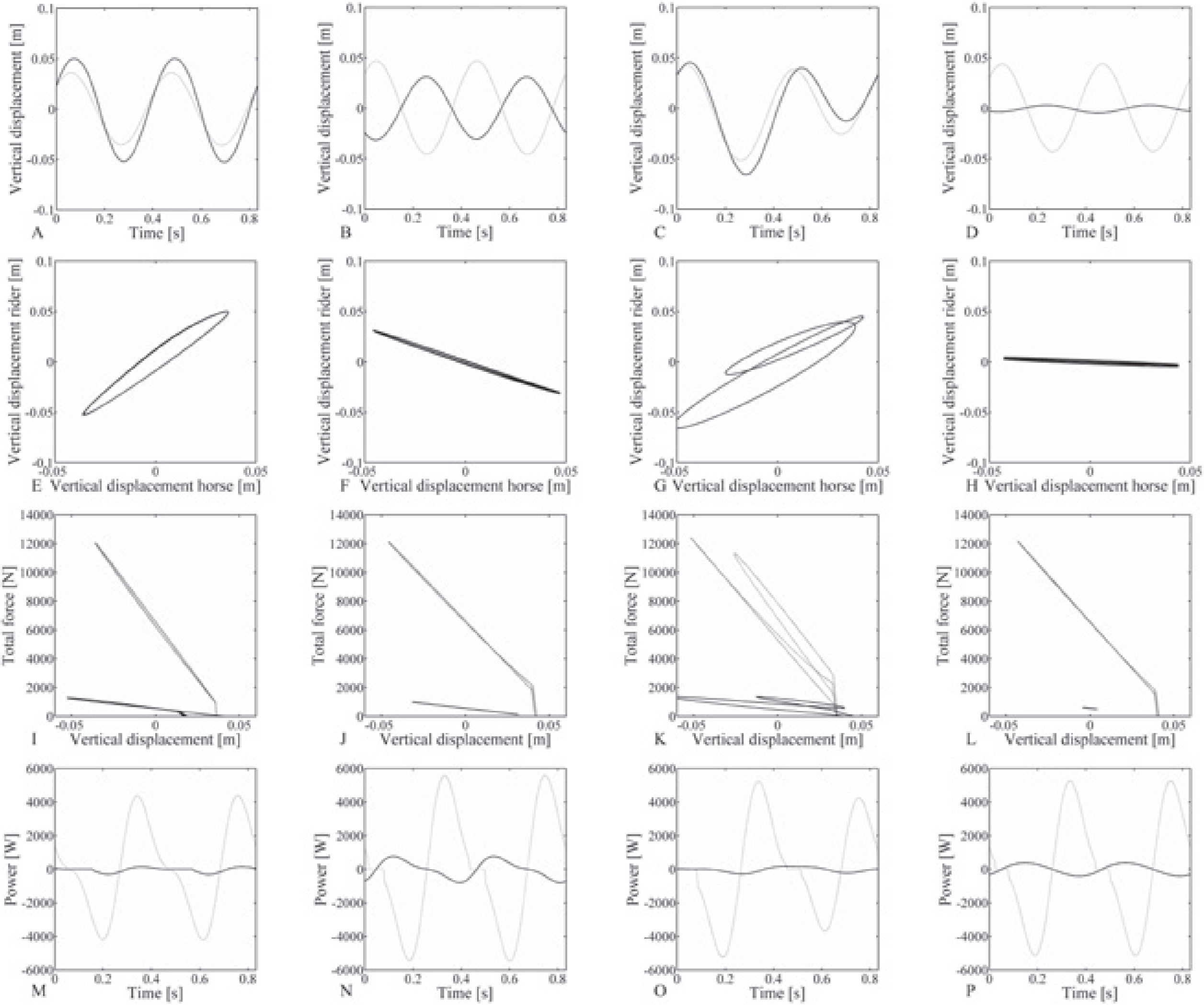


Figure 6:
Result of model optimization based on vertical displacements and minimal peak rider force and minimal work of the horse.

A. vertical displacement during simulated sitting trot;
B. vertical displacement during simulated modern jockey technique;
C. vertical displacement during simulated rising trot with forcing function;
D. vertical displacement during optimal horse riding technique;
E. phase plot simulated sitting trot;
F. phase plot simulated modern jockey technique;
G. phase plot simulated rising trot with forcing function;
H. phase plot optimal horse riding technique;
I. work loops of horse and rider at sitting trot;
J. work loops of horse and rider at modern jockey technique;
K. work loops of horse and rider at rising trot with forcing function;
L. work loops of horse and rider at optimal horse riding technique;
M. power of horse and rider at sitting trot;
N. power of horse and rider at modern jockey technique;
O. power of horse and rider at rising trot with forcing function;
P. power of horse and rider at optimal horse riding technique.

\- - - : vertical displacement, work loops and power horse;
——: vertical displacement, work loops and power rider.

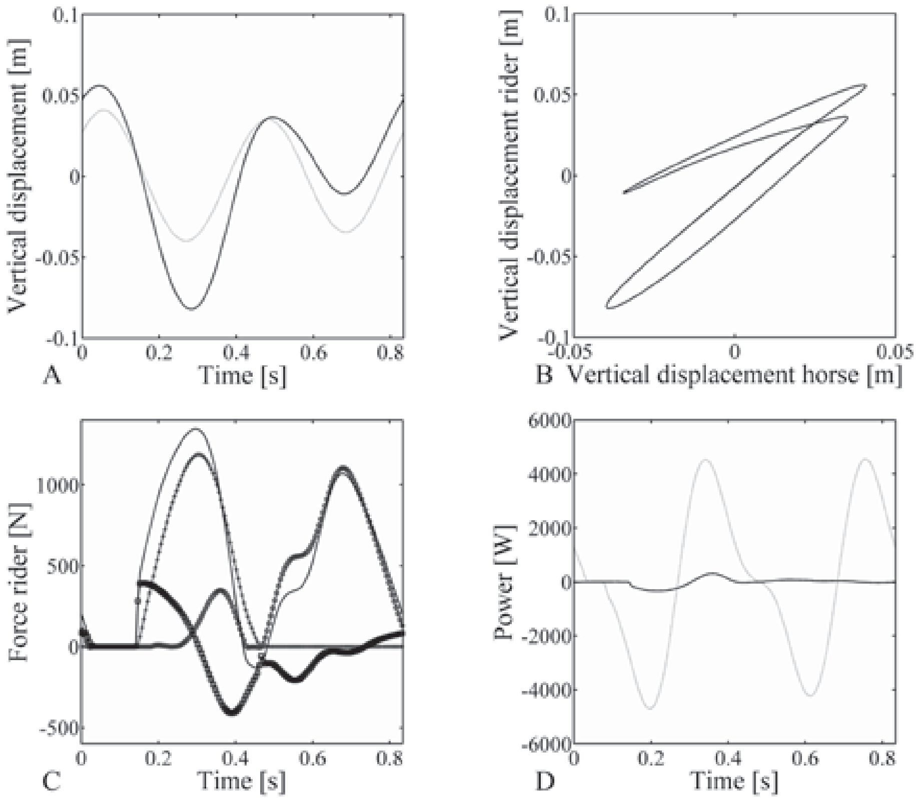


Figure 7

Simulation of rising trot with active spring system for the leg of the rider.

