Analyses of stress
on the locomotor apparatus of sport horses
caused by various riding surfaces

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General Introduction

Equestrian sports and horse racing are popular in many countries of the world. Diseases of the horse’s locomotor apparatus are a major cause of the attrition and culling of racehorses (Setterbo et al., 2009) and sport horses (Clausen et al., 1990). In the racehorse industry, economic losses caused by musculoskeletal injuries are estimated at about one billion dollars per annum (Kobluk, 1998). Thus, not only due to the high economic losses, but also for reasons of animal welfare it is necessary to investigate the factors influencing stress on the horse’s locomotor system. The properties of the track surface were associated with risk of injury and the type of horseshoe or the degree of fatigue of the horse (Pratt, 1997; Barrey, 1999). In the traditional equestrian disciplines, such as dressage and jumping, there is a multitude of surface types so that differences in the sport-functional properties of the surfaces can be expected. The Fédération Equestre Internationale (FEI) is the umbrella organization for equestrian sport disciplines such as dressage or jumping. The FEI code of conduct for the welfare of the horse states that “all ground surfaces on which horses walk, train or compete must be designed and maintained to reduce factors that could lead to injuries. Particular attention must be paid to the preparation, composition and upkeep of surfaces” (FEI, 2012). More precise recommendations are not given. In contrast, the Fédération Internationale de Football Association (FIFA) describes objective testing methods (FIFA, 2009a) and gives field test requirements for football turfs (FIFA, 2009b). However, the development of objective testing methods and recommendations for riding surfaces could help to prevent injuries in sport horses. Some earlier investigations which deal with sport-functional properties of surfaces showed the possibility to measure stress on the horse’s limb by hoof-acceleration measurement (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006; Chateau et al., 2008, Chateau et al. 2009; Setterbo et al., 2009). However, mostly racetracks (Ratzlaff et al., 2005; Chateau et al., 2009; Setterbo et al., 2009) or unusual ground surfaces such as tarmac (Burn, 2006) or sandpaper (Gustås et al., 2006) were investigated. Technical measurement devices, which are easy to handle in field studies on surfaces with footing for dressage and jumping horses, could be useful for surface evaluation, but have not hitherto been published.

The present thesis analysed the stress on the horse’s limbs produced by various riding surfaces, with footing for dressage and jumping horses. An easy-to-handle acceleration measurement system with unrestricted recording time was used for data acquisition on the horse’s limb. Programs for data processing were computed and the effect of different wavelet-
filter for data denoising as well as the use of various variables were analysed. In addition, a technical measurement device was tested on various riding surfaces. The results of the present study illustrate the importance of the riding surface properties with regard to stress on the equine locomotor apparatus. Further, the results could help to developed testing systems and recommendations for riding surfaces.

Chapter One gives an overview of the methods and scientific investigation into gait analyses in horses with the focus on the last ten years. Chapter Two deals with the effect of the riding surface to the acceleration data measured on hoof and fetlock in two directions. The objective of this part was to evaluate the different surfaces by acceleration measurement on the horse’s hoof and fetlock and to compare the results of both sensor applications. The use of wavelet-filtering to denoise hoof-acceleration data as well as the investigation of several variables in time and frequency domain calculated from the acceleration-time curves during the hoof’s landing phase were the subjects of Chapter Three. In Chapter Four, hoof-acceleration data as well as parameters measured by a technical surface-testing device (Artificial Athlete) were illustrated for five different riding surfaces. In addition, the surface composition of the riding surfaces was analysed. Two variables of the hoof-acceleration data as well as three parameters of the Artificial Athlete were analysed and compared to assess the suitability of the Artificial Athlete for testing riding surfaces.

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FEI 2012. The FEI code of conduct for the welfare of the horse. Fédération Equestre Internationale. Lausanne, Switzerland.


Chapter One

Methods and current applications of locomotion analyses in horses – A review

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Abstract

Equine locomotion has always been a subject of scientific investigation. Also today, the analysis of the equine locomotion is the objective of a large number of studies. The objective of the present review is to illustrate current methods and applications of equine locomotion analysis. Acceleration sensors, videographic and optoelectronic systems as well as force plates and force shoes, respectively, are reviewed and the advantages and disadvantages are pointed out. The applications of equine locomotion analysis can be subdivided into three parts: locomotion analysis in general and the effects of various factors on the horse’s locomotion, objective evaluation of the horse’s gait and jumping technique, and objective lameness detection. Studies concentrating on locomotion analysis in general have dealt for example with the recording of kinematic and kinetic parameters in different gaits and various speeds. Additionally, differences between horses of different breeds, ages and levels of training have also been investigated as well as the effect of various horseshoes or ground surfaces. The results of these studies could help to optimise the training conditions and the management of horses. Further, the aim of studies dealing with the objective analysis of the horse’s gait and jumping technique as well as lameness detection is to objectify subjectively perceived motions and changes in movement by locomotion analysis systems. Therefore, the objective of locomotion analysis could help to simplify and improve the assessment of gaits, jumping techniques and lameness. However, in practice, locomotor analysis systems have only been used in a small number of cases.

Keywords

horse, locomotion analysis, gait, motion pattern
Introduction

At least 5,000 years before Christ the domestication of horses started in the Eurasian Steppe region (Ludwig et al., 2009). First, the main focus for the domestication of horses was the production of meat. Later, horses were used as a draught, pack and riding animals (Frömming, 2011). The possibilities of transportation and warfare, which were opened up by the horse, have led to a great relevance of the horse in human history (Ludwig et al., 2009). The first experimental investigations were carried out in the 19th century. Marey (1873, 1894) analysed gait parameters in the horse by using pneumatic sensors and chronophotography. Faster gaits in horses were analysed by Muybridge (1979), who used a special camera technique to illustrate faster gait patterns of locomotion.

The motorisation of society displaced the horse more and more from human working life in western industrialised countries. But the importance of equestrian sport however increased at the same time (Frömming, 2011). Therefore, the importance of the horse’s locomotion became a point of focus. Today, injuries in the equine locomotor apparatus are a major cause of the culling and attrition of racehorses (Setterbo et al., 2009) as well as sport horses (Clausen et al., 1990). In the horse racing industry it is estimated that economic losses due to musculoskeletal injuries runs to one billion dollars per year (Kobluk, 1998). Therefore, it seems logical that also today a large number of studies deal with equine locomotion analysis, since locomotion analysis could help to better understand the origin of locomotor diseases, which is important to prevent injuries of horses. In addition, horses are particularly suitable for the study of quadruped locomotion and gait parameters due to its size and temperament.

This paper presents a review of measurement methods and applications of locomotion analyses of horses. Earlier reviews dealing with the locomotion analysis of horses were published some years ago (Leach and Dagg, 1983a, b; Leach and Crawford, 1983; Dalin and Jeffcott, 1985; Leach, 1987; Clayton, 1996; Barrey, 1999). Hobbs et al. (2010), in the article ‘Motion analysis and its use in equine practice and research’ focused on the analysis of video recording and force plates or instrumented horseshoe data. The present review illustrates in the first part methods such as accelerometry, videographic and optoelectronic systems as well as force plates and force shoes. The second part gives an overview of the applications and results of locomotion analyses of the last ten years.
Methods of locomotion analysis

Acceleration measurement, video recording and force measurement by force plates or special horseshoes are the most important locomotion analysis techniques in horses. Strain gauges, which measure the deformation of body tissue in response to an applied load, have played a limited role in the investigations of the last ten years. In earlier studies by Riemersma et al. (1996a, b) the load distributions on the flexor tendons of ponies were successfully analysed by using strain gauges. Further, the deformation of the hoof have also been evaluated by strain measurement (Hansen et al., 2005). Joint angle changes can be measured by goniometers. Liljebrink and Bergh (2010) demonstrated on horses the reliability of goniometry in illustrating the passive joint range of motion, but nevertheless, goniometers are rarely used. Further, electromyography has also been applied in a small number of equine locomotion analyses: for example, to analyse the muscle activity in horses at different speeds on a treadmill (Robert et al., 2002; Crook et al., 2010) or to illustrate differences in the activity of back and pelvic muscles on lame and non-lame horses (Zaneb et al., 2009).

The following sections present the most important methods for equine locomotion analyses, accelerometry, videographic and optoelectronic systems as well as force plates and force shoes.

Accelerometry

Acceleration is the second derivation of displacement and shows a change in velocity. Positive accelerations illustrate an increase in speed, whereas negative acceleration, called deceleration, describes a decrease in speed. Acceleration values are measured in m/s² or in multiples of gravity (g; 1 g = 9.81 m/s²). Due to the relationship between acceleration (a), force (F) and mass (m), which is given by Newton’s second law of motion (F = m*a), conclusions about force can be illustrated by acceleration measurement (Burn, 2006).

Small and low-weight accelerometer sensors (Gustás et al., 2006a, b) with a large range up to 4905 m/s² (Setterbo et al., 2009) and more have been used in studies dealing with equine locomotion analysis. A low weight and small size is important to reduce the influence of the accelerometer application on the horse’s gait. The range of the acceleration sensor must be appropriate for the relevant study. Acceleration sensors with a larger measuring range show a decrease in sensitivity, while a higher sensitivity is normally given by sensors with a smaller range. Uni-, bi- and triaxial accelerometers could be used in locomotion analyses of horses,
and depending on the test objectives, various sensor mounting have been applied. For example, in many studies, acceleration sensors have been mounted on the sternum or sacrum for general locomotion analysis (Barrey, 1999) or fixed to the head, back or pelvic to detect irregularities in the horse’s gait (Keegan et al., 2002; Keegan et al., 2004; Thomsen et al., 2010; Keegan et al., 2011). Further, acceleration sensors have been fixed to the dorsal or lateral hoof wall, inter alia, in studies which deal with stress caused by different shoeing methods (Benoit et al., 1993; Dallap Schaer et al., 2006), different surfaces (Barrey et al., 1991; Burn, 2006; Gustås et al., 2006a; Chateau et al., 2008; Chateau et al., 2009; Setterbo et al., 2009) or various surface conditions (Ratzlaff et al., 2005; Chateau et al., 2010). To fix the sensors in the desired orientation on the hoof wall, plexiglas (Burn, 2006), polyacrylic (Ratzlaff et al., 2005) or plastic composite blocks (Ryan et al., 2006) as well as triangular aluminium plates (Gustås et al., 2004) have been used. The sensor fixation must be rigid to prevent artefacts which result in vibrations between the horse’s body and the sensor. Further, bone-mounted sensors on the distal limb have been applied in some studies (Willemen et al., 1999; Gustås et al., 2001). The fixation of the sensors in the bone is a meaningful possibility to reduce artefacts in the accelerometer data. But bone-mounted sensors are invasive and cannot be used in field studies.

In most cases, the acceleration data is transferred via cables to a notebook or a data logger. The use of MP3 for data synchronisation and logging was successfully tested by Parsons and Wilson (2006). Ryan et al. (2006) developed and evaluated a wireless acceleration system. The advantage of this system is the possibility to record hoof-acceleration in a minimally invasive manner (Ryan et al., 2006). Equally, Scheibe and Gromann (2006) successfully tested a wireless acceleration system for behavioural analysis of cows and horses. They used radio communication which worked over a distance of up to 200 m (Scheibe and Gromann, 2006). A problem of the acceleration measurement was to some extent the capacity of the data logger and therefore the restricted number of recorded strides. The data capacity inter alia depended on the sampling rate of the data acquisition. The sampling rate of data recording was up to 10 000 Hz in earlier studies (Burn et al., 1997; Gustås et al., 2006b). A sampling rate of a minimum 2 500 Hz were recommended for acceleration measurement on the horse’s hoof in trot on a concrete runway to reduce aliasing (Burn et al., 1997). Due to the fact that over 99 % of the signal energy was below 1 250 Hz, this frequency could be taken as the Nyquist frequency (Burn et al., 1997).
To analyse the recorded acceleration data, different variables have been calculated from the acceleration-time curve: for example, the maximum peak during hoof impact (Burn et al., 1997; Ryan et al., 2006; Setterbo et al., 2009), the still stance time of the hoof during the stance phase (Ryan et al., 2006), duration of the initial deceleration, mean vibration frequency, duration of vibrations or the root mean square value of the acceleration-time curve (Barrey et al. 1991) as well as symmetry scores (Thomsen et al., 2010). In most studies dealing with bi- or triaxial accelerometers, the resultant vector has been calculated and used in further analyses (Dallap Schaer et al., 2006; Ryan et al., 2006; Chateau et al., 2009).

**Videographic and optoelectronic systems**

The motion of the whole horse or a part of the horse’s body have been recorded in videographic analyses. Therefore, videographic analyses are a popular method in kinematic investigations (Clayton and Schamhardt, 2001). Two- and three-dimensional motion analyses are possible (Clayton and Schamhardt, 2001). Due to the fact that video cameras only capture a limited part of view, treadmills and laboratory conditions are frequently used in videographic analyses. But it must be stated that motion on treadmills is different from normal locomotion (Buchner et al., 1994; Couroucé et al., 1999). Further, the controlling of the light is partly significant for video recording (Clayton, 1996; Martens et al., 2007).

In kinematic studies, markers are normally glued or painted to the horse’s body to capture and digitise the position of certain body segments (Clayton, 1996). The markers are divided into active and passive markers. In contrast to passive, reflective markers, active markers send signals such as visible light (Clayton and Schamhardt, 2001). Manual or automated digitising of the markers’ positions is possible. Some problems of automated digitising were described by Clayton and Schamhardt (2001), e.g. markers were placed close together or across each other, no markers on the subject in field studies or a marker was temporarily obscured. Further, optoelectronic systems were used in locomotion analyses, these systems recorded the markers on the horse’s body, but not the whole horse (Corbin, 2004). Therefore, the optoelectronic systems showed advantages with regard to data storage. The CODA-3 system (Cartesian Optoelectronic Dynamic Anthropometer) has been used by some investigators, such as Back et al. (1995, 1999), Clayton et al. (1998), Lanovaz et al. (1999), and is based on photodiode markers, which were glued to the horse’s body (Back et al., 1999). Further, infrared-light based optoelectronic gait analysis systems have also been used in equine locomotion analysis (Meershoek et al., 2001; Scheffer and Back, 2001; Roepstorff et al.,
2002; McGuigan and Wilson, 2003; Gustås et al., 2006a; Rhodin et al., 2009). In these systems, the infrared light of the camera was reflected by retro-reflective markers and return to the camera.

Video recording is performed with various numbers of frames per second. In consideration of the aim of the investigation, video cameras with ordinary frame rates (Clayton et al., 1999; Clayton et al., 2000a; Hodson et al., 2000; Singleton et al., 2003) or special high speed cameras (Butcher and Ashley-Ross, 2002; Leleu et al., 2002; Martens et al., 2006, 2007; Orito et al., 2007) have been applied. In various studies, to analyse the recorded video data, the digitised marker positions were used and parameters such as the joint angle in the different phases of locomotion and the timing of the movement have been calculated (Clayton et al., 1999; Lanovatz et al., 1999; Clayton et al., 2000b; Hodson et al., 2000). However, it must be noted that the markers on the skin do not illustrated the exact movement of the skeleton. This problem exists mainly in the proximal parts of the limb (Clayton and Schamhardt, 2001).

**Force plate**

Force plates or pressure plates have been applied in a large number of equine locomotion analyses. The load, when the horse steps on the plate, is detected by transducers and converted to an electric signal (Clayton, 1996). Force is a directed physical value, which is given in Newton (N; 1 N = 1 kg*m/s²). Forces cause, for example, changes of velocity. Pressure is the vertical force per unit of area and is normally stated in Pascal (Pa; 1 Pa = 1 N/m²).

Force/pressure plates must be mounted in the ground surface and be large enough for the horse to step on them. Therefore, force plates are less suitable to illustrate ground reaction force (GRF) of high speed motion with a stride length > 5 m and in field conditions (Robin et al., 2009). Further, the range and the frequency response of the force/pressure plates must be large enough for use in equine locomotion analyses. Thomason and Peterson (2008) stated that the use of force plates was limited by the low-frequency response of these plates. Concerning the use of pressure plates, Oosterlinck et al. (2010) compared data of force plates with pressure plate data and concluded that pressure plates were a cost-efficient alternative for use in equine practice.

The measurement of ground reaction force or pressure has also been deployed in several studies as a useful method to analyse the load on the horse’s limb (Hodson et al., 2000;
Meershoek et al., 2001; Witte et al., 2004; Dutto et al., 2004; Gustås et al., 2004; Oosterlinck et al., 2011) or to detect lameness (Weishaupt et al. 2001; Ishihara et al., 2005, 2009). The vertical, longitudinal and transverse forces of the stance phase, the stance duration, the time when the peak forces occur as well as the impulse and the centre of pressure have been captured by force plates (Clayton, 1996).

