From the Centre for Applied Sport and Exercise Sciences, University of Lancashire[1], Preston, UK, from the Department of Physical Therapy, The University of Tennessee and Chattanooga[2], Chattanooga, USA, from the School of Public Health & Clinical Sciences, Faculty of Health, University of Central Lancashire[3], Preston, UK, from the Department of Large Animal Clinical Sciences, Michigan State University[4], East Lansing, USA, and from the Department of Exercise, Sport and Leisure Studies, University of Tennessee at Knoxville[5], Knoxville, USA

Motion analysis and its use in equine practice and research

S.J. HOBBS[1], D. LEVINE[2], J. RICHARDS[3], H. CLAYTON[4], J. TATE[5] and R. WALKER[2]

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Summary

Motion analysis techniques have been used in veterinary research for the measurement of normal and pathological gait in horses since the late 19th century. Many of the early studies involved capturing moving images in 2 dimensions, and these techniques are still commonly used in field based research and clinical practice. In recent times, more advanced methods employed in human medicine have been adopted to measure forces and motion in 3 dimensions along with other aspects of locomotion in horses. This paper describes kinematic and kinetic techniques that are currently used in equine veterinary research and reviews normative and clinical data that have been obtained using these methods.

Abbreviations: BM = body mass; EMG = electromyography; GRFs = ground reaction forces

Schlüsselwörter: Lokomotion des Pferdes, Kinematik, Kinetik, Kräfte, Pferd.

Zusammenfassung

Bewegungsanalyse und deren Nutzen in Pferdepraxis und -forschung

Die Methoden der Bewegungsanalyse werden seit dem späten neunzehnten Jahrhundert in der veterinärmedizinischen Forschung für die Messung des normalen und pathologischen Ganges des Pferdes genutzt. Viele dieser frühen Studien beinhalteten die Aufnahme von Bildern in 2 Dimensionen - diese Techniken werden oftmals auch heute noch in der Feldforschung und klinischen Praxis verwendet. In letzter Zeit wurden in der Humanmedizin fortschrittlichere Methoden angewendet und auch für die Messung von Kräften und Bewegungen in 3 Dimensionen aber auch anderen Aspekten der Bewegung bei Pferden adaptiert. Dieser Artikel beschreibt kinematische und kinetische Messtechniken, die heutzugtage in der Forschung beim Pferd verwendet werden, und bewertet normative und klinische Daten, die mit diesen Methoden erhalten werden.

Introduction

In the late 19th century the first motion picture cameras recorded faster gait patterns of locomotion for both humans and animals. In 1877 Muybridge demonstrated, using photographs, that when a horse is moving at a fast trot there is a moment when all of the animal's feet are off the ground. It took him 5 years to develop the capabilities to capture these movements with a series of single lens cameras.

The 20th century saw the development of systems capable of automated and semi-automated computer-aided motion analysis using both manual and automatic marker identification techniques. Both the hardware and software that these systems use has developed rapidly in the last 10 years and a large variety of different methods can now be used to track movement in two (2-D) or three-dimensions (3-D). Most systems use either image based or signal based tracking with one or more cameras or receivers to record the image or signal. All systems require the volume of interest to be calibrated and the number of cameras or receivers used by the system and their capabilities will influence the accuracy of the measurements recorded. The popularity of motion analysis systems in veterinary research is evident from the number of studies conducted since the work of Fredricson and Drevemo in the 1970s.

The latter half of the 20th century has also seen the introduction of other methods of recording movement, including instrumented walkmats, accelerometers and electrogoniometers, which have all contributed to our current knowledge of movement. However these systems have been used sparingly in veterinary medicine due to the cost, and the challenges of adapting software created for bipeds to horses. Veterinary colleges around the world now utilize this technology although it is still an emerging field of research.

The motion analysis laboratory typically contains several pieces of equipment. The first is usually an array of infrared cameras, at least 2 but more typically 5 or more depending on the complexity of the biomechanical model used. Data is acquired at speeds varying from 50 Hz to 1,000 Hz, depending on the speed of the activity. Activities such as gait analysis at walk only require camera speeds of 50 Hz but analyzing activities such as trot, gallop, or a jump require higher speed acquisition to obtain valid data as the angular velocities involved in these activities are much higher. The typical motion capture space (usually termed capture volume) is comprised of an area in which data can be seen by 2 or more infrared cameras. The horse has reflective markers attached to the body at predetermined landmarks that will be used to calculate joint angles (Fig. 1). At least 3 markers are required per body segment to create a local coordinate system. These markers can be as small as 1mm or as large as 25 mm, are lightweight and are easy to replace if they are dislodged. Typically the larger the marker, the better the camera resolution but larger markers may interfere with the movement being observed and it may be difficult to differentiate multiple large markers attached to small body segments. As the horse moves through the capture volume, infrared light emitted from the cameras is reflected off of the markers and back into the camera lens, striking a light sensitive plate that creates a video signal. Computers collect these signals and determine the position of each marker in 3-D space. These systems can also be used in the field with active (light emitting) markers, but wires from the markers to a control device must be attached to the horse.

If markers are impractical, such as in an underwater treadmill, swimming, or on a racetrack, a video-based system can be utilized. Multiple video cameras on tripods collect data, which are transferred to a computer. The points can later be manually or automatically labeled and angles then calculated. The accuracy may suffer, and approximately 10 cubic meters is realistically the largest volume that can be captured, but the versatility is exceptional using these methods. For field work signal based techniques, such as ultrasound emitting diodes can also be used. Often they only require one receiver, but for these systems the emitters must be attached to the horse using wires, which can limit their use at faster gaits. Precision of one system was reported by CHATEAU et al. (2004) to be 0.3 mm and 0.5 degrees for distance and angle measurements, respectively.

Measurements produced from motion analysis systems include displacements of segments, joints angles and their derivatives (velocity and acceleration). These data inherently include errors which are recorded along with the real movement and these errors are removed using filters. Commonly low pass digital filters (such as Butterworth filters), fourier analysis or splines are used to filter equine movement data. The frequencies contained within the recorded measurement will depend on the speed of the movement, the capture frequency and the systematic and random errors that are present. Filters are usually applied to the labeled marker data or the calculated displacement data to remove errors before any derivatives are calculated, as errors are amplified during velocity and acceleration calculations if they have not previously been removed.

Together with a motion analysis system, many labs now contain other commercially available, complementary equipment. One or more force platforms can be embedded into a walkway or measurement volume to collect ground reaction forces together with synchronized motion data, from which muscle forces can be estimated. Muscle activity can be measured during movement using electromyography, transient shock can be measured at foot strike using accelerometry and pressure mats can be used to determine the foot positions or pressure distribution under the foot. In addition, prototype equipment is emerging from veterinary colleges and universities to answer more challenging questions, such as the ultrasound equipment developed by CREVIER-DENOIX et al. (2009) to estimate tendon strain.