A. vertical displacement during simulated rising trot with active spring system;
B. phase plot simulated rising trot with active spring system;
C. rider forces simulated rising trot with active spring system;
D. power of horse and rider at rising trot with active spring system.
- - - : vertical displacement and power horse;
——: vertical displacement and power rider.
Forces in figure 7C:
——: total force rider;
+++: saddle spring force rider;
ooo: leg force spring rider;
□□□: damping force rider.

List of symbols and abbreviations

h	horse
r	rider
m	mass
k	spring stiffness
g	magnitude of gravitational acceleration
$z, \dot{z}, \ddot{z}$	vertical displacement, velocity and acceleration
F_0	amplitude forcing function
ω	angular frequency forcing function
γ	phase difference forcing function
f	frequency of a bounce
t	time
δs_t	static deflection due to the weight of the mass acting on the spring
η	force contact factor
c	damping coefficient
ε	strain
s	saddle spring of the rider
l	active spring system of the leg of the rider

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6. General discussion

6.1 The future of research into horse-rider interaction.

Patricia de Cocq

Future steps in improving welfare and preventing injuries in equine athlete

Welfare is a very important issue in equine sports that is under close societal and political scrutiny. In the Netherlands, the equine industry is organized in one council, the "Sectorraad Paarden". This council is involved in the development of guidelines regarding welfare issues, including the training of horses and the use of training aids. However, the evaluation of welfare of the ridden horse is mainly subjective. It would be a big step forward if more objective criteria for welfare could be developed. Biomechanical measurements could be of great help in this matter, as it is likely that there is a relationship between the forces exerted on the horse and the degree to which the welfare of the animal is affected. Another important reason to develop objective measurement techniques for these parameters, related to the use of the horse, is the high incidence of musculoskeletal disorders, which rank first among the causes of wastage in performance horses (see Chapter 1). These musculoskeletal injuries are almost invariably caused by single or repetitive biomechanical overload.

The equestrian world is especially interested in the effects of training techniques that are considered less conventional and of which the potential to cause harm is debated, such as hyperflexion of the head and neck. The question is if and how this and other techniques can be applied without jeopardizing the welfare of the equine athlete. Recent studies have provided information on hyperflexion. Most studies indicate there is no direct harm, but there is still debate whether this technique is acceptable and if so, under which conditions (Gomez Alvarez et al., 2006; Rhodin et al., 2005; 2009; Sloet Van Oldruitenborgh-Oosterbaan et al., 2006; Van Breda, 2006; Von Borstel et al., 2009; Wijnberg et al., 2010). A more detailed insight in the interaction between rider and horse, could further the discussion of the acceptability of this and other training techniques.

The aim of this PhD thesis is to enhance the understanding of the biomechanical interaction of rider and horse in order to optimize training and performance and prevent injuries. The technological development in this area is progressing rapidly. This chapter considers the contribution made to this research field by the studies performed within the current PhD project, puts these studies in a broad scope and discusses potential further progress in the near future.

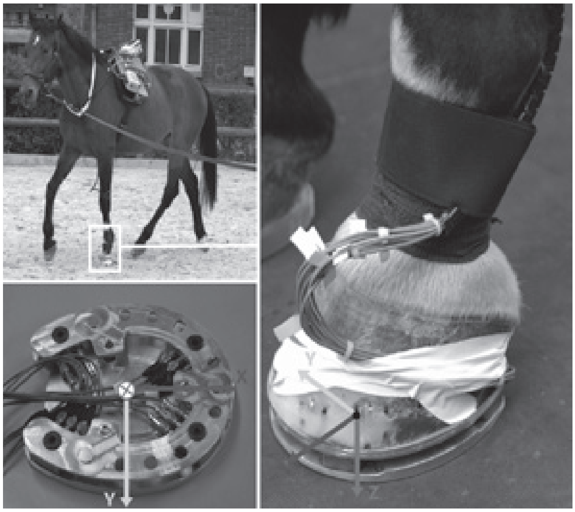
Non-invasive experimental research

Measuring forces between horse and rider

In Chapter 1, an overview was given of the influence of the rider on the biomechanics of the horse and of the biomechanical approaches used to study these influences. It was proposed that a combination of kinematical and force measurements is needed to be able to predict the (over)loading of the musculoskeletal system of both horse and rider and to study the biomechanical effects of riding techniques. The forces that could be measured include: ground reaction force, saddle force, rider's leg force, rein force, stirrup force and rider's feet force. Several of these force measurements have been developed or validated within this PhD project. Saddle force is the topic of Chapter 2. In sections 2.1 and 2.2 two different saddle force measuring devices were tested with respect to validity, reliability and repeatability. Subsequently, they were used to objectify the differences between two saddle fitting methods and to evaluate the effect of a change in rider position on the force distribution beneath the saddle. In section 2.3 a saddle force measuring device was used to measure both the saddle forces and the rider's leg forces during lateral movements in dressage. A stirrup force measuring technique has been developed too and was used to compare sitting and rising trot in Chapter 4.2.

Several limitations of the use of saddle force measurements were addressed in Chapter 1 and 2. The most important limitation is that the sensors in the saddle systems do not measure pressure, as would be expected from their name, but normal force. However, shear forces play a role too and for correct measurements these forces should be taken into account. Unfortunately, it is not possible to measure these non-perpendicular forces when the system is placed underneath the saddle. For the measurement of forces on the horse's back, the system is therefore limited to the summation of the magnitudes of the normal forces and hence carries an inherent error. An alternative, indirect, approach to evaluate the effect of the rider on the horse's back is to use rider kinematics to calculate the force exerted by the horse on the rider. This force has the same magnitude, but is opposite to, the force exerted by the rider on the horse's back. This approach has been used in Chapter 4.3 in a study into the effects of riding technique.

Figure 1 The dynamometric horseshoe
(Chateau et al., 2009; permission of use was granted)



Ground reaction forces can be measured using force plates, but data collection is cumbersome, since the horse has to land with the entire hoof full on the plate for accurate recording. Chateau et al. (2009) have developed and validated a dynamometric horse shoe for the measurement of 3D ground reaction forces (figure 1). This type of instrumented shoe could also be used in the research on horse-rider interaction. The data acquisition system could easily be carried in saddle bags, like the data acquisition system of the stirrup force sensors used in Chapter 4.2. The last force that should be measured is the force underneath the feet of the rider. In fact, the techniques used to measure the force exerted by the saddle and the rider's leg in Chapter 2 originate from technology developed for insoles that are used to measure the force distribution underneath the feet of athletes and patients with foot problems. This technology could be adapted to fit inside a riding boot, which would complete the picture concerning the forces of the horse-rider system.

