Sport Surfaces in Show Jumping

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Cover: Hoof-ground interaction by ‘Nasse’ ridden by Marianne Tenger
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Abstract

Properties of sport surfaces influence the occurrence of injuries and the performance of equine athletes. The sports governing body seeks to develop standards for safety and performance of show jumping surfaces. Limited information is available to guide this process. Objective methods are warranted in order to define surface properties that can be associated to injury and performance data. Description of the discipline-specific interaction between the horse and the ground is important in order to display the characteristics and diversity of loading patterns applied to the sport surfaces as well as to enable understanding of the mechanical challenges that lead to injuries.

The aims of this thesis were to describe the hoof-ground interaction in show jumping and to study functional properties of surfaces through rider assessments and by using a standardized biomechanical method that enables comparisons between arenas.

Hoof landing characteristics of elite horses in jump landing from 1.30–1.50 m competition fences on two different surfaces were evaluated from high-speed videos. Hoof landing kinematics differed among the leading/trailing fore and hind limbs. Data increased our understanding of hoof-ground interaction and related events, which is a prerequisite for developing surface testing devices. Hoof impact was also investigated using hoof-mounted accelerometers in an experimental setup with five horses in canter, jump take-off and landing. Leading/trailing fore and hind limbs, stride types and surface affected the hoof-surface impact. The vertical deceleration at impact ranked in the same order, for three surface conditions, as when the impact from a metal hoof of a biomechanical surface testing device was measured.

Subjective assessments of surface properties by riders were compared to objective in-situ measurements of the same properties with a biomechanical surface tester in 25 show jumping competition and warm-up arena surfaces at top-level events. Significant associations between the subjective and objective assessments were found.

The data from this thesis contribute to the description of the discipline-specific hoof-surface interaction in show jumping. The objective method used for in-situ characterisation of functional surface properties can enable further objective comparisons which in the future can be related to injury and performance data of show jumping surfaces.

Keywords: hoof-ground interaction, hoof impact, acceleration, show jumping, equestrian arena, sport surface, biomechanical surface test, horse

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Dedication

To Anders, Rut and Nils

If confusion is the first step to knowledge, I must be a genius.
Larry Leissner

Ingen konst kan vara onyttig, men att konster och vettenskaper stiga och falla i förhållande till menniskolynnets olika riktningar, äfvensom att deraf måste följa ett ombytligt deras hägn, derom vittna alla tidskiften, och derom vitsordar för sin del ridkonsten.
Adam Ehrengranat, hovstallmästare 1836

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List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Hernlund, E., Egenvall, A. & Roepstorff, L. (2010). Kinematic characteristics of hoof landing in jumping horses at elite level. *Equine Veterinary Journal. Supplement,* vol. 42 (38), pp. 462-467.

II Hernlund, E., Egenvall, A., Peterson, M.L., Mahaffey, C.A. & Roepstorff, L. (2013). Hoof accelerations at hoof-surface impact for stride types and functional limb types relevant to show jumping horses. *The Veterinary Journal,* vol. 198, pp. e27–e32.

III Hernlund, E., Egenvall, A., Hobbs, S.J., Bergh, A., Peterson, M.L. & Roepstorff, L. Peak impact deceleration of the hoof on three surface conditions with comparison to a mechanical surface tester. A pilot study of jumping horses. (Manuscript)

IV Hernlund, E., Egenvall, A., Hobbs, S.J., Peterson, M.L., Northrop, A.J., Bergh, A., Martin, J.H. & Roepstorff, L. Comparing subjective and objective evaluation of show jumping competition and warm-up arena surfaces. (Manuscript)

Papers I-II are reproduced with the permission of the publishers.

The contribution of Elin Hernlund to the papers included in this thesis was as follows:

I Involved in planning of the study, main responsibility for execution of data collection, took part in analysis of the data, shared responsibility for summarizing results, main responsibility for writing and critically revising the article with input from co-authors.

II Shared responsibility for design of the experiment, took part in all data acquisition, involved in data analysis, shared responsibility for summarizing results and main responsibility for writing and critically revising the article with input from co-authors.

III Shared responsibility for design of the experiment, took part in all data acquisition, shared responsibility for data analysis and results, main responsibility for writing the manuscript with input from co-authors.

IV Shared responsibility for conception and design of the study, took no part in data acquisition, shared responsibility for data analysis and results, main responsibility for writing the manuscript with input from co-authors.

Abbreviations

BW	body weight
CSI	Concour de Saut International is a ranking system for show jumping competitions approved by the FEI. A starring system is used, from one (1*) to five (5*). Fence height, price-money and horse age are among the things that increase with higher competition ranking levels i.e. more stars.
CV	coefficient of variation
FEI	International federation for equestrian sports
g	unit for acceleration based on standard acceleration due to gravity, $9.81 m/s^2$.
McIII	third metacarpal bone
OBST	Orono Biomechanical Surface Tester
PVC	polyvinyl chloride
UK	United Kingdom
USA	United States of America

1 Introduction

1.1 General background

It is generally accepted that surfaces affect both the incidence of injuries (Egenvall *et al*., 2013; Murray *et al*., 2010a; Parkin *et al*., 2004a; Hernandez *et al*., 2001) and the performance of equine athletes (Peterson *et al*., 2010). Providing safe surfaces for training and competition presents a challenge for the horse industry. The challenge is in part related to the size of the investment required to produce the surface material, build the facility and provide maintenance of equestrian arenas and racetracks (Peterson *et al*., 2012 p. 2). However, the lack of available scientific understanding and common terminology related to surface properties, construction types and maintenance procedures has made it difficult to develop surfaces that can improve the soundness and performance of the equine athletes in the wide range of equine sports.

Of all of the equestrian sports, show jumping is the largest of the disciplines governed by the International Federation of Equestrian Sports (FEI) (FEI, 2013). The number of jumping competitions has also increased significantly over the last ten years (FEI, 2013). The increasing popularity of sports built on a partnership with the horse raises important questions of how the welfare of the horse within the sport is guaranteed. The sport governing body is taking initiative to find safety and performance standards for surfaces within the equestrian disciplines (FEI, 2014). The growth of the discipline has led to an increasing demand for high quality arenas both for training and competition. The absence of the necessary knowledge required to guide consumers can not only lead to poor investments but can also pose a risk to the health of the horses. A common language and tools that can be used to provide feedback for the manufacturers and installers of arenas can help the industry to develop the design of the surfaces. The perception of the riders to how well horses perform on the surfaces is the most immediate source of information available for the adjustment of the products. However, eventually the risk of injuries must be addressed. Injuries are harder to relate to the surfaces' properties since their aetiology is multifactorial by nature and often occur after a longer duration of use of a surface and may be related to multiple surfaces. Anecdotal information from veterinarians and trainers have revealed a perception of changes occurring in the locomotor injury spectra or injury frequencies of horses, in relation to the introduction of new surface materials or new track geometry. Given the many factors that are in play when an injury occurs and the complex and variable nature of the horses' interaction with the surfaces, these statements should be interpreted with caution. However, such observations have driven the research in the field (Oikawa *et al*., 1994; Cheney *et al*., 1973). Subjecting a population of horses to a change of training and competition surface has been said to be as close to a controlled clinical trial that one can get in the area of surface research (Parkin, 2011). Prerequisites for this approach is however the collection of injury data together with relevant data on surface properties (illustrated in figure 1).

The relevance of the surface to understanding equine injuries and musculoskeletal disease is clear. The tissue of the horse is subjected to loads at every step when the hoof collides with the surface. This collision generates a necessary adaption that increases resilience of the tissues of the locomotor system (Noble *et al*., 2016; Murray *et al*., 2001; Firth *et al*., 1999). However, if this load exceeds the tissue's threshold or if a submaximal load is repeated too frequently to allow for sufficient repair, orthopaedic injury will be the result (Whitton *et a*l., 2010; Fleck & Eifer, 2003). Studies show that the loads and accelerations arising at the interface between the hoof and surface and that transfer up the horse's limbs are affected by many factors such as the horse's gait/movement (Boston *et al*., 2000), speed (Verheyen *et al*., 2006a; Boston *et al*., 2000), shoeing (Back *et al*., 2006; Benoit *et al*., 1993) and anatomical conformation (Wiggers *et al*., 2015). From the perspective of equine management, the rider's choice of training surfaces, the variation in training type, volume and intensity and the shoeing-strategy should be considered in relation to the horse's capability of handling these forces. This capability is governed by the horse's history of all training related activities as well as environment, genetic potential, conformation, nutrition, general management and many more factors. Taken together, the surface is only one of many things that will contribute to the risk of orthopaedic injury. However, unlike many other risk factors we have the potential to control and even perhaps to optimize the arena surface for safety. The investment in improved surfaces will have an effect on all horses using the surface. So how do we go about to manage this risk factor?

As pointed out by the popular saying ”You can’t manage what you can’t measure”, a good starting point to for such a task is to define arena surfaces by objective methods. Quantification of surface properties that are critical to the equine athlete in conjunction with a consistent terminology can provide standardised information about the surface’s function to riders. From a long-term perspective this can help to increase awareness within the sport regarding mechanical characteristics of equine sport surfaces. Development of terminology and measurements of surfaces are important steps on the way towards identification of risk-associated surface properties. This requires a highly interdisciplinary approach (illustrated in figure 1) with input from biomechanical and mechanical sciences, epidemiology, soil and material sciences and equine clinical and pathophysiological disciplines.

For example, the selection of materials for each layer of the surface impacts the performance of the surface. Techniques from materials and soil sciences can be used to develop specification for contents and properties of the materials used for equine surfaces and have been used in laboratory settings (Bridge *et al*., 2015, 2014; Mahaffey *et al*., 2012; Setterbo *et al*., 2012). The construction of both arenas and racetracks should include different materials in top and lower layers (Mahaffey *et al*., 2012; Murray *et al*., 2010b). Normally these are mineral based granular materials of different mineralogy, shape and size; clay, silt, sand and gravel (Mahaffey *et al*., 2012; Barrey *et al*., 1991). Additives of organic materials such as woodchips, as well as synthetic materials (e.g. rubber, polymers, fibres) are often included in the top layer (Tranquille *et al*., 2015; Holt *et al*., 2014; Barrey *et al*., 1991). The lower layers can be anything from aggregates (similar to road beds), concrete floors (in temporary indoor competition arenas) and natural soils (Murray *et al*., 2010b). All of these materials have at least at some point made sense to users from an economic and performance perspective. However, the effect of the materials on risk to the horse is complex.

In order to understand how the materials behave as a part of the complete arena construction, it is critical to understand how the surface will respond to the loading from the horses. In-situ tests have been performed using different mechanical devices (e.g. Lewis *et al*., 2015; Tranquille *et al*., 2015; Kruse *et al*., 2013; Setterbo *et al*., 2013). This approach should enable standardized comparisons between surfaces, however the mechanical tests must be designed using relevant biomechanical information regarding the horse-ground interaction. The granular materials used in surfaces for equine sports are non-linear and strain rate dependent (Guisasola *et al*., 2010; Li *et al*., 2009). This means their reaction force will differ depending on the magnitude and rate of loading applied by the horse. Therefore mechanical in-situ tests of surface response need to be done by applying loads to the surface in a manner that is representative of critical events from the loading pattern the horse would produce. The method should be able to distinguish variation in the functional properties in a way that is relevant to the horse. This understanding cannot be achieved without understanding the horse-surface interaction.

The interaction between the hoof and the surface under real-life training and competition conditions have been studied with kinematic and kinetic methods, measuring movements and forces respectively in several equine sports disciplines (e.g. Symons et al., 2014; Parsons *et al*., 2011). In contrast to stationary placed force plates and high-speed cameras pointed towards a limited region of interest, measurement equipment mounted on the horse offer the benefit of studying this interaction over a larger area of the surface. Hoof-mounted accelerometers, strain-gauges and dynamic force-shoes have been developed and used for such purposes (e.g. Chateau *et al*., 2009; Robin *et al*., 2009; Roland *et al*., 2005; Burn *et al*., 1997; Barrey *et al*., 1991) The research on hoof-ground interaction can help quantify the mechanical demands on the horse's limbs and also open up opportunities to understand the aetiology of discipline-specific orthopaedic injuries in relation to sport surfaces. The conditions arising at the interface between the hoof and surface can potentially be introduced to existing computer models of the horse's limbs (Panagiotopoulou *et al*., 2016; Symons *et al*., 2016) in order to understand how surfaces affect soundness. Injury models could provide a more detailed understanding of tissue loading from experimental data. On a larger scale the mechanical measurements and defined materials of equine sport surfaces can be related to systematically assembled injury and performance data in order to capture the epidemiological picture of injuries in relation to sport surfaces (figure 1).

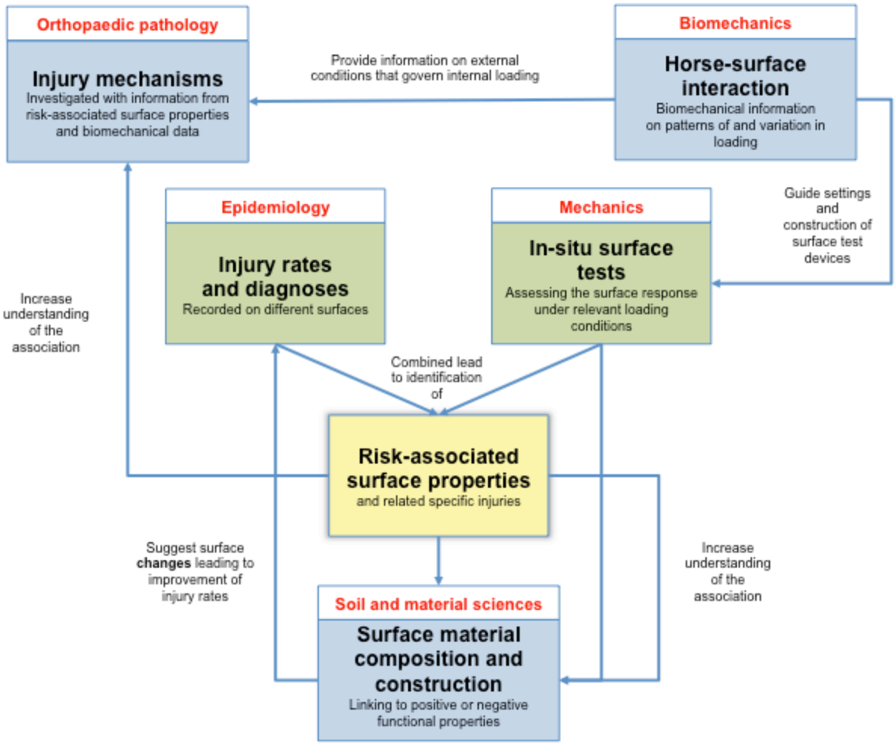

Figure 1. This schematic figure presents the multidisciplinary area of research that aims to improve horse health through identification of risk-associated surface properties. The main task is to link specific surface properties to injuries, which must be founded on surface tests based on biomechanical knowledge on horse-ground interaction.