Kinematic or motion analysis of gait is a powerful tool that can be used to measure movement patterns during gait and other activities, such as jumping. As 3-D motion analysis systems are very expensive and require extensive training to use there is limited information in the veterinary literature regarding 3-D gait analysis. 2-D systems are less expensive, and have a place in clinical gait analy-

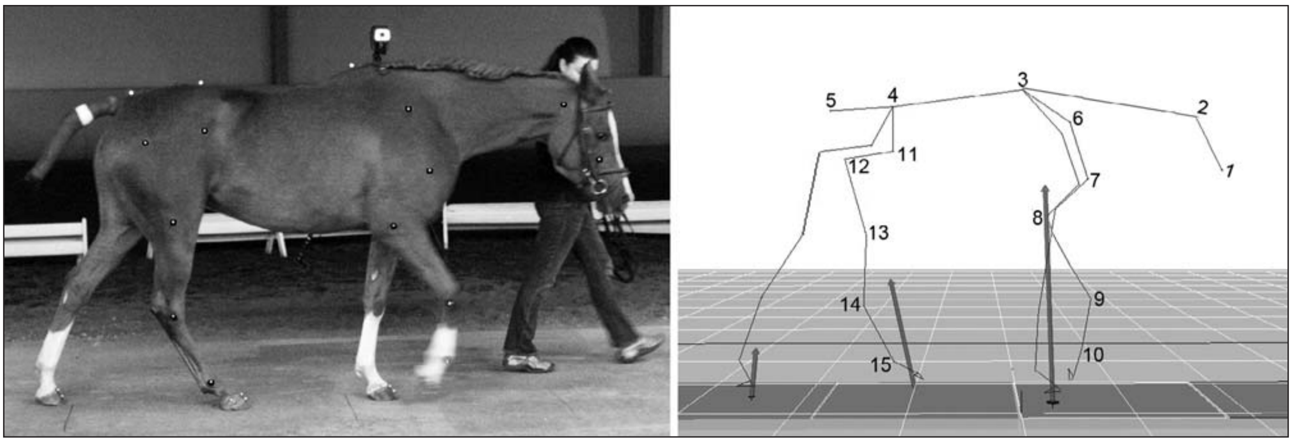

Fig. 1: Photograph (left) and stick figure (right) of a horse walking over a series of force plates; the left hind, right hind and left front limbs are in the stance phase, with each hoof contacting a different force plate. The grey arrows on the stick figure represent the ground reaction force vectors. The marker set shown in this figure is suitable for 2D, sagittal plane analysis. Reflective markers are placed in the following locations: 1: facial crest, 2: wing of atlas, 3: 6th thoracic vertebra, 4: 1st lumbar vertebra, 5: 1st coccygeal vertebra, 6: tuber spinae scapulae, 7: greater tubercle of humerus, 8: lateral humeral epicondyle, 9: ulnar carpal bone, 10: lateral metacarpal epicondyle, 11: ventral part of tuber coxae, 12: cranioventral part of greater tuberosity, 13: lateral femoral epicondyle, 14: talus, 15: lateral metatarsal epicondyle. There are 3 markers on each hoof: midlaterally on the coronet, mid-dorsally on the coronet and mid-dorsally 3 cm distal to the coronet. Hoof markers are proximally located to reduce the risk of contact with the other hooves. This is why the point of application of the ground reaction force at the hoof-ground interface appears is below the position of the hoof markers. (Photo credit: Britt Larson)

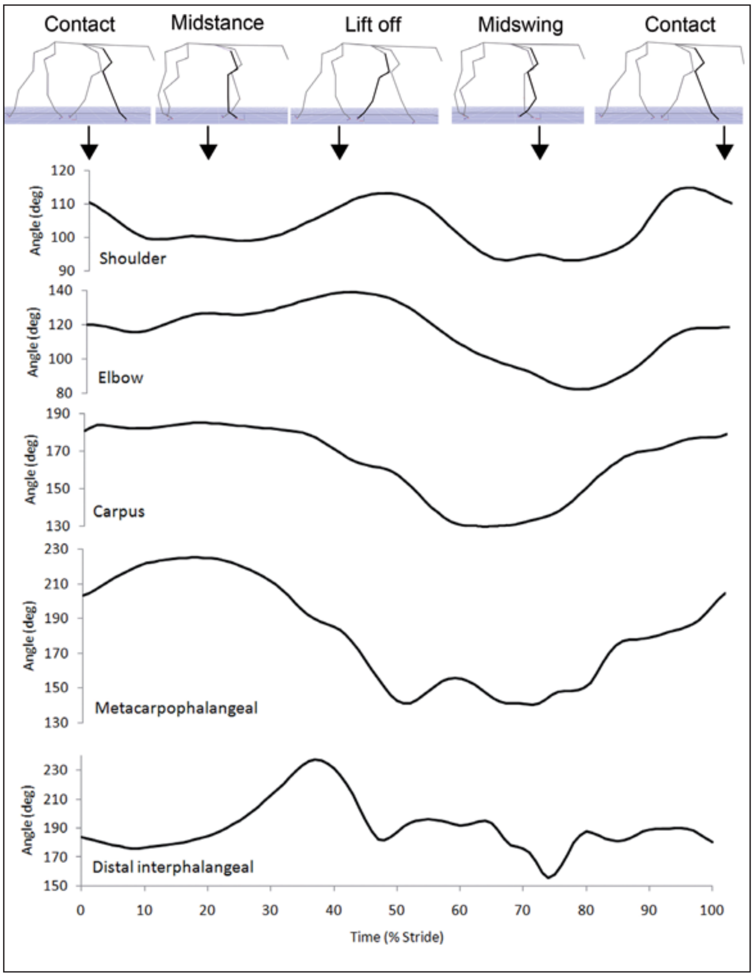

Fig. 2: Forelimb joint angles during one stride at trot starting with hoof contact; the stick figures are taken at the instants of hoof contact, midstance, lift off, midswing and the next hoof contact. The forelimb segments corresponding to the graphs are drawn in black. The arrows beneath each stick diagram indicate the corresponding time during the stride. The joints represented from the top down are the shoulder, elbow, carpal, metacarpophalangeal and distal interphalangeal.

sis for studying sagittal plane motions (flexion and extension movements). To date they have been used more extensively in laboratory and field based studies of equine locomotion, but as rotations are not limited to flexion and extension it may be beneficial in some studies to analyze 3-D movements. Also the additional time and effort required for a full 3-D analysis are substantial and may not be justified if flexion-extension are the movements of primary interest.

Kinematic (motion) analysis of gait in horses

Many research questions are still answered in relation to equine locomotion using 2-D techniques. Sagittal plane kinematics are commonly collected using a variety of lateral marker sets which often simplify the lower limbs, due to the small size of the pastern segments. Consequently the definition of what constitutes a joint in terms of angle calculation varies between methods. Joint movement is also reported to be overestimated due to soft tissue artifacts (WEEREN et al., 1992; DREVEMO et al., 1999; CLAYTON et al., 2002).

