EQUINE SURFACES WHITE PAPER

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This white paper has been drafted as a collection of published scientific papers and data. It is considered a work in progress and will be updated as new scientific studies and surface data become available

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1.0 Introduction

1.1 General introduction

Performance and soundness are key factors in an equine athlete regardless of whether the horse is used for sport, work or leisure. The trainer's ability to keep a horse sound while working at the desired level of performance depends on a complex interaction between the horse and the environment. This white paper has been prepared in recognition of the fact that the surfaces a horse trains, works and competes on play a crucial role both in enhancing or limiting the horse's ability to perform and in determining the risk of injury.

The loads applied to the horse's body during locomotion can have a beneficial training effect that improves the horse's level of fitness but they may also have a detrimental effect in causing injury. Without the stimulus of exercise the musculoskeletal tissues will not become stronger and the cardio-respiratory systems will not improve in fitness. However, if the loading is too great or if the loading is repeated too frequently, then it predisposes to orthopaedic injuries. Overloading injuries may result from a single incident causing, for example, a fracture. More often, however, the effects of minor overloading accumulate over time and eventually result in a wear and tear injury such as osteoarthritis or tendinitis. Factors that contribute to overloading injuries include both intrinsic (within the horse) and extrinsic (external to the horse) factors.

Intrinsic factors, such as anatomical characteristics and physiological functions, affect how the tissues respond to exercise and their predisposition to orthopaedic injuries. Although the whole body is involved in and is responsive to exercise, we will focus on the parts of the body that are most important for locomotion. The bones, cartilage, ligaments and tendons form the locomotor infrastructure and these are the parts of the body affected by orthopaedic injuries. The muscles propel the infrastructure, whilst the circulatory and respiratory organs (heart, lungs, blood) provide fuel and oxygen that are transformed by the muscles in order to perform dynamic work. These activities are controlled by the nervous system which includes the brain, the spinal cord and the nerves. The resulting locomotor patterns are highly individualized and this is one of the determinants of the horse's suitability for specific sports such as show jumping, dressage, sprinting or endurance racing, cutting, etc.

Extrinsic factors interact with the intrinsic factors to affect performance ability and susceptibility to injuries. In this regard the amount, intensity and type of training have a major effect on loading of the locomotor apparatus and, therefore, on both performance and risk of orthopaedic injury. Other extrinsic factors are concerned with prevention and treatment of diseases and injuries, including health checks, vaccinations, parasite control, routine dentistry, nutrition, and attention to the psychological needs of the horse. The local environment, which encompasses everything from stabling conditions to the surfaces the horse trains on, are important throughout the horse's lifetime.

It is obvious that training a horse to achieve a high level of performance while maintaining soundness involves an integrated approach to equine management and training. It requires a great breadth and depth of knowledge and experience to fully understand these interactions. The work surface is an important part of this equation both in terms of the physical properties of the surface itself and the way in which the trainer uses the surface. No single surface is optimal for all purposes but there are a number of surfaces that are adequate for specific uses. Figure 1 illustrates the key factors influencing soundness and performance in sports horses.