This combination of force measuring technologies would provide the possibility to measure the external loading of the musculoskeletal system of both horse and rider. These technologies can be used to answer the questions concerning which horse riding and training techniques should be used to minimize these external forces in order to minimize risk of injury of both horse and rider.

Kinematics

Kinematics describes the motion of bodies and systems without consideration of the forces that cause this motion. Several camera-based techniques have been used to study equine locomotion, including high-speed cameras and multiple infrared camera systems to reconstruct 3D movements. These optical motion capture systems can be used to study the movements of head, neck, limbs and the centre of mass of both horse and rider; they have been used in this PhD project to evaluate the effects of weight on the movements of the horse's back and limbs (Chapter 3), to evaluate the effect of sitting and rising trot on the head and neck position and back movements of the horse (Chapter 4.1), to calculate the acceleration of the centre of mass of a rider and thereby the forces between horse and rider in sitting and in rising trot (Chapter 4.3), and to compare the real vertical displacements of horse and rider in both sitting and rising trot with simulations of three spring-(damper-)mass models (Chapter 5). There are, however, two major drawbacks of these systems for the study of horse-rider interaction: the field of view is limited and it is not possible to study movements of parts of the body that are blocked from view. The first problem can be solved by using more cameras (figure 2). In 2006, the San Diego Centre for Human Performance used 16 Eagle cameras from Motion Analysis Corporation to capture the movements of five dressage combinations (Motion Analysis, 2011). This approach is, however, costly.

The second problem is harder to solve. This is a major issue in the study of horse-rider interaction, since an important part of the back of the horse cannot be viewed directly due to the saddle. It is, however, possible to measure the movements before and behind the saddle and predict the movements beneath the saddle, like it was done in Chapter 3 and 4.1 for the back movements of the horse and in Chapter 5 for the vertical displacement of the horse. A more ideal solution would be to incorporate movement sensors into the saddle. Sensors that can measure movement (inertial sensors) are available and have already been used to study horse-rider interaction (Pfau et al., 2009). Of course, just like all new measurement tools, these sensors need to be tested. Pfau et al. (2005) compared the sensor displacement values with values generated by optical motion capture for individual strides. Their conclusions were that the inertial sensors could capture cyclical movements with comparable accuracy to optical motion capture systems, but that the sensors needed to be improved to extract non-cyclical components of movements.

Figure 2 Measurement setup of 16-camera Eagle system
(Motion Analysis, 2011; permission of use was granted)

If these sensors can be provided in a format small enough to fit in the gullet of the saddle and could be connected to the skin above the underlying vertebrae that are normally blocked from view by the saddle, new information about the interaction between horse and rider could be obtained. Questions on the effect of horse riding and training techniques on back movements of the horse could then be answered using a direct method, instead of extrapolation from movements before and behind the saddle.

Electromyography

In Chapter 5 the biomechanical requirements a rider has to comply with in order to follow the movements of the horse optimally were determined. Three spring-(damper-)mass models were constructed. These models demonstrated which combinations of rider mass, spring stiffness and damping coefficient would result in a sitting and riding trot, the modern riding technique used by jockeys, or other cyclic and non-cyclic behaviours. The spring-damper-mass model was optimized to realise both minimal peak force exerted by the rider and minimal work of the horse. Both optimizations result in a somewhat more "extreme" form of the modern jockey technique. The incorporation of an active spring system for the leg of the rider, was needed to simulate the rising trot. The question how the rider is changing his biomechanical properties, remains to be answered. Bobbert and Casius (2011) reproduced human hopping with a model of the musculoskeletal system comprising four body segments and nine Hill-type muscles, with muscle stimulation as only input. It is likely that the timing of muscle activation is important in the interaction between horse and rider. This can be studied using electromyography (EMG). The use of this technique has been limited in equestrian sports thus far and has only focussed on the upper body of the rider (Terada, 2000; Terada et al., 2004). Terada (2000) found differences in the rider's ability to "maintain posture" depending on experience. In a later study the activation patterns of the muscles in the upper body of the rider were found to be consistent between riders, occurring at key times during the stride (Terada et al., 2004). An important function of the muscles that was identified in this investigation was the stabilization of the rider's movements.

Combining EMG measurements of the upper and lower body of the rider with kinematics and force measurements would enable the development of a horse-rider model with more realistic muscular actuators. Such a model could help to understand how riders change their biomechanical properties (spring stiffness, rest length and damping coefficient) and whether this regulation is intended to minimize peak forces and/or energy expenditure. These insights can subsequently be used to improve horse riding and training techniques.

Modelling equine locomotion

The introduction of modelling and simulation in equine research

In 1993 van den Bogert and Schamhardt introduced modelling and simulation as tools for the theoretical support of equine locomotion research. They stated that, notwithstanding the development of new techniques for the measurement of internal forces and deformations and the modernisation of traditional kinematic and kinetic recording methods, biomechanical research had not been very successful thus far in identifying causal relationships between mechanical variables, anatomical features and (mal)function of the locomotor system. They identified two important areas in which the research of those days was failing: 1) results were difficult to comprehend and interpret; 2) variations were too large for statistically significant conclusions. They attributed both problems to the inherent complexity of the locomotor system. To make these problems manageable, they introduced modelling and simulation, because complex mathematical relationships between internal and external forces and movements can be derived from the basic laws of mechanics. In a simulation, the proper causal relationships between variables should be maintained, enabling the validated model to carry out 'experiments' on the real-world system. This means that muscle forces and activation patterns are inputs and movements and reaction forces are outputs of such a model system. Most simulation models contain simplifications and assumptions because it is, indeed, almost impossible to describe the entire locomotor system mathematically for its vast complexity. Examples of such simulations are the spring-(damper-)mass models that were developed in Chapter 5. These models are a simplification of the real horse-rider interaction. The models are one-dimensional. This simplification was made because the forces in the vertical direction between horse and rider are about 4 times greater than the forward-backward forces and 8 times greater than the sideward forces (Chapter 4.3). Furthermore, the morphology of both horse and rider was extremely simplified. Assumptions were made for the biomechanical properties of both horse and rider. For example, the legs of both horse and rider were modelled as a linear spring (and linear damper). These simple models did, however, provide the answers concerning the optimal riding technique in terms of maximal reduction of peak vertical force between horse and rider and minimization of the mechanical work of the horse. When information is required on maximally sustainable stresses in the anatomical structures of the horse, exceeding which might lead to injuries, or coordination strategies of the rider, more detailed models would be required.