Sport surfaces affecting injury –epidemiological evidence

Orthopaedic injury is the primary reason for veterinary expenditures, health-related career-ending decisions and wastage of riding horses (Sloet van Oldruitenborgh-Oosterbaan *et al*., 2010; Egenvall *et al*., 2006; Wallin *et al*, 2000). In the show jumping discipline, tragic accidents with competing horses sustaining severe orthopaedic injuries have occurred in front of large audiences (e.g. Olympics in Athens 2004 (van Weeren, 2010). This has raised the public's concern about the influence of the arena surfaces on the soundness of the jumping horse, as reported in the popular press (Horse & Hound, 2005-02-17). There is a clear correlation between these injuries and inadequate surfaces in the minds of many stakeholders. However, the scientific evidence for mechanisms that link show jumping surfaces used for training or competition surfaces to orthopaedic injuries is not well established.

The largest portion of epidemiological evidence relating surfaces to injury comes from human sports and Thoroughbred racing. A majority of the research on human sports surfaces has been focused on quality and safety aspects of synthetic compared to natural turf (grass sports fields). Early studies, comparing first generation synthetic turfs with natural turf, established a relationship between surface type and injury frequency with higher rates on the synthetic surface (Stevenson *et al*., 1981; Keene *et al*., 1980; Alles *et al*., 1979). The mechanical properties suggested to be causally related to injuries were; increased levels of stiffness, sliding friction and heat retention (Guisasola, 2008, p.6). Several recent, larger scale studies have not found a higher rate of acute injuries for the improved third generation synthetic turf when compared to natural turf (Kristenson *et al*., 2013; Ekstrand *et al*., 2011, 2006; Bjørneboe *et al*., 2010). This could indicate that the third generation synthetic surfaces have properties that resemble those of good natural turf surfaces. However, in at least one study with higher statistical power the rate of overuse injuries was found to be higher on synthetic compared to natural turf (Kristenson *et al*., 2013). The subjective definition of injuries as well as the risk of injuries not being reported is described as a major limitation to studies within this field (Dragoo & Braun, 2010). Another limitation is the lack of objective surface assessments, which means that no direct causal relationship can be drawn between injuries and the surfaces' mechanical properties. Interpretations of surface properties related to increased injury rates are often made based on seasonal findings or construction/composition types. Several studies draw generalized conclusions as to which ground properties are related to the actual surface information registered (e.g. surface hardness related to season (McMahon *et al*., 1993), friction/traction related to grass type (Orchard *et al*., 2005). This may be accurate but does provide a limited level of evidence. Petrass & Twomey (2013), systematically reviewed studies looking at specified ground conditions and injury risk. They concluded that objective ground measures were critical to the interpretation of the relationship between sports surfaces and injury risk. Surprisingly, only five of the relevant 27 reviewed studies used such techniques. These limitations were also highlighted in a review by Otago *et al*. (2007), where the authors stated that:

> "The quality of any of the reported links between ground condition factors and injury risk is only as good as the information about the ground conditions at the time of injury."

In addition to studies performed with human athletes, the effect of surfaces on racehorses has also been considered. Thoroughbred racehorses train and compete primarily on three types of surfaces; turf (always natural), dirt and synthetic surfaces. Synthetic racetracks have a top layer composed of sand (usually coated with wax), mixed with different types of synthetic fibers and crumb rubber or polyvinyl chloride (PVC) pieces. They are often referred to as "all-weather tracks", since they are constructed to allow racing under bad weather conditions. Several studies have found different racetrack surfaces to be associated with different injury rates. In many places turf surfaces seem to be associated with a lower risk of acute musculoskeletal injury compared to non-turf (Cruz *et al*., 2007; Williams *et al*., 2001; Hill *et al*., 1986). However, as one author pointed out, conclusions drawn from comparisons of injury rates on different surface types should be interpreted with caution unless confounding variables have been controlled for by using multivariable or multiple regression models (Parkin, 2011). The lower prize money and class of all-weather tracks in British horse racing was given as an example of a cofounding effect. Horses with a lower level of performance are likely to compete in these races and since poorer performance can be due to subclinical injury they could be more likely to sustain catastrophic injuries when racing.

Multiple factors influence injury risks of horse populations at different tracks, e.g. training regimen of the local trainers (Verheyen *et al*., 2006a) and weather conditions (Parkin *et al*., 2005). Different types of races have been associated to different levels of risk, with racing over obstacles being related to elevated injury frequencies compared to flat racing (Parkin *et al*. 2004a; Williams *et al*., 2001; Bailey *et al*., 1998;). This finding could potentially be of some relevance to the show jumper. Studies using statistical models that account for multiple variables are still not conclusive as to the effect of different surfaces. In the United States of America (USA), Hernandez *et al*.

(2001) found that horses racing on turf were at higher risk of injury compared to dirt, whilst Mohammed *et al*. (1991) and Parkin *et al.* (2004a), found that turf was associated with a lower risk of injury compared to dirt and synthetic respectively. As for human athletes, the pattern of injuries in Thoroughbred racehorses (not only injury rates) has been found to vary between surfaces. Parkin *et al*. (2004b) investigated data from postmortem examinations of horses sustaining catastrophic fractures on different track surfaces in the United Kingdom (UK). Lateral condyle fractures of the third metacarpal bone (McIII) and biaxial proximal sesamoid bone fractures were more likely to occur on synthetic surfaces whereas fractures of the proximal phalanx were more frequent on turf.

Surface characteristics of the track are regularly reported, prior to the race or race meeting, in order to provide betters with information. Assessments of going (UK), track condition (USA) and track rating (Australia) are made by official stewards. As an example, the UK scale for turf track going have the following official descriptions: 'hard', 'firm', 'good to firm', 'good', 'good to soft', 'soft' and 'heavy' (British Horse Racing Authority, 2014). Table 1 presents terminology used for racetrack surface characteristics in the UK, USA and Australia. These ratings are mainly based on subjective, experience-based evaluations. For turf, the assessment is often aided by the use of a sharp instrument that is pushed into the ground at multiple points. In the UK and some other countries a commercial device is now in common use as well. The GoingStick (TurfTrax, Cambridgeshire UK) measures the depth of penetration and the resistance of the surface to a forward push of the tool (James *et al*., 2008). These two measurements are combined to provide information for the assessment of the turf surface.

Epidemiological studies of racehorses investigating surface characteristics in relation to injuries use these qualitative or semi-qualitative ratings of going/track condition as surface variables. One such study has shown that catastrophic lateral condylar fractures of the McIII were five times as likely to occur on firm or 'hard ground' compared to races on tracks deemed as 'good to firm' down to 'heavy' (Parkin *et al*., 2005). In this study a threshold above 'good to firm' going was found, above which the risk was greatly increased. Other studies have found a more linear increase in risk related to increased firmness/hardness of the track (Parkin *et al*., 2004a; Williams *et al*., 2001; Bailey *et al*., 1998;). The development of new techniques that enable horse-relevant, objective measures of surfaces (such as on-horse measurements) in combination with training, racing and medical data, has been proposed to offer better understanding of the role the surfaces plays in the development of injury in the Thoroughbred horse (Parkin, 2011).

Table 1. *Terminology used for surface description of racetracks in three different countries*

UK		USA		Australia[1]
Turf	Synthetic	Turf	Dirt/Synthetic	Turf
hard	Fast	firm	fast	firm 1 = dry hard
firm	standard to fast	good	good	firm 2 = firm
good to firm	Standard	yielding	muddy	good 3 = good cushion
good	standard to slow	soft	sloppy	good 4 = track with some give
good to soft	Slow	heavy	slow	soft 5 = reasonable amount of give
soft			sealed	soft 6 = moist but not badly affected
heavy				soft 7= more rain-affected
				heavy 8 = rain affected
				heavy 9 = wet
				heavy 10 = heaviest category

[1.] The Australian system was implemented in December 2014, here presented with a short version of descriptions.

Outside of racing very few studies have investigated how the use of different training or competition surfaces affect injury occurrence in riding horses. Egenvall *et al*. (2013) studied how training and management strategies, and the time spent working on various training and competition surfaces, was associated to 'days lost to training' in show jumpers. 'Days lost to training' is an injury measure describing days of unplanned rest due to health problems. In the study 263 horses, trained by 31 professional riders, in four European countries were followed over time using detailed daily activity records. The records included registration of the type of surface used per activity. Surfaces were categorized according to top layer composition. For horses from one country (Sweden), use of competition surface types was also registered. The Swedish data showed that training/competing on sand-wood was a protective factor compared to not using this surface. Limited training use of sand surface, compared to not training on sand, was a risk factor for 'days lost to training'. This outcome is consistent with the finding from a study by Murray *et al*. (2010a), who retrospectively investigated risk factors for owner-reported lameness in UK dressage horses, using a questionnaire-based design. Surface with sand as the major component were associated to the greatest risk for lameness. However, a small reduction in risk was found the more often a sand surface was used, which was thought to illustrate the process of adaptation of the locomotor apparatus. No objective measurements of surfaces' properties/conditions were included in these studies, which limits the external validity of the results.

In summary, very little epidemiological evidence exists that links surfaces to injuries in show jumping horses. However, there is a body of literature that suggests that an association between the sport surface and injury would be consistent with observations in both human athletes and racehorses. Work for these other types of athletes underline the importance accounting for all of the factors influencing injuries when performing such studies. The complicated task of injury definition needs particular attention (Dragoo & Braun, 2010; Stiles *et al*., 2009). In horses, race-day catastrophic injuries, often fractures, are easier to register compared to non-catastrophic soft tissue injury or other chronic problems. Finally, the definition of surface properties used for studies investigating the link between injuries and surface may be as important as the definition of the injuries (Petrass & Twomey, 2013; Otago *et al*., 2007). Classification of surfaces according to general type or construction brings the risk of making associations weak or non-existing and limits the external validity of the results. Defining mechanical properties of surfaces that would be expected to be associated with specific injury risks would provide the opportunity to understand the properties of existing surfaces which are associated with risk. Reducing the surface risk factor and understanding the difference risk profile for different types of surfaces has the potential to reduce overall injury rates while maintaining acceptable surface performance.

1.2 Discipline-specific injury patterns in show jumping horses

Specific orthopaedic conditions appear to be associated with different athletic activities. This is recognized in human sports medicine. For example, a longitudinal study of 1,818 school children showed that broad categories of sports activities were associated with certain diagnoses (Backx *et al*., 1991). The duration of competitive life in warmblood horses has been found to be shorter in the jumping discipline compared to dressage (Ducro *et al*., 2009). Much of the evidence of discipline-specific injuries in horses is based on clinic material with its inherent risk of referral bias. Scintigraphic studies of exercise induced bone response in horses have indicated that there are unique stresses to the bones of horses used for jumping (Ehrlich *et al*., 1998; Metcalf *et al*., 1990). In the study by Ehrlich *et al*. (1998) all 144 horses included in the study were engaged in jumping activities. As such, no discipline related comparison with non-jumping riding horses in the same clinical setting was done. However comparison of the anatomical location of scintigraphic findings within this group indicated that the distal fore limbs showed most frequent signs of exercise induced bone response related to lameness. The proximal phalanx was the bone with most changes, followed by the middle and distal phalanges. In a more recent study by Murray *et al*. (2006) sport discipline and the level of performance of horses referred to a clinic under a five year period were analysed in relation to type of injury. Results showed that show jumpers (75 at elite level and 104 non-elite) had a relatively higher risk of injury to the superficial digital flexor tendon and distal deep digital flexor tendon compared to the risk for horses used for general purpose. The most common injury in elite show jumping horses in this study occurred in the suspensory ligament, followed by the distal deep digital flexor tendon. Non-elite show jumping horses were more frequently injured at the navicular bone/ligaments. In the study by Egenvall *et al.* (2013), where risk-factors associated with 'days lost to training' in show jumpers were investigated, professionally ridden horses of several age groups and competition levels were included. In total 39,028 days at risk were registered of which 2357 (6.0%) were 'days lost to training'. Out of these, 77% resulted from orthopaedic problems. The main diagnoses/reasons were: accidents (20% of the lost training days), inflammation of the metacarpophalangeal or metatarsophalangeal joint (13%), ligament disorders (13%), hoof problems (12%), and back problems (11%). The data often included many short periods of convalescence for the orthopaedic conditions. The short periods were suggested to be related to the use of prophylactic treatment strategies that include one or a few days of recommended rest. However, the case definitions in this study were limited by the involvement of trainer-specific veterinarians. Also, in contrast to the data registered from a referral clinic (Murray *et al*., 2006), Egenvall *et al.* (2013) included many mild problems.

A review by renowned veterinary clinicians and clinical researchers lists the ten most common lameness problems in show jumpers and show hunters (Boswell *et al*., 2011, p. 1100). Foot pain followed by distal hock joint pain and suspensory ligament desmitis were cited as the most common problems in their experience.

The discipline-specific injury pattern in show jumpers is far from well understood. Structures in the distal limb associated with energy absorption at the impact and loading seem to be cited as carrying the highest risks of injury. While more epidemiological data are needed, the study of the forces occurring at the horse-surface interface can provide more information that can help the process of understanding loading of internal structures of the horse's locomotor apparatus.

1.3 The biomechanical interaction between the horse and the surface

Biomechanical information on the horse-surface interaction is important in the process of improving horse health through identification of risk-associated surface properties. More specifically the information is required in order to guide construction of surface testing devices that can evaluate relevant surface properties (Nigg, 1990) and to raise hypotheses regarding loading conditions and surface properties that can be related to injuries (Thomason & Peterson, 2008). Further, it is required to provide input to the process of discovering injury mechanisms related to loading of internal structures of the limb (van Weeren, 2010) (see figure 1).