**Force shoe**

Beside force/pressure plates, force/pressure measurement shoes have been used in equine locomotion analyses to record the forces and pressures, respectively, during impact and stance phase. The advantage of force or pressure shoes is the possibility to record a larger number of strides. In addition, a number of studies have illustrated the suitability of special developed horseshoes for measuring forces (Kai et al., 2000; Rollot et al., 2004; Roland et al., 2005; Chateau et al. 2009; Robin et al., 2009; Setterbo et al., 2009) at the equine hoof under field conditions. Vertical reaction forces (Kai et al., 2000) or three-dimensional forces (Roland et al., 2005; Chateau et al., 2009; Robin et al., 2009; Setterbo et al., 2009) have been measured by force sensors included in the shoe. Problems in using measurement hoof shoes are the weight, which lies between 490 g (Chateau et al., 2009; Robin et al., 2009) and 860 g (Roland et al., 2005; Setterbo et al., 2009) and the height, which was for example 22 mm for the horseshoe used by Robin et al. (2009). The high weight and large height can also influence the motion patterns of the horses. Further, the measurement shoe must normally be nailed into the hoof wall, this could also be a problem in practice (Hobbs et al., 2010).

**Application and actual results of equine locomotion analysis**

A larger number of investigations concerning equine locomotion analyses have been done in the last ten years. The studies thematically focused on the areas of:

- locomotion analysis in general and the effects of various factors on the horse’s locomotion
- objective evaluation of horse’s gait and jumping technique
- lameness detection
Locomotion analysis in general

In locomotion analyses in general, kinematic and kinetic parameters have been analysed during treadmill or over ground locomotion. For example, the kinematics in lateral view have been illustrated for the forelimbs by videographic (Hodson et al., 2000) and optoelectronic systems (Lanovaz et al., 1999). In addition, the first ground contact of the forelimb as well as the limb movement during the swing phase have also been analysed by videographic analysis in frontal view (Martens et al., 2006, 2007). Besides the application of videographic systems, the use of accelerometer devices for kinematic analysis have also been tested successfully by a simultaneously recording of high-speed video and acceleration data (Leleu et al., 2002). The investigation by Leleu et al. (2002) showed inter alia that the measurement of temporal variables of the stride was not significantly different between video analysis and accelerometry. The stride duration as well as the stance duration measured in trot by acceleration sensors, video analysis and force shoes are illustrated in Table 1.

Table 1: Stride and stance phase duration in trot horse’s forelimb

<table>
<thead>
<tr>
<th>Horses</th>
<th>Speed (m/s)</th>
<th>Stride duration (s)</th>
<th>Stance duration (s)</th>
<th>Measurement system</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoroughbred</td>
<td>4.3</td>
<td>0.65</td>
<td>0.29</td>
<td>force-measuring horseshoe, acceleration sensor on the hoof</td>
<td>Kai et al. (2000)</td>
</tr>
<tr>
<td>French trotters</td>
<td>8.73</td>
<td>0.53</td>
<td>0.14</td>
<td>acceleration sensor on the sternum</td>
<td>Leleu et al. (2002)</td>
</tr>
<tr>
<td>French trotters</td>
<td>8.73</td>
<td>0.53</td>
<td>0.14</td>
<td>video analysis</td>
<td>Leleu et al. (2002)</td>
</tr>
<tr>
<td>Thoroughbred</td>
<td>3</td>
<td>0.68</td>
<td>0.31</td>
<td>force-measuring horseshoe</td>
<td>Roland et al. (2005)</td>
</tr>
<tr>
<td>Icelandic</td>
<td>4</td>
<td>0.57</td>
<td>0.22</td>
<td>acceleration sensor on the hoof</td>
<td>Robilliard et al. (2007)</td>
</tr>
<tr>
<td>French trotters</td>
<td>9.78</td>
<td>0.53</td>
<td>0.13</td>
<td>force-measuring horseshoe</td>
<td>Robin et al. (2009)</td>
</tr>
</tbody>
</table>

Further, acceleration measurements and other techniques, such as force plates or force shoes have been used for the kinetic analyses of the horse’s locomotion. For example, the relationships between fore- and hindlimb ground reaction force and hoof-deceleration patterns in trotting horses have been investigated by using acceleration sensors and force plates (Gustás et al., 2004). Differences in the force plate data of fore- and hindlimbs were recorded
e.g. by Gustås et al. (2004). The forelimbs showed greater vertical and horizontal loads than hindlimbs. In the acceleration data, differences between the limbs could not however be found (Gustås et al., 2004).

A number of factors can influence the kinematic and kinetic parameters of the horse’s locomotion and have been analysed in recent studies. The following sections deal with the effects of gait, speed, breed, age, training, rider and equipment as well as shoeing or surface conditions on the horse’s locomotion.

**Gait and speed**

The characterization of various gaits was analysed by Robilliard et al. (2007), who measured hoof-acceleration in walk, tolt, trot, pace, left and right canter as well as left and right gallop in Icelandic horses. It could be shown that in all gaits the duty factor as well as the stance phase and the swing phase decreased with speed (Robilliard et al., 2007). The stride parameters measured by Robilliard et al. (2007) in tolt at various speeds on the left forelimb are illustrated in Figure 1

![Figure 1](image-url)

**Figure 1**: Duration of stride, stance phase and swing phase in tolt measured by an acceleration sensor on the left forelimb (Robilliard et al., 2007)

In addition, Witte et al. (2006) used limb-mounted accelerometers and showed that in galloping horses the duration of the aerial phase of stride changes with speed and the time
when more than one hoof is on the ground decreased with speed and approached zero at a maximum speed level (Witte et al., 2006). Kinetic analyses illustrated larger hoof-deceleration values in vertical and horizontal direction (Gustås et al., 2006b) as well as larger forelimb peak forces (Dutto et al., 2004) in faster trots compared with slower trotting speed. In contrast to the force data measured on the forelimb, the hindlimb peak forces measured on different speeds were constant (Dutto et al., 2004). Due to the fact that some studies have shown the influence of speed on kinematics (Leleu et al., 2002; Witte et al., 2006; Robilliard et al., 2007; Parsons et al., 2011) and kinetic parameters (Dutto et al., 2004; Gustås et al., 2006b; Weishaupt et al., 2010), speed control seems to be fundamental in studies dealing with locomotion analysis. Additional, speed control is important in equine locomotion analysis due to the fact that each horse has an optimum speed, where the variation in the motion cycle is small and makes reproducible analyses possible (Peham et al., 1998).

**Breed**

The effect of the horse’s breed on the locomotion has been the objective of some studies (Back et al., 1999; Galisteo et al., 2001; Barrey et al., 2002). Back et al. (1999) analysed the kinematic of trotting pony and horse foals by using a CODA-3 apparatus. They concluded that horses and pony foals move qualitatively similarly but breed characteristics in the gait quality as well as in the conformation were given (Back et al., 1999). Galisteo et al. (2001) illustrated interbreed differences in the walk of Andalusians, Arabs and Anglo-Arabs by videographic analysis. Further, Barrey et al. (2002) studied the walk and trot of German, French and Spanish saddle horses by acceleration measurement on the sternum and sacrum. Differences in the gaits were shown and they concluded that German horses were more adapted to dressage competition, while Spanish horses were more suitable for collected gaits, which were used in old academic dressage or farm work (Barrey et al., 2002).

**Age, training, rider and equipment**

The age of the horses used can play a role in the locomotion analyses. Butcher and Ashley-Ross (2002) showed with a videographic analysis that fetlock kinematics of thoroughbred racehorses differ with age. The training of the horse influenced the equine gait in addition to the change in gait with age. Biau and Barrey (2004b) collected the movement patterns of 14 horses in the age between three and six years during a dressage test. The test was revised
over a three-year period. The changes in movement patterns, such as stride frequency symmetry and regularity, with the training level were illustrated by an acceleration device on the sternum (Biau and Barrey, 2004b). A change in the stride frequency and the dorsoventral displacement of the sternum during training could be shown (Biau and Barrey, 2004b). Besides the age and the training of the horse, the saddle and the rider also had an effect on the movement patterns (de Cocq et al., 2004) and gait-variability (Peham et al., 2004). Clayton et al. (1999) illustrated by force plate measurements and video recording that a horse rode in trot showed other ground reaction forces and fetlock angles than a horse trotted in hand. The influence of the rider on the horse plays a role in addition to the rider’s mass. For example, it has also been shown that the motion patterns of a horse are influenced by the head and neck position, which is controlled by the rider (Rhodin et al., 2009) or reins (Biau et al., 2002a). Further, Powers and Harrison (2002) illustrated the effect of the rider on jumping horses by videographic analysis. They concluded that the effect of the rider primarily results from the rider’s instruction (Powers and Harrison, 2002).

**Shoeing and surface**

A number of studies have focused on the effect of different shoeing on the equine locomotion. Videographic analyses and force/pressure plates have often been used in investigations dealing with effect of shoeing (Roepstorff et al., 1999; Pardoe et al., 2001; Scheffer and Back, 2001; Eliashar et al., 2002; Back et al., 2003; Girtler et al., 2003; Rogers and Back, 2003; Singleton et al., 2003; Chateau et al., 2006; Hinterhofer et al., 2006; Peham et al., 2006; van Heel et al., 2006; Rogers and Back, 2007). But also acceleration measurements have allowed the evaluation of different horseshoes and can be easy applied under field conditions (Dallap Schaer et al., 2006). It has been illustrated that shoe types, such as toe grab shoes, can have an effect on the acceleration values during impact and break over (Dallap Schaer et al., 2006). Further, the effect of shoeing has been illustrated in an in-vitro model with acceleration sensors being fixed at the hoof wall as well as in the metacarpal bone and in the proximal phalanx (Willemen et al., 1999). Besides shoeing, the ground surface also plays a role in the stress on the horse’s limb (Setterbo et al., 2009). Surface properties are associated with the pathogenesis of musculoskeletal injuries (Robin et al., 2009). Therefore, several studies have illustrated the effect of stress on the horse’s limb produced by different surfaces. Acceleration measurement on the hoof have often been used in studies dealing with surface testing (Barrey et al., 2001; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006a; Chateau et al., 2008;
Chateau et al., 2009; Setterbo et al., 2009). The acceleration pattern of the hoof during impact relates to the stress on the horse’s limb. Therefore, differences in the sport-functional properties of various surfaces have been detected. Larger deceleration values have been measured on tarmac and asphalt, respectively, compared to sand surfaces (Burn, 2006; Chateau et al., 2010). Ryan et al. (2006) measured larger acceleration values during galloping on a grass surface than on an indoor dirt arena and a standard dirt racetrack. Larger deceleration values are associated with higher loads on the horse’s limb and with harder surfaces. Harder surfaces are associated with an increase in injuries (Williams et al., 2001). In some studies dealing with acceleration measurements on different surfaces additional measurements such as force shoes (Setterbo et al., 2009) or force plates (Gustås et al., 2006a) were used. Further, Robin et al. (2009) successfully tested force measurement shoes to evaluate different surfaces.

Objective evaluation of horse’s gait and jumping technique

The evaluation of the horse’s gait with objective testing devices has been the focus of a few motion analysis investigations. Leleu et al. (2004) used an acceleration sensor on the sternum to test the locomotion of trotter horses. They were able to show a high reproducibility of this measurement method (Leleu et al., 2004). To detect which stride parameters indicate a ‘good’ gait, locomotion analysis data is said to be related to performance index (Leleu et al., 2005). For example, investigations in trotters have shown differences in stride parameters, such as stride frequency and propulsion duration, in elite and medium level trotters (Leleu et al., 2005). Significant higher stride frequencies and longer stance and propulsion durations have been found in elite level trotters compared with trotters at medium level (Leleu et al., 2005). In thoroughbred racehorses, by using acceleration measurement on the sternum it has been shown that a larger relative ground contact duration as well as a higher stride frequency is given in horses that win short distance races compared to horses that win longer distance races (Barrey et al., 2001). Therefore, locomotion analysis could be useful to quantify gait efficiency in racehorses and to estimate the racing ability (Leleu et al., 2005)

Further, the acceleration measured on the sternum has been used to describe gait transitions in dressage horses objectively (Biau et al., 2002b) and to compare stride characteristics and scores in dressage test (Biau and Barrey, 2004a). Biau and Barrey (2004a) showed that only a few correlations between the stride parameters measured in experienced horses and dressage test scores were given. In younger horses, better marks were for example associated with a
slow, regular and symmetric walk and a trot with a good longitudinal activity and dorsoventral displacement (Biau and Barrey, 2004a).

In addition to the locomotion analysis in thoroughbreds, trotters and dressage horses, the motion of horses during jumping has been investigated in some studies at the last ten years (Meershoek et al., 2001; Powers and Harrison, 2002; Reininger, 2002; Dutto et al., 2004; Santamaria et al., 2004a, b; Lewczuk et al., 2006; Hernlund et al., 2010). Video recording (Meershoek et al., 2001; Powers and Harrison, 2002; Dutto et al., 2004; Hernlund et al., 2010), force plates (Meershoek et al., 2001; Dutto et al., 2004) as well as acceleration measurement (Barrey and Galloux, 1997; Reininger, 2002) have all been used to investigate kinematics and the kinetics of the horse’s jumping. Inter alia the joint moments on the distal forelimbs during the landing have been analysed by videographic analysis and differences between the joint moments of the trailing and leading forelimb during landing were shown (Meershoek et al., 2001). Further it was illustrated by Meershoek et al. (2001) that the peak flexor joint moments in the coffin and fetlock joints during landing exceeded literature values for trot up to 82%.

Studies by Barrey and Galloux (1997) and Santamaria et al. (2004a, b) focused on the analysis of the jumping technique. Santamaria et al. (2004b) showed that each horse had an individual jumping technique (Santamaria et al., 2004b). Differences between jumping techniques were shown by variation in the vertical velocity of the center of gravity at the take-off phase (Santamaria et al., 2004b). In addition, investigations illustrated that the characteristics of the jumping technique do not changed during growth (Santamaria et al. 2004a). Therefore, it could be possible to estimate the jumping performance later in life (Santamaria et al., 2004a). The differences in the jumping technique between good and poor jumpers were analysed by Barrey and Galloux (1997), who used an accelerometric belt. Higher mean forelimb acceleration peaks were illustrated in poor jumpers at take-off as well as a higher forelimb/hindlimb ratio between the acceleration peaks (Barrey and Galloux, 1997). Further good jumpers showed a higher approach stride frequency than poor jumpers (Barrey and Galloux, 1997).
Analysis of lameness

Lameness detection plays an important role in research and practice. The evaluation of whether a horse is lame or not and to determine the affected limb is often subjective (Dyson, 2009) and especially the detection of low grade lameness has shown high variations within and between observers (Keegan et al., 1998; Keegan et al., 2010; Thomsen et al., 2010). Parkes et al. (2009) stated that the human brain is not able to detect slight lameness, which induces only a small gait asymmetry. Therefore, objective systems for lameness detection seems to be useful to evaluate lameness, e.g. before and after block anesthesia or surgery (Pfau et al., 2007). Kinematic and kinetic methods, such as video data (Schobesberger and Peham, 2002; Keegan et al., 2003; Keegan et al., 2004; Kramer et al., 2004; Orito et al., 2007), acceleration sensors (Barrey and Debrosse, 1996; Weishaupt et al., 2001; Keegan et al., 2002; Keegan et al. 2004; Thomsen et al., 2010; Keegan et al., 2011) or initial sensors (Pfau et al., 2007; Church et al., 2009) as well as force plates (Weishaupt et al., 2001; Ishihara et al., 2005, 2009;) have all been used in lameness detection in horses.

Weishaupt (2008) stated that the measurement of the ground reaction force is a dependable method for lameness detection, while temporal stride variables were less suitable for the analysis of lameness. Force plates showed in lame horses an irregular distribution of forces during impact. For example, the peak vertical force of the fore- and hindlimbs in sound, subtle, mild and moderate lame horses are illustrated in Table 2: the peak vertical force of the affected limb decreased with the increase of lameness grade.

| Table 2: Changes in the peak vertical force (in N/kg) of the horse’s limbs with increasing fore- and hindlimb lameness (Weishaupt, 2008) |
|---|---|---|---|---|---|---|---|---|
| | left forelimb lameness | | left hindlimb lameness | | left forelimb lameness | | left hindlimb lameness | |
| left forelimb | right forelimb | left hindlimb | right hindlimb | left forelimb | right forelimb | left hindlimb | right hindlimb |
| sound | 11.07 | 11.07 | 9.75 | 9.76 | 11.09 | 11.08 | 9.85 | 9.80 |
| subtle lameness | 10.67<sup>a</sup> | 10.97 | 9.66 | 9.69 | 10.98 | 10.99 | 9.63 | 9.82 |
| mild lameness | 10.10<sup>ab</sup> | 11.01 | 9.52<sup>a</sup> | 9.83 | 11.16 | 11.10 | 9.20<sup>ab</sup> | 9.91 |
| moderate lameness | 8.47<sup>ab</sup> | 11.18 | 9.12<sup>ab</sup> | 9.96<sup>ab</sup> | 11.07 | 10.93 | 8.38<sup>ab</sup> | 9.94 |

<sup>a</sup> Significant difference (p < 0.05) compared with the sound condition
<sup>b</sup> Significant difference (p < 0.05) compared with the preceding condition
However, force plates showed some disadvantages in practice, because repeated measurements were necessary to record a sufficient number of strides and in addition data of all four limbs had to be acquired for lameness detection (Keegan, 2007; Weishaupt, 2008). Under laboratory conditions, these disadvantages could be reduced with a treadmill, which included a dynamometric platform (Keegan, 2007; Weishaupt, 2008). The use of a treadmill has the further advantage that the speed of the horse can be controlled.