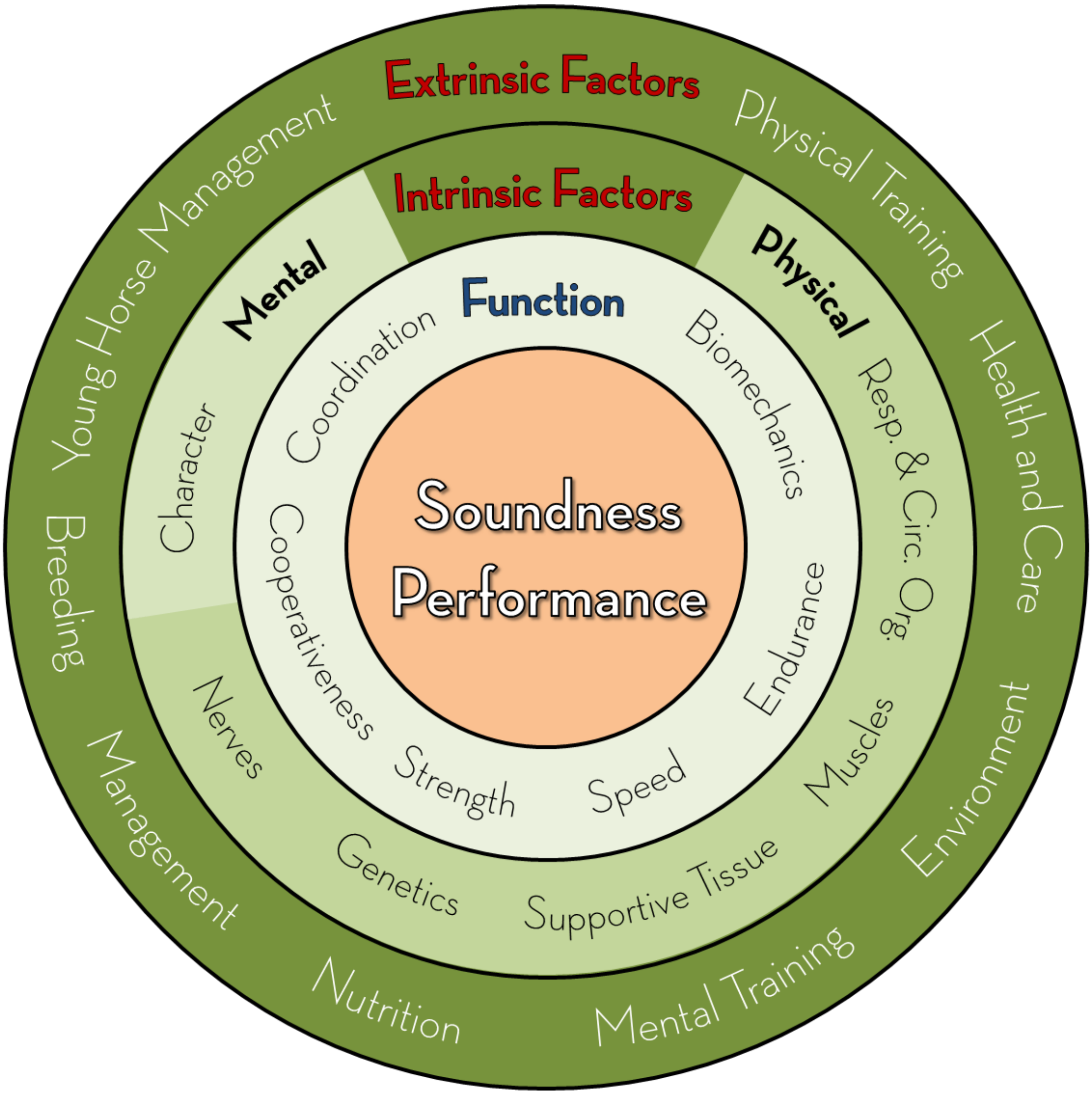

Figure 1: Key factors influencing soundness and performance.

1.2 Arena surface introduction

There is a growing worldwide demand for high quality equine arena surfaces for training and competition and consequently the number of manufacturers and products available has increased dramatically in recent years. Many factors have driven this consumer-led market, including more participation in horse sport, more competitions at every level, new and innovative temporary venues, weather patterns, higher demands on horses and better awareness of injury risk factors. The variation in products on offer worldwide are diverse, and often region specific, and there are currently no regulations or guidelines on materials, installation, maintenance and preparation, end of life re-use/disposal, or, importantly, an acceptable range of surface functional properties and characteristics.

Performance and safety are important concepts with regard to surfaces; a combination of properties that create a surface that is consistent, offers sufficient support to prevent injury and assists in achieving an optimal performance is essential (Baker and Canaway, 1993). The surface a horse works on has been documented as a risk factor for injury (Chateau *et al.*, 2009b; Crevier-Denoix *et al.*, 2009; Murray *et al.*, 2010a, b; Peterson *et al.*, 2012; Reiser *et al.*, 2000; Riggs, 2010; Robin *et al.*, 2009; Setterbo *et al.*, 2009; Williams *et al.*, 2001), but the decisions riders make can also be influential. This was highlighted at the 2004 Olympic Games in Athens when three show jumping horses sustained injuries that were attributed to the interaction between the studs they used and the surface.