Technical development and affordability of sensors that can record movements, forces and strains have led to a substantial increase of knowledge in this field. Both kinematic methods, describing motion in terms of displacement, velocity and accelerations as well as kinetic methods describing forces are used to understand how actions from the horse result in loads at the hoof-surface interface. The use of equipment mounted under or on-hoof has contributed with relevant data. These portable methods provide the opportunity to study horse-surface interaction at exercise or competition speeds on actual training or competition surfaces.

In every step the horse meets the surface through two overlapping collisions. The first collision occur between the most distal segments of the limb pendulum (distal phalanges) and the ground, followed by a collision between the descending central mass of the horse and the fairly well planted hoof and limb (Thomason & Peterson, 2008).

The impact phase of the stance is described by Thomason & Peterson (2008) as occupying the first third of the stance duration and to be subdivided into two impacts, a primary and a secondary. They are related to the two collisions presented above, but describe two phases of movement of the hoof on the surface. Many authors do not make this subdivision. Instead they speak of one foot impact phase followed by the loading in the support phase (Parkes & Witte, 2015; Parsons *et al.*, 2011). The primary impact, when the hoof first collides with the surface is described as a 'low mass high acceleration event'. Forces are applied over a short time span and the hoof is rapidly decelerated. The secondary impact is often overlapping and is attributed to the beginning of the second collision between body and surface putting increasing load on limb and hoof. This produces a second forward push of the hoof, which is most evident if the surface is firm, allowing little vertical penetration of the hoof.

1.3.1 The hoof-surface impact

The first foot impact, primary impact, is often described as an 'impact shock', that sends shock waves up the horse's limb (Gustås *et al*., 2001). The mechanics of collision dictate that this event is affected by the momentum of the impacting object (effective mass times velocity), the area of contact and the stiffness of the surface and of the impacting object (shoe and involved distal segments). The proportion of the horse's mass involved in this collision (only hoof or also more proximal segments?) has been investigated in some recent studies. Warner *et al*. (2013) computed the effective mass involved in the impact at slow trot. In the forelimb 0.53%, and in the hind limb 0.19%, of the horse's body weight (BW) was engaged in the collision (see Supplementary table 12, in Warner *et al*., 2013). This would correspond to the weight of the limb up to the fetlock (Nauwelaerts *et al*., 2011; Buchner, *et al*., 1997; Sprigings & Leach, 1986). Whereas Munoz-Nates *et al*. (2015) presented figures for the effective mass of 0.27% and 0.26% of BW or 1.39-1.37 kg in fore and hind limbs respectively in a 522 kg horse studied at high speed trot. In a third study Chateau *et al*. (2010) calculated a higher figure, < 5 kg for the mass involved. These studies do not reach a consensus on whether only the hoof or also the proximal phalanges are engaged in the primary impact.

The velocity of the hoof just prior to impact has been recorded to as much as 8 m/s at the gallop (Parsons *et al*., 2011). The horizontal motion of the hoof is not decelerated as instantly as the vertical, which is especially evident on many hard ground surfaces (Chateau *et al*., 2010). Alterations in hoof landing velocities have been related to changes in surfaces' deformability and ground reaction force (Chateau *et al*., 2010; Crevier-Denoix *et al*., 2010; Burn & Usmar, 2005) but it remains unclear if these changes relate to actions by the horses in order to accommodate impact, or the subsequent loading, or if it is a passive surface effect leading to changes in the dynamics of locomotion.

The lateral heel is cited as the most common point of first contact between the hoof and the surface (Wilson *et al*., 2016; Chateau *et al*., 2010; Chateau *et al*., 2006; van Heel *et al*., 2006). The hoof orientation at landing is affected by gait (with a more heel oriented landing at the walk compared to the trot), hoof conformation (a more acute dorsal angle leads to increased toe-first tendencies) and it shows a substantial inconsistent pattern within individuals (Wilson *et al*., 2016). A 'heel first' hoof impact has been found to produce higher impact accelerations compared to flat or 'toe-first' impacts in a cadaver study (McCarty *et al*., 2015a).

Hoof-mounted accelerometers are the preferred types of sensors for recording the primary impact given the high frequencies of this phenomenon (Munoz-Nates *et al*., 2015; Thomason & Peterson, 2008; Burn *et al*., 1997). Recorded decelerations traces are characterised by a high vertical and a considerably smaller horizontal deceleration peak (e.g. Chateau *et al*., 2010; Gustås *et al*., 2004). Variations in the patterns have been found to exist between strides (Gustås *et al*., 2006a, b; Ratzlaff *et al*., 2005; Barrey *et al*., 1991;) and systematically between horses (Chateau *et al*., 2010).

The vibration frequencies of the impact shock arising from the hoof-surface collision are efficiently dampened as they spread up the limb (Gustås *et al*., 2001; Willemen *et al*., 1999; Lanovaz *et al*., 1998). In vitro, simulating impact at higher speeds, considerable energy has been recorded to remain at the level of the McIII with possible implications to limb soundness (McCarty *et al*., 2015a). A surface that produces a longer impact duration and that specifically allows a certain forward slide of the hoof at impact is believed to reduce the stress from this event (Gustås *et al*., 2001) and also to reduce strain on the proximal phalanx under the following loading (Singer *et al*., 2015).

The repetitive impact shock experienced by the horse in this first collision is an often cited cause of bone injury and joint disease (McCarty *et al*., 2015b; Munoz-Nates *et al*., 2015; Chateau *et al*., 2010; Burn *et al*., 1997; Hjertén & Drevemo, 1994;). There seem to be a dearth of recent evidence to support a direct link between this biomechanical events and pathology, but early studies of rabbits and sheep did established such a link (Radin *et al*., 1982; Serink *et al*., 1977; Dekel & Weissman, 1978).

1.3.2 The support phase

Thomason & Peterson (2008) describe the support phase to extend from 5–90% of the duration of stance. The division of the stance phase into separate events is relevant, but can be complicated given the overlap of events as well as their patterns dependence of limb function and surface characteristics. During support the accelerations on the hoof cease and the weight of the horses central mass is transferred to the hoof. In contrast to the primary impact this is a 'low acceleration high force' event. At the hoof surface interface force measuring shoes have enabled relevant studies of the loads arising in this event (Chateau *et al*., 2009; Roland *et al*., 2005). The load increases rapidly and the rate of loading varies up to the mid stance peak (Setterbo *et al.*, 2011; Robin *et al*., 2009). The vertical loading rate has been seen to increase linearly with speed at the trot (Crevier-Denoix *et al*., 2014a). During the load increase there is an associated bending force on the McIII (Pratt, 1997). The vibrations present in the limb at this time are dampened by the superficial and deep digital flexor muscles (Wilson *et al*., 2001). The peak in vertical force is reached at around mid stance. Peak values vary with limb type (leading or trailing) gait, speed, surface (Crevier-Denoix *et al*., 2010; Setterbo *et al*., 2009) and have been reported to approach 2.5 times the body weight at a fast gallop (Witte *et al*., 2004). During the support phase the horizontal force starts out braking the body's forward motion, then moves to zero and changes to propulsive force (Schamhardt *et al*.,1991).

The magnitude of the load and the peak rates of loading are logically associated to occurrence of injury. The alignment of the bone segments and direction of application of the force vectors are thought to be important for safety aspects during limb loading (Singer *et al*., 2015) and can be affected by fatigue (Butcher *et al*., 2007). Bone responds with increased strength when cyclically loaded and the strength is achieved in the direction of loading (Firth, 2006) which could mean that unexpected loading directions could be hazardous.

1.3.3 The roll over

The roll over (also called breakover or lift-off) is the last part of stance where the hoof again starts to move. If the surface top layer is soft the toe rotates into the substrate as the centre of pressure moves towards the toe (van Heel *et al*., 2004). Properties of both hoof, shoe and surface are said to influence the stress applied to the deep digital flexor tendon at this event (Parkes & Witte, 2015; Weishaupt, *et al*., 2014).

1.3.4 Specific challenges for the show jumping horse

In human sports, jumps are considered to increase the risk of injury (Backx *et al*., 1991; Dufek & Bates, 1991). As earlier mentioned such indications have been found for racehorses where races over obstacles are associated with higher injury rates compared to flat races (Parkin *et al*. 2004a; Williams *et al*. 2001; Bailey *et al*. 1998). In the warmblood riding horse the duration of competitive life is shorter for jumping than for dressage (Ducro *et al*., 2009).

Biomechanical data describing the hoof-ground interaction in show jumping at high level are scarce, but growing evidence suggests that loads on the forelimbs during jump landing may place high demands on the horse. In the literature it has been suggested that the trailing fore limb of a horse jumping a fence of 1.5 m or above, would experience a peak vertical load considerably higher than two body weights, although very little evidence currently exists to support this (Schamhardt *et al*., 1993). The stance duration of the trailing limb during landing is reported to be shorter than the leading (Clayton & Barlow, 1991a; Deuel & Park, 1991). In Grand Prix jumping horses the trailing forelimb is described as aligned almost vertically on landing, whereas the leading limb is more horizontally oriented (Clayton & Barlow, 1991a). The trailing limb experiences higher peak loads and loading rates (Crevier-Denoix *et al*., 2015a, 2013a,; Schamhardt *et al*., 1993), higher joint moments (Meershoek *et al*., 2001a) and increasing flexor tendon loads with increasing jump height (Meershoek *et al*., 2001) compared to the leading limb. The leading limb with its more horizontal orientation on landing (Clayton & Barlow, 1991a) experiences higher braking forces (Crevier-Denoix *et al*., 2015a, 2013a; Schamhardt *et al*., 1993), and greater hoof slide (Meershoek *et al*., 2001).

Fence heights and the speed at which the fence is approached has been said to be of decisive importance to energy changes during the jump (Bobbert & Santamaría, 2005). High speed turns are also an important task during show jumping and may be associated to increased injury risk. Only limited information is available describing the biomechanics at such events (Crevier-Denoix *et al*., 2014b).

1.3.5 The shoe –a factor in the hoof-surface interaction

When studying hoof-surface interaction the shoe is inevitably at the centre of events. The addition of a shoe or alteration in hoof shape by trimming is suggested to influence this interaction due to several factors. The weight changes to the distal segment can effect inertia of the limb during the swing phase, the material properties of the impacting object (hoof and shoe) and the shape of the contacting surfaces can alter the conditions of the interface and the biomechanics of the hoof during loading and roll-over (affected by changes in lever arms, support area, restriction of heel expansion etc.). Changes to medio-lateral and heel-toe balance of the hoof displaces the point of force application and affects the unloading pattern (Wilson *et al*., 1998). Adding shoes to an unshod hoof and the use of different shoe designs and shoe materials are recorded to alter the hoof's swing phase trajectory, impact conditions and roll-over (Back *et al*., 2006; Dallap *et al*., 2006; Roepstorff *et al*., 1999; Benoit *et al*., 1993).

1.4 Design and materials in show jumping surfaces

Surfaces in human sports are often described as natural, artificial or synthetic (Bartlett, 1999). A natural surface is formed by the preparation of an area and includes turf (grass), loose mineral layers, ice and snow (Nigg & Yeadon, 1987). Artificial surfaces are man made whereas synthetic surfaces are man made and also have a major polymeric component, such as various elastomeric surfaces and artificial turf (Bartlett, 1999).

In the show jumping sport most surfaces would be classified as artificial. Situated indoors or outdoors these surfaces use construction principles with a loose upper layer (normally composed of sand), which allows motion of the hoof early in the stance phase, supported by an underlying firm base. Worldwide, there is a great variation of materials used in surfaces for equestrian sports (Hobbs *et al*., 2014). During the outdoor season show jumping competitions are often held on natural turf surfaces. Different types of synthetic surfaces are common as well (Murray *et al*., 2010b; Egenvall *et al.*, 2013) where hydrocarbon paraffin-based high-oil content waxes, rubber particles, polymer fibers, PVC pieces and cloth or felt strips in different proportions are used to mix with the sand in the top layer (Bridge *et al*., 2014; Hobbs *et al*., 2014). Synthetic material can also be part of the base layers. Some arena producers use polymeric mats under the top layer sand in both temporary competition arenas and permanent installations. These mats are said to regulate water content, provide shock absorption and provide stability. In Swedish arenas it is not uncommon to find a layer of rubber pieces underneath the top layer but above the aggregate base (Egenvall *et al*., 2013). This is thought to provide area elasticity to the surface –a deflection of a larger area of the surface in response to loading (Nigg & Yeadon, 1987). This construction type arose from the work with track safety in trotters performed by professors Fredricson and Drevemo, starting in the seventies. In addition to changes in track geometry (Fredricson *et al*., 1975), force reducing base layers of woodchip were used (Drevemo & Hjertén, 1991) which was then adapted for riding arenas as ‘rubber grounds’.

The granular composite materials, sands with or without additives, used in the top layer of equestrian surfaces can be thought of as composed by a ‘mineral skeleton’ of sand particles with pores between them that are partly filled with air and partly with water. The amount of pore space (the degree of compaction) is important to the surface function and is routinely adjusted by mechanical maintenance like harrowing and rolling. The effect of such maintenance differ for different material compositions (Tranquille *et al*., 2015). Particle size distribution, particle shape and water content will all affect how easily the material compacts (Hobbs *et al*., 2014). The compaction of material in response to loading by the hoof, is an important feature of the surface in order to provide energy dissipation during horse-surface collision (Setterbo *et al*., 2009). With use, increased compaction will affect the loading response of the material, with higher loads experienced by the horse (Kai *et al*., 1999).

Therefore the material should preferably be somewhat compliant under loading and at the same time resist excessive compaction. Appropriate choice of sand sorting, water content and help from additive materials are used to accommodate this demand. The addition of fibres and rubber particles is shown to add elastic recovery from impact and reduce compaction (Serensits *et al*., 2011; Setterbo *et al*., 2011).