Video recording and acceleration sensors can illustrate for example the motion and acceleration of the head in forelimb lameness and respectively of the sacrum or tuber coxae in hindlimb lameness as well as the motion and acceleration of the limbs. Asymmetries in the motion or acceleration parameters normally indicate lameness. However, lameness detection by video recording is most powerful by using a treadmill. Keegan et al. (2011) illustrated that the measurement of asymmetry of the head and pelvic movements by inertial sensors is repeatable enough for clinical use in lameness detection and could be used under field conditions. Therefore, acceleration measurement is more practicable under field conditions than video recording (Keegan et al, 2004).

Concerning the potential source of errors in objective lameness detection, it must be noted that lame horses adapt their motion pattern. For this, Peham et al. (2001) showed a lower stride variability of lame horses than of horses without orthopaedic pain during trotting on a treadmill. Further, in horses with hindlimb lameness, prominent compensatory motions of the ipsilateral forelimb and head were illustrated by videographic analysis (Kelmer et al., 2005). Conversely, forelimb lameness could affect the motion of the hindquarter, but in a slighter manner (Kelmer et al., 2005). Weishaupt et al. (2004, 2006) analysed the redistribution of loads in lame horses by using a treadmill, which included a dynamometric platform. Compensatory load redistributions were shown in forelimb lameness but were not illustrated in hindlimb lameness (Tab 2). Further, lameness and back pain are said to be related to each other, since on the one hand orthopaedic pain in the hindlimbs influences the motion pattern of the thoracolumbar back (Gomez Alvarez et al., 2008) and on the other hand the motion pattern of the limbs could be influenced by back pain (Weishaupt, 2008). Also, it must be taken into account that if the horse is ridden during lameness detection the rider could influence the equine gait (Licka et al., 2004).
Conclusion and outlook

Various methods, such as accelerometry, video recording and optoelectronic systems as well as force plates and shoes, have been used in equine locomotion analyses. The method used in locomotion analysis must be chosen with regard to the objective and design of the study. Acceleration measurement can be used in studies dealing with kinematic or kinetic analyses in the field. Areas of application for acceleration measurement are for example the analysis of various horseshoes, riding or track surfaces or the detection of lameness. Disadvantages in acceleration measurement are the fact that the sensor’s axis is orientated towards the body segment where the sensor is fixed, and skin- or hoof-mounted acceleration sensors can help to assess the accelerations of the bones and tendons, but do not show the real accelerations of the underlying structures. Further, some kinematic parameters, such as joint angles, cannot be illustrated by accelerometry. Also, forces during impact can be estimated but not really measured by acceleration sensors. Therefore, videographic or optoelectronic systems were superior in kinematic analyses. But laboratory conditions and the use of a treadmill for data recording have been preferred in studies dealing with videographic and optoelectronic systems. Further, it must be noted that skin-mounted markers, which have been used in analyses with videographic or optoelectronic systems, do not exactly illustrate the motion of the skeleton. If the real ground reaction force during impact is to be measured, force measurement devices must be used. Force plates have the weakness that they must be mounted in the ground surface and be large enough for the horse step on them. These problems do not exist for force shoes. But the disadvantages of force shoes are the large height and weight, but nevertheless they are easier to handle in field conditions than force plates and have been among other things successfully tested in investigations dealing with the effect of different surfaces.

With regard to the applications, the effect of factors such as the horse’s gait, speed and breed as well as different horseshoes or ground surfaces on the equine locomotion, has been the object of a number of investigations. For example the speed of the horse has an important influence with regard to kinematic and kinetic stride parameters. With an increase in speed, the stance phase and the stride duration decrease, while the deceleration and forces on the forelimb increase. This illustrates the importance of speed control during locomotion analyses. Further the training level as well as the rider and the equipment influence the horse’s gait. Horses, which are ridden by a rider show other ground reaction forces and fetlock angels during impact. In addition to the rider’s weight, the rider’s level of instruction
influences the locomotion of the horse. The effect of various shoeing and surfaces on the load on the horse’s locomotor apparatus has been the subject of a number of investigations. It has been shown that for example grass surfaces induce higher loads on the horse’s limb. Higher loads are associated with higher risk of injuries. Therefore, studies dealing with the effect of different factors on the horse’s locomotion could help to optimise training conditions and to reduce injuries in sport horses.

The aim of studies dealing with the objective analysis of the horse’s gait and jumping technique as well as lameness detection is to objectify subjectively perceived motions and changes in movement by locomotion analysis systems. Therefore, the use of locomotion analysis systems could help to simplify and improve the assessment of gaits, jumping techniques and lameness. It was inter alia shown that differences exist between the stride parameters such as stride frequency and propulsion duration of elite and medium level trotters. In addition, thoroughbreds which have won short distance races show different stride parameters than thoroughbreds which have won longer distance races. Differences in locomotion parameters can equally be illustrated between good and poor jumpers. Therefore, the use of locomotion analysis systems may be useful to quantify the ability of horses objectively.

In lameness detection, a high suitability of accelerometers or force plates has been demonstrated. Especially the detection of low grade lameness is difficult for the human brain and shows high variations within and between observers. In consequence, the use of objective analysis systems seems to be meaningful for the early detection of lameness.

It must be noted that technical progress has made a large number of motion analyses possible, however, in practice these objective analysis systems have only been used in a small number of cases. Therefore, the development of simple motion analysis systems and evaluation methods for use in field conditions is desirable to optimise the management and the training conditions of sport horses and to objectify the evaluation of the horse's gait and jumping technique as well as the detection of lameness.

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of equine subclinical lameness induced by pressure to the sole of fore- or hindlimb.


Chapter Two

Effects of different riding surfaces on the hoof- and fetlock-acceleration of horses

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Abstract

In the traditional equestrian disciplines such as dressage and jumping there is a multitude of riding surface types. Properties of riding surfaces are associated with risk of injury. The aim of the present study was to analyse the sport-functional properties of five different riding surfaces by acceleration measurements on horse’s hoof and fetlock. Six riding horses were used. The acceleration data were collected while the horses were trotted by hand on the different surfaces. Larger acceleration values during hoof landing were measured in outdoor arenas compared to indoor arenas. Larger values were associated with a harder surface. The acceleration values of hoof and fetlock were positively correlated. In conclusion differences in the sport-functional properties of various riding surfaces would be demonstrated. Concerning the sensor application it must be noted that the sensor mounting on horse’s hoof as well as on horse’s fetlock would be suitable for testing riding surfaces.

Keywords

riding surface, horse, hoof, fetlock, acceleration, injury risk
Introduction

Diseases of the locomotor apparatus are a major cause of sport horses’ culling and attrition (Clausen et al., 1990). In addition to other factors, such as the type of horseshoe and the degree of fatigue of the horse, properties of riding surfaces are associated with risk of injury (Pratt, 1997; Barrey, 1999). Studies on racehorses have demonstrated that the hardness of racetrack surfaces has an influence on the risk of limb injury of racehorses. Harder racing surfaces have been associated with an increase in injuries (Williams et al., 2001). To assess the effects of different ground surfaces on the horses’ limbs, the measurement of hoof-acceleration can be a useful method (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006; Chateau et al., 2009; Setterbo et al., 2009). In previous studies, which deal with sport-functional properties of surfaces, mostly racetrack surfaces (Ratzlaff et al., 2005; Chateau et al., 2009; Setterbo et al., 2009) as well as unusual ground surfaces such as tarmac (Burn, 2006) and sandpaper (Gustås et al., 2006) have been investigated. Further, thoroughbreds (Ratzlaff et al., 2005; Burn, 2006; Setterbo et al., 2009) and standardbred trotters (Gustås et al., 2006; Chateau et al., 2009) have mostly been used in these investigations and in the majority of cases only a few strides performed by a small number of horses have been analysed. However, previous studies have also shown a high variability between as well as within horses (Chateau et al., 2009) and the necessity to record a larger number of strides from several horses.

In traditional equestrian disciplines such as dressage and jumping there is a multitude of riding surface types, so that differences in the sport-functional properties of the surfaces, such as hardness and shearing strength, could be expected. For surfaces with footing for dressage or jumping horses, measurement devices, which were easy to use and supplied satisfactory results, were not established in practise. Further, investigations into acceleration data on riding surfaces, which have used several warmblood horses as well as a greater number of strides, have not been yet conducted.

The aim of the present study was to analyse the sport-functional properties of different riding surfaces by acceleration measurement on horses’ hoof and fetlock with an easy-to-handle measurement device. Another objective of this investigation was to record hoof- and fetlock-acceleration simultaneously to compare the measurement results of both sensor applications. In the present investigation different warmblood horses were used for surface testing and the acceleration-time curves were recorded over approximately 65 seconds.
Materials and methods

Horses and ground surfaces

Six Holsteiner warmblood geldings between the ages of five and six years were used in the present investigation. The body mass of each horse was between 542 kg and 603 kg and each had a stick measure between 165 cm and 177 cm. Furthermore they were shod with standard steel shoes. Each horse was trained to trot by hand on the different surfaces. Five riding surfaces were tested: two outdoor arenas; one with a grass surface (grass outdoor) and one with a sand surface (sand outdoor) as well as three indoor arenas; one with a sand-synthetic fibre surface used for lunging (sand-synthetic indoor I), one with a sand-synthetic fibre surface used for jumping horses (sand-synthetic indoor II) and one with a sand-sawdust surface used for dressage horses (sand-sawdust indoor). All five tested riding surfaces were in good condition and regularly maintained.

Device description

In the present investigation a motion analysis system developed by Noraxon (Noraxon U.S.A. Inc., Scottsdale, Arizona) was used. The motion analysis system consisted of two small biaxial accelerometers and a measurement station (MyoTrace 400) as well as special software (MyoResearch XP). The accelerometers had a weight of 2.8 g and a range of +/- 98.1 m/s² with a sensitivity of 981 mV/m/s². The acceleration data were stated in multiples of acceleration due to gravity (1 g = 9.81 m/s²). One accelerometer device was fixed to the lateral hoof wall of the left forelimb (Fig. 1). The other accelerometer device was fixed laterally on the fetlock of the same leg (Fig. 1). Fixation was performed using double sided adhesive tape and fabric tape. The y-axes of the two accelerometers were aligned to the ground and the x-axes were oriented against the direction of movement. The two acceleration devices were connected via a cable with the measurement station. Self-adhesive bandages were used to fix the cables on the horse’s limb. The measurement station was fixed to a surcingle, which the horse was wearing during data acquisition. Via Bluetooth the measurement station transferred acceleration data simultaneously to a notebook. The notebook was used for starting and stopping the data acquisition as well as for measurement control. Data acquisition was performed at 1 004.03 Hz. A 500 Hz anti-aliasing filter was included in the motion analysis system.
Data acquisition

As mentioned before, five riding surfaces were tested. Each surface was tested with the six horses. The data was logged for 65 seconds while the horse was trotted by hand on a defined circle with a diameter of 16 meters. In the first step the horses were adapted to the accelerometer devices. Data acquisition was checked with the notebook and was performed as soon as the horse trotted in a regular cadence. Each run was filmed with a video recorder. The videos were used to calculate the mean speed of each horse on each surface. Therefore, the time, which was needed by the horse for trotting three circles, was stopped and the mean speed was calculated by the following expression:

\[ \text{mean speed} = \frac{3d\pi}{t_S} , \]

in which \( d \) is the diameter of the circle in meters and \( t_S \) is the time in seconds, which was needed by the horse for trotting three circles.

To reduce the influence of sensor application to data recording, all five surfaces were tested with one horse before the sensors were attached to the next horse, and so on. The order of the tested riding arenas differed from run to run.

Data processing and statistical analysis

The acceleration-time curves were cut in single hoof strikes by using an algorithm written in MATLAB (MATLAB, version R2010a, The MathWorks Inc., Natrick, Massachusetts). The algorithm detected the stance phase of the hoof where the acceleration of the y-axis approached for minimum 60 ms near zero. Preliminary tests showed that the largest number of correctly detected stance phases could be found with the mentioned algorithm. In a second step the single hoof strikes were cut into the hoof’s take-off and landing phase. In the present study only the landing phase beginning with the second half of the swing phase and ending at
the end of the hoof’s breaking phase were used for statistical analysis. This approach was chosen because the hoof’s landing phase is particularly important for the stress on the horse’s limb (Drevemo et al., 1994). Figure 2 shows a part of the acceleration-time curves measured on hoof and fetlock in y- and x-direction.

**Figure 2**: An exemplarily chosen part of the acceleration signal on hoof and fetlock in y-direction (A) and x-direction (B) of horse 5 on the sand outdoor arena (speed 2.98 m/s); HT = hoof’s take off phase; HL = hoof’s landing phase; SP = stance phase of the hoof
For the evaluation of the sport-functional properties of the riding surfaces six acceleration data sets were used. Besides the analysis of the y-axis and x-axis of both acceleration sensors, the total acceleration represented by the resultant vector, which were also used in similar investigations (Dallap Schaer et al., 2006; Ryan et al., 2006; Chateau et al., 2009) was considered in this study:

- y-axis hoof-acceleration (yHOOF)
- x-axis hoof-acceleration (xHOOF)
- resultant vector of the hoof-acceleration (rHOOF)
- y-axis fetlock-acceleration (yFETLOCK)
- x-axis fetlock-acceleration (xFETLOCK)
- resultant vector of the fetlock-acceleration (rFETLOCK)

All six acceleration data sets were cut into single hoof’s landing phases with the mentioned MATLAB program, which used the hoof’s acceleration-time curves in y-axis direction. Between 61 and 78 strides of each horse on each surface were recorded. For the acceleration-time curves during the hoof’s landing phase of the six mentioned data sets, the root mean square value (RMS) was calculated by the formula:

\[ RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2} \]

in which \( x_i \) is the i-th observation of the acceleration signal and \( n \) is the total number of observations in the acceleration signal. The RMS-value integrates, in contrast to extreme values, several acceleration values. Barrey et al. (1991) stated that the RMS-value relates to the power content of vibrations during the hoof’s breaking phase. Vibrations are associated with damaging effects on the locomotor apparatus of sport horses (Rooney, 1974). Additionally, the absolute value of the maximum deceleration (MAX) during impact, which was associated with the maximum stress on the horse’s limb, was determined for each stride. Because of the fact that the MAX-values did not follow a normal distribution for all six data sets, only the maximum deceleration of the y-axis of the hoof-mounted sensor (yMAX) was statistically analysed.

The RMS-values of yHOOF, xHOOF, rHOOF, yFETLOCK, xFETLOCK and rFETLOCK as well as yMAX were statistically analysed by using a mixed model (SAS, version 9.1, SAS Institute Inc., Cary, North Carolina). The model included the riding surface as a fixed effect, the horse and the interaction between horse and surface as random effects. The least square means were tested for significant differences between the surfaces including a Tukey-Kramer adjustment for multiple testing. In a second step, the acceleration data of hoof and fetlock were compared. The correlation coefficients for the residuals of the hoof- and fetlock-
acceleration were calculated. Further, the correlation between the residuals of the x-axis and the y-axis of both sensors were computed.

**Results**

The results of the mixed model showed a highly significant effect ($p < 0.01$) of the fixed effect surface for yMAX and the RMS-values of all six acceleration data sets. The repeatability of the random effect horse was 0.28 for the variable yMAX, between 0.39 and 0.49 for the RMS-values of the hoof-mounted sensor (yHOOF, xHOOF, rHOOF) and between 0.19 and 0.23 for the RMS-values of yFETLOCK, xFETLOCK and rFETLOCK.

Table 1 shows the least square means of the variable yMAX and the RMS-values of the acceleration data measured on hoof (yHOOF, xHOOF, rHOOF) and fetlock (yFETLOCK, xFETLOCK, rFETLOCK). The riding surfaces were sorted according to the size of the least square means of yMAX, starting with the highest value. A higher acceleration value was associated with a higher degree of hardness of the surface. Both outdoor arenas showed higher hoof- and fetlock-acceleration values compared to the values of the three indoor arenas. The number of significant differences, which were determine between the least square means of the riding surfaces, differs among yMAX and the RMS-values of six data sets. The variable yMAX showed four significant differences ($p < 0.05$) between the investigated riding surfaces. Concerning the RMS-values of the y-axis hoof-acceleration (yHOOF), six significant differences ($p < 0.05$) could be found. Considering the values measured on the y-axis of the fetlock-mounted sensor (yFETLOCK), the three indoor arenas differ significantly ($p < 0.05$) from the grass surface. Also the sand-synthetic I arena and the sand-sawdust indoor arena were significantly different ($p < 0.05$) from the sand outdoor arena. Concerning the x-axis of the hoof- and fetlock-acceleration (xHOOF, xFETLOCK) three significant differences between the least square means of the riding surfaces were determined. Therefore, a smaller number of significant differences could be found between the least square means of the x-axis acceleration compared with the y-axis acceleration. Furthermore, it should be noted that for the variable yMAX as well as the RMS-values of the five data sets yHOOF, yFETLOCK, xHOOF, rHOOF and rFETLOCK the acceleration values of the grass outdoor arena differ significantly ($p < 0.05$) from the indoor arenas. Concerning the values of the resultant vector of both sensors (rHOOF, rFETLOCK), the order and the significant differences between the least square means of the riding surfaces are similar to the results of the single axes data sets.
There were significant differences (p < 0.05) between the grass surface and the indoor arenas, and no significant differences between the indoor arenas (Tab. 1).