Van den Bogert and Schamhardt refer to computer modelling as the combination of the set of mathematical equations that describes the system of interest, the gathering of appropriate data and the incorporation of these equations and data in a computer program. Modelling can for example be used to calculate internal forces from measured external forces and movements. It is not necessary to include the entire body in the model; only the area of interest and everything distal to it is relevant to the solution. This type of analysis is also known as inverse dynamics and is used in Chapter 4.3. Both modelling and simulations can be used to answer questions about functional anatomy and aetiology of overload-related injuries and may serve for the optimization of sports performance.

For the research on horse-rider interaction whole body models of horses could be combined with whole body models of humans. In 1989 van den Bogert et al. presented a method to simulate equine locomotion using a mixed forward-inverse dynamics approach. A 20-segment rigid body numerical model of the horse was constructed. They proposed that in future studies muscles should be modelled as force generators rather than torque generators, acting between the anatomical origin and insertion points. For more realistic models, information on the anatomy and inertial properties of horses would be required. In 2000, Herr and McMahon constructed a two-dimensional horse model that was formed by a series of rigid bodies connected by joints. There was a total of 10 degrees of freedom, two per leg, as well as a back and a neck joint. Telescoping joints at the knees and elbows allowed the leg lengths to change. The ground was modelled as a field of linear springs and dampers that were compressed when the trotting model strikes the ground. The model was used to study the effect of trotting speed, stride frequency, leg length and spring stiffness on energetics and stability of motion. In 2001, Herr and McMahon used a similar model to study the mechanics and energetics of gallop. The control strategies for the trotting model were distinct from the control strategies of the galloping model. Based on these two models, Herr et al. (2002) constructed 6 models for running mammals, ranging from chipmunk to horse. They used these models to study scale effects of quadrupedal running. This type of modelling provided a quantitative framework for testing hypotheses that relate to limb control, stability and metabolic costs.

Inertial properties of the horse

Although information on the inertial properties of the segments used in mathematical models is essential, there is limited information available about the horse on this topic. Buchner et al. (1997) determined the inertial properties (mass, density, centre of mass, inertial tensor) of 26 segments of six Dutch Warmblood horses (figure 3).

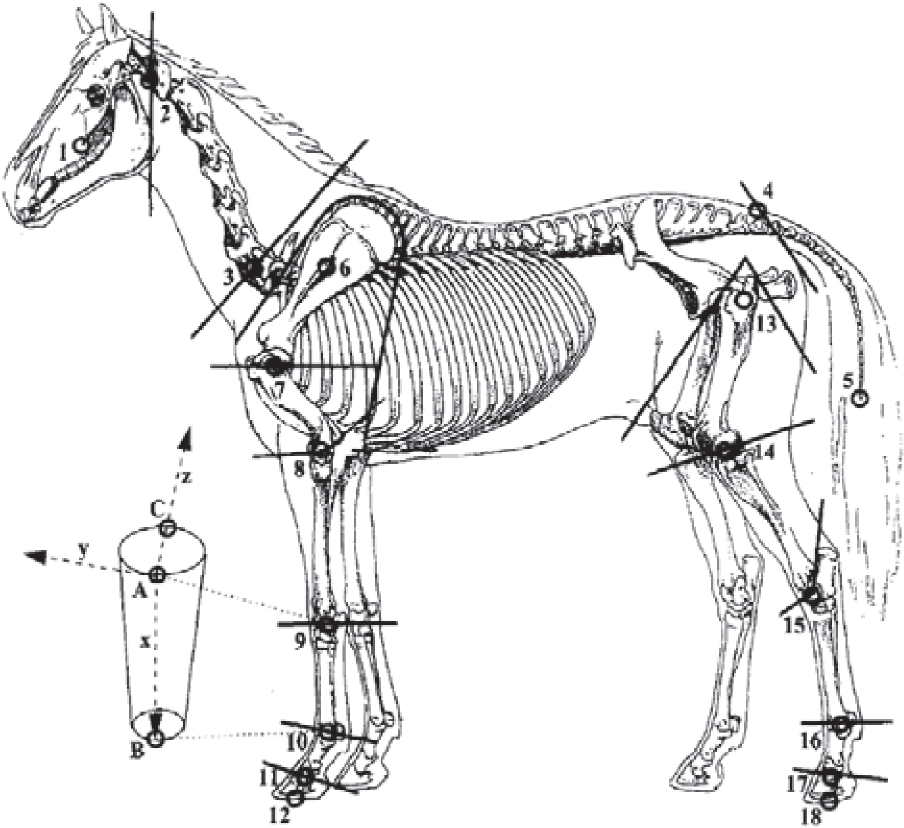


Figure 3 Twenty-six-segment model
(Buchner et al., 1997; permission of use was granted)

Based on the measured data, a linear regression model was developed for the estimation of inertial properties in living horses. The segments chosen were based on the simulation model described by van den Bogert et al. (1989), including the tail segment. This was the first study that presented complete 3D data on the position of the segment centre of mass and thereby enabled the calculation of the body centre of mass from kinematical analysis for each possible body posture. This was later done for both the sound and the lame horse (Buchner et al., 2000; 2001). The largest part of the body mass of the horse is contained in the trunk. In the above mentioned studies, this segment was assumed to be rigid. Nauwelaerts et al. (2009) questioned the validity of this assumption. They quantified changes in the position of the trunk's centre of mass due to external shape changes by measuring the kinematics of a mesh encompassing the trunk (figure 4).

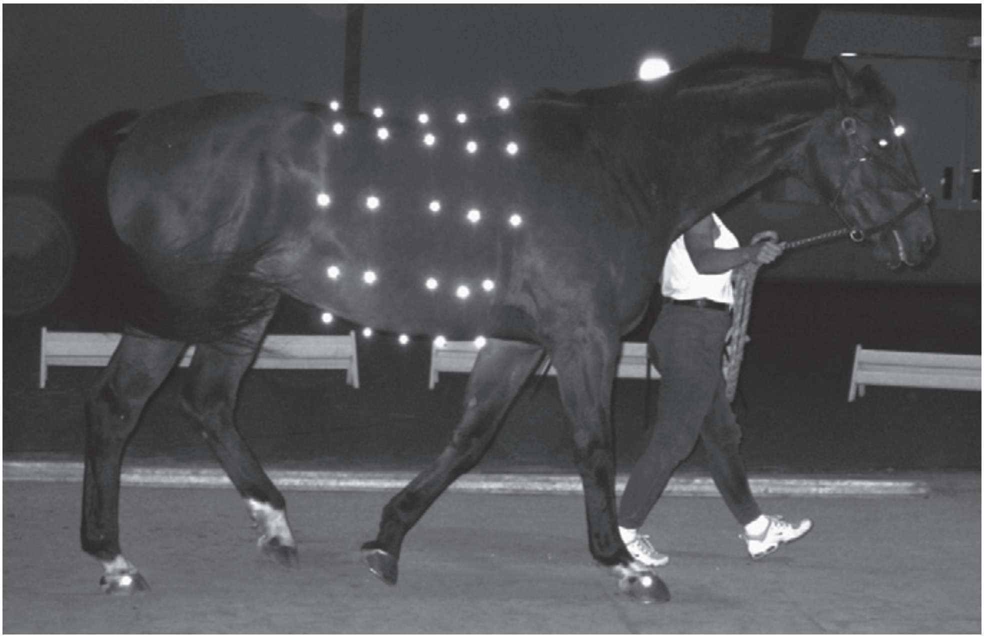


Figure 4 Markers attached to the trunk of the horse
(Nauwelaerts et al., 2009; permission of use was granted)