The pore size is also important for the permeability (drainage) and water holding capacity of the material (Caple *et al*., 2012). Retained water creates tension forces between particles and in pores, providing an apparent cohesion in the material. This increases the shear resistance of the surface. But the *amount* of water is of imperative importance. The apparent cohesion is removed when the material is very dry or saturated. When saturated, water pressure builds up between particles. In both cases particles can slide past each other more easily, resulting in a low resistance to shear (Powrie, 2009). The degree of compaction will additionally affect the shear strength by altering the particle contact area (Lewis *et al*., 2015) which increases the frictional forces between particles as they are forced to roll or slide against each other. The particle shape will also be of importance to this, with less friction between rounder particles (Bridge *et al*., 2014). Addition of fibre is another method to stabilize the material in order to increase shear resistance (Baker & Richads, 1995). Likewise, addition of wax produces a strong cohesion of the material (Lewis *et al.*, 2015; Orlande *et al*., 2012), which allow for selection of a sand with larger pore sizes that will provide good drainage, like the ‘all-weather’ synthetic surfaces. Thus, reducing the effect of water has been said to decrease the variability of these surfaces in racing (Peterson *et al*., 2012). Wax, is however sensitive to changes in temperature (Bridge *et al*., 2015), which creates different surface responses to the horses, evident by changing race times (Peterson *et al*., 2010).

The granular composite materials used in surfaces for equine sports have a non-linear character in response to loading. Most often they show an increase in stiffness when load increases in vertical and horizontal directions (Lewis *et al*., 2015). This is partly related to increased material compaction and means that a change in applied load magnitude will not produce a linear change in amount of deformation. The stratification of the materials of the entire surface construction further complicates this, since the different layers can have different material characteristics (as seen in the force-displacement plot in Crevier-Denoix *et al*., 2015b). The materials are also strain rate sensitive, meaning that changing the loading rate applied to the material will have different effects on the response. This is connected to the viscoelastic properties of the materials. Hobbs *et al*. (2014) describe that the nature of the deformation of an arena can be divided into: a) elastic: deflects under load but recovers completely to original shape as load is removed, b) plastic: deforming without recovery and c) viscoelastic: having some elastic characteristics but will also deform due to viscous flow which is not recovered. Guisasola *et al*. (2010) described the soils used in human sport surfaces as having a viscoplastic behaviour when subjected to the first cycles of repetitive dynamic compression and more viscoelastic in later loading cycles.

Many choices in the construction, material selection and maintenance will affect the complex behaviour of the show jumping surface. Integrating knowledge from the field of soil science with biomechanical information on loading conditions at the hoof-surface interface can produce a leap forward in the understanding of how we can control surface properties.

1.5 Assessment of surface mechanical behaviour and functional properties

The term 'functional property' is used to describe the mechanical behaviour of surfaces in response to the physical forces applied by the horse and how it 'feels' to the horse and rider (Hobbs *et al*., 2014). In addition the functional properties are thought to be of importance to the horse's orthopaedic soundness and performance. It is a complicated matter to understand which specific characteristics in the mechanical behaviour of the surface that are most critical to this aspect and at what levels and rates of loading they should be assessed.

The use of horse-mounted equipment that registers the response from the surface ensures the measurements' relevance to the horse. Still, choosing appropriate parameters from recorded signals in the time or frequency domain has to be done with care. The variability in the horse's loading patterns attributed to individuals, movements, stride-to-stride and even limbs-within-stride variations adds to the complexity. On-horse registrations of surface responses incorporate this variability and are therefore limited in their ability to make standardised between-surface comparisons.

Assessment of human sports surfaces in-situ, is routinely made since the eighties, using mechanical test devices that imitate critical portions of the athlete-surface interaction (Caple, 2011). These devices have the advantage of being fast, cheap and more reliable compared to biomechanical measurements of athletes (Kolitzus, 2003). Evaluation of how well these devices represent important biomechanical events is an ongoing process (Guisasola, 2008; Stiles *et al*., 2007) and development of new test equipment is made to accommodate assessment of more specific sports conditions (Caple *et al*., 2011).

For equine surfaces, several in-situ test devices have been used (Setterbo *et al*., 2013; Peterson *et al*., 2008a; Oikawa *et al*., 2000; Ratzlaff *et al*., 1997; Drevemo *et al*., 1994; Clanton *et al*., 1991; Pratt, 1984; Cheney *et al*., 1973;), with the more recent emphasizing the importance to be commensurate to the loading pattern of the horse-surface interaction.

As described earlier very few studies have tried to associate injury or performance to mechanical specifications of surface behaviour. However, biomechanical studies of the hoof-ground interface have provided hypotheses-generating information regarding the importance of specific surface features. Parkes & Witte (2015) suggested that impact, peak load, grip and vibration all play essential roles in the link between surface, performance and injury.

Certain mechanical properties of sports surfaces have been acknowledged for their effect on the biomechanics of human athletes during locomotion, and some have been cited as factors causing injuries (Caple, 2011; Kerdok *et al.*, 2002). The two most important characteristics acknowledged by several authors are behaviour during impact (vertical loading), and the horizontal behaviour relating to the grip of shoes on the surface (Petrass & Twomey, 2013; Stiles *et al.*, 2009; Orchard, 2002; Nigg, 1990). To some extent these surface properties are said to be a 'double-edged sword', where ultimately high performance and safety are antagonists (Hobbs *et al*., 2014; Stiles *et al*., 2009).

Vertical loading

The surface's response to vertical loading is described by several terms and mechanical properties.

Stiffness, refers to the deformation of the material in response to loading, the stress-strain behaviour. The level of strain (deformation) exhibited for a certain level of stress (load) is typically quantified in terms of moduli, determined from the slopes of stress-strain loading curves (Bridge *et al*., 2014).

Hardness, does not have an unequivocal use in the literature. In general terms it is often said to describe the ability of the surface to absorb impact forces (Orchard, 2002). This frequently refers to the plastic (permanent) deformation of the ground where impact energy is lost through hysteretic strain. Hardness is sometimes used interchangeably with 'firmness' (Parkes & Witte, 2015) or surface 'strength' (Caple, 2011). The decrease of peak loads or peak accelerations by prolonging the time of impact through deflection can however be achieved also by elastic deformation. In fact, hardness is also described as a function of a number of physical properties including stiffness and resilience (Baker & Canaway, 1993). Reduction of the amplitude of the impact peak from a collision between the athlete and the surface is often also called ‘cushioning’ (Benanti *et al*., 2013). Practical measurements used to assess hardness often include a collision between the surface and an object where peak force of deceleration is measured. The methods used apply very different pressures to the surface by either using flat-faced impactors (e.g. Clegg, 1980) assessing ‘impact-hardness’, or a pointed devices (e.g. Orchard *et al*., 2005) assessing ‘penetration-hardness’.

Biomechanical data show that the vertical loading conditions provided by the horse is composed of two events, created by the two collisions occurring between the hoof and surface, and then between the central mass, the hoof and the surface, as described in section 1.4. These events are overlapping and sometimes undistinguishable in the load trace recorded under-hoof, depending on limb action and surface characteristics. However, since load magnitudes, loading rates and masses involved in these events are conceptually different, it seems logical that the vertical behaviour of the surface response should be assessed by representation of the two distinct events. Hobbs *et al*. (2014) point out that stiffness of the surface will be influenced by the surface top layer during the primary impact, but then as more force is applied it will reflect the response by the entire surface composition, including the base materials.

In terms of performance and safety the vertical behaviour of the ground in response to the collisions with the horse, has partly opposing effects. In order to minimize potentially harmful forces on the locomotor system, the vertical stiffness and hardness should be low (cushioning high). But the surface also needs to be supportive enough to allow ‘efficient’ movement. Lower peak forces and a prolonged time to peak load recorded in the support phase have been seen to relate to higher stride frequencies in order to keep a constant speed (Crevier-Denoix *et al*., 2010; Robin *et al*., 2009). However, the increased energy consumption in locomotion related to less stiff/less hard surfaces (Sloet van Oldruitenborgh-Oosterbaan *et al*., 1991), is also thought to be a risk factor creating fatigue-related injuries (Butcher *et al*., 2007).

Energy return

It does not always seem to be the case that increased stiffness relates to increased performance and decreased energy consumption. The concept of a surface ‘tuned’ to the human athlete has been introduced in early work (McMahon & Greene, 1979). They calculated the time required to rebound from a running track as a function of track compliance. The matching of the stiffness of the track to the spring stiffness of the runner resulted in development of a surface that was claimed to produce faster running times, improved comfort and reduced incidence of injury compared to the original ‘untuned’ track that had a higher stiffness. Decreased stiffness of a surface has been associated both to decreased metabolic rate (Kerdok *et al*., 2002) and to significantly higher energy cost (Binnie *et al*., 2014). The difference is thought to relate to the elastic component of the surfaces deflection as well as the tuning (Kerdok *et al*., 2002). The perfect tuning of an equestrian surface seems to be a very complex matter. The horse limb is described as composed of two springs in series (McGuigan & Wilson 2003). Also the rate of loading and load magnitude differ substanially between different movements and individuals, which will provoke different responses in terms of stiffness from the surface given the non-linearity and strain rate dependency of the material.

Horizontal loading

Biomechanical data show that loading of the surface material in the horizontal plane is done with different load magnitudes, load rates and directions also within single stance phases. This makes the assessment of friction or resistance to shear of the material complicated to assess with a single test device (Lewis *et al*., 2015) that should be relevant to the horse. As for human athletes the shear strength can probably be both too low and too high from an injury perspective (Stiles *et al*., 2009). The need for the hoof to move freely on the surface during primary and partly during secondary impact, has been said to be of importance to the dissipation of impact forces (Gustås *et al*., 2006b). At the same time, slip during impact and push-off is often considered to be a problem relating to injury (Clayton *et al*., 1991b).

Functional properties of equestrian surfaces can be categorically characterised by the response to the types of loading events described here. The simplification of the response into single measureable parameters is a challenge. Also the standardized magnitudes and rates of loading applied by in-situ test devices can bring questions regarding the relevance to the horse. However, accurate and reliable surface measurements as well as comprehensible and unequivocal descriptions of surface characteristics are critical to the research relating surface to injury and performance (van Weeren, 2010). An increased understanding of the surface's mechanical behaviour in response to relevant loading conditions and how this relates to material composition, arena design and maintenance would ultimately provide insight into specific mechanisms relating surfaces to horses' performance and injury.

2 Aims of the thesis

The general aims of this thesis were to study the discipline-specific interaction between the hooves of show jumping horses and relevant training and competition surfaces and to evaluate functional properties of show jumping surfaces by using a biomechanically based mechanical test device and subjective rider assessments. This was done in order to enable objective comparisons between surfaces, which are needed in order to enable future investigations of risk- and performance-associated properties of show jumping surfaces.

The specific aims were to:

- Investigate the hoof landing and hoof braking characteristics of the leading/trailing fore/hind limbs respectively of elite show jumping horses that jump 1.30–1.50 m competition fences on two different surfaces using high-speed video (Paper I).
- Describe hoof accelerations, from first hoof impact to hoof standstill, for different strides and for functional limb types relevant to the show jumping horse (Paper II).
- Study the influence of two specified arena surfaces on peak hoof impact deceleration at hoof landing in jumping horses, with one surface measured at two levels of water content (Paper III).
- Semi quantitatively compare on-hoof-measurements of peak impact decelerations to impact decelerations of a mechanical surface tester used on two specified arena surfaces, with one surface measured at two water content levels (Paper III).
- Investigate the material composition and to quantify the dynamic behaviour in-situ of high-level show jumping competition and warm-up arenas (Paper IV).
- Compare subjective and objective assessment of functional properties of show jumping competition and warm-up arenas (Paper IV).

3 Hypotheses

The following hypotheses were raised:

- Kinematics of hoof landing and hoof-surface impact are different for trailing and leading, fore- and hind limbs respectively as well as for different stride types in show jumping horses (papers I and II).
- Surfaces with different composition and water content will have different effect on the hoof-surface impact in show jumping horses (paper III).
- A mechanical surface tester will compare show jumping surfaces' impact firmness in a comparable way to on-hoof measurements (paper III).
- There is an association between subjective and objective assessments of functional properties of high level showjumping arenas (paper IV).

4 Material and methods

In this section, a general description of materials and methods used in the studies performed for this thesis is presented. Details regarding procedures can be found in each of the papers. The Uppsala Ethical Committee on Animal Research approved the research protocols and procedures involving the use of animals.

4.1 Study designs (papers I-IV)

Paper I: The aim of this observational study was to register how hooves of show jumping horses approach and impact the ground in jump landings during elite level competition. Digital high-speed video recordings of the landing distal limbs of horses were made during one international Concour de Saut (CSI) 2* and one national elite-level show jumping competition in Sweden during the outdoor season. The competitions were selected as accessible high ranked events in the geographical region around Stockholm during May and June 2009. Landing spots were chosen based on distance to the arena border. The camera was placed safely outside the arena, but was close enough to provide a good field-of-view. The location for registration was also chosen to make sure that the approach and departure from the jump was in a straight line in order to minimize errors due to out of plane movement. The study design allowed no interaction with the subjects. Thus, markerless tracking was performed to study hoof movement in the recorded files from within the calibrated area.

Paper II and III: An experimental study was designed to investigate hoof-surface impact accelerations in horses during canter, jump take-off and landing. Three riders, who rode the same horses throughout the experiment, and five warmblood show jumpers, were recruited from the Equine Studies program at the Swedish University of Agricultural Sciences. All four hooves of the horses were equipped with two uniaxial accelerometers mounted orthogonally on the lateral hoof wall. Fences were randomly varied for each horse between two types (up-right/oxer) and three heights (0.9-1.3 m, adjusted to the horses' competition levels). To enable a preliminary investigation of how surface type and level of water content affected hoof-surface impact accelerations, the experiment was repeated in two arenas with one of the two surfaces tested at two levels of water content. An in-situ surface testing device (OBST) was used to record impact accelerations on the surfaces that could be compared to corresponding parameters from the horses' hooves.

Paper IV: The study was designed to describe the construction, material composition and functional properties of show jumping competition and warm-up arenas in highly ranked events (CSI 4-5*) by objective and subjective methods. We also aimed to investigate how the objective, in-situ measurements of arena functional properties from an OBST, were associated with top-level riders' perceptions of these properties. Nine international show jumping events, in six European countries, were selected based on the likelihood of having the same riders participate in several events and for geographical accessibility to facilitate moving the test equipment. Twenty-five competition and warm-up arenas in these events were assessed. A questionnaire was developed for the subjective assessments of the arenas. All riders on the starting lists for the events were asked to evaluate the surfaces subjectively using visual analogue scales.