**Table 1:** Mean speed of the horses (in m/s) as well as the least square means (in g) of yMAX and the RMS-values of the acceleration data measured on hoof and fetlock during the hoof’s landing phase on the five riding surfaces

<table>
<thead>
<tr>
<th></th>
<th>Mean speed (S.D.)</th>
<th>yMAX (S.E.)</th>
<th>yHOOF (S.E.)</th>
<th>yFETLOCK (S.E.)</th>
<th>xHOOF (S.E.)</th>
<th>xFETLOCK (S.E.)</th>
<th>rHOOF (S.E.)</th>
<th>rFETLOCK (S.E.)</th>
</tr>
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<tbody>
<tr>
<td>Grass outdoor</td>
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</tr>
<tr>
<td></td>
<td>3.33 (0.13)</td>
<td>7.88a</td>
<td>1.62a</td>
<td>1.25a</td>
<td>1.81a</td>
<td>1.80a</td>
<td>2.45a</td>
<td>2.20a</td>
</tr>
<tr>
<td>Sand outdoor</td>
<td>2.99 (0.19)</td>
<td>7.27ab</td>
<td>1.56ab</td>
<td>1.21ab</td>
<td>1.66ab</td>
<td>1.76ab</td>
<td>2.29ab</td>
<td>2.15ab</td>
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<tr>
<td>Sand-synthetic</td>
<td></td>
<td></td>
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<tr>
<td>indoor I</td>
<td>3.43 (0.22)</td>
<td>6.55bc</td>
<td>1.44bc</td>
<td>0.99c</td>
<td>1.51b</td>
<td>1.60bc</td>
<td>2.11bc</td>
<td>1.89c</td>
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<tr>
<td>Sand-synthetic</td>
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<td></td>
</tr>
<tr>
<td>indoor II</td>
<td>3.18 (0.32)</td>
<td>6.46bc</td>
<td>1.43cd</td>
<td>1.06bc</td>
<td>1.56b</td>
<td>1.63ac</td>
<td>2.13bc</td>
<td>1.95bc</td>
</tr>
<tr>
<td>Sand-sawdust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>indoor</td>
<td>3.37 (0.27)</td>
<td>5.46c</td>
<td>1.31d</td>
<td>0.99c</td>
<td>1.47b</td>
<td>1.58c</td>
<td>1.99c</td>
<td>1.87c</td>
</tr>
</tbody>
</table>

Different superscript letters within a column indicate significant differences (p < 0.05)

The residuals of the variable yMAX and the RMS-values of yHOOF were high positively correlated (r = 0.81). Further, positive correlations between the residuals of the hoof and fetlock RMS-values for both axes (r_y-axis = 0.43; r_x-axis = 0.52) and the resultant vector (r_resultant = 0.63) were found. Equally, the x-axis and the y-axis of the hoof-mounted sensor (xHOOF, yHOOF) were positively correlated (r_froof = 0.44) as well as the values of yFETLOCK and xFETLOCK (r_fetlock = 0.68). All calculated correlations were highly significant (p < 0.01).

Comparing the least square means of both sensor applications, the least square means of the hoof-mounted sensor were higher in the y-axis direction (yHOOF) and for the resultant vector (rHOOF) than the least square means of yFETLOCK and respectively rFETLOCK. Further, the values of the x-axis of both sensors were larger than the values of the y-axis of the respective sensor.
Discussion

The present study was designed to analyse sport-functional properties of different riding surfaces by acceleration measurement on horse’s hoof and fetlock.

The measurement system, being used in the present study included two biaxial sensors. The sensors were fixed on the lateral hoof wall and fetlock with the y-axes directed to the ground and the x-axes were oriented against the direction of movement. Because of the shape of the hoof, the vertical hoof-acceleration would not be fully recorded. Further, the acceleration of the transversal (medio-lateral) axis would not be acquired. The capture of all three axes seems to be quiet better, but during the hoof impact only a small transversal acceleration could be expected. Equally, similar investigations by Burn (2006), Gustås et al. (2006) and Setterbo et al. (2009) did not integrated the transversal hoof-acceleration.

Further, it must be noted that the used acceleration sensors had a relatively small range compared with accelerometers, being used in earlier investigations (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006; Chateau et al., 2009). The results of the statistical analysis of the variable yMAX showed that the range was sufficient for measure hoof-acceleration data in slow trot on riding surfaces. But a larger range seems to be more suitable especially for harder surfaces and faster gaits, because among others Burn (2006) measured on average a maximum hoof-acceleration of 17 g during impact in trot on sand and 504 g on tarmac.

Additionally, the sampling rate of the acceleration measurement system was relatively low, compared with previous studies (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006; Chateau et al., 2009). Burn et al. (1997) concluded that a sampling rate of minimum 2 500 Hz was needed, because more than 98.2 % of the hoof-acceleration signal energy, which was measured in trot on a concrete surface, was below 625 Hz and over 99 % of the energy was below 1 250 Hz. But on riding surfaces, which were investigated in the current study, lower frequencies could be expected, than on a concrete runway. Therefore, a sampling rate of 1 000 Hz seems to be sufficient for data recording and would equally used in similar studies by Witte et al. (2004) and Setterbo et al. (2009). Advantages of the acceleration sensors, being used in this study, were the wireless data transfer and the possibility to control data acquisition simultaneously using a notebook. Because of the unrestricted recording time it was possible to record a large number of acceleration data. The repeatability of the random effect horse was between 0.19 and 0.49; this showed the high variability within horses. These results were in line with Chateau et al.
(2009), who demonstrated a high variability within horses in acceleration data during hoof impact on the ground as well as a high between-horse variability. Therefore, the recording of a sufficiently large database was necessary for robust statistical results.

In the current study, the order of the least square means of the different riding surfaces was comparable for the six data sets. The number of significant differences, determined by the statistical analysis, varied between yMAX, yHOOF, xHOOF, rHOOF, yFETLOCK, xFETLOCK and rFETLOCK. This outcome could be explained by the different orientation of x- and y-axes during the hoof’s landing phase as well as by the characteristics of impact power during hoof landing. Further, the acceleration values of the x-axis represented the shearing strength, while values of the y-axis illustrated the force reduction. In the present investigation the values of the x-axis were larger for both sensors (xHOOF, xFETLOCK) than the respective y-axis acceleration. Therefore, the load on the x-axis during hoof landing was higher than in the y-axis direction. However, the consideration of the resultant vector could be useful to reduce the influence of the orientation of the axes during hoof landing and to illustrate the total acceleration.

The highest yMAX-value as well as the highest RMS-values on hoof and fetlock in both directions as well as the resultant vector were recorded on the grass surface and the sand outdoor arena. These results were expected because both surfaces showed a low vertical deformation when the hoof touched the ground. Equally, these results are partly similar to previous investigations. Likewise, Ryan et al. (2006) obtained larger acceleration values measured on a grass paddock compare to an indoor arena and a standard dirt racetrack. Larger acceleration values generally result in increased root mean square values and indicate a higher degree of hardness of the ground surface. Harder track surfaces have also been associated with an increase in injuries (Williams et al., 2001). The sand-sawdust indoor arena in the study is normally used for dressage horses and showed the lowest acceleration values for all six data sets. This outcome could be explained by the larger vertical deformation shown when the hoof touched the ground. Furthermore, arenas with footing for dressage horses are mostly softer than surfaces for jumping horses. Lower acceleration values are associated with a softer surface and a decrease in the stress on the horse’s limb. But nevertheless, too soft surfaces could result in injuries on the horse’s locomotor system. The levels of yMAX and the RMS-values, which were measured in the current study, were in line with the maximum deceleration and the RMS-values measured by Barrey et al. (1991) on sand, sand-sawdust, gravel-sand and wood chips surfaces. It must be noted that in earlier studies larger hoof-
acceleration values during impact in trot were recorded. For example Gustås et al. (2006) recorded vertical hoof-accelerations during trotting (3.0-5.7 m/s) on sand up to approximately 400 m/s². The differences between the acceleration values recorded in the present study and values measured in earlier investigations could be explained by differences in the used acceleration sensors, sensor mounting, horses gait and surface properties.

Comparing the values of the hoof- and fetlock-mounted sensor, the fetlock-acceleration (rFETLOCK) showed lower acceleration values than the resultant vector of the hoof-mounted sensor (rHOOF). This outcome was expected, because the fetlock-mounted sensor was fixed on the skin, which was able to attenuate high acceleration amplitudes during hoof landing by skin displacement. Additionally the anatomy of the hoof and the interphalangeal joints (Gustås et al., 2001) as well as the metacarpophalangeal joint buffered the acceleration during the hoof’s landing phase to prevent damage caused by high impact of force.

**Conclusion**

The present study illustrates that both sensor applications as well as both axes and the resultant vector are suitable for the assessment of the sport-functional properties of riding surfaces. Concerning the riding surfaces it must be noted that the grass outdoor arena showed the highest degree of hardness, while the sand-sawdust indoor arena was the softest surface. A final evaluation whether a riding surface is too hard or too soft could not be done. This questioning could be the subject of further investigations.

**References**


Chapter Three

Application of wavelet filtering to analyse acceleration-time curves of horses trotted on different surfaces

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Abstract

The objective of the present study was to illustrate the possibilities of wavelet filtering to denoise hoof-acceleration data measured on different surfaces. Further, three variables from the time-domain acceleration signal and two variables from the single-sided amplitude spectrum of the Fourier-transformed signal were statistically analysed to detect differences between the riding surfaces as well as to compare the results of the different variables. For data recording, six warmblood horses were trotted on five different riding surfaces. The recorded acceleration data were smoothed by wavelet filtering on three levels by using the Haar-wavelet as well as the fourth-order Daubechies-wavelet. The hoof’s landing phase was extracted from the acceleration signal by a special algorithm and analysed due to its significance with regard to a horse’s injury risk. More correct hoof’s landing phases could be detected by the algorithm in the first and second approximations of both wavelet-filtered signals than in the original signal. The dissected hoof’s landing phases were used to calculate the variables mentioned above. The statistical analysis showed similar results within the variables of the time-domain signal and within the variables of the single-sided amplitude spectrum. The least square means of the original signal and the first and second approximation of both wavelet-filtered signals were on a similar level. In conclusion, it was shown that wavelet filtering is a suitable method to denoise acceleration-time curves. Further, the results of the five variables showed that the insertion of time- and frequency-domain variables was significant in the analysis of the acceleration data.

Keywords

horse, hoof, acceleration, riding surface, wavelet filtering
Introduction

The determination of the stress on a horse’s limb has been investigated in several studies since diseases of the locomotor apparatus are a major cause of the culling and attrition of sport horses (Clausen et al., 1990). Several investigations have shown that acceleration measurement is a suitable method to find differences in the stress on the horse’s limb caused by various shoeing (Benoit et al., 1993; Dallap Schaer et al., 2006) or different surfaces (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006; Chateau et al., 2009; Setterbo et al., 2009). Measurement data, such as acceleration-time curves, often include noise which influences the results. Therefore, data processing is important for the interpretation of the recorded data. In previous studies which have dealt with the analysis of a horse’s gait by acceleration measurement, Butterworth filters have been used for data denoising (Gustås et al., 2006; Chateau et al., 2009; Setterbo et al., 2009). These filters have not always yielded satisfactory results (Ismail and Asfour, 1999). Wavelet filtering is an alternative method to smooth data (Wolkenstein et al., 1997). Previous investigations by Ismail and Asfour (1999) have shown the superiority of wavelet filtering in human kinematic data compared to Butterworth digital filtering.

Wavelet filtering is based on the ‘wavelet transform’, which transfers the original time-domain signal into the time-frequency domain (Lu et al., 2003). Therefore, the wavelet transform is similar to the ‘Short-Time-Fourier-Transform’. In Short-Time-Fourier-Transform a rigid analysis window is passed along the time axis of the signal and brings the signal out as a linear combination of sine and cosine function. This method is popular in the analysis of non-stationary signals, but it does not work well for signals with high- and low-frequency components (Dai et al., 1994). The wavelet transform displaces the wavelet and the scaling function along the time axis of the signal and scales these functions for the best fit to the signal at that specific time. Consequently, a better adaptation to complicated non-periodic signal-structures, such as abrupt changes or trends can be efficiently captured by the wavelet transform (Wolkenstein et al., 1997; Gençay et al., 2002). Therefore, low-frequency signals as well as high-frequency signals can be illustrated at high resolution (Chui, 1992; Daubechies, 1992; Chau, 2001; Gençay et al., 2002; Kiencke et al., 2008).

The present investigation deals with acceleration data, measured on a horse’s hoof while trotting on different surfaces. The study presents the use of the wavelet transform in denoising acceleration data of horses. Furthermore, five variables used to analyse acceleration-time curves were investigated. Three variables were calculated from the time-domain signal and
two variables were calculated from the frequency domain of the acceleration signal. The aim of the present study was to analyse the influence of wavelet filtering and the use of various time- and frequency-domain variables on the results of hoof-acceleration measurement on different surfaces.

Materials and Methods

Horses and ground surfaces

Data recording took place on the equestrian centre of the Holsteiner Verband in Elmshorn (Germany). Six warmblood horses (Holsteiner) between the ages of five and six years were used. All the horses were geldings and each had a stick measure of between 165 cm and 177 cm and a body mass of between 542 kg and 603 kg. The horses were shod with standard steel shoes. Further, five different riding surfaces were investigated: two outdoor arenas; one with a grass surface (grass outdoor) and one with a sand surface (sand outdoor) as well as three indoor arenas; one with a sand-synthetic fibre surface used for lunging (sand-synthetic indoor I), one with a sand-synthetic fibre surface used for jumping (sand-synthetic indoor II) and the other one with a sand-sawdust surface used for dressage (sand-sawdust indoor). All the riding surfaces were in a good condition and regularly maintained.

Device description and data recording

A motion analysis system (Noraxon U.S.A. Inc., Scottsdale, AZ, USA) was used for data recording. The system included two biaxial acceleration sensors with a weight of 2.8 g, a range of +/- 98.1 m/s² and a sensitivity of 981 mV/m/s². Additionally, a measurement station (MyoTrace 400) as well as a special software (MyoResearch) were contained in the system. One sensor was mounted on the lateral hoof wall on the horses’ left forelimb (Fig. 1).

Figure 1: Sensor application and alignment of the sensor axis on the horse's hoof
The sensor was fixed to the hoof wall with double-sided adhesive tape and fabric tape. This study analysed the y-axis of the sensor, which was aligned to the ground and parallel to the lateral hoof wall (Fig. 1). The sensor was connected to the measurement station via a cable. The measurement station was fixed on a surcingle, which was worn by the horse. The data were transferred to a notebook in real time via Bluetooth. The notebook was used to start and stop data recording as well as for measurement control. Data recording was performed at 1004.03 Hz. The acceleration values were stated in multiples of gravity ($1\,g = 9.81\,\text{m/s}^2$). Further, the sensor system included a 500 Hz anti-aliasing filter. Data acquisition was performed while each horse was trotted by hand on all five riding surfaces. First, the horses were adapted to the measurement system. Then data recording was started as soon as the horses trotted in a regular cadence in a defined circle with a diameter of 16 meters. The data were recorded for 65 seconds, which corresponded to approximately 75 strides. To reduce the influence of the sensor application on the acceleration data, all five surfaces were tested with one horse before the sensor was attached to the next horse. The mean speed of each horse on each surface was calculated from video data, which were filmed while collecting the data. The time, needed by the horse for trotting three circles, was stopped and the mean speed was calculated by the formula: $\text{mean speed} = \frac{3d\pi}{t_S}$, in which $d$ is the diameter of the circle in meters and $t_S$ is the time in seconds, which was needed by the horse for trotting three circles.

Data processing and statistical analysis

Data processing took place in three stages. In the first stage, wavelet filtering was used to denoise the acceleration-time curve. In the second stage, the hoof’s landing phase was dissected. This procedure was carried out to improve comparability and due to the importance of the hoof’s landing phase for the stress on the horse’s limb. In the third stage, five variables were calculated from the original signal as well as from the wavelet-filtered (denoised) acceleration signal of the hoof’s landing phase. The calculated variables were used for statistical analysis.
Data denoising

To denoise the acceleration signal, wavelet filtering, based on the wavelet transform, was used. The following section gives a short overview on the wavelet transform; more information can be found in the cited literature. The wavelet transform is based on a function $\psi$ with average value zero, which becomes zero out of a finite time domain (Kruse et al., 2011). This function is called the mother wavelet (Chui, 1992; Daubechies, 1992; Wolkenstein et al., 1997; Gençay et al., 2002; Kiencke et al., 2008). Various mother wavelets with different properties have been generated so far (Liò, 2003). In addition to the mother wavelet $\psi$, a scaling function $\phi$ is needed for the wavelet transform. Figure 2 shows the Haar-wavelet and its scaling function.