Despite this concern, little variation is found for intra-individual stride characteristics in the sagittal plane using 2-D methods, provided speed is controlled. Greater variability is documented for inter-individual stride characteristics, particularly where differences in breed and conformation are evident (GALISTEO et al., 2001). BACK et al. (1996) studied the kinematics of walk (1.6 $m{\cdot}s^{-1}$) and related stride length, joint angles and range of motion of joints at trot (4.0 $m{\cdot}s^{-1}$) on a treadmill using a CODA-3 system. For 24 Dutch Warmblood horses stride length at trot (2.7 m) was 1.6 times that of walk and the increase was due to an increase in protraction of 1.6 degrees in the forelimb and 1.4 degrees in the hind limb. Except for the fetlock joint, similar patterns were reported for joint angle time diagrams for the limb joints at walk and trot. However, absolute differences in temporal and spatial kinematics were observed. In walk 2 extension maxima were recorded whereas at trot there was only one maximum. Variability in range of motion in both limbs was highest in the higher motion joints, so the range of motion (mean, SD) for the forelimb fetlock, forelimb carpus and hind limb fetlock joints were 80.6 ± 7.1, 90.8 ± 7.1 and 85.0 ± 7.7 degrees, respectively, at trot. Forelimb joint angles are illustrated in Fig. 2 for one full stride at trot.

Recent studies have reported detailed 3-D kinematics for the digital joints, including pastern joint rotations (CHATEAU et al., 2004; HOBBS et al., 2006; CLAYTON et al., 2007a,b). Flexion of the pastern joint occurs early in the stance phase. The joint then extends to a peak at the start of breakover after which rapid flexion is seen to toe off. As the range of motion is small the variability is greater. HOBBS et al. (2006) reported a coefficient of variability of 22 % for stance phase range of motion for this joint at walk for 4 horses. CHATEAU et al. (2004), who studied 4 trotters, reported inter-individual variability for the lower limb segments and joints to be greater than intra-individual variability for all rotations at walk. Sagittal plane hoof rotations were reported to vary at foot strike by 5.2 degrees and landing kinematics of the hoof together with global adduction of the limb were thought to be mainly responsible for out of plane movements of the distal joints (CHATEAU et al., 2004; HOBBS et al., 2006; CLAYTON et al. 2007a,b).

3-D kinematic analyses and correction algorithms for 3-D skin displacement have been described for the tibia, third metatarsus (LANOVAZ et al., 2004) and the radius (CLAYTON et al., 2004; SHA et al., 2004). Bone fixed markers were used as a reference to model the 3-D displacement patterns of 6 markers on the skin of the equine radius by SHA et al. (2004) and 6 markers on the skin of the tibia and third metatarsus by LANOVAZ et al. (2004). Skin displacements were greater at the proximal end of the segments, often due to greater musculature, and SHA et al. (2004) found the largest skin movements in the longitudinal direction, which supports the findings of WEEREN et al. (1992).

Clinical studies using kinematic techniques

As motion analysis systems advanced towards the end of the 20th century 2 prominent research groups carried out a number of 2-D kinematic clinical studies with horses. Hilary Clayton investigated clinical lameness conditions using high speed cinematography, some years later a team from Utrecht investigated changes in gait factors due to experimentally induced lameness with a CODA-3 system. In both studies temporal patterns and relationships between stride variables and lameness were explored overground (CLAYTON, 1986a,b, 1987a,b, 1988) and using treadmills (BUCHNER et al. 1995a,b, 1996a,b).

Lame horses that are led in hand tend to reduce variables such as stride length and stride duration so their overall speed is reduced (CLAYTON, 1986a; BUCHNER et al., 1995a), whereas on treadmills where speed can be controlled, the lame horse maintains speed using shorter, quicker strides than a sound horse moving at the same speed (BUCHNER et al., 1995a; KEEGAN et al., 1997). In supporting limb lameness a shortening of the swing phase and increased stance duration is usually seen in both lame and sound limbs (BUCHNER et al., 1995a). Head and neck motion in forelimb lameness and croup motion in hind limb lameness are asymmetrical; vertical displacement increases during stance of the sound limb and decreases during stance of the lame limb (BUCHNER et al., 1996a). In addition, the suspension phase following stance of the lame limb is reduced at trot (CLAYTON, 1986a; BUCHNER et al., 1995a) and placement of the lame forelimb usually precedes the diagonal hind limb. In the lame horse there is a need to reduce load on the lame limb and compensate for this by redistributing the load to the other limbs (WEISHAUPT, 2008). Passive distal joint rotations reflect the reduction in loads upon them, with flexion of the coffin joint and extension of the fetlock joint being reduced during weight bearing of the lame limb (BUCHNER et al., 1996b). For this reason fetlock joint rotation is often used as an indicator of supporting limb lameness, which is supported by evidence indicating a direct relationship between fetlock joint extension and magnitude of the peak vertical force (McGUIGAN and WILSON, 2003). However, PELOSO et al. (1993) found that fetlock extension did not consistently characterize lameness. Proximal joints then actively control braking and act as load dampers through active increases in flexion of the shoulder and tarsal joints (BUCHNER et al., 1996b).

Studies of alterations in hoof balance, on sagittal and out of plane distal joint rotations have been carried out at walk and trot (NILSSON et al., 1973; WILLEMEN et al., 1999; SCHEFFER and BACK, 2001; CHATEAU et al., 2006; PEHAM et al., 2006). Heel or toe wedges are commonly recommended for various orthopaedic conditions and knowledge of their effects on distal joint rotations is important although conflicting results exist in relation to fetlock joint rotation. Earlier 2-D studies using simpler non-invasive modeling techniques (NILSSON et al., 1973; WILLEMEN et al., 1999; SCHEFFER and BACK, 2001) reported a decrease in maximum fetlock extension using heel wedges during gait. A more recent study using ultrasound emitting diodes and invasive techniques found an increase in maximal flexion of the pastern and coffin joints and no significant differences in maximal extension of the fetlock joint for heel wedges and generally the opposite (except for pastern joint extension) using toe wedges (CHATEAU et al., 2006). In addition, heel and toe wedges appear only to influence sagittal plane and not out of plane joint rotations (CHATEAU et al., 2006; HOBBS et al., 2009). In another study using a 3-D 6 camera system and non-invasive techniques PEHAM et al. (2006) reported that hind limb heel wedges increase flexion of the coffin and hock joints and decrease extension of the fetlock joint during the stance phase. Differences in these results may relate to different marker sets, soft tissue artefacts present using non-invasive markers and/or the effects of using invasive techniques. Confirming the changes in maximal joint rotations are important as increasing or reducing a joint angle will alter tendon and ligament strain (LAWSON et al., 2007) and therefore influence the success of treatment, rehabilitation and pain management.

As the spine is central to the body, lameness forcibly affects motion of the trunk and vertebrae (GOMEZ ALVAREZ et al., 2008) and using 3-D motion capture systems researchers are beginning to take advantage of this technology to explore lateral bending and axial rotation together with flexion-extension. One study of the effects of induced hind limb lameness (GOMEZ ALVAREZ et al., 2008) found increased axial rotation of the pelvis together with an overall increase in thoracolumbar flexion-extension at walk, whereas at trot there was reduced flexion-extension in the lumbosacral spine. Another study of limb and trunk motion developed kinematic indices to quantify locomotion symmetry using sound and lame horses (AUDIGIE et al., 1998). Markers used to detect body and limb motion were successfully used by STROBACH et al. (2006) to detect coordination competence in ataxic horses and baseline data of horses with stringhalt have also been measured using similar techniques (KAUFMANN et al., 2008).