4.2 Study populations (papers I-IV)

4.2.1 Horses

A summary of information regarding the horses included in studies I-III are presented in table 2. Since hoof-ground interaction was studied in these horses, the available level of information about shoeing is included in the table. In paper IV no horses were directly observed. However riders' assessments of the surfaces were made after riding one or several horses on the arenas. In this sense the group of ridden horses acted as a mediator for the riders experience of the surfaces' properties. Details of the horses' attributes were not compiled, but given the regulations of the competitions in which the study was performed, the age group of the horses was greater than seven years. In order to qualify for these competitions the horses must have been at the top performing level in the international show jumping sport. Mares, geldings and stallions from different warmblood breeds and Thoroughbred-warmblood crosses are normally represented in this group (Boswell et al. 2011).

Table 2. *Summarized data for horses in studies I-III.*

Study	Number of horses per study	Breed	Age mean ± standard deviation	Sex	Competition level	Shoeing
I	39	European warm-bloods	10.4 ± 2.3 years	18 mares 17 geldings 4 stallions	National elite International CSI 2* (1.40-1.45 m fence heights)	Information on shoe types not available Screw-in studs were used on the turf arena
II and III	5	European warm-bloods	10.6 ± 2.9 years	2 mares 3 geldings	Novice (1.10 m) to Intermediate, (1.30 m)	All horses wore regular steel shoes

4.2.2 Arenas

Information about the arenas included in the studies performed for this thesis is summarized in table 3. In total 29 arenas were studied, of which 70% had a sand-fibre top layer, 14% turf, 10% sand and 3% (one arena each) sand-woodchip and waxed sand-fibre. In the temporary arenas (66%) surface material was placed on top of existing floors in indoor sports arenas. Permanent arenas generally use a multi-layered base construction of compacted aggregate.

Table 3. *Summarized data for arenas in studies I-IV.*

Study	Arenas per study (n)	Indoor/ Outdoor	Type of top layer composition	Temporary / Permanent	Primary use: Training/ Competition/ Warm-up	Material specification available
I	2	Outdoor	Sand	Permanent	Training and competition	No
		Outdoor	Turf	Permanent	Competition	No
II & III	2	Indoor	Sand-Fibre	Permanent	Training and competition	Yes, in paper III
		Indoor	Sand-Woodchip	Permanent	Training	Yes, in paper III
IV	25	Outdoor	Sand	Permanent	Warm-up	Yes
		Outdoor	Sand	Permanent	Warm-up	Yes
		Outdoor	Turf	Permanent	Competition	No
		Outdoor	Natural turf	Permanent	Warm-up	No
		Outdoor	Natural turf	Permanent	Warm-up	No
		Outdoor	Sand-Fibre	Permanent	Competition	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Competition	Yes
		Outdoor	Sand-Fibre	Temporary	Competition	No (missing)
		Outdoor	Sand-Fibre	Temporary	Warm-up	No (missing)
		Indoor	Sand-Fibre	Temporary	Warm-up	No (missing)
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Competition	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Competition	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Competition	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Warm-up	Yes
		Indoor	Sand-Fibre	Temporary	Competition	Yes
		Indoor	Sand-Fibre with waxed sand below	Temporary	Competition	Yes
		Indoor	Waxed sand-Fibre	Temporary	Warm-up	Yes

4.2.3 Riders

The riders (n=3) included in the experiment described in papers II and III were second and third year students at the Equine Studies Program at the Swedish University of Agricultural Sciences in Sweden. All of the riders were female, aged 22-26 years who weighed 52-65 kg and competed at intermediate to advanced level (1.20 to 1.40 m fence heights). Age, weight and gender, and weight were not recorded for the riders in studies I and IV. All of these riders were from the elite ranks for the sport, and in study IV the riders were at the very top international level.

4.3 Kinematic methods (papers I, II, III)

The cinematographic recordings of hoof movements prior to and during surface impact in paper I were performed using a digital high-speed camera (Fastec Imaging, TroubleShooter 1000). The recording rate was 1000 frames/s and the resolution 640 x 480 pixels. The height over ground of the camera aperture was 98 cm and the horizontal distance to the expected centre of landing area 320 cm. The camera was tilted approximately 17° downwards. Calibration was made by filming a folding ruler, giving a vertical and horizontal reference, at three different distances from the camera in the region of interest that provided calibration factors accommodating for hoof landing position (in depth). A software for markerless tracking (Qualisys Video Analysis, QUALISYS) was used to determine the movements of four points on each hoof using pattern recognition algorithms. Based on these data, the best fit rigid body transformation were calculated in MatLab (MathWorks Inc.), after application of a fourth order forward-backward Butterworth low-pass filter with a cut-off frequency of 200 Hz. This resulted in 2 translations and one rotation (hoof pitch). Total landing speeds as well as vertical and horizontal components, were calculated as an average from position data over 5 ms pre-impact. The angle between the horizontal plane and the movement path of the landing hooves was determined by calculating a continuous slope (regression) over 6 consecutive data points prior to impact. From the moment of first contact with the ground to the end of hoof braking, the maximal value for vertical deceleration and the maximal value of horizontal deceleration were calculated. The temporal differences between these peaks were described.

The acceleration data from hoof-surface impacts in paper II and III were produced using two single axis ± 250 g accelerometers (ADXL193, Analog Devices) attached to the hoof by a metal fixture (total weight of 22 g). The accelerometers were placed orthogonally in vertical and fore-aft direction.

Signal wires from the accelerometers were plugged into a 14-bit data logger (DataLOG MWX8, Biometrics) which was carried by the riders in a waist bag. Sampling rate was set to 1000 Hz. From the collected data, 15 strides around the jumps were selected with a custom written MatLab script. The signal was filtered with a fourth order forward–backward low-pass Butterworth filter with a cut-off frequency of 400 Hz. In the impact complex at the beginning of the stance, the peak vertical deceleration was identified. The range between maximal horizontal deceleration and acceleration was used as a measure of the magnitude of horizontal ground interaction during impact. The quotient of the acceleration vectors was calculated in order to describe the relation between the horizontal and vertical ground interaction in the early hoof-surface interface. Break duration was calculated as time in milliseconds from the first vertical deceleration peak to hoof standstill. Each impact was classified as leading or trailing forelimb or hind limb respectively and stride types (canter, jump take-off or landing) was assigned.

4.4 In-situ measurements of functional properties using the Orono Biomechanical Surface Tester (papers III and IV)

The OBST was used for objective, standardized surface assessment in paper III and IV. The device interacts with the surface in both vertical and horizontal directions. A metal hoof connected to a heavy mass, guided by angled rails, was dropped on to the surface (see supplementary material to paper IV). As the hoof impacts the ground the falling mass above transfers additional load onto the hoof by a shorter vertical axis compressing the spring and damper, at the same time allowing a forward slide of the hoof. In paper III the device's long guiding rails were positioned in a more acute angle to the vertical compared to the settings used in paper IV. In table 4 modifications of the original design by Peterson *et al.* (2008a) of the test device is presented. Tri-axial accelerations, tri-axial loads and position data were acquired from the device through nine channels of data recorded with 16-bit resolution at 5000 Hz using a custom written MatLab data acquisition and analysis script. In paper III only the peak vertical deceleration of the metal hoof was used.

Parameters derived from the sensor outputs from the OBST were used to measure functional properties of the surfaces (see descriptions in table 5). Each measurement was chosen based on its appropriateness to define the biomechanics of the property. Impact firmness was characterized by the peak vertical deceleration of the metal hoof at impact, aimed to represent the shock experienced by the horse at hoof impact. Cushioning, describing the surfaces ability to absorb and reduce peak force, was determined using the peak vertical force from the tri-axial load cell. Grip was represented by the amount of forward slide of the metal hoof on the surface during loading. Responsiveness relates to the deformation and elastic recovery of the surface and was measured as a quotient of the compression and recoil time of the spring-mass-damper system. Uniformity, representing the spatial variation over the arena, was calculated by taking the ensemble mean of the coefficients of variation (CV), defined as 'the standard deviation divided by the mean', for each functional property; impact firmness, cushioning, grip and responsiveness of that arena. For detailed descriptions of signal processing, parameter calculations and graphical representation of the signals in the time domain see Supplementary material to Paper IV and additional results in section 4.8.

Table 4. *Adjustments to the Orono Biomechanical Surface Tester compared to the original design described in Peterson et al. (2008a)*

Settings/design	Peterson et al. 2008a	Paper III	Paper IV
Hoof and shoe	Hoof cast from a two part casting rubber (Duo-Matrix Neo, Smooth-On, Easton, PA, USA)	Metal hoof with a standard iron shoe size 2	Metal hoof with a standard iron shoe size 2
Drop height (vertical)	1.83 m	0.84 m	0.84 m
Weight of falling mass	30 kg	33 kg	33 kg
Impact energy	540 J	272 J	272 J
Angle of long rails (from vertical)	12°	8°	12°
Angle of short rails (from vertical)	7°	0° (hoof lands flat)	0° (hoof lands flat)
Spring + damper	Gas spring (EFA 20- 50-FC, Efdyn, Tulsa, OK, USA)	Metal spring (Ashfield Springs Ltd. s421) + Industrial damper (Enidine OEM 2.0Mx4CMS 100mm, setting #2)	Metal spring (Ashfield Springs Ltd. s421) + Industrial damper (Enidine OEM 2.0Mx4CMS 100mm, setting #2)

4.5 Laboratory material tests (papers III and IV)

In order to characterise the arena surface materials of the top layers a material sample of approximately 1 kg was collected from the surfaces investigated in Papers II, III and Paper IV. The turf arenas in Paper IV could not be sampled and from one event in this study the collected material was misplaced (marked as missing, see table 3). Particle size distribution was determined by sieving and sedimentation, water content was measured by drying samples at 45°C to a constant mass, the percentage of organic content was determined by burning off the organic materials from an oven dried sample in a furnace, and when applicable, the wax content was registered using the Soxhlet extraction method. In paper III a bulk density test was also performed which describes how the material compacts under different moisture conditions.

4.6 Questionnaire (paper IV)

In study IV a questionnaire was developed to record riders' assessments of functional properties of the arenas at the show jumping events. The properties and the words describing them were selected on the basis of being of biomechanical relevance to the horse, familiar to the riders and also possible to measure mechanically. One questionnaire, per event and rider, was used to evaluate properties and overall scores for each arena by using visual analogue scales. Short descriptions of the properties and the verbal anchors of contrasting adjectives used at the end-points of each scale are presented in table 5. The visual-analogue scores were measured 0-100 ordinal scale and then transformed to a 0 to 5-rating, with the resolution unchanged. Written definitions and in depth explanations in English of each of the functional properties (according to Hobbs *et al*., 2014 pp. 20-21) were given to the riders the first time they were approached with the questionnaire to facilitate interpretation. The riders were provided a translated version of the explanation and questionnaire in French or German if they wished. The riders were asked to evaluate the arenas in comparison to arenas on other events of CSI 3* or higher ranking, that they had participated in during the last five years. Riders assessed surfaces after they had ridden at least one horse on all included surfaces at the event.

Table 5. *Functional properties of arena surfaces used in the questionnaire. The verbal anchors describe end-values for each property and the short version of description was given to each visual-analogue scale*

Functional property	'High-end' verbal anchor	'Low-end' verbal anchor	Short description
Impact firmness	Hard	Soft	The shock experienced by the horse and rider when the hoof contacts the surface.
Cushioning	Deep	Compacted	How much a surface is supportive compared to how much it gives when riding on it.
Grip	High grip	Slippery	How much the horse's hoof slides during landing, turning and pushing off.
Responsiveness	Active	Dead	How active or springy the surface feels to the rider.
Uniformity	Uniform	Variable	How regular the surface feels when the horse moves across it.
Consistency	No change	Changeable	How much the surface changes with time and use.

4.7 Statistical methods (papers I-IV)

The statistical analyses in this thesis were performed using the statistical software SAS (SAS Institute Inc., USA). Mixed models were used for data acquired in all four papers. Several fixed effects and their interactions were studied using these models and the hierarchical structures of the data and repeated observations (non-independence of data points) was accounted for by adding random effects (horses, riders, events or their combinations). In Paper III a Student's T-test was also used to investigate the difference in measured impact deceleration from the OBST on the different surfaces. Normality of the distributions of the outcome variables was always tested as described in the papers.

4.8 Additional OBST data from training and competition arenas

As a reference material to the arena measurements made with the OBST, presented in paper III and IV, additional data from a selection of competition, warm-up and training surfaces are presented here. Descriptive statistics can be found in table 6 and examples of signal traces in the time domain are given in figures 2-5. The signals are chosen to display both typical characteristics and more extreme signal patterns found in measurements from these arenas. Measurements were performed from 2012 to 2015. The OBST settings were identical to those in paper IV. Arena attributes have not been specified since these data are provided to enable a general comparison that highlights the between and within arena variation in measured values. Sample points (drop places) within the arenas were spaced approximately in a 15-20 m grid, resulting in 9-12 drop places in an average-sized indoor training arena. Data are presented for 94 measurement occasions on competition and warm-up arenas on 4 and 5* FEI competitions in Sweden and Germany and for 428 training arenas in Sweden and UK. Each arena can have been measured at several occasions (different days and different preparations). For competition arenas (n=94) there were 56 unique arenas, the mean number of times an arena was measured were 1.68 and the median was 1. For training arenas (n=428) there were 164 unique arenas, the mean number of times an arena was measured were 2.48 and the median was 2.