![Haar-wavelet and its scaling function](image)

**Figure 2**: Haar-wavelet and its scaling function

For time-discrete signals, such as the acceleration-time curves in the current study, a discrete wavelet transform (DWT) could be used. The DWT describes the original signal by a linear combination of the scaled (a) and time-displaced (b) mother-wavelet $\psi_{a,b}$ and scaling function $\phi_{a,b}$. In the study, the original signal was decomposed in a low-pass-filtered signal, which were given by the linear combination of the scaling function $\phi_{a,b}$ and a high-pass-filtered signal given by the linear combination of the wavelet function $\psi_{a,b}$. The low-pass-filtered signal includes the low-frequency components of the original signal and is called the approximation ($A_1$) (Fig. 3). The details ($D_1$) included the high-frequency components of the original signal and were high-pass-filtered (Fig. 3) (Chau, 2001). Further, the resulting approximation signal ($A_1$) could be decomposed by DWT on the second level. In doing so, a second approximation signal ($A_2$) and a second detail signal ($D_2$) resulted. This procedure can be repeated on n-levels (Fig. 3).
A DWT up to the third level was performed to filter the acceleration data using the Haar-wavelet as well as the fourth-order Daubechies-wavelet (Db4) (Fig. 4). These two wavelets were also chosen by several studies in the literature (Wachowiak et al., 1997; Ismail and Asfour, 1999; Gençay et al., 2002). Due to the fact that the details were associated with noise, the approximation signal mostly contained the important part of the original signal (Kara and Dirgenali, 2007). Therefore, in the present study the approximation signal of the wavelet-transformed data was considered.

**Figure 3:** The system of wavelet decomposition

**Figure 4:** The original acceleration-time curve and its third level Haar-wavelet-filtered approximation during a hoof’s landing phase given as an example
Dissection of the hoof’s landing phase

In order to improve comparability and due to the importance of the hoof’s landing phase for the stress on the horse’s limb the acceleration-time curves of all horses and all riding surfaces were cut in single hoof’s landing phases by using an algorithm written in MATLAB (MATLAB, version R2010a, The MathWorks Inc., Natrick, MA, USA).

The algorithm detected the stance phase of the hoof, where the acceleration values were near zero for more than 60 ms. Based on the detected stance phases, the acceleration-time curves were cut into single strides. Then the single strides were dissected in the take-off phase and the hoof’s landing phase. The hoof’s landing phase began with the second half of the swing phase and ended with the end of the hoof’s breaking phase (Fig. 5). In order to verify that the algorithm worked correctly, all dissected hoof’s landing phases were controlled by hand.

![Figure 5](image_url)

**Figure 5:** Part of the original acceleration-time curve of horse 5 on the sand outdoor arena given as an example; HT = hoof’s take off phase; HL = hoof’s landing phase; SP = stance phase of the hoof

The original acceleration data as well as the Haar- and Db4-wavelet-filtered signals on three approximation levels were dissected with the algorithm mentioned. This approach was chosen to verify how the filtering influenced the findings of the hoof’s landing phases, i.e. whether a larger number of correct strides could be found by the approximation signals (denoised) compared with the number of strides found in the ‘noisy’ original signal.
Calculation of various variables and statistical analysis

Five variables of the original signal of the hoof’s landing phases as well as the Haar- and Db4-wavelet-filtered signals up to three levels were statistically analysed. To assure comparability of the statistical results obtained from the original signal and the wavelet-filtered signals, the hoof’s landing phases for all data sets were detected from the first level approximation of the Db4-wavelet-filtered signal. The three time-domain variables as well as the two frequency-domain variables, which were calculated for statistical analysis, are described in the following:

\[ RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2}, \] in which \( x_i \) is the \( i \)-th observation of the acceleration signal and \( n \) is the total number of observations. The root mean square value (RMS) relates to the power content of vibrations during the hoof’s landing phase (Barrey et al., 1991). Equally, Barrey et al. (1999) used the RMS to analyse acceleration data.

\[ MEAN = \frac{1}{n} \sum_{i=1}^{n} |x_i|, \] in which \( x_i \) is the \( i \)-th observation of the acceleration signal and \( n \) is the total number of observations. The variable MEAN is the mean deviation from zero of the considered acceleration signal.

\[ MAX = \text{absolute value of the maximum negative acceleration value in the considered signal; this value was associated with the strength of the deceleration during the hoof’s landing phase.} \]

Further, two variables were obtained from the single-sided amplitude spectrum of the Fourier-transformed signal. The Fourier transform transferred the time-domain acceleration signal into a frequency-domain signal by emitting the signal as a linear combination of sine and cosine function. In doing so, the acceleration data were analysed in the time domain and in the frequency domain. This approach was chosen because of the importance of time-located variables as well as the importance of the acquisition of frequency variations for the stress on the horse’s limb. The Fourier transform was done by the Fast Fourier Transform in MATLAB.

\[ FREQ = \text{is the frequency at which the half strength of the single-sided amplitude spectrum is attained.} \]

\[ QUOT = \sum_{i=1}^{25} y_i \sum_{i=1}^{m} y_i, \] in which \( y_i \) is the amplitude of the \( i \)-th frequency of the single-sided amplitude spectrum and \( m \) is the highest frequency in the single-sided amplitude spectrum.
The variable QUOT indicates the relationship between the low-frequency components and the high-frequency components in the considered signal.

The statistical analysis of the various variables of the original signal and the wavelet-filtered acceleration signals were carried out using a mixed model (SAS, version 9.2, SAS Institute Inc., Cary, NC, USA), which included the riding surface, the wavelet filtering and the interaction between riding surface and wavelet filtering as fixed effects and horse, as well as the interaction between horse and riding surface as a random effect. The least square means were tested for significant differences with multiple comparisons of mean and a Tukey-Kramer adjustment. The significance level was chosen as $p < 0.05$. Furthermore, the Pearson correlation coefficients between the residuals of the various variables were calculated with SAS.

**Results**

In the original signal, a total of 2 200 strides were found by the algorithm which detected the stance phases of the hoof. For the first level approximation signal, 2 211 strides were found in the Haar-wavelet-filtered signal and 2 214 in the Db4-wavelet-filtered signal. On the second and third level approximation signal, 2 200 and 2 142 strides could be detected in Haar-wavelet-filtered signal as well as 2 214 and 2 212 strides in the Db4-wavelet-filtered signal. Therefore, the largest number of correct strides was found in the first and second approximation of the Db4-wavelet-filtered signal. For the third approximation level of both wavelets, the number of detected strides became smaller than the number of strides found in the first and second approximation.

The statistical analysis revealed that the fixed effects riding surface, wavelet filtering and the interaction between riding surface and wavelet filtering were significant for all calculated variables. The least square means and the standard errors of the various variables of the original acceleration signal are presented in Table 1. The order of the least square means of the different riding surface was the same for the variables RMS, MAX, FREQ and QUOT. For the variable MEAN, the positions of the surfaces sand-synthetic indoor I and the sand-synthetic indoor II changed, but these surfaces were not significantly different. Concerning the variables RMS, MEAN, MAX and FREQ the riding surfaces grass outdoor and sand outdoor showed larger least square means than the indoor arenas. Considering the variable FREQ, which refers to the single-sided amplitude spectrum, the larger means were associated with higher frequencies in the acceleration signal. The variable QUOT was based on the
single-sided amplitude spectrum and showed lower least square means for the grass outdoor and the sand outdoor arena compared to the indoor arenas. Lower means for the variable QUOT were related to a greater share of high frequencies in the acceleration signal. The significant differences between the various surfaces differed from variable to variable.

**Table 1:** Mean speed of the horses (in m/s) as well as the least square means of the various variables (RMS, MEAN, MAX in g; FREQ, QUOT without a unit) of the original acceleration signal during hoof’s landing phase on the five riding surfaces

<table>
<thead>
<tr>
<th>Riding Surface</th>
<th>Mean speed (S.D.)</th>
<th>RMS (S.E.)</th>
<th>MEAN (S.E.)</th>
<th>MAX (S.E.)</th>
<th>FREQ (S.E.)</th>
<th>QUOT (S.E.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass outdoor</td>
<td>3.33 (0.13)</td>
<td>1.63 \textsuperscript{a} (0.12)</td>
<td>0.93 \textsuperscript{c} (0.07)</td>
<td>7.88 \textsuperscript{a} (0.59)</td>
<td>33.31 \textsuperscript{a} (0.80)</td>
<td>0.69 \textsuperscript{a} (0.06)</td>
</tr>
<tr>
<td>Sand outdoor</td>
<td>2.99 (0.19)</td>
<td>1.57 \textsuperscript{a,b} (0.12)</td>
<td>0.91 \textsuperscript{a} (0.07)</td>
<td>7.27 \textsuperscript{a,b} (0.59)</td>
<td>31.87 \textsuperscript{a,b} (0.80)</td>
<td>0.74 \textsuperscript{a,b} (0.06)</td>
</tr>
<tr>
<td>Sand-synthetic indoor I</td>
<td>3.43 (0.22)</td>
<td>1.45 \textsuperscript{b,c} (0.12)</td>
<td>0.86 \textsuperscript{a,b} (0.07)</td>
<td>6.55 \textsuperscript{b,c} (0.59)</td>
<td>30.22 \textsuperscript{b,c} (0.80)</td>
<td>0.87 \textsuperscript{a,b} (0.06)</td>
</tr>
<tr>
<td>Sand-synthetic indoor II</td>
<td>3.18 (0.32)</td>
<td>1.44 \textsuperscript{b,c} (0.12)</td>
<td>0.87 \textsuperscript{a,b} (0.07)</td>
<td>6.48 \textsuperscript{b,c} (0.59)</td>
<td>29.07 \textsuperscript{c} (0.80)</td>
<td>0.91 \textsuperscript{b} (0.06)</td>
</tr>
<tr>
<td>Sand-sawdust indoor</td>
<td>3.37 (0.27)</td>
<td>1.32 \textsuperscript{c} (0.12)</td>
<td>0.83 \textsuperscript{b} (0.07)</td>
<td>5.47 \textsuperscript{c} (0.59)</td>
<td>25.13 \textsuperscript{d} (0.80)</td>
<td>1.21 \textsuperscript{c} (0.06)</td>
</tr>
</tbody>
</table>

\textsuperscript{a,b,c} Different superscript letters within a column indicate significant differences (p < 0.05)

The correlation coefficients of the various variables are illustrated in Table 2. Medium and high correlation coefficients were estimated between variables, which were based on the time-domain signal (RMS, MEAN, MAX). Equally, the variables of the single-sided amplitude spectrum (FREQ, QUOT) were highly correlated, but in a negative direction. The correlations between the variables based on the time-domain signal (RMS, MEAN, MAX) and the variables of the single-sided amplitude spectrum (FREQ, QUOT) were only at a medium and low level.

**Table 2:** Pearson correlation coefficients of the various variables of the original acceleration signal

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>MAX</th>
<th>FREQ</th>
<th>QUOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>0.91</td>
<td>0.81</td>
<td>0.32</td>
<td>-0.33</td>
</tr>
<tr>
<td>MEAN</td>
<td>0.59</td>
<td>0.14</td>
<td>-0.16</td>
<td>-0.47</td>
</tr>
<tr>
<td>MAX</td>
<td>0.49</td>
<td>0.47</td>
<td>-0.47</td>
<td>-0.86</td>
</tr>
<tr>
<td>FREQ</td>
<td></td>
<td></td>
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</tbody>
</table>
Figure 6 presents the least square means of the RMS values of the original acceleration signal (Original) and the wavelet-filtered signals during the hoof’s landing phase on the five riding surfaces. The results of the variables RMS, MEAN, MAX, FREQ and QUOT of the wavelet-filtered signals are similar to the presented results of the original signal, therefore only the variable RMS of the wavelet-filtered signals is illustrated (Fig. 6). Concerning the calculated least square means of the RMS the original signal, HaarA1 and Db4A1 did not differ significantly. Equally, the values of HaarA1 and Db4A2 showed no significant differences. In contrast, the calculated least square means of HaarA2 and the third approximations of both wavelets (HaarA3, Db4A3) differed significantly from each other and from the other filtering stages (Fig. 6).

![Figure 6](image)

**Figure 6**: Least square means of the RMS values of the original acceleration signal and the filtered signals during the hoof’s landing phase on the five riding surfaces

For the original signal as well as the first and second approximation of the Haar-wavelet (HaarA1, HaarA2) and the Db4-wavelet-filtered signal (Db4A1, Db4A2), the grass outdoor arena differed significantly from the three indoor arenas. Equally, the sand outdoor arena was significantly different from the sand-synthetic II and sand-sawdust indoor arena. On the third approximation level of the Haar-wavelet-filtered signal (HaarA3) as well as the Db4-wavelet-
filtered signal (Db4A3) the grass outdoor arena differed significantly from the sand-sawdust indoor arena.

Discussion

The present study was designed to describe data denoising by wavelet filtering and the use of several variables to analyse hoof-acceleration data on different riding surfaces. Acceleration measurement is a relevant method to evaluate stress on the horse’s limb (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006; Chateau et al., 2009; Setterbo et al., 2009). Due to the fact that the sensor system and the sensor application often induce noise in the recorded data, data processing is an important part for analysing acceleration data. It should be noted that the measurement system used in the present study had a relatively small range compared to accelerometers used in earlier investigations (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006; Chateau et al., 2009; Setterbo et al., 2009). Nevertheless, the results of the statistical analysis of the variable MAX demonstrated that the range was sufficient to measure hoof-acceleration data during trotting on various riding surfaces. Additionally, the sampling rate of the acceleration measurement system was relatively low, compared to previous studies (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006; Chateau et al., 2009). Burn et al. (1997) demonstrated that when trotting on concrete, more than 98.2% of the signal energy was below 625 Hz and over 99% of the energy was below 1 250 Hz. In consequence, they concluded that a sampling rate of 2 500 Hz minimum was needed. Nevertheless, on the riding surfaces investigated in the current study, lower frequencies could be expected than on a concrete runway. Therefore, a sampling rate of 1 000 Hz seemed to be sufficient for data recording and was used by Setterbo et al. (2009) and Witte et al. (2004, 2006). An advantage of the measurement system used was the possibility to record a large number of acceleration data. This was important since previous studies had shown a high within horse variability as well as a high between horse variability (Chateau et al., 2009). In the present study, six horses were used and a comparatively large number of strides on the different riding surfaces could be recorded, which was important to obtain robust statistical results. Further, it is to mention that an oscillation of the sensor could not be completely excluded because of the way the sensor was fixed. To minimize the error induced by the sensor fixation, the fixation on the horse’s hoof was not changed during testing all five riding surfaces. The results and the
 repeatability of preliminary tests showed the suitability of the used sensor fixation. Further, the data presented in the current study illustrated the accelerations in y-direction of the sensor, which was aligned to the ground. Therefore, mainly the hardness of the surfaces was demonstrated, while the shearing strength was not recorded. For the fact that the sensor was not completely vertically to the ground, a small percentage of the vertical acceleration was lost.

With regard to the selected wavelets, Ganesan et al. (2004) and Walker (2008) illustrated that the Db4 had a better adaptation on smoothly varying signals, while the Haar-wavelet was more suitable for signals with discontinuous jumps. Therefore, the inclusion of the Haar-wavelet and the Db4-wavelet seemed to be interesting, in order to demonstrate the influence of the wavelet selection on the results. The outcome of the present study did not really illustrate a better adaptation of the Haar-wavelet or the Db4-wavelet. Both wavelets showed a high adaptation to the acceleration data, which is illustrated by the similar results of the statistical analyses. But nevertheless it must be noted that the Haar-wavelet-filtered signal showed larger differences from the original signal than the Db4-filtered signal. These were shown by the smaller number of correctly found strides in the Haar-wavelet-filtered signal compared with the number of correct strides found in the Db4-filtered signal and in the results of the statistical analyses, illustrated in Figure 6. In addition to the selection of the wavelet, the selection of the filtering level was important. Therefore, the algorithm which detected the hoof’s landing phase was tested on the original acceleration signal and the wavelet-filtered signals on three levels. The differences in the number of strides found in the first and second approximation signal of both wavelet filters were only small, but a larger number of detected strides could be found compared to the original signal and the third level approximation signal. This outcome showed a better adaptation of the first and second approximation to the algorithm than the original signal. In contrary to the first and second approximation, the third approximation showed a deterioration in finding the hoof’s landing phases. This result suggested that the third level of approximation led to an over-filtered signal. Also the calculated least square means of the statistical analyses illustrated a larger deviation in the third approximation compared to the other filtering stages. Further, the number of significant differences decreased with this higher approximation level, so that only one significant difference on the third approximation level ($A_3$) for both wavelets (Haar, Db4) could be found. These results indicate an over-smoothing of the acceleration signal on higher approximation levels.
Concerning the various variables of the hoof’s landing phase, the correlation coefficients show a higher relationship within the variables of the time-domain signal (RMS, MEAN, MAX) as well as between the variables of the single-sided amplitude spectrum (FREQ, QUOT). This outcome showed the relevance of analysing acceleration signals in both the time and frequency domains. The variables based on the time-domain signal (RMS, MEAN, MAX) demonstrated the hardness of the riding surfaces. The grass outdoor showed larger acceleration values compared to sand-sawdust indoor. Larger acceleration values were associated with harder surfaces and an increase in load on the horses’ limbs (Williams et al., 2001). The variables FREQ and QUOT illustrated differences in frequency spectrum of the acceleration signals on the five riding surfaces. FREQ and QUOT were negatively correlated, this could be explained by the fact that the variable FREQ increased in the presence of higher frequencies, while the variable QUOT is a quotient and decreased in the presence of higher frequencies. The results show higher frequencies on harder surfaces, such as grass outdoor, compared to softer surfaces, such as sand-sawdust indoor. High frequency vibrations are associated with diseases of locomotor systems in humans (Radin et al., 1972) and horses (Rooney, 1974). Due to the high correlation coefficients, it seems to be less important which of the variables mentioned in the time domain and the frequency domain was considered. But nevertheless it must be noted that the time-domain variable MAX, which was inter alia used by Benoit et al. (1993) and Setterbo et al. (2009), implies only one acceleration value during the hoof’s landing phase. This value was influenced amongst others by the sampling rate of data recording. In contrast, the RMS and the MEAN included all acceleration values during the hoof’s landing phase. Further, the squaring of the acceleration values, which was performed by calculating the RMS, resulted in an increase of distances between the values. Large acceleration values obtained a greater emphasis than small values. Therefore, it was possible to explain the higher number of significant differences for the RMS values of the various riding surfaces compared to the variable MEAN.