Currently 2-D motion analysis is more commonly used as a diagnostic tool, as it is more versatile and as an example has been documented recently to aid clinical farriery treatment (WOODALL et al., 2008). In contrast 3-D techniques are mainly used in research to extend knowledge and understanding of clinical conditions and treatment. However, more novel studies are emerging such as the study by CLAYTON et al. (2008) where the effect of tactile stimulation on gait was explored. These and other work investigating the benefits of physical therapies may, in time, enhance equine rehabilitation methods.

Kinetics (measurement of forces) in horses

Force plates or instrumented horseshoes are the 2 types of force transducers commonly used to measure GRFs during equine locomotion. Force plates are considered a basic and fundamentally important tool for gait analysis. The first recording of force measurements dates back to the late 19th century when MAREY (1873) used a wooden frame on rubber supports. ELFTMAN (1939a) used a similar method with a platform on springs. However, it was not until the advancement of computers and electronic technology that the readings could be accurately measured. In 1965, PETERSEN and co-workers developed one of the first strain-gauge force plates. A plethora of publications now exists on the applications of such devices in both clinical research and sports. Since 1965 forces plates have undergone considerable development by 3 internationally accepted manufacturers, Kistler Instruments, AMTI and the Bertec Corporation. Advances have made the plates more accurate (reducing crosstalk), with increased sensitivity (increasing the natural frequency), and better portability (RICHARDS and THEWLIS, 2008).

Force plates simply measure forces as the limbs strike them (ground reaction forces [GRFs]) and relay the information to the computer as analog data. This analog data is a continuous measure of voltage as the sensors in each corner of a force plate generate a voltage as they are deformed. The sensors are typically stacked in each corner (3 high, one for each axis). This data is then converted to digital data (though mathematical equations), which allows it to be viewed as a unit of force. The digital data can be reported as force components; vertical forces (z), longitudinal or braking and propulsive forces (y), and medio-lateral forces (x), and can be displayed as a 3-D force vector making it helpful for visualization of the effects. A number of measurements can be reported from the force graphs produced, which include peak forces, times to peak forces, averages force over the stance phase, limb loading rate and impulse (force multiplied by time).

Force plates can also be used to measure the center of pressure during stance, walking, trotting, or other activities (see Fig. 3). Center of pressure analysis has been shown to be a reliable tool for tracking movements of the horse's center of pressure during standing (CLAYTON et al., 2003) and this technique has been applied to assess the effects of sedation with detomidine on the horse's balance (BIALSKI et al., 2004). Center of pressure analysis is also a promising technique for the detection of neurological diseases (CLAYTON et al.,1999).

The force plate is either mounted within a raised platform (Fig. 3) or embedded in the floor (Fig. 4) so that it is even with the surface and unnoticeable to the horse. A walkway of adequate length is essential to ensure a steady state gait pattern is achieved. Many systems have timing lights that are triggered as the handler and horse approach and cross the force plate to allow the calculation of mean velocity and acceleration. Control of velocity and acceleration within an appropriate range is essential for repeatable data collection, because these greatly affect the force placed on each limb (McLAUGHIN and ROUSH, 1995).

A force plate can be used to provide objective measures of weight-bearing on limbs when proper technique is utilized. Comparing the changes in forces over time is extremely valuable to monitor the progression of a disease (such as osteoarthritis), or to assess a conservative treatment (such as an anti-inflammatory or analgesic medication), or surgery (DEULAND et al., 1977).

Force plates of varying sizes are usually concealed under examination tracks and walkways (see Fig. 5) (SCHRYVER et al., 1978; MERKENS and SCHAMHARDT, 1994; GUSTAS et al., 2004), arenas or treadmills (WEISHAUPT et al., 2004), and have been used with a number of different coverings (WILSON and PARDOE, 2001). Inter-horse variability in GRFs between strides at a particular gait and speed is small (CLAYTON, 2005), but regulating speed can be problematic. In addition, the size of the plates will influence the ability to obtain successful foot strikes at different speeds. WEISHAUPT et al. (2004) incorporated a force plate into a treadmill to overcome this problem, but as multiple hooves contact the force plate, individual hoof forces must be derived mathematically. A drawback to this system is that only the vertical force component is measured.

Instrumented or force shoes provide an alternative method of force measurement, are able to record forces during a number of strides (DALIN and JEFFCOTT, 1985) and are particularly useful at higher speeds where stride length may be over 5 m. Several designs have been developed and tested (BJÖRK, 1958; FREDERICK and HENDERSON, 1970; RATZLAFF et al., 1987, 1993; HJERTEN and DREVEMO, 1994; BARREY, 1990; ROLLOT et al., 2004; ROBIN et al., 2009), but depending on the design, differences in reliability and accuracy have been reported. With the exception of the boot developed by BARREY (1990) all of the instrumented horse shoes require some farriery work in order that testing may take place, which may limit their use for clinical gait analysis. Furthermore, the weight of the force shoes, which tend to be considerably heavier than steel horse shoes, may affect limb kinematics, especially in the swing phase.

During normal gait peak vertical forces (Fig. 6) were found to be 6 body mass (BM) at walk (SCHRYVER et al., 1978; RIEMERSMA et al. 1996), approximately 10 BM at trot (SCHRYVER et al., 1978; HJERTEN and DREVEMO, 1994; MERKENS and SCHAMHARDT, 1994) and 17.5 BM at gallop (RATZLAFF et al., 1993). At walk the vertical force profile has a double peak for both forelimbs and hind limbs. The first peak occurs at about 20 % of the stance phase and the point where the superficial digital flexor tendon experiences peak strain (JANSEN et al., 1993). At midstance the centre of mass approaches its highest point, decelerating the body in its upwards motion at which point the vertical GRF reduces (MERKENS and SCHAMHARDT, 1994) and the suspensory ligament was found to

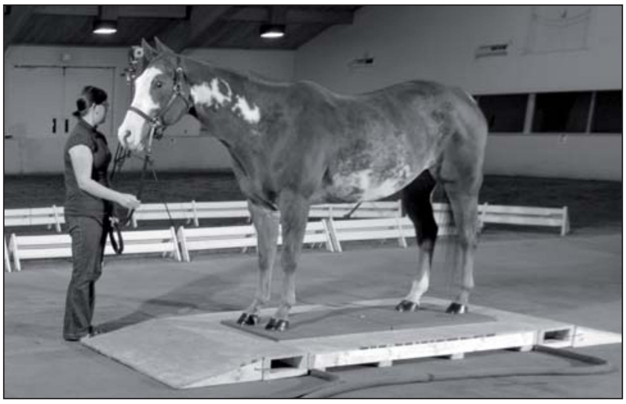

Fig. 3: Horse standing on a platform with embedded 2 force plates to measure the location and movements of the horse's center of pressure (Photo credit: Erin Grooms)

Fig. 4: Horse cantering over the force plate system in the Mary Anne McPhail Equine Performance Center at Michigan State University; the runway is viewed from behind the screen of the Motion Analysis System (Motion Analysis Corp., Santa Rosa, CA). The screen shows a real time image of the horse as a stick figure, including the corresponding ground reaction force vectors. 3 of the 10 infrared cameras arranged around the data collection volume. are visible behind the horse (Photo credit: Britt Larson)

Fig. 5: View of the data collection runway and alcove in the Mary Anne McPhail Equine Performance Center at Michigan State University; the horse is standing on the force plates in the center of the data collection volume and several cameras are visible distributed around this volume. (Photo credit: Britt Larson)