They suggest using extra markers on the trunk during movement analysis to correct for the shift in the centre of mass. Nauwelaerts et al. (2011) extended the original work by Buchner et al. (1997) by determining the inertial properties of 38 horses of different breeds and sizes. They found that the mass distribution does not change with size for animals less than 600 kg and that segment inertial properties are not affected by morphotype. The information from this type of study is invaluable for the optimisation of whole body models of horses and thus for the study of horse-rider interaction.

Human models: possibilities to combine equine and human models

Complex musculoskeletal models and computer simulations are becoming an integral part of analysing human locomotion (Neptune et al. 2009b). These models can help to understand a large number of topics that range from fundamental muscle coordination principles to potential injury mechanisms. The musculoskeletal system is highly complex and nonlinear by nature, which makes understanding of the relationship between neural control inputs, muscle forces and power output, and of specific task performance very difficult. Additionally, simulations may enable estimation of quantities that are difficult or impossible to measure *in vivo*. Figure 5 gives an example of a musculoskeletal model and optimization framework used to generate forward dynamics simulations.

Biomechanical models are used in a wide range of sporting disciplines, ranging from high and long jumping (Alexander, 1990; Seyfarth et al., 2000) to competitive running (Behncke, 1993), cycling (Wang and Hull, 1997; Yoshihuku and Herzog, 1999), ice skating (Houdijk et al., 2003) and skiing (Gerritsen et al., 1996). The models are used to optimize equipment and techniques and to identify potential injury mechanisms.

These models of human athletes could potentially be combined with models of horses to establish a comprehensive model of the interaction between horse and rider that may provide insight into performance limits and may help to identify mechanisms that could lead to injury. This modelling approach should, however, always be combined with experimental research to test the hypotheses generated by the model.

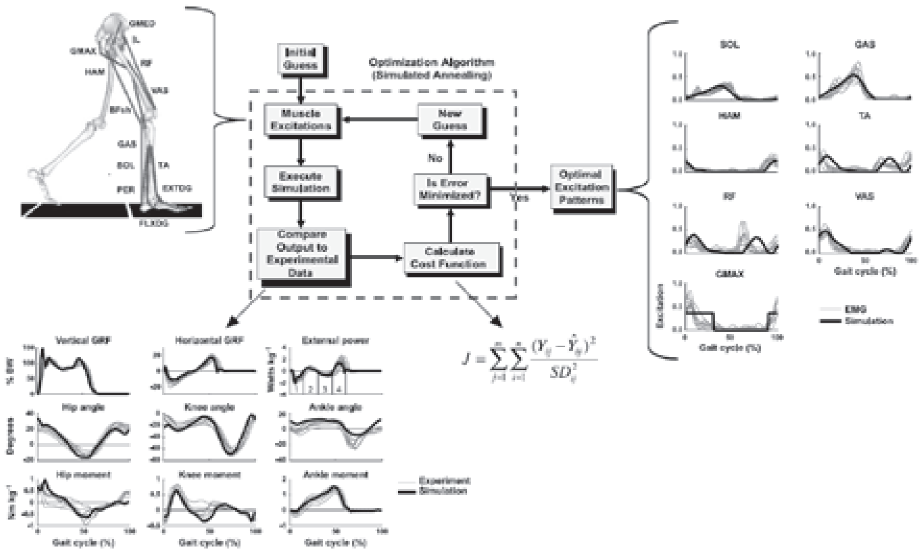


Figure 5 A musculoskeletal model and optimization framework used to generate forward dynamics simulations
(Neptune et al., 2009a; permission of use was granted)

Perspective

In the future research on the interaction between horse and rider may strongly benefit from the combination of several approaches. These can be used to answer questions concerning the external biomechanical loading of horse and rider and related equine back kinematics of several horse riding and training techniques. Techniques that minimize risk of injury of both horse and rider could possibly be identified, ensuring the welfare of the equine athlete. Mathematical models can help to identify mechanisms that could lead to injury and help to understand how a rider can minimize peak forces, enabling the development of new, ‘horse-friendly’ riding techniques.

Non-invasive experimental research can be improved by using the newest technology for kinematic measurements. Optical motion capture systems can be combined with inertial sensors that are capable of measuring motions of body parts that are blocked from view. The kinematics can be combined with kinetic measurements of the ground reaction force, saddle force, rider’s leg force, rein and stirrup force and rider’s feet force. Saddle force and rider’s leg force measurements are described in this PhD thesis. Rein force has already been measured by a variety of researchers and this equipment is commercially available at the moment. Dynamometric horseshoes that can measure 3D ground reaction forces have been developed and validated, but are not (yet) commercialized. They are a good alternative for the cumbersome and laboratory-bound measurements with force plates. Rider’s feet forces can be measured using force measuring insoles. Another good additional measuring technique that would be highly interesting to use in experimental research is electromyography (of both horse and rider) to study the timing of muscle activation.

The experimental approaches should more often be complemented by mathematical modelling. The existing models of equine locomotion can be improved by using the latest data on the inertial properties of the horse’s body segments. Biomechanical models have proven very useful for the understanding of a wide variety of topics, ranging from fundamental aspects of muscle coordination to potential injury mechanisms in many human sports activities. When these human models would be combined with an improved equine model, the interaction between horse and rider could be described mathematically in detail. If combined with data from an experimental approach, this could lead to new insights into performance limiting factors in equine sports and into the underlying mechanisms that may lead to injury. This information would then be most useful for the design of prevention strategies that aim to reduce injury incidence in both horse and rider.

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7.2 Acknowledgements

Patricia de Cocq

It is already a while ago that the idea of doing this PhD project got shape. During my veterinary research master, I got a first glimpse of doing research. My daily supervisor, Wim Back, thought that I was really talented and he advised me to look for an opportunity to continue my research. Although the creativity of doing research really appealed to me, I was looking for a bit more variety. At that moment, the combination of research, teaching and patient care seemed to form the ideal job. But, was teaching indeed the alteration I was looking for? To be sure that teaching suited me, I applied for an internship at the University of Applied Sciences HAS Den Bosch.