**Conclusion**

The present study has shown that wavelet filtering as well as the use of several variables seem to be suitable methods to filter and analyse acceleration-time curves. Nevertheless, the selection of the wavelet basis, the wavelet filtering level and the considered variables must be chosen by the scientist and are dependent on the respective data. In the present study, the wavelets selected showed a lesser effect on the results than the approximation levels. Further,
it can be concluded from the results that the acceleration signals recorded included only a small percentage of noise, so that wavelet filtering on higher levels induced over-filtering. Concerning the riding surfaces it must be noted that the used acceleration measurement device and the mentioned data analysis are a useful method to evaluate the sport-functional properties of surfaces objectively. These were important to maximise the performance and to reduce the risk of injury of the horses. In the present study, both outdoor arenas showed a greater hardness than the sand-sawdust indoor arena. Harder surfaces were associated with a higher stress on the horse’s limb. But nevertheless, too soft surfaces can lead to a quicker fatigue and therefore equally to a higher risk of injury. A final evaluation whether a riding surface is too hard or too soft was not carried out.

Role of the founding source

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References


Chapter Four

The use of a technical device for testing the sport-functional properties of riding surfaces

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Abstract

The riding surface is an important and modifiable factor in the development injuries in sport horses. An objective and simple examination of the sport-functional properties of riding surfaces, such as shock absorption and energy restitution, is thus desirable. The aim of the present study was to evaluate the use of a handy device to test the sport-functional properties of riding surfaces. Therefore, a technical device, called Artificial Athlete, was used on five riding surfaces, two sand-synthetic indoor arenas, one sand-sawdust indoor arena and two outdoor arenas, one with a sand footing layer and one grass surface. The shock absorption, the energy restitution as well as the vertical deformation were acquired by the Artificial Athlete. Additionally, the hoof-acceleration of six warmblood horses trotting by hand on the five investigated riding surfaces was recorded. The parameters of the Artificial Athlete and the acceleration data during hoof landing were compared. The outcome of the statistical analysis illustrated that the shock absorbing parameter was not in agreement with the results of the acceleration data during hoof landing. Whereas the results of the vertical deformation parameter, measured by the Artificial Athlete, were mostly in accordance with the results of the hoof-acceleration measurement. In conclusion the use of the Artificial Athlete for testing the sport-functional properties of riding surfaces was assessed as critical, because of the large deviations between the results of the shock absorption measured by the Artificial Athlete and the hoof-acceleration data. However, it could be shown that the vertical deformation parameter, measured by the Artificial Athlete, could be helpful in the assessment of the sport-functional quality of a riding surface.

Keywords

horse, riding surface, sport-functional properties, hoof-acceleration, Artificial Athlete
**Introduction**

Earlier studies on racehorses have shown, that injuries are multi-factorial event (Robinson et al., 1988). The track surface is one issue in this multi-factorial event, which is an important and modifiable factor. In the traditional riding disciplines such as dressage and jumping, injuries and in particular diseases of the locomotor apparatus are a major cause of the culling and attrition of sport horses (Clausen et al., 1990). Further, there is a multitude of riding surface types. For example sand, sawdust and synthetic fibre are used as footing layers in riding arenas. Therefore, differences in the sport-functional properties of riding surfaces can be expected. Some previous studies have shown the possibility to illustrate the influence of the surface on the stress on the horse’s limbs by acceleration measurements on the horse’s hooves (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustás et al., 2006; Chateau et al., 2009; Setterbo et al., 2009; Kruse et al., in press). But a high variability between horses as well as a high variability within horses have been found in acceleration data (Chateau et al., 2009). Therefore, several horses as well as a greater number of recorded strides must be investigated, to obtain robust statistical results. Thus, the acquisition of differences in the sport-functional properties of riding surfaces with an objective technical device would be easier and more favorable. In human sports, such as football, a simple technical device, called Artificial Athlete, and field test requirements are recommended (FIFA, 2009a, b). Therefore, it is possible to evaluate objectively the sport-functional quality of human sports arenas. In equestrian sports, a few technical devices for racetrack testing have been developed (Cheney et al., 1973; Pratt, 1985; Zebarth and Sheard, 1985; Clanton et al., 1991; Drevemo and Hjerten, 1991; Ratzlaff et al., 1997; Oikawa et al., 2000; Peterson et al., 2008), but they have not been successfully established in practice. The disadvantages of these surface-testing systems are that often a motor vehicle is needed to deploy such devices (Oikawa et al., 2000; Peterson et al., 2008) or the devices reproduce the impact power inadequately during hoof landing (Barrey et al., 1991; Peterson et al., 2008; Thomason and Peterson, 2008). Further, in the studies mentioned only racetracks were tested with technical devices. Therefore, the development of a handier testing device for riding surfaces with footing for dressage and jumping horses will be useful.

In the present study, five different riding surfaces were tested by the Artificial Athlete and by acceleration measurement on the horse’s hoof. At impact of the Artificial Athlete on a concrete surface, 6600 N were loaded; this force corresponds to the data of a trotting horse supplied by Dohne (1991). The aim of the investigation was to compare the results of the
Artificial Athlete with the results of the hoof-acceleration to evaluate the use of this technical device to testing the sport-functional properties of riding surfaces.

**Material and Methods**

**Riding surfaces**

The data recording was carried out at the equestrian centre of the Holsteiner Verband in Elmshorn (Germany). Five riding surfaces, two outdoor arenas and three indoor arenas were tested by the Artificial Athlete and hoof-acceleration measurement. One outdoor arena had a grass surface (grass) the other one a sand surface (sand). Two indoor arenas had a sand-synthetic fibre footing layer, one used for lunging (sand-synthetic I) and the other one used for jumping (sand-synthetic II). Further one indoor arena was used for dressage and had a sand-sawdust footing layer (sand-sawdust) (Tab. 1). For the surface testing a circle with a diameter of 16 m was defined on each surface. A disturbed sample of the footing layer was taken from each investigated riding surface at a randomly chosen location on the defined circle. The sample contained at least 341 g and was taken immediately after surface testing by the Artificial Athlete and the measurement of hoof-acceleration. Each sample was weighed before and after drying in a drying cabinet with a temperature of 105°C for 24 hours. To obtain the organic substance a minimum of 45 g of each sample was taken and burnt out in a muffle furnace with a temperature of 550°C over three hours. Afterwards the sample was weighed again. The particle size distribution as well as the content of synthetic substance of the five riding surfaces were obtained by dry and wet sieving (Fig. 1). Therefore, 201 g of the dried sample was sieved in accordance with the relevant standard (DIN, 2011). The determinations of the water content, the organic substance and the synthetic substance were calculated by the following expressions:

\[
\text{water content} = \frac{(m_1 - m_2)}{m_1} \times 100, \\
\text{organic substance} = \frac{(m_2 - m_3)}{m_2} \times 100, \\
\text{synthetic substance} = \frac{m_4}{m_2} \times 100,
\]

where

\(m_1\) is the mass [kg] of the sample before drying,

\(m_2\) is the mass [kg] of the sample after drying for 24 h in a drying cabinet with a temperature of 105°C,
\( m_3 \) is the mass [kg] of the sample after three hours of burn out in a muffle furnace with a temperature of 550°C,

\( m_4 \) is the mass [kg] of the synthetic substance in the sample, which were filtered out by sieving.

Table 1 and Figure 1 present the five investigated riding surfaces and the results of the surface composition analysis.

**Table 1**: Description and composition of the riding surfaces

<table>
<thead>
<tr>
<th>Riding surface</th>
<th>Type of riding arena</th>
<th>Water content [%]</th>
<th>Organic substance [%]</th>
<th>Synthetic substance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>outdoor riding</td>
<td>27.82</td>
<td>23.56</td>
<td>0.00</td>
</tr>
<tr>
<td>Sand</td>
<td>outdoor riding</td>
<td>20.56</td>
<td>1.43</td>
<td>0.00</td>
</tr>
<tr>
<td>Sand-synthetic I</td>
<td>indoor lunging</td>
<td>10.91</td>
<td>2.36</td>
<td>1.33</td>
</tr>
<tr>
<td>Sand-synthetic II</td>
<td>indoor jumping</td>
<td>6.33</td>
<td>3.80</td>
<td>2.97</td>
</tr>
<tr>
<td>Sand-sawdust</td>
<td>indoor dressage</td>
<td>17.16</td>
<td>8.56</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Figure 1**: Particle size distribution of the five riding surfaces
**Technical device - Artificial Athlete**

The Artificial Athlete (Fig. 2) consists of a guided falling weight (1, 3), with a mass of 20 kg (± 0.1 kg), which dropped from a height of 55 mm (± 0.25 mm) vertically to a testing foot (DIN, 2005a). The testing foot had a circular steel base plate (8) with a diameter of 70.0 mm (± 0.1 mm) and included a spiral spring (5) and a hardened upper plate (4) (DIN, 2005a). The spiral spring, which damped the impact of the falling weight, is over a range of 0.1 kN to 7.5 kN linear with a spring rate of 2 000 ± 60 N/mm (DIN, 2005a). A force-sensing device (7) was built into the steel based plate (DIN, 2005a). The sampling rate of the force data was 1 219.5 Hz.

![Diagram of Artificial Athlete](image)

**Figure 2: Artificial Athlete (based on DIN (2005a))**

The Artificial Athlete was designed to simulate the impact of a human athlete on the ground. Three parameters, shock absorption (SA), energy restitution (ER) and vertical deformation (VD) could be calculated by the measurement values. The determination of shock absorption (SA) was a measurement method based on DIN (2005a). The shock absorption (SA) was calculated from the following formula:

\[ SA = (1 - F_t/F_r) \times 100 \]

where \( SA \) is the shock absorption in percentage [%], \( F_t \) is the measured maximum peak force of the testing surface, expressed in Newton [N]. \( F_r \) is the reference force and comprises 6.6 kN (± 0.25 kN) for a calibrated measurement device, which corresponds to the maximum peak force [N] for a rigid, non-vibrating, smooth and even concrete floor (DIN, 2005a). Five testing spots on each riding surface were investigated. Each testing spot was randomly chosen on the circle where the acceleration measurement with the horses was performed. Three impacts of the falling weight were measured for each testing
spot. Due to the three successive impacts at each testing spot, the compression of the surface, which was created by the impact of the falling weight, could be illustrated. The $SA$-values of the first ($SA_1$), second ($SA_2$) and third ($SA_3$) impacts were statistical analysed. Additional, in conformity with the relevant standard (DIN, 2005a), the $SA_S$-value for a single testing spot was calculated as the mean of the shock absorption results of the second and third impacts. In accordance with Heinrich et al. (2011), the energy restitution ($ER$) and the vertical deformation ($VD$) were calculated from the data of the shock absorption measurements. Therefore, the acquisition of $VD$ was not in line with the relevant standard (DIN, 2005b). The $ER$ of the first ($ER_1$), second ($ER_2$) and third ($ER_3$) impacts were analysed. In addition, the $ER_S$-value of each testing spot, which was given by the mean of the second and third impacts, was investigated. The energy restitution ($ER$) could be calculated by the following expression (Heinrich et al., 2011):

$$ER = \frac{E_a}{E_b} * 100,$$

where

$ER$ is the energy restitution in percentages [%],

$E_a$ is the energy [J] after impact and was defined by:

$$E_a = 0.5 * m_{fw} * v_a^2,$$

where $m_{fw}$ is the mass of the falling weight (20 kg) and $v_a$ is the maximal take-off velocity [m/s]. The take-off velocity ($v_a$) was calculated by numerical integration of the acceleration data, which were calculated from the measured force values of the Artificial Athlete.

$E_b$ is the energy [J] before impact and was defined by:

$$E_b = 0.5 * m_{fw} * v_b^2,$$

where $m_{fw}$ is the mass of the falling weight (20 kg) and $v_b$ is the initial impact velocity [m/s]. The impact velocity ($v_b$) was calculated by the drop height of the guided falling weight (55 mm) and the gravity (9.81 m/s$^2$). The air resistance would be ignored by the calculation of $v_b$.

The vertical deformation ($VD$) was calculated from the following formula (Heinrich et al., 2011):

$$VD = -1 * (D_{fw} - D_s),$$

where
$VD$  is the vertical deformation [mm],

$D_{fw}$  is the displacement [mm] of the falling weight, which was calculated by numerical integration of the calculated acceleration values of the Artificial Athlete two times. The acceleration values were determined by the measured force values.

$D_s$  is the maximum deformation [mm] of the spring and could be calculated by

$$D_s = F_i / R,$$

where

$F_i$  is the impact force [N] measured by the Artificial Athlete,

$R$  is the spring rate of the spring (2 000 N/mm).

For each testing spot the vertical deformation was considered at the first ($VD_1$), second ($VD_2$) and third ($VD_3$) impacts. Further, the $VD_S$-value for each testing spot was determined by the $VD$-value measured at the first impact ($VD_1$) minus the $VD$-value measured at the third impact ($VD_3$) (Heinrich et al., 2011).

**Acceleration measurement**

Six Holsteiner warmblood horses were used for acceleration measurement. Table 2 shows the description of the horses and the mean trotting speed of each horse.

<table>
<thead>
<tr>
<th>Horse</th>
<th>Sex</th>
<th>Years</th>
<th>Stick measure [m]</th>
<th>Body mass [kg]</th>
<th>Shoeing</th>
<th>Mean speed ± S.D. [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horse 1</td>
<td>gelding</td>
<td>5</td>
<td>1.76</td>
<td>572</td>
<td>standard steel</td>
<td>3.41 ± 0.34</td>
</tr>
<tr>
<td>Horse 2</td>
<td>gelding</td>
<td>5</td>
<td>1.70</td>
<td>542</td>
<td>standard steel</td>
<td>3.17 ± 0.28</td>
</tr>
<tr>
<td>Horse 3</td>
<td>gelding</td>
<td>6</td>
<td>1.69</td>
<td>593</td>
<td>standard steel</td>
<td>3.32 ± 0.27</td>
</tr>
<tr>
<td>Horse 4</td>
<td>gelding</td>
<td>5</td>
<td>1.77</td>
<td>607</td>
<td>standard steel</td>
<td>3.32 ± 0.27</td>
</tr>
<tr>
<td>Horse 5</td>
<td>gelding</td>
<td>5</td>
<td>1.65</td>
<td>546</td>
<td>standard steel</td>
<td>3.11 ± 0.19</td>
</tr>
<tr>
<td>Horse 6</td>
<td>gelding</td>
<td>5</td>
<td>1.71</td>
<td>603</td>
<td>standard steel</td>
<td>2.21 ± 0.21</td>
</tr>
</tbody>
</table>

The horse’s speed was calculated by filming the horse during data collection and recording the time needed to trot three defined circles. The chest measurement and the body length of
each horse were measured to calculate the body mass of the horses by the formula given by Carroll and Huntington (1988):

\[
\text{body mass [kg]} = \text{chest measurement}^2 \text{[cm]} \times \text{body length [cm]} / 11900.
\]

The acceleration measurement is described in Kruse et al. (in press) and was performed using a measurement system manufactured by Noraxon (Noraxon U.S.A. Inc., Scottsdale, AZ, USA). The system include two biaxial acceleration sensors with a range of ±98.1 m/s², a sensitivity of 981 mV/m/s² and weight of 2.8 g. One sensor was fixed with double-sided adhesive tape and fabric tape on the lateral hoof wall of the left forelimb with the y-axis aligned to the ground and parallel to the lateral hoof wall (Fig. 3) and the other one was fixed laterally to the fetlock. In the current study the acceleration values of the y-axis of the hoof-mounted sensor were considered due to the fact that the y-axis was nearly vertically and the Artificial Athlete measured in a vertical direction.