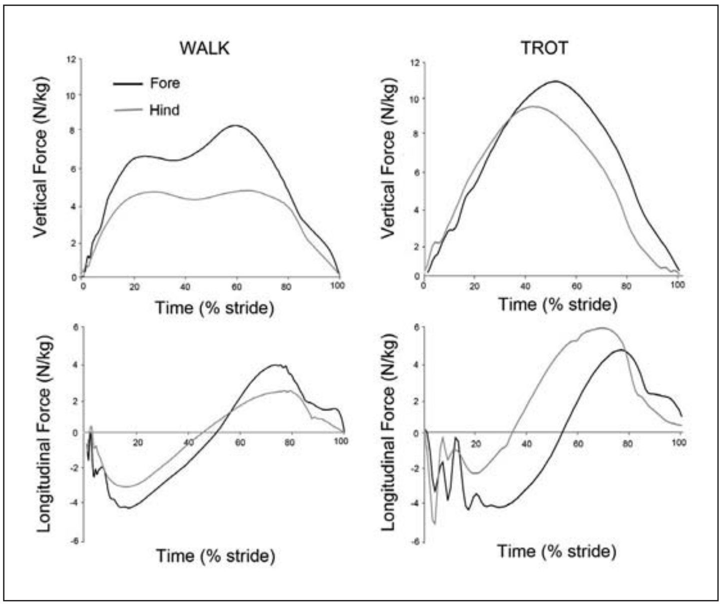

Fig. 6: Vertical (above) and longitudinal (below) ground reaction forces for a horse at walk (left panel) and trot (right panel); black lines represent the forelimbs, grey lines represent the hind limbs. Forces are normalized to body mass (N/kg) and time is normalized to stride duration (% stride).

experience peak strain (JANSEN et al., 1993). The centre of mass then lowers as the limb retracts. The second vertical force peak and peak propulsion are found close to heel off and during breakover, after which the limb is gradually unloaded (MERKENS and SCHAMHARDT, 1994). At faster gaits only a single vertical peak is observed (SCHRYVER et al., 1978; RATZLAFF et al., 1993; HJERTEN and DREVEMO, 1994; MERKENS and SCHAMHARDT, 1994). Fig. 6 illustrates the force patterns and differences in vertical and longitudinal force profiles between fore and hind limbs at walk and trot.

Clinical studies using kinetic techniques

Force data is useful to clinicians, as the lame horse will modify its gait to reduce loads on the lame limb and compensate by redistributing the load to the other limbs. In addition, to provide the momentum for propulsion they will increase the time the lame limb is on the ground as a means of maintaining the impulse with a lower peak vertical force. Force platforms measure the force produced over time, so these adaptations can be captured from this equipment. WEISHAUPT et al. (2001) compared force measurements to the results of traditional orthopaedic examinations and suggested that they were a helpful complementary tool, but data should be carefully interpreted and related to clinical observations. BOCKSTAHLER et al. (2008) also suggested that force data alone was useful, but had diminished value as an evaluation of joint fuction was not possible.

For this reason laboratory based studies often collect both force and motion data. One such study (CLAYTON et al., 2000b) measured changes in force and motion of the distal forelimb following induced superficial digital flexor tendinitis. Lower peak vertical GRFs along with changes at the pastern and fetlock joint were reported in the lame limb and increased braking forces and impulse in the sound limb. Another study investigated the effect of heel wedges in horses with experimentally induced superficial digital flexor tendinitis. Force and motion data were collected at trot after the application of heel wedges (CLAYTON et al., 2000c), tendon forces were then estimated from an in vitro model (MEERSHOEK et al., 2002). Superficial digital tendon force was calculated to increase in the contralateral sound limb and tendon forces did not decrease following the application of heel wedges in either limb. The results indicated that heel wedges are not beneficial in horses with this condition and instead may exacerbate the problem.

Calculation techniques (known as inverse dynamics) can also be used to estimate muscle and tendon forces at each joint when force and motion data are combined. This can be useful for studying normal locomotion (CLAYTON et al., 1998), the effect of interventions such as farriery (SINGLETON et al., 2003), the changes associated with lameness (CLAYTON et al., 2000a) and the effects of therapeutic interventions (CLAYTON et al., 2000c). McGUIGAN et al. (2005) used this method to estimate the deep digital flexor tendon loads at trot in ponies with distal phalangeal rotation compared to normal ponies. GRFs were reduced in the ponies with rotation, but more importantly tension on the deep digital flexor tendon was zero for the first 40 % of the stance phase and then increased to reach a peak of 6.41 BM in the breakover phase. It was suggested that treatment should aim to reduce forces during breakover in horses with this condition.

Navicular disease has also been studied using force platforms and motion analysis. WILLIAMS (2001) carried out a principal component analysis of force data from the beginning and end of the stance phase in normal horses and horses with navicular disease. Horses with navicular disease were found to exhibit abnormal limb loading patterns both before and after a palmer nerve block. WILSON et al. (2001) used a force platform together with radiographs and motion analysis to determine the contact area between the deep digital flexor tendon and the navicular bone and compressive stress on the navicular bone in vivo. Stresses on the navicular bone were much higher in early stance in horses with navicular disease, which was reported to be due to contraction of the deep digital flexor muscle resulting in unloading of the heels. In another study (McGUIGAN and WILSON, 2001) a bilateral palmer digital nerve block was administered to horses with navicular disease. A reduction in compressive force on the navicular bone was found throughout the stance phase, which was thought to be a general response to a reduction in heel pain, although force patterns did not return to the shape reported for normal horses.

Other studies have found force platforms useful for diagnostic purposes and to evaluate the effects of different treatments. ISHIHARA et al. (2009) used a force platform to differentiate between horses with hind limb lameness and horses with spinal ataxia. From these results it was suggested that peak lateral force and the variation in vertical force could be used to differentiate between the 2 conditions. The effects of different dosages of a COX-2 inhibitor were evaluated in horses with osteoarthritis using a force platform to determine the optimal dose for reducing lameness (BACK et al., 2009). Peak vertical force was used to quantify lameness severity and found to be a reliable measure. As no significant differences were found between 0.1 mg/kg and 0.25 mg/kg the lower dose was considered to be effective in the control of pain and inflammation.

Future Applications

Currently, the biggest need is to develop morphometric models that can be used with inverse dynamic methods to determine joint loading (that is, moments and joint reaction forces). This research is currently underway and will enhance the field of gait analysis in veterinary practice greatly in years to come.

The use of either surface or fine wire electromyography (EMG) is also in its infancy in veterinary motion analysis. Fine wire needle electrodes are reported to affect gait or other motions to a large degree whereas surface electrodes developed for humans have been used more successfully equine studies to date (JANSEN et al., 1992; WIJNBERG et al., 2003, 2004, 2009; ZANEB et al., 2008). As this technology develops, we can learn more about the timing of muscles and when they are active in the gait cycle or other activities. While EMG provides some quantitative information about the force of a muscle contraction during gait, the relationship between EMG activity and muscle force is not linear and depends on many factors. What EMG does provide is the timing of the firing sequences of the muscles involved which provides a more complete picture of how locomotion is achieved.