And then a vacancy at another University of Applied Sciences speeded things up. They were looking for about 30 PhD students. It turned out there was funding for teachers at Universities of Applied Sciences to do a PhD study. Wim read the advertisement and thought if this University can do this so can HAS Den Bosch. And they said yes! I can never thank Wim enough.

Wim also helped me finding a promotor. I met Johan in something that felt like a job interview but without a vacant position. Johan, fatherly, asked me if I was really sure. Did I know what I was getting into and how hard it would be? To be honest, I didn’t know then, but I was up for the challenge. Fortunately, the Experimental Zoology Group had just broadened their research field into equine biomechanics. My topic, of horse-rider interaction fitted well into this new line of research. So also Johan wanted to take up the challenge. I secretly think, that he also didn’t really know what he was getting into. Johan, thank you very much for your confidence, patience and critical advice.

So there I was, half time teaching in Den Bosch and half time doing research in Wageningen. I thought that it would be easiest to do most of the work in Den Bosch and only visit Wageningen when necessary. I couldn’t have been more wrong. The research group and the people in it, are the ones that make it happen. Even if the research topics are totally different. Of course, my daily supervisor, first Kees Spoor and later Mees Muller, were in Wageningen, but also my fellow PhD students; David, Mark, Ansa, Wijbrand, Maurijn, Sebastian and Elsa, my Master students; Heleen, Nirja, Femke, Tess, Mariken and Nynke, my Bachelor students; Marlies, Debby, Sarah and Lenie, and the EZO staff were in Wageningen. EZO crew and CBI friends, thanks for your inspiration, friendship and help!

In the first period Kees Spoor was my supervisor. Unfortunately we were only able to work together for a very short period. In this time we tried to make a horse out of a mosquito. And although this might seem odd, I think we succeeded quite well. Kees, thank you for your help, the musquito tracking routine and your very detailed advice.

I will particularly remember all the Wednesday afternoons I spend with Mees. Mees lectured me a course of Biomechanics. In the first week it could easily have been Chinese. I think the other students were a bit irritated by all the questions I asked. And Mees must have thought that I did not enjoy the course, because he was very surprised that I was so happy that he became my daily supervisor. I knew he was the person who could really help me out. Even though he is not interested in horses at all (he says that the love for horses has skipped a generation). We spend the Wednesday afternoons studying mathematics and physics. Mees is convinced that you can learn everything by practising “Üben Sie es eintausend Mal”. So I had to practise. But in-between the hard work there was a lot of entertainment and laughter. One time, when Mees and Celine were just back from their vacation in Bulgary, they even gave me a private performance with gaida music and Balkan songs. Mees, thanks for all the stories, the lovely food, the laughter and your tutorship.

But also outside EZO, I got a lot of help. René van Weeren was the other supervisor of my veterinary research master and he continued to help me out during my PhD study. I have discussed all the ideas for experimental studies with him. Furthermore, he helped me out when I needed measurement equipment that was not available in Wageningen. René has a very good feeling for what is ‘hot’ in equine research and also has a broad international network in the field of equine locomotion. René, thank you for all your advice.

We worked together with the Dutch Equestrian Centre in Deurne. They provided the research facilities, horses, riders and a lot of practical experience. Marion and Mark, thank you for all the arrangements you made for my experimental studies. Special thanks go to Carolien for our combined effort to let equine sports and research benefit from one another. Good luck with your own business Moxie and your PhD study, thanks for standing by my side at the final moment.

I did also get help from outside The Netherlands. Hilary Clayton, invited me to her lab in the summer of 2006 and 2007. It felt like a candy store. The McPhail Equine Performance Center had all the facilities that I could wish for. Although the time available was limited, especially since we had problems with the equipment and I didn’t have the software licences back at home, we were able to collect lots of data. This was only possible with the help of LeeAnn Kaiser and the ‘angels’ at the center. Hilary, thank you for your hospitality.

Of course I owe thanks to my employers at HAS Den Bosch. Jan, Jeroen and Stef, thanks for giving me the opportunity to do a PhD study.

I was the first PhD student of HAS Den Bosch, but I know I will not be the last. I know you think that the employees are the gold of an organisation and that you should cherish talent, because that will lead to excellence. I will do my best to help achieve this mission. Fenna, thank you for supporting me in getting my job, for all your advice afterward and for your support of my PhD project from the first until the last moment. Joep Bartels, lector innovative entrepreneurship in the equine industry at HAS Den Bosch, helped me to get in touch with the main players in the equine industry, amongst which his wife Tineke and daughter Imke. Horse Event, an educational event for people interested in horses, organised by Academy Bartels, always was a good platform to make the results of my research public to a broad audience of equine entrepreneurs, athletes and all other people interested in horses. Gijs and Mirella, thank you for these opportunities. At HAS Den Bosch all efforts were made to make the combination of my teaching job and my PhD as good as possible. Several Bachelor theses were performed within my research area. Nicolle, Bibi, Liselotte, Noëlla, Marleen, Lisette, Maartje and Anneke thank you very much for all your help. Of course I want to thank all my colleagues at HAS Den Bosch especially the colleagues of the department of Biology, Animal and Environment. Hopefully, we will have a lot of good working years together.

I also want to thank all the other people who contributed to my PhD thesis. Especially, Kayo Terada and Maarten Bobbert, thanks for the cooperation and advise.

Finally, thanks to all my family and friends. Mom and dad, thank you for your support and for the fact that you believe in me. Rob and Nel, thanks for all the help with our new house and all the diners and showers we could enjoy. Angela and Rudi, thank you for all the times I could sleep over in Doornenburg and thanks for making me a very proud aunt of Melissa and Thijs. Angela, you are really the best sister I could wish for. It is a shame that you didn’t work at Wageningen anymore when I started there (the username cocq001 did belong to my sister).

And above all, Menno thank you for all the love, patience and support. For keeping up with me with my two half time jobs (and at the end one full time job as deputy director and a PhD thesis that still needed to be finished). Thanks for all your creativity and for making me a “Yes, and” instead of a “Yes, but” person. Thank you for always standing by my side. I am really looking forward to the future with the three of us.