Table 6. *Descriptive statistics of data from measurements performed with the OBST from 2012 to 2015. Means over arena-mean values are presented for vertical peak load, peak load rate and acceleration. The coefficient of variation (CV) for the parameters was computed for each arena and then averaged for the arena group presented (competition/warm-up or training) to indicate mean within-arena variability.*

	Mean	Mean within arena CV	Median	Standard deviation	5th percentile	95th percentile
Competition & warm-up arenas measurements n=94						
Peak vertical load (kN)	14.7	12%	14.9	1.5	12.0	16.9
Peak vertical loading rate (kN/s)	4670	33%	4284	1655	2934	8517
Peak vertical acceleration (g)	87	28%	86	19	62	126
Training arena measurements n=428						
Peak vertical load (kN)	11.7	20%	11.7	3.6	7.2	17.4
Peak vertical loading rate (kN/s)	3000	57%	2779	1986	1194	5963
Peak vertical acceleration (*g*)	75	94%	73	30	16	123

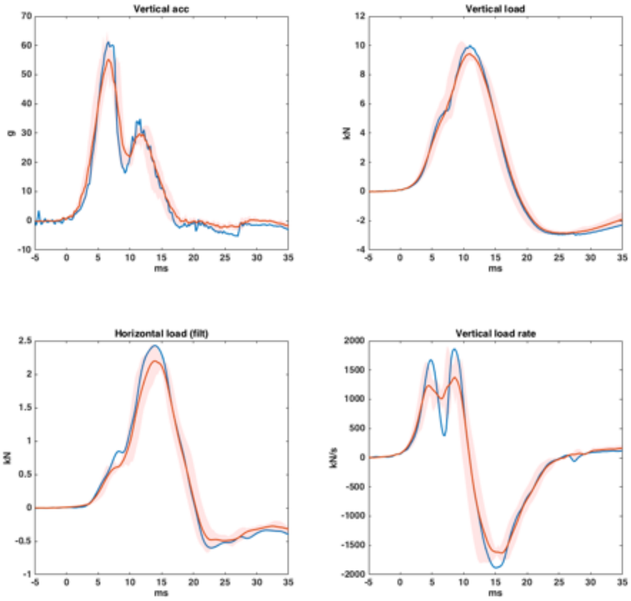

Figure 2. To the upper left vertical acceleration, registered on the metal hoof is presented in g. In the upper right panel the vertical load from the triaxial load cell is displayed in kN. The lower left panel shows the horizontal load in kN and to the right vertical loading rate in kN/s is presented. All graphs show time in milliseconds on the x-axis from 0 to 35. Red lines display mean values, the shaded areas the 25th to 75th percentiles and the blue lines the most typical curve .The ‘most typical curve’ was calculated by comparing each time series of data (one drop) with all the rest from the arena. The curve with the lowest sum of least mean squares distance over all data points was selected.

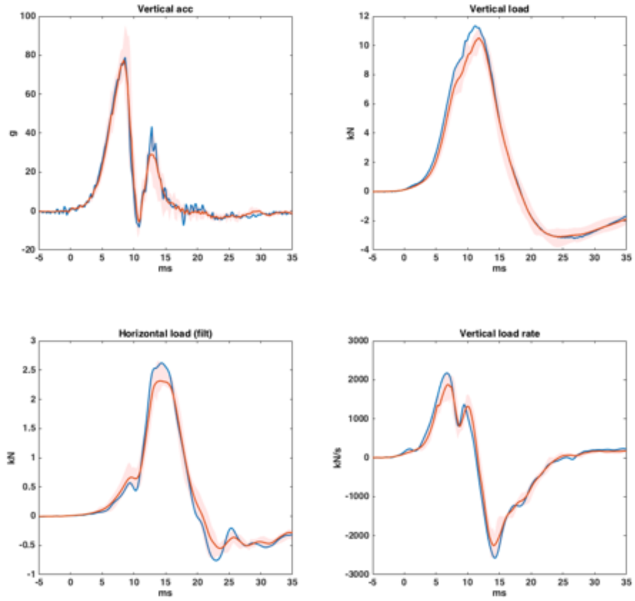

Figure 3. Signal representation as described in figure 2. Note the difference in the two loading rate peaks compared to figure 2.

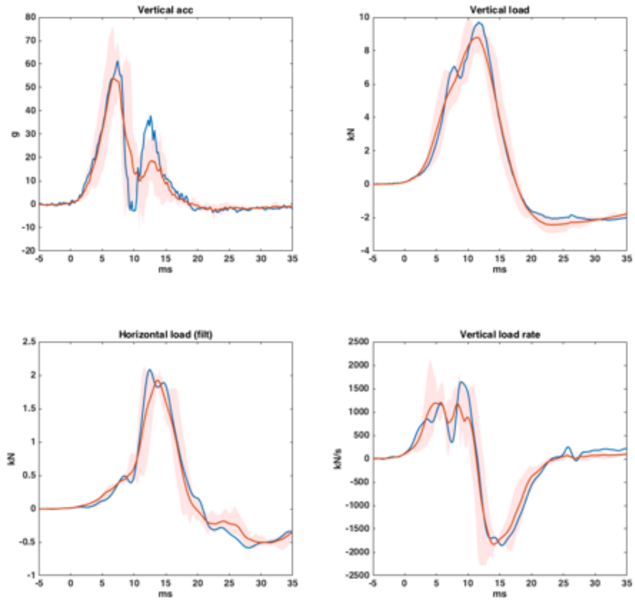

Figure 4. Signal representation as described in figure 2. Note that the vertical load has more of a double peak nature compared to figures 2 and 3.

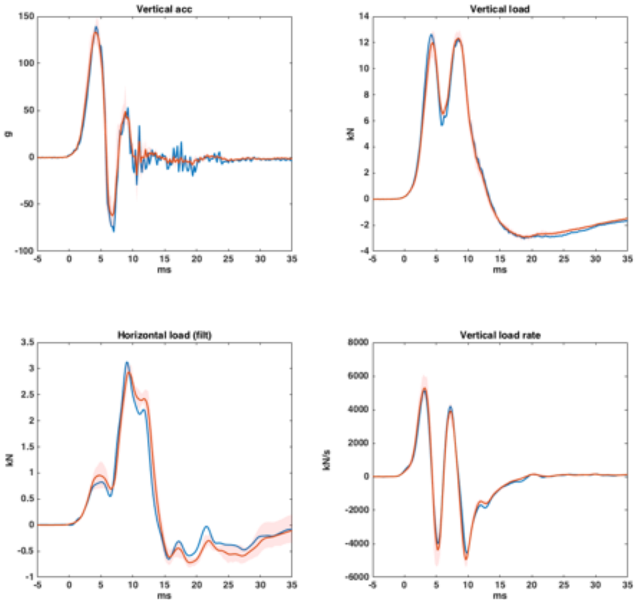

Figure 5. Signal representation as described in figure 2. This is an extreme signal both in magnitude of peak acceleration and loading rate. Note the accentuated double peak in vertical load.

5 Main results

5.1 Paper I

Recordings from 39 horses providing 64 hoof landings from a total of 42 jumps on the two surfaces were included for analysis. Different pre-impact speeds and landing trajectories were found in leading/trailing, fore and hind limb hooves in jump landings in elite level competitions on a sand and on a turf surface. The fences over which the horses jumped were a 1.3 m up-right fence and a 1.4 m triple bar on the turf surface and a 1.4 m oxer and a 1.5 m triple bar on the sand surface. Model output show that mean landing speeds for the hooves ranged from approximately 4.4–7.1 m/s. The forelimb hooves approached the ground at lower total landing speeds and with lower horizontal velocities, than the hind limb hooves. The horizontal velocity was clearly lower in the trailing fore compared with the other limbs. The leading limb hooves approached the ground with a more acute angle towards the horizontal plane than the trailing limb hooves. The trailing forelimb hooves landed with a mean trajectory of 75° (63°-89° =95% confidence interval (CI)) to the horizontal plane and a mean speed of 4.4 m/s (3.9 m/s - 5.0 m/s = 95% CI). The leading forelimb hooves had a mean trajectory prior to impact of 41° (37°- 46° = 95% CI) and a total speed of 5.6 m/s (5.2 m/s – 6.0 m/s = 95% CI).

5.2 Paper II

The five horses were observed in a total of 154 trials, which resulted in 474 hoof impacts from jump take-offs, 470 from jump landings and 3785 from regular canter strides. The leading limbs exhibited higher absolute and relative horizontal interactions with the ground at the canter than the trailing (non-leading) limbs within forelimb and hind limb pairs. The hooves of the trailing limbs exhibited less interaction with the ground in the horizontal direction (fore-aft), but had a more distinct vertical deceleration. The highest vertical and horizontal impact accelerations were produced at jump take-off. Vertical hoof decelerations were more elevated during the jump landing compared to the normal canter stride, but only the landing forelimb hooves had accelerations as high as those generated by the corresponding limbs during the jump take-off strides.

5.3 Paper III

The five horses performed 62 successful trials on the wet sand–fibre surface, 21 on the dry sand–fibre surface and 71 on the sand–woodchip surface. In total 4558 hoof impacts were obtained. Results showed that the surfaces' effects were significant on the vertical hoof impact deceleration. All two-way interactions were significant in the model, which meant that the surface effect interacted with limb type and stride type. The sand-fibre surface with the highest water content produced the lowest impact decelerations comparing within limbs and stride types. The 5% water content decrease (from 25 to 20%) in the sand-fibre surface was associated with a 27-28% increase in hoof impact decelerations comparing within limb (the 6% increase in the non leading hind limb was not significant). Comparing within stride type the increase in hoof impact decelerations for the drier arena condition was 25 and 29% for the normal and landing stride (11% in the jump take-off which was not significant). Comparing the wetter sand-fibre arena to the sand-woodchip arena the hoof impact decelerations increased with 36, 43 and 92% for normal, landing and take-off strides respectively. Within limb differences between the wetter sand-fibre arena and the sand-woodchip showed an increase of 49-65%. The measurements of vertical deceleration recorded on the metal hoof of the OBST also showed significant differences between the three surface conditions. In the lower water content condition the impact decelerations increased with 45% in the sand-fibre arena compared to the high water content condition. The sand-woodchip arena produced a 100% increase in mean peak deceleration compared to the wetter sand-fibre arena. As such, results from the surface tester agreed with the horse measurements in terms of ranking, but arena mean values were higher than the means from on-hoof recordings.

5.4 Paper IV

Twenty-five competition (n=9) and warm-up (n=16) arenas were included in the study. The most common construction type (68% of arenas) was a sand-fibre top layer placed above a concrete or tarmac base, typical of temporary arenas. Mean top layer depth was 17 cm (standard deviation 4 cm). Material analyses from the top layer showed that the size distribution of the granular mineral components of most arenas were concentrated to the 0.06-0.2 mm span, corresponding to fine sand. Three arenas had the majority of their material in the span 0.2-0.6 mm (sand) and of those two were the waxed sand arenas. The below 0.06 mm sized component, often referred to as “fines”, were in most cases separated as coarse silt, silt, fine silt and clay-sized in the material analyses. From 1.9-21% of the total weight of the mineral components in the samples were “fines” (less than 0.06 mm), but the specifications showed that the clay-sized proportion was never more than 3%.

In-situ mechanical measurements of the arenas, performed with the OBST showed that the range of arena means for the functional properties were 55-178 *g* for impact firmness, 17.6-11.5 kN for cushioning, 3.8-8.6 mm for grip, 0.37-0.89 for the responsiveness quotient and 0.11-0.33 (mean CV) for uniformity. The mean number of measured drop sites per arena was 8.5, with a spatial resolution of approximately 15 m between drops.

In total 749 subjective arena evaluations from 198 riders were obtained which gave a response rate of 57%. In the mixed models 669 arena evaluations were included since 80 of the arena assessments had at least one missing value. Rider, entered as a random effect, explained on average 22% of the variation in the observed values according to the variance component estimate (ranging from 6% for cushioning to 31% for grip).

Significant associations were found between the mechanical measurements of impact firmness, cushioning, grip and responsiveness and the rider’s perception of these properties. Objectively measured uniformity showed no useful association to riders’ perception.

6 General discussion

6.1 Discussion of main results

6.1.1 Horse movements contributing to the hoof-surface impact in show jumping (paper I, II)

In this thesis the study of the hoof-surface impact is focused on kinematic methods. This means that displacements, speeds and accelerations involved are described, not the forces causing these movements. The data display hoof impact speeds in jump landing during elite-level competitions and add information related to how the primary impact and events up to hoof-standstill are affected by some of the show jumping horse's movements.

The mean total landing speeds of the hooves (resultant velocity per limb type) in jump landing presented in paper I, ranged between 4.4-7.1 m/s for trailing and leading- fore and hind limbs. These speeds were high and can be compared to hoof landing speeds of 5 m/s at a fast trot (horse speed almost 10 m/s) (Johnston *et al*., 1991) and 7.5-8.1 m/s for Thoroughbreds at full gallop (horse speeds 11-19 m/s) (Parsons *et al*., 2011). The data show large variations in horizontal and vertical velocity components of the different hooves (leading/trailing, fore/hind) prior to impact in jump landing over these high fences at competition speeds. The horizontal velocity component ranged from 0.6-5.9 m/s for the four limbs, which is a larger range compared to velocities recorded at the canter ≈1-2.4 m/s (only forelimbs) (Crevier-Denoix *et al*., 2013b) and 5.1-7.0 m/s at the gallop (Parsons *et al*., 2011). Interestingly comparing the horizontal velocity of leading and trailing limbs, the reverse relationship was found in the jump landings studied compared to data from canter and gallop. Trailing limbs in canter and gallop show higher horizontal velocity prior to impact compared to leading limbs (Crevier-Denoix *et al*., 2013b; Parsons *et al*., 2011), which is opposite to the findings in paper I. The vertical component was significantly higher in the trailing hind hoof in jump landing, which also differs from galloping horses in the study by Parsons *et al*. (2011). These discrepancies highlight the need to study discipline specific movements in order to understand the sport's specific demands put on both horses and surfaces.

A relevant question to ask is how important the hoof landing velocity is to the actual stress arising at the impact shock when the hoof hits the ground. Data from a study that simultaneously recorded hoof landing velocities, peak force and accelerations of the impact indicate that hoof velocities must be interpreted with caution when inferring to expected impact forces on different surfaces (Crevier-Denoix *et al*., 2013b). The velocity contributes to the impact energy of the collision. But other factors such as contact area and effective mass over the course of the collision are of great importance. The area and mass of the impact are most likely not constant throughout the collision event. Studies calculating effective mass of the hoof-surface impact have not reached conclusive results regarding whether only the distal phalanx is involved in this impact or all phalanges (Munoz-Nates *et al*., 2015; Warner *et al*., 2013; Chateau *et al*., 2010). It is also possible that velocity recordings underestimate the rotational energy at impact. The 'heel first' impact induces a forward rotation of the hoof and has been suggested to be particularly stressful to the distal limb in terms of impact vibrations (McCarty *et al*., 2015a). The leading forelimb at the canter has been seen to land with a more 'heel-first' orientation (Crevier-Denoix *et al*., 2013c), compared to the trailing, which could then contribute to the leading versus trailing limb differences of the hoof impact.