Motion analysis has been employed in human medicine for decades and has been used for a variety of purposes including surgical planning, evaluating the effectiveness of surgery or implementation of treatment intervention, and evaluating range of motion needed for a particular activity. As the hardware systems and software applications advance, the usefulness of motion analysis within equine veterinary medicine will continue to evolve.

References

AUDIGIE, F., POURCELOT, P., DEGUEURCE, C., DENOIX, J.-M., GEIGER, D. (1998): Kinematic analysis of limb and trunk motion symmetry in equine lameness. The Journal of Biochemistry **31**, 121-121.

BACK, W., MACALLISTER, C.G., HEEL, M.C. van, POLLMEIER, M., HANSON, P.D. (2009): The use of force plate measurements to titrate the dosage of a new COX-2 inhibitor in lame horses. Equine Veterinary Journal **41**, 309-312.

BACK, W., SCHAMHARDT, H.C., BARNEVELD, A. (1996): Are kinematics of the walk related to the locomotion of a warmblood horse at the trot? Veterinary Quarterly **18**, 79-84.

BARREY, E. (1990): Investigation of the vertical hoof force distribution in the equine forelimb with an instrumented horseboot. Equine Veterinary Journal **9**, 35-38.

BIALSKI, D., LANOVAZ, J.L., BOHART, G.V., MULLINEAUX, D.R., CLAYTON, H.M. (2004): Effect of detomidine on postural sway in horses. Equine and Comparative Exercise Physiology **1**, 45-50.

BJÖRCK, G. (1958): Studies on the draft forces of horses. Acta Agriculturae Scandina (Suppl. 4), 1-109.

BOCKSTAHLER, B., MÜLLER, M., HENINNGER, W., MAYRHOFER, E., PEHAM, C., PODBREGAR, I. (2008): Kinetische und kinematische Analyse der Bewegung (Ganganalyse) der Vorderextremitäten bei gesunden Militärhunden - Erhebung von Basiswerten. Wiener Tierärztliche Monatsschrift - Veterinary Medicine Austria **95**, 127-138.

BUCHNER, H.H.F., SAVELBERG, H.H.C.M., SCHAMHARDT, H.C., BARNEVELD, A. (1995a): Temporal stride patterns in horses with experimentally induced fore or hind limb lameness. Equine Veterinary Journal (Suppl. 18), 161-165.

BUCHNER, H.H.F., SAVELBERG, H.H.C.M., SCHAMHARDT, H.C., BARNEVELD, A. (1995b): Bilateral lameness in horses - a kinematic study. Veterinary Quarterly **17**, 103-105.

BUCHNER, H.H.F., SAVELBERG, H.H.C.M., SCHAMHARDT, H.C., BARNEVELD, A. (1996a): Head and trunk movement adaptations in horses with experimentally induced fore or hind limb lameness. Equine Veterinary Journal **28**, 71-76.

BUCHNER, H.H.F., SAVELBERG, H.H.C.M., SCHAMHARDT, H.C., BARNEVELD, A. (1996b): Limb movement adaptations in horses with experimentally induced fore or hind limb lameness. Equine Veterinary Journal **28**, 63-70.

CHATEAU, H., DEGUEURCE, C., DENOIX, J.M. (2004): Evaluation of three-dimensional kinematics of the distal portion of the forelimb in horses walking in a straight line. American Journal of Veterinary Research **65**, 447-455.

CHATEAU, H., DEGUEURCE, C., DENOIX, J.-M. (2006): Three-dimensional kinematics of the distal forelimbs in horses trotting on a treadmill and effects of elevation of heel and toe. Equine Veterinary Journal **38**, 164-169.

CLAYTON, H.M. (1986a): Cinematographic analysis of the gait of lame horses. Journal of Equine Veterinary Science **6**, 70-78.

CLAYTON, H.M. (1986b): Cinematographic analysis of the gait of lame horses. II. Chronic sesamoiditis. Journal of Equine Veterinary Science **6**, 310-320.

CLAYTON, H.M. (1987a): Cinematographic analysis of the gait of lame horses. III. Fracture of the third carpal bone. Journal of Equine Veterinary Science **7**, 130-135.

CLAYTON, H.M. (1987b): Cinematographic analysis of the gait of lame horses. IV. Tarsal degenerative joint disease. Journal of Equine Veterinary Science **7**, 274-278.

CLAYTON, H.M. (1988): Cinematographic analysis of the gait of lame horses. V. Fibrotic myopathy. Journal of Equine Veterinary Science **8**, 297-301.

CLAYTON, H.M. (2005): The force plate: established technology, new applications. The Veterinary Journal **169**, 15-16.

CLAYTON, H.M., BIALSKI D., LANOVAZ J.L., MULLINEAUX D.L. (2003): Reliability of a technique to measure postural sway in horses. American Journal of Veterinary Research **64**, 1354-1359.

CLAYTON, H.M., LANOVAZ, J.L., SCHAMHARDT, H.C., WILLEMEN, M.A., COLBORNE, G.L. (1998): Net joint moments and powers in the equine forelimb in the stance phase of the trot. Equine Veterinary Journal **30**, 384-389.

CLAYTON, H.M., SCHAMHARDT, H.C., LANOVAZ, J.L., COLBORNE, G.R., WILLEMEN, M.A. (2000a): Net joint moments and joint powers in horses with superficial digital flexor tendinitis. American Journal of Veterinary Research **61**, 197-201.

CLAYTON, H.M., SCHAMHARDT, H.C., WILLEMEN, M.A., LANOVAZ, J.L., COLBOURNE, G.R. (2000b): Kinematics and ground reaction forces in horses with superficial digital flexor tendinitis. American Journal of Veterinary Research **61**, 191-196.

CLAYTON, H.M., SCHOTT, H.C., LITTLEFIELD, L., LANOVAZ, J.L. (1999): Center of pressure analysis in normal and neurological horses. Journal of Veterinary Internal Medicine **13**, 241.

CLAYTON, H.M., SHA, D., STICK, J.A., MULLINEAUX, D.R. (2004): Three-dimensional carpal kinematics of trotting horses. Equine Veterinary Journal **36**, 671-676.

CLAYTON, H.M., SHA, D.H., STICK, J.A., ELVIN, N. (2007b): 3D kinematics of the equine metacarpophalangeal joint at walk and trot. Veterinary and Comparative Orthopaedics and Traumatology **20**, 86-91.

CLAYTON, H.M., SHA, D.H., STICK, J.A., ROBINSON, P. (2007a): 3D kinematics of the interphalangeal joints in the forelimb of walking and trotting horses. Veterinary and Comparative Orthopaedics and Traumatology **20**, 1-7.

CLAYTON, H.M., SINGLETON, W.H., LANOVAS, J.L., PRADES, M. (2002): Sagittal plane kinematics and kinetics of the pastern joint during the stance phase of the trot. Veterinary and Comparative Orthopaedics and Traumatology **15**, 15-17.

CLAYTON, H.M., WHITE, A., KAISER, L., NAUWELAERTS, S., LAVAGNINO, M., STUBBS, N. (2008): Short-term habituation of equine limb kinematics to tactile stimulation of the coronet. Veterinary and Comparative Orthopaedics and Traumatology **21**, 211-214.