7.3 Curriculum Vitae

Patricia de Cocq

Patricia de Cocq was born on the 20th of April in 1980 in Aarle-Rixtel, the Netherlands. Her parents moved to Vredepeel when she was ten years old. In Vredepeel she got acquainted with pony riding and she joint the pony club in Westerbeek. This hobby started the interest in the horse-rider interaction. In 1998 she graduated from secondary school and started her study of veterinary medicine at Utrecht University. After obtaining her master in Veterinary Medicine in 2002, she started an excellent track leading to a Master in Veterinary Research in 2004. Her thesis was entitled: "The horse under pressure – The influence of the saddle on the horse and its locomotion". In 2005 she finished her internships and obtained the degree of Doctor of Veterinary Medicine. She directly started working as a teacher of veterinary health at the University of Applied Sciences HAS Den Bosch. HAS Den Bosch supported her to start a PhD study at the Experimental Zoology Group of Wageningen University. She won the Junior Scientist Prize of the Veterinary Journal in 2006 for her paper "Saddle pressure measuring: validity, reliability and power to discriminate between saddle-fits". She obtained her pedagogical and didactical certificate at the University of Applied Sciences STOAS in 2007. She was a member of the winning "Flight artists" team of the Annual Dutch Acadamic Award in 2010 and co-chair of the scientific committee of the ISES 2011 conference. In 2010, she changed positions at HAS Den Bosch. She is now the deputy director of the department Biology, Animal and Environment.

7.4 Publication list

Patricia de Cocq

Published journal papers

De Cocq, P., van Weeren, P.R. and Back, W. (2004) The effect of girth, saddle and weight on movements of the horse. Equine Veterinary Journal, 36, 758-763.

De Cocq, P., van Weeren, P.R. and Back, W. (2006) Saddle pressure measuring: validity, reliability and power to discriminate between different saddle-fits. The Veterinary Journal, 172, 265-273. Winner Junior Scientist Prize TVJ 2006.

De Cocq, P., Clayton, H.M., Terada, K., Muller, M. and van Leeuwen, J.L. (2009) Usability of normal force distribution measurements to evaluate asymmetrical loading of the back of the horse and different rider positions on a standing horse. The Veterinary Journal, 181, 266-273.

De Cocq, P., Prinsen, H., Springer, N.C.N., van Weeren, P.R., Schreuder, M., Muller, M. and van Leeuwen, J.L. (2009) The effect of rising and sitting trot on back movements and head-neck position of the horse. Equine Veterinary Journal, 41, 423-427.

De Cocq, P., Duncker, A.M., Clayton, H.M., Bobbert, M.F., Muller, M., and van Leeuwen, J.L. (2010) Vertical forces on the horse's back in sitting and rising trot. Journal of Biomechanics, 43, 627-631.

De Cocq, P., Mooren, M., Dortmans, A., van Weeren, P.R., Timmermans, M., Muller, M. and van Leeuwen, J.L. (2010) Saddle and leg forces during lateral movements in dressage. Equine Veterinary Journal, 42, Supplement 38, 644-649.

Van Beek, F.E., de Cocq, P., Timmerman, M. and Muller, M. (2011) Stirrup forces during horse riding: a comparison between sitting and rising trot. The Veterinary Journal, doi:10.1016/j.tvjl.2011.10.007.

Wijnberg, I.D., Schrama, S.E.A., Elgersma, A.E., Maree, J.T.M., de Cocq, P. and Back, W. (2009) Quantification of surface EMG signals to monitor the effect of a Botox treatment in six healthy ponies and two horses with stringhalt: Preliminary study. Equine Veterinary Journal, 41, 313-318.

Book chapter

De Cocq, P. and van Weeren, P.R. (2012) Functional biomechanics: the effect of the rider and tack. In: The Athletic Horse: Principles and Practice of Equine Sports Medicine 2nd edition. Eds David R. Hodgson, Catherine M. McGowan and K. H. McKeever. Elsevier, in press.

Submitted journal papers

De Cocq, P., Muller, M., Clayton, H.M. and van Leeuwen, J.L. (2012) Modelling biomechanical requirements of a rider for different horse-riding techniques at trot.

Conference abstracts

De Cocq, P. (2004) Effects of a girth, a saddle and weight on the movements of the horse. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 221.

De Cocq, P., van Weeren, P.R. and Back, W. (2006) Saddle pressure measuring: validity, reliability and power to discriminate between different saddle-fits. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 325.

De Cocq, P., Back, W. and Weeren, R. van (2006) Effects of a girth, a saddle and weight on the movements of the horse. In: Abstracts of the Annual Main Meeting of the Society for Experimental Biology. - Comparative Biochemistry and Physiology, 143 (Part A), S96.

De Cocq, P., van Weeren, P.R. and Back, W. (2006) The effect of a girth, a saddle and weight on the movements of the horse. Pferdeheilkunde, 5, 697-698.

De Cocq, P. and Clayton, H.M. (2008) Pressure measurements to evaluate rider position. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 330.

De Cocq, P., Prinsen, H., Springer, N.C.N., van Weeren, P.R., Schreuder, M., Muller, M. and van Leeuwen, J.L. (2008) The effect of rising and sitting trot on back movements and head-neck position of the horse. Book of abstracts of the 6th International Conference on Equine Locomotion, 2.

De Cocq, P., Muller, M. and van Leeuwen, J.L. (2008) Horse-rider interaction: A simple model for different riding techniques at trot. In: Abstracts of the Annual Main Meeting of the Society for Experimental Biology. - Comparative Biochemistry and Physiology, 150 (Part A), S81-S82.

De Cocq, P. and van Middelaar, T. (2009) Rein Force measurements to evaluate horse-rider interaction. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 369-370.

De Cocq, P. (2010) Girth forces at stance, walk, trot and canter with and without a rider. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 330.

De Cocq, P., A.M. Duncker, H.M. Clayton, M.F. Bobbert, M. Muller and J.L. van Leeuwen (2010) Vertical forces on the horse's back in sitting and rising trot. Conference Proceedings ISES Sweden 2010, 22.

De Cocq, P. and Munsters, C. (2010) Performance monitoring in equine sports. Proceedings Measuring Behavior 2010, 13-15.

De Cocq, P. and van Weeren P.R. (2011) Review on biomechanical interaction between horse and rider. Conference Proceedings ISES The Netherlands 2011, 49.

Oosterhuis, N.R. and de Cocq, P. (2010) Effect of gaits and temp on saddle force. Scientific Proceedings Voorjaarsdagen International Veterinary Congress, 330-331.

Van Beek, F.E., de Cocq, P., Muller, M. and van Leeuwen, J.L. (2008). Stirrup force measurements during equine locomotion. In: Abstracts of the Annual Main Meeting of the Society for Experimental Biology. - Comparative Biochemistry and Physiology, 150 (Part A), p. S83.

Other scientific publications

De Cocq, P., van Weeren, P.R. and Back, W. (2007) Saddle pressure measuring: Validity, reliability and power to discriminate between different saddle-fits (Zadeldrukmetingen bij het Paard: Validiteit, Herhaalbaarheid en de Mogelijkheid Verschillende Zadelpasvormen te Onderscheiden). Tijdschrift voor Diergeneeskunde, 132, 436-437.

De Cocq, P. (2010) Symposium: Improving sports performance. Proceedings Measuring Behavior 2010, 11-12.

Van Dierendonck, M., de Cocq, P., Visser, K. (2011) Conference proceedings 7th International Equitation Science Conference.