![Figure 3: Sensor application and alignment of the sensor axis on the horse’s hoof](image)

The acceleration sensor was connected with a measurement station (MyoTrace 400), which was mounted on a surcingle, worn by the horse. The measurement station transferred the acceleration data in time to a notebook via Bluetooth. During data recording, the horses were trotted in hand on the defined circle with a diameter of 16 m. The data recording was started when the horses trotted in a regular cadence and ended after 65 seconds, which corresponded to approximately 75 strides. The sampling rate was 1 004.03 Hz. A 500 Hz anti-aliasing filter was included in the system. All riding surfaces were tested with one horse before the sensor was attached to the next horse. This approach was chosen to reduce the influence of the sensor application to data recording. Afterwards the acceleration-time curves of the y-axis
were cut in single hoof-strides by an algorithm computing in MATLAB (MATLAB, version R2010a, The MathWorks Inc., Natrick, MA, USA). The algorithm detected stance phases, where the hoof-acceleration becomes near zero for more than 60 ms. All in all between 430 and 444 strides were recorded on each surface. Because of the importance of the hoof’s landing phase for the development of limb injuries (Burn et al., 1997; Chateau et al., 2009; Johnston and Back, 2006), the acceleration data of this phase were analysed. To do this, the strides were dissected in the hoof’s landing phase and the hoof’s take-off phase, while the hoof’s landing phase began with the second half of the swing phase and ended with the end of the hoof breaking (Fig. 4).

![Figure 4: Part of the original acceleration-time curve and the dissected hoof’s landing phases as an example; HT = hoof’s take off phase; HL = hoof’s landing phase; SP = stance phase of the hoof](image)

The variables $MAX$ and $RMS$ of the acceleration signal were calculated for each hoof’s landing phase by the following expression:

$MAX$ = absolute value of the maximum negative acceleration value in the considered signal; this value was associated with the strength of the deceleration during the hoof’s landing phase.

$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2}$, in which $x_i$ is the $i$-th observation of the acceleration signal and $n$ is the total number of observations in the acceleration signal. The $RMS$-value integrates, in
contrast to extreme values, several acceleration values and was analysed in an earlier study by Barrey et al. (1991). Further, the \textit{RMS}-value relates to the power content of vibrations during the hoof’s breaking phase (Barrey et al., 1991). Vibrations are associated with damaging effects on the locomotor apparatus of sport horses (Rooney, 1974).

\textit{Statistics}

To illustrate the repeatability of the measurements by the Artificial Athlete, for each parameter (\textit{SA}, \textit{ER}, \textit{VD}) a mixed model (SAS, version 9.2, SAS Institute Inc., Cary, NC, USA) was calculated. This included the impact-number as a fixed effect and the riding surface as well as the interaction between riding-surface and impact-number as a random effect.

The differences between the three impacts of the falling weight on each riding surface were analysed for the \textit{SA}-, \textit{ER}-, and \textit{VD}-values. A mixed model for repeated measures was used, which included the riding surface, the impact number and the interaction between riding surface and impact number as a fixed effect and the testing spot within a riding surface as a random effect. To study the differences between the properties of the five riding surfaces, the parameters of the Artificial Athlete were statistical analysed for the three impacts as well as \textit{SA}_S, \textit{ER}_S, \textit{VD}_S. Therefore, the mentioned model without the fixed effect impact-number and without the repeated statement was used. In addition, the correlations between the parameters were calculated from the residuals. The variables \textit{MAX} and \textit{RMS} of the hoof-acceleration data were analysed with a mixed model. The mixed model included the riding surface as a fixed effect and the horse as well as the interaction between horse and riding surface as a random effect. The least square means of the models were tested for significant differences including a Tukey or a Tukey-Kramer adjustment for multiple testing. The level of significances was defined at \( p < 0.05 \).

\textit{Results}

The repeatability of the parameters of the Artificial Athlete was 0.76 for \textit{SA}, 0.50 for \textit{ER} and 0.85 for \textit{VD}. The repeatability of the parameters showed the ratio of the variance within the riding surfaces and the variance between the riding surfaces.

Figure 5 presents the values of the parameters \textit{SA}, \textit{ER}, \textit{VD} measured by the Artificial Athlete at the three impacts on the five riding surfaces. The sand-sawdust surface showed the highest \textit{SA}- and \textit{VD}-values, followed by the grass surface, both sand-synthetic surfaces and the sand
surface. The order of the riding surfaces changed with regard to the energy restitution. With regard to the shock absorption-values, the decrease in the curve illustrated the compression of the surface material, which was produced by the impact of the falling weight. A smaller compression was produced by the sand-sawdust indoor arena and grass outdoor arena compared to sand-synthetic I, sand-synthetic II and the sand arena.

![Graph showing shock absorption percentages for different surfaces.](image)

**Figure 5**: Least square means of the parameters shock absorption (A), energy restitution (B) and vertical deformation (C) at the three impacts on the five riding surfaces.
Figure 5: Least square means of the parameters shock absorption (A), energy restitution (B) and vertical deformation (C) at the three impacts on the five riding surfaces
The least square means for the parameters $SA_1$, $ER_1$, $VD_1$, $SA_S$, $ER_S$ and $VD_S$, as well as the variables $MAX$ and $RMS$ of the hoof-acceleration are presented in Table 3. The statistical analysis showed similar results to the illustrated parameters of the Artificial Athlete with regard to the second and third impacts of the parameters $SA$, $ER$, $VD$. For the variables, which were calculated from the hoof-acceleration data, the repeatability of $MAX$ was 0.28 and 0.48 for the variable $RMS$.

Table 3: Least square means and standard errors of the parameters of the Artificial Athlete and the parameters of the hoof-acceleration

<table>
<thead>
<tr>
<th></th>
<th>$SA_1$</th>
<th>$ER_1$</th>
<th>$VD_1$</th>
<th>$SA_S$</th>
<th>$ER_S$</th>
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<th>$RMS$</th>
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<tr>
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<td>(0.11)</td>
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</table>

$^a,b,c,d$ Different superscript letters within a column indicate significant differences ($p < 0.05$).

Large differences between the illustrated variables are presented in Table 3 with regard to the order of the riding surfaces and the significant differences between the surfaces. For the parameters $SA_1$ and $ER_1$ the grass outdoor, the sand outdoor and the sand-synthetic indoor II showed no significant differences whereas both outdoor arenas differed significantly from the sand-sawdust indoor arena. A significant difference between the outdoor arenas could be found for the parameter $VD_1$. Further, the sand-sawdust indoor arena differed significantly from the other arenas. The $SA_S$ and $ER_S$ parameters of the Artificial Athlete showed inter alia significant differences between the grass outdoor arena and the sand outdoor arena, but no significant differences between grass outdoor and sand-sawdust indoor. The grass outdoor differed significantly from the sand-synthetic indoor I and the sand-sawdust indoor for the parameter $VD_S$. The grass outdoor arena differed significantly from the three indoor arenas with regard to the maximal negative acceleration values of the hoof’s landing phase ($MAX$). Further, the sand outdoor differed significantly from the sand-sawdust indoor. The least
square means of the variable $RMS$ showed significant differences between both outdoor arenas (grass and sand) and the sand-synthetic II as well as the sand-sawdust indoor arena. Further, both outdoor arenas (grass and sand) did not differ significantly from the variables of the acceleration signal ($MAX, RMS$).

The correlation coefficients of the parameters measured by the Artificial Athlete are presented in Table 4. Medium correlations were calculated between the parameters $VD_S$ and $SA_S$ as well as $ER_S$. High correlations were illustrated between the other parameters. Negative correlation between the values of the energy restitution ($ER_I, ER_S$) and the shock absorption ($SA_I, SA_S$) as well as the vertical deformation values ($VD_I, VD_S$) would be expected, because of the different type of measurement data. The correlations between the illustrated parameters and the values of the second and third impacts were at a similar level, besides the correlation between the $VD_I$ and $VD_S$, which was low and non-significant.

<table>
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</table>

**Discussion**

The aim of the present investigation was to evaluate the use of the Artificial Athlete to test riding surfaces. The evaluation was performed by comparing the measurement results of the Artificial Athlete ($SA, ER, VD$) with the results of hoof-acceleration measurement ($MAX, RMS$) on five different riding surfaces. The composition of the riding surfaces was also analysed. The analysis illustrated differences between the surfaces with regard to the surface composition, but testable statements for the relationship between the surface composition and the sport-functional properties could not be made. It must be noted that the sample of each surface was taken from only one randomly chosen location. It would seem more appropriate to take more samples from each surface to detect differences in the surface composition within the riding surface. In addition, it could be assumed that the surface composition and construction of the riding surface had a multi-factorial influence to the sport-functional properties. Since Ratzlaff et al. (1997, 2005) demonstrated a relationship between water
content and the sport-functional properties of a racetrack and Peterson and McIlwraith (2008) illustrated an effect of track maintenance on the mechanical properties of a racetrack, it seems to be meaningful to record more parameters, such as the depth of the footing layer as well as the construction of the substructures. Further, a larger number of investigated riding surfaces were needed to analyse the interaction between the single surface-parameters.

With regard to the parameters of the Artificial Athlete it must be noted that the recording of the vertical deformation (VD) was not in line with the relevant standard. Therefore, this parameter must be considered with caution. The repeatability of the parameters of the Artificial Athlete was at a medium and high level respectively. Figure 5 above shows the SA-, ER- and VD-values at the three impacts of the falling weight. Significant differences between the values of the second and third impacts are shown for the shock absorption and the energy restitution. Therefore, the use of the mean of the second and third impacts of these parameters, as stated in the relevant standard for the determination of shock absorption (DIN, 2005a), must be questioned critically. With regard to the shock absorption, the values presented in Figure 5 show a smaller compression of the grass surface during the three impacts, compared to the sand-synthetic surfaces as well as the sand outdoor surface: this was to be expected. In contrast, the small compression of the sand-sawdust arena, illustrated by the SA-values during the three impacts, was not to be expected. However, this outcome could be explained by the elastic properties of sawdust compared to sand and synthetic fibres.

The results of the statistical analysis differ from parameter to parameter with regard to the order of the riding surfaces and the significant differences found between the surfaces. However, the calculated correlation coefficients between the investigated parameters of the Artificial Athlete illustrated medium and high correlations.

The level of the SA₃-value of the grass outdoor was similar to the reference values given for football arenas (FIFA, 2009b). The FIFA (2009b) field test requirements for shock absorption (measured with the Artificial Athlete) were between 55 % and 70 %. A slightly smaller SA₃ of 50 % was measured on the grass outdoor arena. The smaller shock absorption value on the grass outdoor arena compared to the FIFA-requirements could be explained by the larger compaction of the grass riding surface. The SA₃-values of the sand, sand-synthetic and the sand-sawdust arenas were in line with the values measured by Heinrich et al. (2011) on similar riding surfaces. For both sand-synthetic indoor arenas as well as the sand outdoor arena the recorded shock absorption values (SA₃) were lower than the SA₃-values measured on the grass and sand-sawdust surfaces. This outcome indicated that both sand-synthetic indoor...
arenas as well as the sand outdoor arena were harder than the grass outdoor and the sand-sawdust indoor. These results were not in line with the recorded acceleration values during hoof landing. Larger least square means of the parameters $MAX$ and $RMS$ illustrated harder surfaces with regard to hoof-acceleration. Therefore, the grass outdoor showed a greater hardness than the three indoor arenas. This outcome was in line with previous investigations by Kruse et al. (unpublished), who demonstrated larger hoof-acceleration values during impact on grass arenas compared with sand arenas. Equally, Ryan et al. (2006) measured larger acceleration values on a grass paddock compared to an indoor arena and a standard dirt racetrack. Further, the levels of the parameters $SA$, $ER$, $VD$ at the three impacts were in line with the data measured by Heinrich et al. (2011).

The results showed that the Artificial Athlete did not illustrate the shock absorption ($SA$) the same way as the horses did. This outcome was in line with Peterson et al. (2008) and Thomason and Peterson (2008), who criticised that testing devices which use a dropping weight do not produce the impact in the same manner as the horse’s hoof. The similar results of $VD_S$ and the hoof-acceleration values ($MAX$, $RMS$) could be explained by the fact that a larger $VD_S$ indirectly is indicative of a deeper sinking of the horse’s hoof during impact. In turn, a larger deformation during hoof impact induced a lower level of hoof-deceleration. Therefore, maybe the parameter $VD_S$ could be a more comprehensive means of evaluating the sport-functionality of riding surfaces. The results of the parameter $ER$ were difficult to compare with the hoof-acceleration data, because the energy restitution was not captured by the hoof-acceleration measurement.

**Conclusion**

It should be noted that the use of the Artificial Athlete as a testing device for riding surfaces was assessed as critical, because of the large deviations between the results of the hoof-acceleration measurement and the parameter $SA$ of the Artificial Athlete. Nevertheless, the parameter $VD_S$ could be helpful for the assessment of the sport-functional quality of a riding surface.
Acknowledgments

We are deeply indebted to the Holsteiner Verband for permitting the measurements on the various riding arenas and to Prof. Heinrich, Prof. Ellmann, Petra Große Erdmann and Roman Neubert from the University of Applied Sciences Osnabrück for providing the Artificial Athlete and their support in the data processing and analysis.

References


General Discussion

The aim of the present study was to analyse the effect of stress on the horse’s locomotor apparatus produced by different riding surfaces. Firstly, acceleration sensors were applied to measure the load on the horse’s limb during impact and wavelet-filtering as well as several variables were used to analyse the acceleration data. Secondly, a technical testing device was tested on different riding surfaces and evaluated by comparing the results of the technical device with the acceleration data measured on the horse’s hoof.

The following sections discuss important issues of the current study, such as the investigated riding surfaces, the applied acceleration sensors, the data recording and data processing as well as the use of the technical testing device.

Riding surfaces

In traditional equestrian disciplines, a large number of different ground surfaces are used. Besides the differences in the construction of the riding surface a greater number of materials are applied for footing layer: for example, various types of sand, sawdust, woodchips, synthetic fibres, rubber, grass and mixtures. In the last few years, the addition of synthetic fibres to the sand of the footing layer as well as wax-coated surface materials has become an increasing trend. The trend towards artificial surfaces (Murray et al., 2010) could be explained by the fact that the riding surface must fulfil a large number of requirements such as shock absorption, elastic properties, slip resistance, independence from weather conditions, or they must be dust-free, non-toxic, durable and subject to low maintenance.

The riding surfaces chosen in the present investigation illustrated typical surfaces with footing for dressage or jumping horses. The sand-sawdust indoor arena showed a softer footing layer, which is often desired in dressage arenas. In contrast, in jumping arenas a harder surface is preferred, because these surfaces allowed faster speeds in straight lines as well as in the turns. In the present investigation, the grass and the sand outdoor arena illustrated harder surfaces, which were shown by the acceleration data and the vertical deformation parameter measured by the Artificial Athlete. On harder surfaces, larger deceleration values were measured compared with softer surfaces (Burn, 2006; Chateau et al., 2010). Larger deceleration values during impact were associated with higher load on the horse’s locomotor apparatus. Further, higher vibration frequencies during hoof landing were measured in the present study (see Chapter Three) and by Barrey et al. (1991) on harder surfaces. High-frequency vibrations are...
associated with damaging effects on the locomotor apparatus of sport horses (Rooney, 1974). Equally, Williams et al. (2001) illustrated an increase in injuries with harder surfaces. Soft surfaces showed lower deceleration values during impact and therefore a decrease in load on the horse’s limbs (Chateau et al., 2010). However, soft surfaces could lead to faster fatigue (Thomason and Peterson, 2008) and thereby to a higher risk of injury. Therefore, surfaces which are too hard and too soft are undesirable in indoor and outdoor riding arenas, but a final evaluation of whether a riding surface is too hard or too soft was not performed. This could be the objective of further studies, for example on the basis of lameness frequencies on different riding surfaces, expert surveys or in vitro analyses.