CLAYTON, H.M., WILLEMEN, M.A., LANOVAZ, J.L. SCHAMHARDT, H.C. (2000c): Effects of a heel wedge in horses with superficial digital flexor tendinitis. Veterinary and Comparative Orthopaedics and Traumatology **13**, 1-8.

CREVIER-DENOIX, N., RAVARY-PLUMIOËN, B., EVRARD, D., POURCELOT, P. (2009): Reproducibility of a non-invasive ultrasonic technique of tendon force measurement, determined in vitro in equine superficial digital flexor tendons. Journal of Biomechanics **42**, 2210-2213.

DALIN, G., JEFFCOTT, L.B. (1985): Locomotion and gait analysis. Veterinary Clinics of North America: Equine Practice **1**, 549-572.

DEULAND, R., BARTEL, D.L., ANTONSEN, E. (1977): Force-plate technique for canine gait analysis of total hip and excision arthroplasty. Journal of American Animal Hospital Association **13**, 547-552.

DREVEMO, S., JOHNSTON, C., ROEPSTORFF, L., GUSTAS, P. (1999): Nerve block and intra-articular anasthesia of the forelimb in the sound horse. Equine Veterinary Journal (Suppl. 30), 266-269.

ELFTMAN, H.O. (1939): The force exerted by the ground in walking. Arbeitsphysiologie **10**, 485-491.

FREDERICK, F.H., HENDERSON, J.M. (1970): Impact force measurement using preloaded transducers. American Journal of Veterinary Research **31**, 2279-2283.

FREDRICSON, I., DREVEMO, S. (1971): A new method of investigating equine locomotion. Equine Veterinary Journal **3**, 137-140.

GALISTEO, A.M., MORALES, J.L., CANO, M.R., MIRO, F. AGUERA, E., VIVO, J. (2001): Inter-breed differences in equine forelimb kinematics at the walk. Journal of Veterinary Medicine **48**, 277-285.

GOMEZ ALVAREZ, C.B., BOBBERT, M.F., LAMERS, L., JOHNSTON, C., BACK, W., WEEREN, P.R. van (2008): The effect of induced hindlimb lameness on thoracolumbar kinematics during treadmill locomotion. Equine Veterinary Journal **40**, 147-152.

GUSTÅS, P., JOHNSTON, C., ROEPSTORFF, L., DREVEMO, S., LANSHAMMAR, H. (2004): Relationships between fore- and hindlimb ground reaction force and hoof deceleration patterns in trotting horses. Equine Veterinary Journal **36**, 737-742.

HJERTÉN, G., DREVEMO, S. (1994): Semi-quantative analysis of hoof-strike in the horse. Journal of Biomechanics **27**, 997-1004.

HOBBS, S.J., MATHER, J., ROLPH, C., RICHARDS, J. (2009): The effects of limb posture on relationships between in vitro radial hoof strain, load and joint angles. Equine Veterinary Journal **41**, 229-232.

HOBBS, S.J., RICHARDS, J., MATUSZEWSKI, B., BRIGDEN, C. (2006): Development of non-invasive marker clusters to assess three-dimensional kinematics of the lower forelimb of the horse. American Journal of Veterinary Research **67**, 1511-1518.

ISHIHARA, A., REED, S.M., RAJALA-SCHULTZ, P.J., ROBERTSON, J.T., BERTONE, A.L. (2009): Use of kinetic gait analysis for detection, quantification and differentiation of hind lim lameness and spinal ataxia in horses. Journal of the American Veterinary Medicine Association **234**, 644-651.

JANSEN, M.O., BOGERT, A.J. van den, RIEMERSMA, D.J., SCHAMHARDT, H.C. (1993): In vivo tendon forces in the forelimb of ponies at the walk, validated by ground reaction force measurements. Acta Anatomical **146**, 162-167.

JANSEN, M.O., RAAIJ, J.A.G.M. van, BOGERT, A.J. van den, RIEMERSMA, D.J., SCHAMHARDT, H.C., HARTMAN, W. (1992): Quantitative analysis of computer-averaged electromyographic profiles of intrinsic limb muscles in ponies at the walk. American Journal of Veterinary Research **53**, 2343-2349.

KAUFMANN, V., ZANEB, H., PEHAM, C., LICKA, T. (2008): Gait pattern and pattern of limb raises in horses with stringhalt. In: Proc. of the 6th International Conference on Equine Locomotion, Cabourg, France. 16th-19th June, 2008, p. 52.

KEEGAN, K.G., WILSON, D.J., WILSON, D.A., FRANKENY, R.L., LOCH, W.E., SMITH, B. (1997): Effects of anesthesia of the palmar digital nerves on kinematic gait analysis in horses with and without navicular disease. American Journal of Veterinary Research **58**, 218-223.

LANOVAZ, J.L., KHUMSAP, S., CLAYTON, H.M. (2004): Quantification of 3D skin displacement artifacts on the equine tibia and third metatarsus. Equine and Comperative Exercise Physiology **1**, 141-150.

LAWSON, S.E.M., CHATEAU, H., POURCELOT, P., DENOIX, J.-M., CREVIER-DENOIX, N. (2007): Effect of toe and heel elevation on calculated tendon strains in the horse and the influence of the proximal interphalangeal joint. Journal of Anatomy **210**, 583-591.

MAREY, E.J. (1873): Animal mechanism: a treatise on terrestrial and aerial locomotion. New York: Appleton. (International Scientific Series, 11).

MCGUIGAN, M.P, WILSON, A.M. (2001): The effect of bilateral palmar digital nerve analgesia on the compressive force experienced by the navicular bone in horses with navicular disease. Equine Veterinary Journal **33**, 166-171.

McGUIGAN, M.P, WILSON A.M. (2003): The effect of gait and digital flexor muscle activation on limb compliance in the forelimb of the horse *Equus caballus*. The Journal of Experimental Biology **206**, 1325-1336.

McGUIGAN, M.P., WALSH, T.C., PARDOE, C.H., DAY, P.S., WILSON, A.M. (2005): Deep digital flexor tendon force and digital mechanics in normal ponies and ponies with rotation of the distal phalanx as a sequel to laminitis. Equine Veterinary Journal **37**, 161-165.

McLAUGHLIN, R., ROUSH, J.K. (1995): Effects of increasing velocity on braking and propulsion times during force plate gait analysis in Greyhounds. American Journal of Veterinary Research **56**, 159-161.

MEERSHOEK, L.S., LANOVAZ, J.L., SCHAMHARDT, H.C., CLAYTON, H.M. (2002): Calculated forelimb flexor tendon forces in horses with experimentally induced superficial digital flexor tendinitis and the effects of application of heel wedges. American Journal of Veterinary Research **63**, 432-437.

MERKENS, H.W., SCHAMHARDT, H.C. (1994): Relationship between ground reaction force patterns and kinematics in the walking and trotting horse. Equine Veterinary Journal (Suppl. 17), 67-70.

NILSSON, G., FREDRICSON, I., DREVEMO, S. (1973): Some procedures and tools in the diagnostics of distal equine lameness. Acta Veterinaria Scandinavica (Suppl. 44), 63-79.

PEHAM, C., GIRTLER, G., KICKER, C., LICKA, T. (2006): Raising heels of hind hooves changes the equine coffin, fetlock and hock angle: a kinematic evaluation on the treadmill at walk and trot. Equine Veterinary Journal (Suppl. 36), 427-430.