This is an important observation to bring to the discussion of the results in paper II where differences in impact accelerations were investigated in canter and jump take-off and landing. In this study leading limbs showed higher horizontal interactions with the ground, registered as the range of maximum and minimum peaks of fore-aft direction in all of canter, jump take-off and landing. Given the above discussion this could be attributed both to a greater horizontal velocity component in the landing but also to systematic differences in hoof orientation at impact. The differences observed between strides are relevant in the discussion of discipline specific challenges. However, these jumps were not fully comparable to the more extreme heights and speeds that can be observed at high-level competitions.

A limitation of the studies in this thesis describing hoof-surface interaction, is the lack of reported horse speed. Take-off speed and fence height are thought to contribute greatly to energy changes observed in the jumping horse (Bobbert & Santamaría, 2005). At the trot and gallop speed has been found to have a linear relationship to hoof landing velocities (Parsons *et al*., 2011; Johnston *et al*., 1991). But these relationships could be more complicated in jumping.

Horses are reported to slow down before jumping over a fence but a considerable variation has been observed as to what extent this happens (Bobbert & Santamaría, 2005; Schamhardt *et al*., 1993). Recording speed for the different stride types in study II would have demanded a more complicated set up, which was not feasible. Also surfaces have been shown to influence hoof landing velocities (Chateau *et al*., 2010; Burn & Usmar, 2005) which might partly be reflected by the significant interactions between limb, stride type and surface variables in paper II and III. However, there was still a between limb difference within both surface and stride type.

The relationship between impact accelerations and impact forces has been demonstrated (Munoz-Nates *et al*., 2015). Another study points out that differences comparing force peaks to acceleration peaks of impact registered on and under-hoof can be found and these could possibly be attributed to the differences in recorded frequency spectra by the two sensor types. The impact peak force and accelerations/vibration energy that can be measured under the sole or on the hoof wall respectively do not have a clear causal relationship to specified injuries occurring in the distal limb. The horse's limb appears to have efficient passive damping mechanisms (Gustås *et al*., 2001; Wilson *et al*., 2001) that deal with this event. These do not rely on active muscular control since the muscular control of impact is anatomically limited in the horse. The small volume and short fibres of the muscle regulating the distal spring of the limb is the reason for this limitation (Biewener, 2006).

It is important to point out that limb and stride type differences presented in this thesis are attributed to the hoof-surface impact and can not be extrapolated to the loads that arise during the support phase (e.g. Crevier-Denoix *et al*., 2015b; Crevier-Denoix *et al*., 2013). Recent studies of jumping horses have however confirmed that leading and trailing forelimbs in the jump landing display different loading patterns (Crevier-Denoix *et al*., 2015a, b, 2014a, 2013a). The effect of limb orientation on internal loading of the limb that can be related to specific pathologic conditions has the potential to be elucidated in the development of biomechanical models of the limb, where also the surface effect can be incorporated (e.g. Symons *et al*., 2016).

Many discipline specific movements need further evaluation. Quick, sharp turns are common challenges to show jumping horses and hence show jumping surfaces. In a few studies investigations of this event have been initiated (Crevier-Denoix *et al*., 2014b; Chateau *et al.*, 2013; Camus *et al*., 2012;)

In a broader context, comparing to other findings, the relatively high and variable hoof landing velocities presented in paper I gives an indication of the initial conditions that govern hoof impact in jump landings. The results from study II highlight that the jump take-off and fore limb impact in jump landing deserve special attention in the discussion of impact related stresses in the show jumper. The variation detected in the kinematic profile of the primary impact is of importance when discussing how standardized surface tests compare to real-life horse loading. The choice of a single loading condition for a test device will enable comparisons between surfaces but can obviously not represent the entire spectra of impact and loading patterns produced by horses within the discipline.

6.1.2 The surface's effect on the hoof-ground impact in show jumping

The effect of the surface on the characteristics of the hoof-surface impact cannot be isolated from the contribution of the horse. The effect on the impact of the surface properties is of course a significant factor. This thesis provides data from horse-surface impacts from four surfaces (papers I, II and III). However, the lack of specification of the surface material, the unbalanced study design and the limitation of horses wearing studs on the turf surface limits the conclusions that are possible regarding the surfaces' contributions to the recorded deceleration of the hoof at impact in study I. However in the experiment performed for papers II and III the surface effects can be considered. The interacting effect between limb type, stride type and surface found in this experiment can in part be related to specific movement modifications related to active or passive surface effects as described earlier, leading to different hoof landing velocities (Chateau *et al.*, 2010; Burn & Usmar, 2005). A relevant contribution to this interaction can also be the non-linear and strain-rate dependent behaviour of surfaces, creating unique responses to different loading conditions. The most elevated vertical impact decelerations were found on the sand-woodchip when compared to the two conditions from the sand-fibre arena. The effect from the material characteristics on the hoof impact should be studied using more controlled surface composition arena differences but the measurable effects make it clear that the materials and conditions are important factors. For example comparing surfaces with sand-only top layers would isolate the effects of for example particle size distribution, mineralogy, particle shape etc. This would allow detailed understanding of the effects on hoof-impact changes mediated through material changes. However, the broad particle size distribution of the sand-woodchip arena is likely to result in greater compaction(Guisasola *et al.*, 2010), which could be a relevant explanation to the elevated impact accelerations on this surface. Holt *et al.*, (2014) showed that the effect of compaction was imperative to impact decelerations produced by surface materials and that the effect of increased water content was inferior. Increased water content in the sand-fibre surface reduced impact decelerations. This must be evaluated from the perspective of how the compared levels of water content relate to the water content of a specific material at maximum bulk density. Water up to a specific limit will lead to increased compaction of the granular material. Above the maximum limit the addition of more water will increase the volume of the material and act as a lubricant between the particles. This explains, at least in part, why different studies have found different effects of increased water content on impact accelerations and loads (Holt *et al*., 2014; Mahaffey *et al*., 2013; Chateau *et al*., 2010; Ratzlaff *et al*., 1997). To further investigate the surfaces effect on the hoof impact, vibration energy in different frequency ranges produced by three surface conditions would have been interesting to add to the analysis in paper III.

6.1.3 Assessment of functional properties of show jumping arena surfaces

In the fourth paper functional properties of show jumping surfaces were evaluated using subjective rider assessments and by objective measurements using an OBST. Results show significant associations between objective and subjective assessments of impact firmness, cushioning, responsiveness and grip. No useful association was found for uniformity.

The OBST has been used for objective in-situ surface assessments in several scientific publications (Mahaffey *et al*., 2016; Northrop *et al*., 2016; Lewis *et al*., 2015; Tranquille *et al*., 2015; Holt *et al*., 2014; Mahaffey *et al*., 2013; Peterson *et al*., 2008a; Peterson & McIlwraith, 2008b). There are currently four machines operating mostly in the USA, the UK and Sweden. Blueprints, sensor specifications, operator's manuals and source codes are publically available at: http://www.bioappeng.com/Horse/OBST.html.

There are many aspects to consider regarding the performed evaluations of functional properties. Firstly, the true importance of assessed properties (impact firmness, cushioning, responsiveness, grip and uniformity) can be questioned. As described in the introduction section 1.6, biomechanical data from both human and horse interaction with the surface indicate that both vertical and horizontal response are important aspects of how properties from the surface relates to the athletes performance and risk of injury (Parkes & Witte, 2015; Nigg & Yeadon, 1987). But also other properties (e.g. damping) could be of value (McCarty *et al*., 2015a, 2015b) that were not assessed in the current thesis. The properties chosen were, as described in paper IV, based on surface descriptions used by participants in the sport, considered in combination with evaluation of biomechanical relevance and the possibility to measure them mechanically. However, these properties are clearly insufficiently associated to actual measures of injury and performance. Performance of the horse on the surface can likely be relevantly evaluated by riders (as addressed in paper IV) but could also be assessed using more objective measurements, for example through extensive collection of data from competitions describing horse speeds and frequency of cleared fences (controlling for other factors such as horse, course design etc.). Also injury frequencies should be used related to surfaces to prove that certain properties truly are associated to risk. But evidently, this demands assessment of mechanical behaviour of surfaces, which brings us back to the same starting point.

The second main aspect to consider is the relevance of the methods used to describe the selected properties. Aspects on validity and reliability of the rider questionnaire used for subjective assessments are discussed in section 6.2.

The most evident methodological issues with the OBST are related to how well the device represents loading conditions encountered in real-life horse-surface interactions that arise during sport-specific movements. This is important given the non-linear and strain rate dependent response of the surface materials. The angle of impact, peak load, loading rate and slip distance are discussed in relation to data from the literature in the supplementary material of paper IV, and hoof-impact is compared to on-horse measurements on the same surfaces in paper III. Some relevant issues should be further highlighted. The OBST challenges the surface to an elevated extent compared to existing biomechanical data. Both peak loads that should be commensurate to the peak load of the support phase and the loading rates show high magnitudes. However, biomechanical data describing these parameters from high jumps at competition speeds are lacking. So to what extent the surfaces may be 'over challenged' using the OBST will be elucidated as the biomechanical data describing these events grow. The additional data provided in the results section, highlight that the load magnitudes in paper IV are high, compared to those from other arenas that have been measured. Peak loading rates when compared to estimated peak rates from load-time graphs in published biomechanical articles, do seem to exceed horse values substantially. This could be addressed with future design changes to the machine. Such potential modifications should however be weighed against the loss of comparability to a large amount of already collected data. One suggested modification to the system could be reduction of the loading rate. This can be done by reducing the spring rate and reducing the damping so that it remains at 95% of critical damping, C_c, where:

$$C_c = 2 * \sqrt{km}$$

where k is the spring constant and m is the mass of the secondary load above the spring on the system. In all cases the loading rate will not be a single value but will decrease with time during the loading event as a result of the reduced damping effects. The current settings of the OBST use a spring with a spring constant of approximately 15 kN/m. By halving the spring constant the initial loading rate for the secondary loading will be reduced by 30% which will make the OBST match the upper range of the loading rate reported in biomechanics literature for lower jumps. By further reducing the spring rate to one eighth of the current rate the loading rate of the surface will be reduced by 65% from the current settings. In all three cases the damping is held at 95% of critical to minimize the bounce of the hoof on the surface (Figure 2).

When a more complete model of the limb interaction and additional data are available from the two phases of loading of the OBST that can also be adapted to incorporate both non-linear springs and longer travel (extended compression distance). This would produce lower initial stiffness as well as lower overall strain rate for the testing.

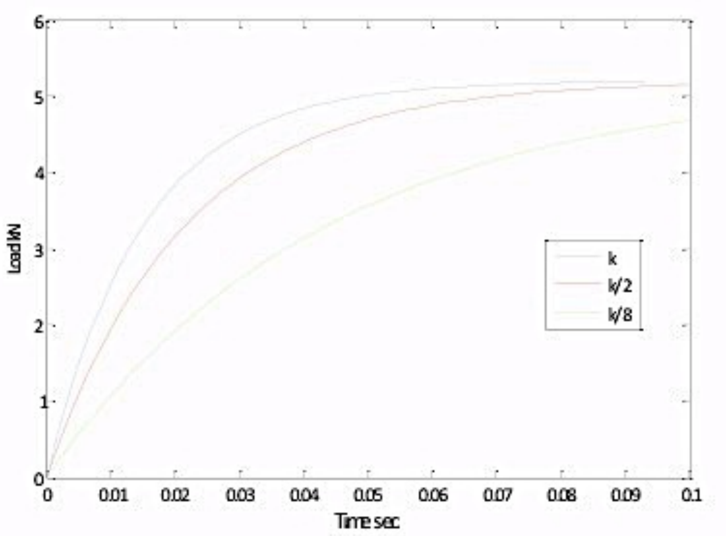

Figure 6. The effect of changing the spring rate of the secondary loading system on the loading rate, while holding damping constant at 95% of critical. k is the present spring constant.

The assessment of grip (shear resistance of the surface) and responsiveness (energy return) are complicated given the complex biomechanical background of these events, addressed in the introduction of this thesis. OBST measurements of these properties, derived from sensor output, are described in the supplementary material to paper IV. Again, the rate of loading applied to the surfaces as these signals are recorded is likely of importance. The granular materials of arena surfaces resist horizontal shear to different degrees depending on the amount and rate of load that is simultaneously applied in vertical direction. Adding to the complexity is the stratification of arena material, where different layers can have very different shear-resistance. Grip and responsiveness can be further evaluated and adjusted as data from biomechanical or physiological studies that address these questions can be compared to OBST measurements. The angled impact between the OBST and the surface has the benefit of allowing assessment of horizontal resistance to shear in the surface material as well as the response to vertical impact. Simple measurements of energy restitution from the surface that can be used in vertically free falling surface test devices (Kruse *et al.*, 2013; Hopper *et al.*, 2014) are however not allowed by this design.

A clear benefit of the OBST is the possibility to assess the surface's response in both vertical and horizontal directions by using only one device. The open access to the design and source codes provides the possibility of a wide spread use of the machine that allow collection of large amounts of comparable data that could contribute substantially to the research field. The production cost and weight of the machine, making it non-portable are negative factors that could limit the number of end-users.

6.2 Additional aspects on material and methods

6.2.1 Study protocols and study populations

The observational design and study protocol of paper I clearly limited the ability to draw conclusions related to fence types, heights and surfaces. Thus, the emphasis on study results should be on pre-impact hoof speeds. The horses, arenas and fences could not be randomly selected. It is not likely that this would have affected between limb comparisons of hoof speeds to any large extent but the choice and size of the recorded volume could have led to some systematic bias excluding horses that landed unexpectedly far from the fence.

The horses included in the studies of this thesis are described in table 2. They represent a quite homogenous population of mainly European warmblood horses with high jumping skills and experience. The experiment presented in paper II and III however included horses that were less experienced but were still well accustomed to jumping. Novice jumping horses have been seen to produce unexpectedly high loads when jumping smaller fences (Schamhardt et al., 1993).