7.5 Training and Supervision Plan

Patricia de Cocq

Education and training 2006-2011 ECTS

The basic package 3.0

WIAS Introduction course
Course on Philosophy of science and ethics

Scientific exposure 27.3

International conferences, seminars, workshops and presentations

SEB, Canterbury, United Kingdom 2006 (poster)
SEB, Marseille, France 2008 (oral)
ESpoM, Aachen, Germany 2006 (oral)
ICEL, Cabourg, France 2008 (oral)
Voorjaarsdagen, Amsterdam, The Netherlands 2006 (oral)
Voorjaarsdagen, Amsterdam, The Netherlands 2008 (oral)
Voorjaarsdagen, Amsterdam, The Netherlands 2009 (oral)
Voorjaarsdagen, Amsterdam, The Netherlands 2010 (oral)
ISES, Uppsala, Sweden 2010 (oral)
ISES, Hooge Mierde, The Netherlands 2011 (oral)
Measuring Behavior, Eindhoven, The Netherlands 2010 (oral)
ICEEP, Cape Town, South Africa 2010 (poster)
WIAS Science Day, Wageningen, The Netherlands 2008
Workshops Annual Dutch Academic Award, The Netherlands 2010
Healthy as a (sport)horse, Wageningen, The Netherlands 2011 (oral)

In-Depth Studies 23.8

Disciplinary and interdisciplinary courses, advanced statistics courses, PhD students' discussion groups, MSc level courses

Functional Zoology course
Biomechanics course
Engineering mechanics – statics and dynamics
Mechanical vibrations
Mathematical modelling in Biology
Signal processing
The observer XT training
Longitudinal data and repeated measures
EZO PhD lectures: paper discussions and presentations

Professional Skill Support Courses	**17.3**
Didactic and pedagogic skills training	
Project- and time management	
PhD Competence assessment	
Presentation skills	
Research Skills Training	**7.0**
Preparing own PhD research proposal	
Equine body check special research assignment	
Didactic Skills Training	**25.7**
Lecturing, supervising practicals, MSc and BSc theses, preparing course material	
High speed filming (Phantom and Casio camera)	
Practical locomotion horse, Applied Animal Biology	
Practical locomotion horse, Functional Zoology	
Guidelines practical locomotion horse	
Supervising 6 MSc theses	
Supervising 9 BSc theses	
Management Skills Training	**10.0**
Organisation of seminars and courses, membership of committees	
Organisation seminar “The horse under pressure”	
Organisation symposium “Improving sports performance”	
Member of the “flight artists” team: winner Annual Dutch Academic Award: organisation of media exposure and courses for participants	
Member of the scientific committee of the ISES conference 2011	
Education and Training Total	**114.1 ECTS**

1 ECTS equals a studyload of 28 hours

7.6 Samenvatting

Patricia de Cocq

De krachten die door de ruiter op het paard uitgeoefend worden, hebben een directe invloed op de mechanische belasting van het paard en zijn bewegingen. Het doel van dit proefschrift is om de biomechanische interactie tussen ruiter, zadel en paard te onderzoeken. Op deze wijze wordt inzicht verkregen in de belasting van het paard en mogelijkheden om blessures te voorkomen.

De invloed van de ruiter op het paard wordt uitgeoefend via harnachement, wat dient als een interface tussen het paard en de ruiter. Aangezien het harnachement vaak verbonden is met zowel paard als ruiter, is het geschikt om meetapparatuur in op te nemen. Deze meetinstrumenten kunnen de krachten tussen ruiter en paard objectiveren.

Zadelkrachtmeetsystemen zijn gebruikt om de pasvorm van zadels te onderzoeken en zouden een bruikbaar instrument kunnen zijn om de interactie tussen ruiter en paard te bestuderen. Er was helaas weinig bekend van de validiteit, betrouwbaarheid en herhaalbaarheid van deze instrumenten bij het gebruik bij paarden. Daarom is dit eerst onderzocht. Het FSA systeem was alleen betrouwbaar in zeer gestandaardiseerde omstandigheden. Het Pliance systeem bleek betrouwbare en herhaalbare resultaten te geven en kan gebruikt worden in onderzoek naar de interactie tussen paard en ruiter. Het Pliance systeem werd gebruikt om het effect van de houding van de ruiter op de krachtenverdeling onder het zadel en om de signalen die de ruiter aan het paard geeft tijdens zijgangen in dressuur te bestuderen.

Eén van de belangrijke mechanische eigenschappen van de ruiter die het paard beïnvloeden is het gewicht van de ruiter. De invloed van harnachement en gewicht op de bewegingen van het paard werd onderzocht. Gewicht zorgt voor een holle houding van de paardenrug. Dit zou kunnen bijdragen aan rugblessures bij het paard.

Tijdens draf, kan de ruiter iedere pascyclus opstaan uit het zadel (lichtrijden) of blijven zitten (doorzitten). Lichtrijden wordt vaak gebruikt en er wordt aangenomen dat deze rijtechniek de belasting op de paardenrug verminderd. De rugbewegingen tijdens lichtrijden lijken deels op doorzitten en deels op de onbelaste situatie, met een hoge maximale strekking in de zit-fase en een lagere maximale strekking in de sta-fase. In de sta-fase zijn de krachten op de stijgbeugels groter, maar is de totale verticale belasting van de paardenrug kleiner. Dit ondersteunt de aanname dat lichtrijden minder belastend is.

Drie veer-demper-massa modellen zijn ontwikkeld om de biomechanische eigenschappen van de ruiter tijdens doorzitten, de moderne jockey houding en lichtrijden te evalueren. De modellen laten zien welke combinaties van ruitermassa, veerstijfheid en dempingscoëfficient leiden tot de genoemde rijtechnieken. Een "extreme" moderne jockey houding, die in de praktijk niet door ruiters wordt gebruikt, leidt tot de laagste piekkrachten tussen ruiter en paard en de laagste arbeid van het paard. Om lichtrijden te kunnen simuleren is de introductie van een actief veersysteem voor het been van de ruiter noodzakelijk.

In de algehele discussie wordt beargumenteerd dat een combinatie van benaderingen nodig is om het begrip van de interactie tussen ruiter en paard verder te vergroten. Experimenteel onderzoek, gebruik makend van bewegingsonderzoek van ruiter en paard, krachtmetingen en activatiepatronen van spieren, zou gecombineerd moeten worden met wiskundige modellen. Deze gecombineerde aanpak kan vragen over de interne en externe belasting van zowel paard als ruiter tijdens diverse rij- en trainingstechnieken beantwoorden. Technieken die het risico op blessures bij zowel paard als ruiter kunnen verminderen, zouden op deze wijze geïdentificeerd kunnen worden. Hierdoor zouden welzijnsproblemen bij paarden voorkomen kunnen worden.

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