Chapter Four illustrates the composition of the footing layer of the investigated riding surfaces. It must be noted that not only the material of the footing layer but also the construction of the sub-area, the water content and maintenance influence the surface properties. The water content of the surfaces investigated in the present study was between 6.3 % and 20.6 % for the sand and sand-mixture surfaces, these values were mostly in line with Murray et al. (2010), who recommended water contents between 8 % and 17 % for sand surfaces. A larger water content (27.8 %) was measured on the investigated grass outdoor arena. It must be noted that the water content must always be considered with the material of the footing layer, because each surface material has its own optimal area of water content. No universally valid statements could be given in the present investigation for the relationship between surface properties and the surface composition because of the low sample size. In an earlier investigation, wax-coated materials as well as sand and rubber were associated with low injury risk and fine sand was recommended (Murray et al., 2010). The construction of the sub-area of the five riding surfaces was not analysed in the current study due to the fact that by analysing the sub-area, the riding surface could be damaged. But the sub-area could have an important influence on the vertical and horizontal response of the surface. Further, the five investigated riding surfaces were in a used condition during the data recording, in order to illustrate the surface properties in common training and competition conditions. Peterson and McIlwraith (2008) showed that maintainance could have an effect on the sport-functional properties.
Acceleration sensors

In the present study, two biaxial acceleration sensors were used. Earlier investigations showed the suitability of hoof-acceleration measurement to detect the stress on the horse’s limb produced by different surface properties (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006a; Chateau et al., 2009; Setterbo et al., 2009). In the present study, one sensor was fixed on the lateral hoof wall of the left forelimb and the other one were mounted on the fetlock with the y-axes directed to the ground and the x-axes were oriented to the direction of movement. Therefore, the vertical hoof-acceleration would not be fully recorded, because of the shape of the hoof. In earlier studies, special appliances such as plexiglas blocks (Burn, 2006) or triangular aluminium plates (Gustås et al., 2004) were used, to fix the sensors in the desired orientation on the hoof wall. In addition, the acceleration of the transversal (medio-lateral) axis would not be acquired by the biaxial sensors. Thus, the use of triaxial sensors seems to be better. However, only a small transversal acceleration could be expected during the hoof landing and also in similar studies by Burn (2006), Gustås et al. (2006b) and Setterbo et al. (2009) the transversal hoof-acceleration during the hoof impact was not recorded. Further, it must be critically noted that the sensor was mounted using double-sided adhesive tape and fabric tape, because the sensors fixation had to be rigid to inhibit vibrations between the sensor and the body. Additionally, skin- or hoof-mounted acceleration sensors did not acquire the real acceleration of the underlying structures, such as bones, joints and tendons. Thus, bone-mounted sensors, which have been used by Willemen et al. (1999) and Gustås et al. (2001) among others, are advantageous to reduce artefacts in the accelerometer data. However, bone-mounted sensors are invasive and can only be used under laboratory conditions. Another critical point is that the range of the acceleration sensors applied in the current study was relatively small compared with accelerometers used in earlier investigations (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006a, b; Chateau et al., 2009). It could be illustrated by the values of the variable \( y_{MAX} \) (see Chapter Two) that the range was sufficient to measure hoof-acceleration data in slow trot on riding surfaces. But acceleration sensors with a larger range are needed for harder surfaces and faster gaits, because Burn (2006) among others measured a maximum hoof-acceleration of 17 g on average during impact in trot on a sand surface and 504 g on tarmac. In addition, the sampling rate of the applied acceleration measurement system was 1 004.03 Hz and therefore relatively low, compared with previous studies (Barrey et al., 1991; Benoit et al., 1993; Ratzlaff et al., 2005; Burn, 2006; Dallap Schaer et al., 2006; Gustås et al., 2006a, b; Chateau et al., 2009). Earlier investigations by Burn et al. (1997) illustrated that a
sampling rate of minimum 2 500 Hz was needed, because more than 98.2 % of the hoof-acceleration signal energy which was measured in trot on a concrete surface was below 625 Hz and over 99 % of the energy was below 1 250 Hz. However, it must be noted that lower frequencies could be expected on the investigated riding surfaces than on a concrete runway. Also, Witte et al. (2004) and Setterbo et al. (2009) used a sampling rate of 1 000 Hz in similar investigations. The advantages of the acceleration sensors used were the small size and low weight as well as the wireless data transfer and the possibility to control data acquisition simultaneously using a notebook. Further, the acceleration sensor system was easy to handle in practice and can be used under field conditions.

In pre-test of the present study, additional high-speed videos were recorded simultaneously to the acceleration data. Therefore, the phases of the limb cycle could be compared with the acceleration data. The use of the high-speed cameras for measurement on different surfaces was difficult, due to the fact that only a few strides could be filmed per session. Further, illumination is important to detect and track the markers, but this is difficult under field conditions. In earlier investigations, beside acceleration sensors and videographic systems, force plates (Gustås et al., 2006a) or force measurement shoes (Robin et al., 2009; Setterbo et al., 2009) have been tested on different surfaces. Force plates have the disadvantage that they must be mounted in the ground surface. Therefore, force plates are less suitable for analyses in the field (Robin et al., 2009). Force measurement shoes are easy to handle and can be used under field conditions, but normally they must be nailed into the hoof wall and could have an effect of the horse’s motion, because of their larger weight (Hobbs et al., 2010). Nevertheless, the real force during impact and during the stance phase can only be captured with force measuring devices. Therefore, force shoes could be superior in analysing the load on the horse’s limb compared with acceleration measurements.

Data recording

In the present study, the acceleration data were simultaneously transferred to the notebook via Bluetooth at a range of approximately 10 to 20 meters. Therefore, the horses were trotted by hand on a defined circle around the notebook to allow undisturbed data transfer. In previous studies dealing with the testing of track surfaces, straight test tracks were used (Barrey et al., 1991; Ratzlaff et al., 2005; Burn, 2006; Gustås et al., 2006a; Chateau et al., 2009; Robin et al., 2009; Setterbo et al., 2009). The advantage of the simultaneous data transfer was the possibility to control the data acquisition. Additionally, an unrestricted recording time was
given, so that a large number of strides could be recorded. Further, trotting on a 16 meter-circle is not unusual in the training of dressage and jumping horses. However, differences in the kinematic during straight and circular locomotion were given. Falaturi (1998) showed that in walk and trot the stance phase of the inside limb was longer in a circle while the stance phase of the outside limb decreased, thus the difference between the length of the stance phase of the inside limb and the outside limb increased with a decrease in circle diameter. In addition to the differences in kinematic parameters of the inside and outside limbs, differences between kinetic parameters could be expected. In the current investigation, the acceleration was measured on the inside forelimb. On this limb, a larger load could be expected. In addition, Gustâs et al. (2004) measured higher forces in trot on the horse’s forelimb compared to the hindlimbs.

Some current studies have shown the influence of speed on the kinematic parameters (Leleu et al., 2002; Witte et al., 2006; Robilliard et al., 2007; Parsons et al., 2011) and the kinetic parameters (Dutto et al., 2004; Gustâs et al., 2006b; Weishaupt et al., 2010) of equine locomotion. Therefore, speed control is an important point in locomotion analysis. In the present study, the speed of each horse on each surface was calculated after data recording by video data. Mean speeds between 2.99 m/s on the sand outdoor arena and 3.43 m/s on the sand-synthetic I surface were given. A simultaneously speed control for example with a radar gun or a global positioning system (GPS) seems to be preferable. Further, it must be stated that in the current study the horses trotted at low speed. Larger deceleration values at impact could be expected with an increase in speed (Gustâs et al., 2006b), faster gaits or during jumping. It must be noted that with faster gaits and increasing jumping height the importance of the surface’s shock absorption, shearing strength and slip resistance increased. Therefore, the analysis of the effect of stress produced by different surfaces on the horse’s locomotor apparatus at faster speeds and during jumping seems to be important.
Data processing

During locomotion, the movement of the horse’s limbs can be dissected into four phases:

1. landing phase
2. stance phase
3. take-off phase
4. swing phase

The loading of the horse’s limb changes with the phases of the locomotion and the ground surface must fulfil different requirements in each phase. During the landing phase, the hoof touches the ground and decelerates. The deceleration values during impact are correlated with the stress on the horse’s limb (Burn, 2006). Larger deceleration values are associated with a higher load on the horse’s limb and a lower shock absorption of the surface. In the stance phase, the limb is weighted with (a part of) the body mass, and the superficial flexor tendon and the suspensory ligament are at maximum load (Hertsch, 2003). During the end of the stance phase, the horse pushes off from the ground surface. Depending on the surface properties, the toe digs into the ground during the limb’s take-off, thus the deep digital flexor tendon is relieved. If the surface is too hard, the toe cannot dig into the ground and the load on the deep digital flexor tendon increases.

In the present thesis, the hoof’s landing phase was analysed, because of the importance of this phase to the development of horse’s injuries (Burn, 2006). The hoof’s landing phase was determined as the phase beginning with the second half of the swing phase and ending with the end of hoof breaking. A more precise detection of impact and hoof breaking could be more suitable for data analysis. But it must be noted that, in contrast to harder surfaces, on which the impact could be easy detected by a large deceleration peak, it could be difficult to detect the impact peak on soft surfaces, because of the small deceleration values on these surfaces. The stance phase, when the limb of the horse is loaded at maximum, is also important in the development of injuries. But the load during the stance phase cannot be detected with acceleration sensors. To analyse the load during the stance phase, the use of force measuring devices is necessary.

Data denoising is often of major importance in data processing. Wavelet filtering of the acceleration-time curves and the use of various time- and frequency-domain variables were investigated in Chapter Three. However, it must be noted that in the acceleration data of the present study only a small percentage of noise was included and a denoising by wavelet
filtering showed an over-smoothing as of the third approximation level. In the findings of the hoof’s landing phases, a larger number of strides were found in the first and second approximation signal of the Haar- and fourth-order Daubechies-wavelet filters. This outcome showed a better adaptation of the first and second approximation to the algorithm which detected the hoof’s landing phases than the original signal. But nevertheless, other filter methods were not tested in the present study; therefore a universal statement of whether wavelet filtering is superior in denoising hoof-acceleration data cannot be made.

The analysis of the time- and frequency-domain variables, which were performed in the third chapter, illustrated medium and high correlations within the variables of the time domain and within the variables of the frequency domain, while low or medium correlations were given between the time- and frequency-domain variables. Therefore, analysing time- and frequency-domain variables seems to be necessary.

**Technical testing device**

In Chapter Four, a technical testing device was used for surface testing. The development of an easy-to-handle testing device for racetracks or riding surfaces has also been investigated in several earlier studies (Cheney et al., 1973; Pratt, 1985; Zebarth and Sheard, 1985; Clanton et al., 1991; Drevemo and Hjerten, 1991; Ratzlaff et al., 1997; Oikawa et al., 2000; Ratzlaff et al., 2005, Peterson et al., 2008). The problem of technical testing devices is mostly that they produce impact power inadequately compared with the impact of the horse’s hoof (Barrey et al., 1991; Peterson et al., 2008; Thomason and Peterson, 2008). Peterson et al. (2008) developed a testing device for racetracks which mimics the impact of the forelimb of a horse at gallop. Therefore, the hardness and the shearing strength of the surface during impact can be illustrated. But this system is not yet established in practice to test riding surfaces with footing for dressage and jumping horses. A further disadvantage of this surface testing device is the fact that a motor vehicle is needed to deploy the device.

The Artificial Athlete used in the present study (see Chapter Four), is an easy-to-handle measurement system, which is inter alia the standard test method for shock absorption tests of football fields (FIFA, 2009). The load of the Artificial Athlete on the ground surface during impact is similar to the load illustrated by Dohne (1991) during impact of a trotting horse. Heinrich et al. (2011) tested the Artificial Athlete on different riding surfaces and calculated the energy restitution and vertical deformation parameters from the data of the Artificial Athlete in addition to shock absorption. Shock absorption values between 35 % and 40 %
were recommended by Heinrich et al. (2011) for riding surfaces with footing for jumping horses and shock absorption values between 45 % and 50 % for riding surfaces with footing for dressage horses. But comparisons with data measured on horses were not given. In the present study, the parameters measured by the Artificial Athlete on the five investigated riding surfaces were compared with the results of the hoof-acceleration measurement. It must be concluded that the Artificial Athlete seems to be unsuitable for the evaluation of the shock absorption of various riding surfaces, because of the large deviations between the results of the hoof-acceleration measurement and the shock absorption parameter measured by the Artificial Athlete. The energy restitution parameter was difficult to compare with the hoof-acceleration data, therefore it was not possible to make statements about the suitability of this parameter. The vertical deformation parameter, which was also acquired by the Artificial Athlete, showed similar results to the hoof-acceleration data with regard to the riding surfaces. But it must be noted that in the present investigation the vertical deformation parameter was calculated from the measured force-time curve of the Artificial Athlete; this approach can lead to errors and was not in line with the relevant standard (DIN 2005). However, it was shown that the interaction between hoof and ground surface during impact was not really comparable with the impact of a vertical drop weight. This result was in line with Peterson et al. (2008) and Thomason and Peterson (2008), who stated that drop tests do not produce the impact in the same manner as the horse’s hoof. It must be noted that beside the vertical response, which describes the hardness of the surface, the horizontal response, which is related to the shearing strength, is important for the sport-functional properties of surfaces (Peterson et al., 2008). But drop tests, such as the Artificial Athlete, do not illustrate the shearing strength. Therefore, the use of a testing device which produces the impact in a similar manner as the horse’s hoof and collects the vertical and horizontal response of the surface seems to be important for the analysis of sport-functional properties of riding surfaces.

References


Summary

Diseases of the locomotor apparatus are a major cause of the attrition and culling of sport horses. The sport-functional properties of riding surfaces are considered to be an important factor in the risk of injuries, thus, their investigation seems to be important not only for the economic losses, but also for animal welfare. The aim of the present study was to analyse the effect of different riding surfaces in indoor and outdoor arenas on the horse’s limb. Therefore, acceleration sensors were mounted on the horse’s hoof and fetlock to capture the deceleration during hoof landing. Additionally, the use of a technical measurement device to test the sport-functional properties of riding surfaces was evaluated.

Chapter One contains a review of current methods and applications of locomotion analyses in horses. Acceleration sensors, videographic and optoelectronic systems as well as force plates and force shoes, respectively, are illustrated and advantages and disadvantages are pointed out. The fields of application are subdivided in three parts:

- locomotion analysis in general and the effects of various factors on the horse’s locomotion
- objective evaluation of horse’s gait and jumping technique
- lameness detection

Studies concentrating on locomotion analysis in general have dealt inter alia with the recording of kinematic and kinetic parameters in different gaits and various speeds. Further, differences between horses of different breeds, ages and levels of training are analysed as well as the effect of various horseshoes or ground surfaces. The results of these studies could help to optimise the training conditions and the management of horses. The aim of investigations dealing with the objective analysis of horse’s gait and jumping as well as lameness detection is to objectify subjectively perceived motions and changes in movement by locomotion analysis systems. Therefore, the objective locomotion analysis could help to simplify and improve the assessment of gaits, jumping techniques and lameness. However, in practice locomotor analysis systems have only been used in a small number of cases so far.

Chapter Two deals with the effect of different riding surfaces on the horse’s hoof- and fetlock-acceleration during the hoof landing. The stress on the horse’s limb during hoof landing was captured by two biaxial acceleration sensors. One sensor was mounted on the lateral hoof wall and the other one was mounted laterally on the fetlock. The y-axis of both sensors was orientated to the ground surface and the x-axes aligned against the direction of movement. For data recording, six riding horses were trotted in hand on a circle on five
different riding surfaces and the acceleration values were capture for 65 seconds on each riding surface. Three indoor riding arenas, one with a sand and synthetic fibre footing layer used for jumping horses, another one used for lunging with a sand-synthetic fibre footing layer and an indoor arena with a sand-sawdust footing layer used for dressage were investigated. Further, two outdoor riding arenas were analysed, one with a sand surface and one with a grass surface. Based on the stance phase of the hoof, the acceleration-time curves were dissected in the hoof’s take-off and landing phases. The acceleration values during the hoof’s landing phase were used to analyse the properties of the five riding surfaces, because this phase is important in the risk of injury. The maximum negative acceleration value and the root mean square value during the hoof’s landing phase were used for statistical analyses. Both outdoor arenas showed in the y- and x-direction as well as for the resultant vector larger hoof- and fetlock-acceleration than the indoor arenas. Larger acceleration values illustrated harder surfaces and higher loads on the horse’s limb. The hoof and fetlock-acceleration values showed similar results with regard to the riding surfaces. Therefore, both sensor applications seemed to be suitable for testing surface properties.

In the Chapter Three, the application of wavelets to denoise the acceleration-time curve of the hoof (see Chapter Two) were investigated as well as the suitability of several parameters for data analysis. Three variables were calculated from the acceleration-time curves and two variables were captured from the single-sided amplitude spectrum of the Fourier-transformed signal. The results of the wavelet-filtering showed on the one hand that more correct strides can be found in the first and second approximation of the Haar- and Daubechies-filtered signal. On the other hand, only small differences were shown between the results of the original signal and the first and second approximation of both wavelet-filtered signals with regard to the five riding surfaces. In contrast, the third approximation level illustrated large derivations, which pointed out an over-filtering. The comparison of the results of the different variables revealed that the three variables from the acceleration-time curve obtained similar results with regard to the riding surfaces. Also, the variables of the single-sided amplitude spectrum were highly correlated.

In contrast to other sports, such as football, there are no standardised methods for surface testing in equestrian sports. Therefore, the investigations of Chapter Four illustrate the use of a technical device to test the sport-functional properties of riding surfaces. The Artificial Athlete, a testing device for human sports surfaces, was applied on the five riding surfaces described in Chapter Two. The parameters shock absorption, vertical deformation and energy
restitution were recorded and compared with the results of the hoof-acceleration measurement (see Chapter Two). Clearly deviations were shown between the shock absorption of the five riding surfaces and the results of the hoof-acceleration measurement. The energy restitution parameter, which was recorded by the Artificial Athlete, was difficult to compare with the hoof-acceleration data, because the energy restitution was not captured by the hoof-acceleration measurement. Therefore, this parameter could not be evaluated. The vertical deformation parameter in the assessment of riding surfaces showed results similar to those for the hoof-acceleration measurement. Therefore, the vertical deformation parameter could be helpful for the assessment of the sport-functional quality of a riding surface.
Zusammenfassung


In Kapitel Eins wird zunächst eine Übersicht über die Methoden und Anwendungsfelder der Bewegungsanalyse bei Pferden gegeben. Beschleunigungssensoren, videobasierte und optoelektronische Systeme sowie Kraftmessplatten beziehungsweise Kraftmesshufeisen werden vorgestellt. Die Anwendungsfelder werden in drei Gebiete unterteilt:

- allgemeine Ganganalyse und der Einfluss von verschiedenen Faktoren auf die Bewegung des Pferdes
- objektive Bewertung des Ganges und der Springtechnik des Pferdes
- Erfassung von Lahmheiten


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