Adequate descriptions of arena construction and material composition are important to all research on equine surfaces. This was largely neglected in papers I and II with more adequate descriptions provided in papers III and IV. Specification of surface particle size distribution below 0.063 mm sizes, appear important in order to understand the surfaces' properties (Mahaffey *et al*., 2012). This small-sized material, consist of clay and silt and is sometimes referred to as 'fines'. Fines are often unspecified in regular sieve analyses with the fine materials characterized simply as a portion of the material passing a particular sieve (ASTM C136, 2006), which are provided as the most basic consumer information about these materials. The arenas in study IV had the majority of this portion of material as larger silt sizes, and very little clay. This has critical implications to the mechanical behaviour and moisture management of the material (Mahaffey *et al*., 2012).

6.2.2 Kinematic methods

High-speed camera

The relatively low resolution of the high speed camera used in study I was in part improved by the pattern recognition technique providing an output of displacement below pixel level. Estimations of errors due to out of plane movement, by simple trigonometric calculations are presented in the paper. Some subjective decisions were made during data processing with impact definitions relying on manual scrutiny of data as well as on assumptions regarding rigidity of the hoof. These methodological uncertainties were hard to eliminate. Data on the pitch-rotation of the hoof at impact was calculated but not presented in the manuscript. It could have been a useful addition to the paper. The approximate scaling factor used is another limitation to the method in paper I.

Hoof-mounted accelerometers

An important methodological issue when using accelerometers is that they are linear and do not record rotations. Their output is however influenced by rotations, which should be considered during data interpretation. This type of methodological issue is described by (Holden-Douilly *et al*., 2013) investigating hoof-slip at hoof impact. The projection of the centripetal acceleration onto the translational movement axis should be considered. The accelerometers used in papers II and III were mounted to the hoof via a metal jig. This mounting system had a natural frequency which was much lower than the impact data of interest and thus was easily separated by only considering the data associated with the impact of the hoof on the surface. In general filter settings were based on information from frequency analyses of the signals, but a certain amount of subjectivity is almost always included in the choice of settings.

6.2.3 Rider questionnaire

The rider questionnaire used in study IV is presented in the supplementary material. Visual analogue scales have previously been used for human athletes to assess surfaces (Andersson *et al*., 2008) and subjective judgments of ground properties have been compared to objective measurements showing variable results depending on the property assessed (Twomey *et al*., 2014). The validity of the assessments using the rider questionnaire was difficult to evaluate since there was no gold standard to compare to. Actually as none of the methods had gold standard status, we considered using agreement analysis to present the results, but failed to reach a useable method. To increase understanding of the specific properties an in-depth explanation according to a pre-written text was provided at the first assessment occasion. This was done to ensure that the rider actually scored the intended property. A limitation to this was the potential language barrier given the mixed nationalities of the riders. To overcome this the questionnaire was translated into German and French. No back-translation was performed, which could have made it possible to assess the quality of the translation. If the terminology was well understood, the riders included in this study were assumed to relevantly assess performance related properties of the surfaces such as responsiveness. However between-rider variability evaluation was quite high. The personal reference to the scale could not be avoided but was hopefully limited (and controlled for using random effects in the analysis) by instructions given to riders to compare the arenas to other arenas encountered on 3* or higher ranked events within the last five years.

6.3 Concluding remarks

The work performed for this thesis adds information to the area of research aiming to create safer surfaces for show jumping horses. The thesis work is part of a larger project where researchers communicate closely with stakeholders and sports participants and collaborate with the sports governing body in order to increase knowledge about safety of training and competition surfaces. As research into horse-surface interaction expands, further development of surface testing devices will result in systems that are better able to replicate the loading conditions that are the most relevant to the safety and performance of the horse.

The feasibility of in-situ objective measurements and rider assessments of surfaces at high-profile competitions is shown by the work in the last study (paper IV). During the data collection critical support was provided by the sports governing body, excellent acceptance resulted from event organizers and genuine interest was expressed from most riders. This support was evident in spite of the potential for disruption and the critical timing for the focus of the competitors. This experience demonstrated that surface assessments can be routinely implemented at large show jumping events in the future. The assessment would provide crucial data that would allow the development of standards for safe high performance competition surfaces. Together with injury registrations a strategy to identify risk and performance assessment that are associated to surface properties could be possible.

The complexity of the effect surfaces on injury is not restricted to the variable loading patterns of the hoof-ground interaction. Factors related to horse movements, conformation, shoes, studs and the surfaces' properties are all important. Training and management of the horse will of course also be a major determinant of injury occurrence. The rider's or trainer's choice of volume, intensity, type and periodization of training as well as amount and timing of rest will have the largest influence on the loading and adaptation of the locomotor apparatus of the horse. This will govern chances of restitution and repair. Choice of surface is only one part of the strategic planning associated with a training program that will keep a horse sound.

7 Conclusions

- There is a systematic variation in the hoof-surface impact, introduced by common types of movements (canter and jumping) and functional limb type (leading or non-leading) in show jumping horses.
- In jump landing relatively high hoof landing velocities were found as well as a large variability in horizontal and vertical velocity components between leading/trailing fore and hind limbs.
- Jump take-off and forelimb jump landing resulted in elevated impact shocks to the hooves, which should be considered with regard to possible injury mechanisms.
- Surfaces with different composition and water contents have different effects on the hoof-surface impact in show jumping horses.
- Increasing water content in the surface will likely decrease hoof-impact shock, if the moisture levels are above the level leading to maximum bulk density at standardised compaction of the specific material.
- The degrees of impact firmness of three surface conditions, evaluated by peak vertical impact accelerations, were ranked in the same order by on-horse recordings and by a mechanical surface tester (the OBST). The surface tester recorded higher mean values per arena.
- OBST objective assessments of the functional properties impact firmness, cushioning, responsiveness and grip, were found to be significantly associated to top-level riders' subjective assessments of the same properties made on competition and warm-up arenas in 4* and 5* show jumping events.

8 Future research

An increased understanding of surface behaviour in response to the most challenging discipline-specific movements of the show jumping horse could provide more insight and generate hypotheses about the specific mechanisms relating to injuries in show jumping horses. This should include high jumps (take-off and landing) at competition speeds, sharp turns and high rate speed changes. This information is needed to guide and compare settings and design choices of surface testing equipment such as the OBST. These devices need to be commensurate to critical portions of loading patterns produced by horses, including the more challenging events. As biomechanical data grow, adjustments of surface testing equipment, leading to even more discipline specific measurements of surfaces can be made.

The use of standardised in-situ surface tests (e.g. the OBST) and other objective measurement devices provide the opportunity to study how controlled changes to surface materials such as different mineralogy of the sand, particle shapes, particle size distributions, additives, water content and maintenance interventions affect the surface response. This is easily studied if horse variation can be eliminated, but of course depend on the validity of the test used. Also the temporal variation of surfaces due to compaction over time or wear of materials in response to loading would be interesting to study.

Continued rider evaluation of surfaces' functional properties could be compared to OBST measurements on a population of surfaces with a wider spread in properties, than the ones studied in paper IV, including both competition and training arenas. This could lead to riders using a wider range of the visual analogue scales, which should enable further understanding of the (statistical) relationships between OBST parameters and rider ratings. Comparison of riders´ over-all ratings of arenas to OBST measurements would increase knowledge about which properties and property levels that are perceived as ‘good’ or ‘bad’. This could guide the development of thresholds for acceptance of surface properties to ensure safe and fair competition surfaces that allow sufficient performance.

Most essentially, mechanical measurements of surfaces properties have the potential to be associated to injury data from horses using (training or competing on) the same surfaces. This could lead to identification of risk-associated surface properties. The mechanical responses from the surfaces can also be studied related to maintenance, construction and materials of the surfaces. This could then lead to changes of surfaces or their maintenance that, based on scientific evidence, would benefit the health of the horses.

9 Populärvetenskaplig sammanfattning

En av de faktorer som påverkar hur hästen presterar och som kan innebära skaderisker är underlaget som den tränas och tävlas på. Inom galopp- och travsport har banunderlag därför sedan länge varit ett område för vetenskaplig forskning. Inom ridsporten har tävlingsunderlag också länge varit en uppmärksammad fråga, men då utan att det funnits objektivt stöd för olika uppfattningar. Underlagets potentiella skadeverkan i samband med tävling har uppmärksammats. Under OS i Aten 2004 drabbades tre hopphästar av akuta senskador inne på banan, som ledde till avlivning eller avslutad karriär. Skadorna kopplades samman med banunderlaget. Det resulterade i att det internationella ridsportförbundet FEI tog initiativ till vetenskaplig forskning för att öka förståelsen kring ridunderlag och att få fram kvalitéts- och säkerhetsstandarder för tävlingsunderlag.

När hästens hov kolliderar med underlaget i samband med varje hovisättning uppstår krafter som påverkar vävnaderna i hästens ben. Till viss del uppstår en tillpassning till belastningen genom att vävnaderna blir starkare, till exempel blir skelettet tätare och mer hållfast. Vid viss mängd och intensitet av belastning kan istället skador uppstå. Hästens interaktion med marken i varje steg kan beskrivas som bestående av två överlappande kollisioner. Den första, när hoven med sin begränsade vikt slår i marken och snabbt bromsas upp ger inte så höga totala belastningar men ger en kraftig stöt som skickar vibrationer upp längs nedre delen av benet. Den andra kollisionen sker mellan hästens centrala kroppsmassa och marken via hoven. Hoven har vid det laget i princip bromsats upp. Vid den andra kollisionen uppstår mycket höga krafter. Under landning efter hinder på upp till 130 cm har belastningen på en framhov uppmätts till två gånger kroppsvikten, alltså cirka 1000 kg på en enda hov för en medelstor häst.

Det som komplicerar hur krafterna bestäms mellan häst och underlag är att underlaget svarar olika beroende på med vilken styrka och med vilken hastighet det belastas. Om man vill studera vad underlaget ger för svar, alltså vilka motkrafter som uppstår när hästen rör sig över det, måste man mäta underlaget genom att lägga på belastningar som efterliknar hästens två kollisioner. Hastigheten som hästen springer med, och vilken rörelse den utför, är ytterligare saker som påverkar hur kraftiga de båda kollisionerna blir.

Underlagets egenskaper kan delas in efter hur underlaget påverkar hästen i olika delar av steget. De beskriver hur underlaget ”känns” för hästen och hur ryttaren upplever hästens prestation och kallas för underlagets *funktionella egenskaper.* För att hitta en mätmetod som på ett objektivt sätt kan utvärdera underlagets funktionella egenskaper krävs detaljerad kunskap om hur hästens interaktion med underlaget sker. Man måste förstå faktorer som påverkar interaktionen just för den sportdisciplin man är intresserad av och sedan efterlikna den belastningen på ett standardiserat sätt.

Det övergripande syftet med studierna i den här avhandlingen var att undersöka hästens interaktion med underlaget i situationer som är relevanta för hopphästar. Ett särskilt syfte var att använda den kunskapen för att tolka data från en mekanisk och objektiv underlagsmätare, the Orono Biomechanical Surface Tester (OBST), samt att föreslå sätt att vidareutveckla sådana mätmetoder.

För att studera på vilket sätt hästens hovar slår i marken i landningen efter hinder filmades hästar under elittävlingar på två olika underlag med höghastighetskamera. Hovarnas landningshastigheter, landningsvinklar och uppbromsningstid registrerades. Beräkningar från 64 hovlandningar från 39 hästar visade att landningshastigheterna var höga. De var högre än för travare i fullt tempo och nästan upp till samma hastigheter som registrerats för fullblodsgaloppörer i tävlingstempo. Hastigheterna varierade påtagligt mellan de olika benen i landningen.

För att mäta och förstå vilken påverkan olika typer av steg (till exempel vanliga galoppsteg eller landningssteg) och ben (fram- eller bakben, inner- eller ytterben) har på hovens uppbromsning så användes accelerometrar (som mäter hastighetsförändringar) monterade på hovarna hos 5 hästar som galopperade och hoppade hinder av olika typ och höjd. Försöket visade att hovlandningen ser olika ut mellan galopp över plan mark, avsprång och landning, samt att de olika benen inom varje språng påverkar den vertikala och horisontella uppbromsningen. Avsprånget och frambenens landning gav upphov till kraftigast uppbromsning mellan hoven och underlaget. Försöket utfördes på två olika underlag, ett sand-fiberunderlag och ett med sand och träflis i topplagret. Sand-fiberunderlaget användes med två olika nivåer av vatteninnehåll. Sand-fiberunderlaget gav en större dämpning av hovuppbromsningen jämfört med sand-träflis och mer vatten ökade stötdämpningen ytterligare. Graden av hovuppbromsning i vertikal riktning, enkelt uttryckt stötdämpningen av underlaget mätt på hästarnas hovar jämfördes med ett motsvarande mått från underlagstestaren OBST. Det visade sig att OBSTn rankade banornas stötdämpning på samma sätt som hästmätningarna men att OBSTns mätningar var något högre.

För att undersöka funktionella egenskaper hos tävlings- och uppvärmningsbanor på internationella hopptävlingar av högsta nivå (4* och 5* FEI-tävlingar) genomfördes mätningar med OBSTn och tävlande ryttare fick bedöma underlaget. Tävlingarna var 9 stora tävlingar med totalt 25 banor. Banornas konstruktion och materialkomposition av topplagret beskrevs också. En jämförelse mellan de båda mätningarna visade tydliga samband mellan testmaskinens (OBST) mätningar och ryttarnas bedömning av viktiga funktionella egenskaper hos underlaget: ythårdhet, dämpning, grepp och elasticitet. För enhetlighet kunde ingen tolkningsbar koppling hittas. Den objektiva mätmetoden kunde därför konstateras vara relevant för hur underlaget bedöms av toppryttare inom hoppsporten.

För att kunna koppla skadeuppkomst och prestation hos hästar till underlagens egenskaper behövs en metod för att jämföra underlag på ett objektivt sätt. Metoden ska vara relevant både jämfört med de belastningar som uppstår mellan hästen och underlaget inom den aktuella sportdisciplinen men också vara relevant för sportutövarnas uppfattning om underlagets prestation. I den här avhandlingen presenteras användandet av en sådan metod med jämförelse till hästens och underlagets interaktion samt ryttarbedömningar. I framtiden kan kartläggning av funktionella egenskaper hos underlag kopplas till registrering av skador för att möjliggöra att bättre och säkrare underlag.

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