PELOSO, J.G., STICK, J.A., SOUTAS-LITTLE, R.W., CARON, J.C., DECAMP, C.E., LEACH, D.H. (1993): Computer-assisted three dimensional gait analysis of amphotericin-induced carpal lameness in horses. American Journal of Veterinary Research **54**, 1535-1543.

PETERSEN, W.A., BROOKHART, J.M., STONE, S.A. (1965): A strain-gage platform for the force measurements. Journal of Applied Physiology **20**, 1095-1097.

RATZLAFF, M.H., GRANT, B.D., FRAME, J.M., HYDE, M.L. (1987): Locomotor forces of galloping horses. Equine Exercise Physiology **2**, 574-586.

RATZLAFF, M.H., WILSON, P.D., HYDE, M.L., BALCH, O.K., GRANT, B.D. (1993): Relationship between locomotor forces, hoof position and joint motion during the support phase of the stride of galloping horses. Acta Anatomica **146**, 200-204.

RICHARDS, J., THEWLIS, D. (2008): Measurement of force and pressure. In: RICHARDS, J. (ed.): Biomechanics in clinic and research. Churchill Livingstone, St. Louis, p. 89-102.

RIEMERSMA, D.J., BOGERT, A.J. van den, JANSEN, M.O., SCHAMHARDT, H.C. (1996): Influence of shoeing on ground reaction forces and tendon strains in the forelimbs of ponies. Equine Veterinary Journal **28**, 126-132.

ROBIN, D., CHATEAU, H., PACQUET, L., FALALA, S., VALLETTE, J.P., POURCELOT, P., RAVARY, B., DENOIX, J.M., CREVIER-DENOIX, N. (2009): Use of a 3D dynamometric horseshoe to assess the effects of an all-weather waxed track and a crushed sand track at high speed trot: preliminary study. Equine Veterinary Journal **41**, 253-256.

ROLLOT, Y., LECUYER, E., CHATEAU, H., CREVIER-DENOIX, N., (2004): Development of a 3D model of the equine distal forelimb and of a GRF shoe for non-invasive determination of in vivo tendon and ligament loads and strains. Equine Veterinary Journal **36**, 677-682.

SCHEFFER, C.J.W., BACK, W. (2001): Effects of navicular shoeing on equine distal forelimb kinematics on different track surface. Veterinary Quarterly **23**, 191-195.

SCHRYVER, H.F., BARTEL, D.L., LANGRANA, N., LOWE, J.E. (1978): Locomotion in the horse: kinematics and external and internal forces in the normal equine digit in the walk and trot. American Journal of Veterinary Research **39**, 1728-1733.

SHA, D.H., MULLINEAUX, D.R., CLAYTON, H.M., (2004): Three-dimensional analysis of patterns of skin displacement over the equine radius. Equine Veterinary Journal **36**, 665-670.

SINGLETON, W.H., CLAYTON, H.M., LANOVAZ, J.L. PRADES, M. (2003): Effects of shoeing on forelimb swing phase kinetics of trotting horses. Veterinary and Comporative Orthopaedics and Traumatology **16**, 16-20.

STROBACH, A., KOTSCHWAR, A., MAYHEW, I.G., PEHAM, C., LICKA, T. (2006): Gait pattern of the ataxic horse compared to sedated and nonsedated horses. Equine Veterinary Journal (Suppl. 36), 423-426.

WEEREN, P.R. van, BOGERT, A.J. van den, BARNEVELD, A. (1992): Correction models for skin displacement in equine kinematic gait analysis. Journal of Equine Veterinary Science **12**, 178-192.

WEISHAUPT, M.A., WIESTNER, T., HOGG, H.P., JORDAN, P., AUER, J.A. BARREY, E. (2001): Assessment of gait irregularities in the horse: eye vs. gait analysis. Equine Veterinary Journal (Suppl. 33), 135-140.

WEISHAUPT, M.A., WIESTNER, T., HOGG, H.P., JORDAN P., AUER, J.A. (2004): Vertical ground reaction force-time histories of sound Warmblood horses trotting on a treadmill. The Veterinary Journal **168**, 304-311.

WEISHAUPT, M.A. (2008): Adaptation strategies of horses with lameness. Veterinary Clinics of North America: Eqine Practice **24**, 79-100.

WIJNBERG, I.D., BACK, W., JONG, M. de, ZUIDHOF, M.C., BELT, A.J. van den, KOLK, J.H. van der (2004): The role of electromyography in clinical diagnosis of neuromuscular locomotor problems in the horse. Equine Veterinary Journal **36**, 718-722.

WIJNBERG, I.D., FRANSSEN, H., JANSEN, G.H., BACK, W., KOLK, J.H. van der, (2003): Quantitative electromyographic examination in myogenic disorders of 6 horses. Journal of Veterinary Internal Medicine **17**, 185-193.

WIJNBERG, I.D, SCHRAMA, S.E.A., ELGERSMA, A., MAREE, J.T.M., DE COCQ, P., 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: a preliminary study. Equine Veterinary Journal **41**, 313-318.

WILLEMEN, M.A., SAVELBERG, H.H.C.M., BARNEVELD, A. (1999): The effect of orthopaedic shoeing on the force exerted by the deep digital flexor tendon on the navicular bone in horses. Equine Veterinary Journal **31**, 25-30.

WILLIAMS, G.E. (2001): Locomotor characteristics of horses with navicular disease. American Journal of Veterinary Research **62**, 206-210.

WILSON, A.M., MCGUIGAN, M.P., FOURACRE, L., MACMAHON, L. (2001): The force and contact stress on the navicular bone during trot locomotion in sound horses and horses with navicular disease. Equine Veterinary Journal **33**, 159-165.

WILSON, A.M., PARDOE, C.H. (2001): Modification of a force plate system for equine gait analysis on hard road surfaces: a technical note. Equine Veterinary Journal (Suppl. 33), 67-69.

WOODALL, P., HOBBS, S.J., ROLPH, C. (2008): A case study of clinical farriery treatment for dropped fetlock. In: Proc. of the 6th International Conference on Equine Locomotion, Cabourg, France. 16th-19th June, 2008, p. 18.

ZANEB, H., STANEK, C., PEHAM, C., KAUFMANN, V., LICKA, T. (2008): Kinematic and surface electromyography (sEMG) study of equine back and hindlimbs in clinically sound and lame horses. Proc. of the 6th International Conference on Equine Locomotion, Cabourg, France. 16th-19th June, 2008, p. 54.

Authors´ address:
Sarah J. Hobbs, BEng (Hons), PG CERT, PhD, Jim Richards, PhD. MSc., BEng, Darwin Building 110, Preston, PR1 2HE Lancashire, UK; Hilary Clayton,BVMS, PhD, MRCVS, D202 Veterinary Medical Center, East Lansing, MI 48824.1314, USA; Jeremiah J. Tate, PT, MS, 1914 Andy Holt Avenue, 322 HPER Bldg, Knoxville, TN 37996-2700, USA; David Levine, PT, PhD, DPT, OVS, CCRP, Randy Walker jr., PT, PhD, DPT, CMP, 615 McCallie Ave Dept # 3253, Chattanooga, TN 37403, USA.
e-mail: SJHobbs1@uclan.ac.uk