Not only does this highlight the need for guidelines, it also shows that the body of research to date has only begun to understand the risk factors in relation to arena surfaces. This is primarily because the interaction is complex and multi-factorial, but also because there are no standards from which we can compare our results and learn from each other. The development of guidelines requires the development of standardized equipment and procedures, against which other equipment/data can be validated. This type of approach will contribute towards developing an optimal arena surface that combines performance and consistency with safety (Peterson *et al.*, 2012).

1.3 Objectives for the work

This white paper focuses on arena surfaces within the broad context of providing training and competition arenas for sport horses that facilitate maximal performance while minimizing the risk of injury. It includes a description of the physical properties of the surface that determine how the horse perceives the footing and the effects of the footing on the horse's physiological and biomechanical responses. It also covers aspects of composition, construction, and maintenance that are necessary to build and maintain arenas with the desired physical properties. Current methods of measuring the physical properties of the surface are described using terms that are easily understood by riders, trainers, course designers and arena builders. It is hoped that this information will provide a basis to guide future progress in this area.

2.0 Intrinsic factors

Intrinsic factors that influence soundness and performance include the mental as well as the physical wellbeing of the horse. A nervous, tense horse may well increase the intensity of load on their body compared to a relaxed horse, which will then influence the loading response of tissue. So, although tissue response and injury development is mainly considered below in relation to loading, consideration of how that loading occurs with respect to the horses' temperament should be taken into account.

2.1 Tissue response to loading and injury development

Musculoskeletal development occurs through appropriate exercise, causing an adaptive response in bone (Boyde, 2003; Verheyen et al., 2006; Orsini, 2012), tendons (Kasashima et al., 2002; Firth, 2006) and joints (Reed et al., 2012). It is apparent that connective tissues are influenced by the type of management regime early on during growth (Nielsen et al., 1998; Firth et al., 2011; Firth et al., 2012) and that each tissue requires specific loading (Firth, 2006; Dahlgren, 2007; Reed et al., 2012). The volume of exercise determines the level of stress imposed on the tissues, which can promote modelling, skeletal growth, and increases in the strength.

Overload can represent a single event, where the magnitude of stress exceeds the ultimate strength of the material under load causing an acute injury, such as a pastern bone fracture or collateral ligament tear. Equally, if stress exceeds tolerable limits during repetitive loading this will cause micro-trauma and eventually lead to changes in orthopaedic health (van Weeran, 2010), which are usually described as chronic or overuse injuries. Overuse injuries tend to be degenerative in nature, so as the injury develops, the material properties of the tissues deteriorate, the maximum stress limits are reduced, movement patterns are modified and so more of the surrounding structures are subjected to overload, which then also deteriorate, and so on.

The concern that a surface may be implicated in injury in humans arose in the 1960s when the use of artificial surfaces became more popular (Nigg and Yeadon, 1987). The synthetic surfaces were associated with negative effects on the locomotor system in comparison to naturally occurring turf or dirt, although more recently it has been noted that predisposition to injury can be reduced by training and competing on suitable surfaces (Willardson, 2007). The increasing use of artificial surfaces in the equine industry has also been associated with an increase in reported injuries. These reports are primarily from race tracks (Bailey et al., 1998; Parkin et al., 2004). Sports specific musculoskeletal injuries have been reported by a number of authors in show jumpers (Dyson, 2002; Boswell et al., 2011; Parkes et al., 2013), dressage horses (Gibson et al., 2002; Murray et al., 2006; Murray et al., 2010b; Parkes et al., 2013) and event horses (Singer et al., 2008) although these injuries may be caused for a number of reasons other than surface.

Hard surfaces have been found to increase the likelihood of bone and joint-related injury in the distal limb, in part, due to the high frequency vibrations and concussive forces associated with primary impact (Radin et al., 1973; Barrey et al., 1991; Bailey et al., 1998). Foot soreness has been recognised in the general horse population, and front foot soreness and concussive injuries have been particularly linked to show jumpers competing on hard ground, due to large deceleration peaks and high loading rates (Boswell et al., 2011). Foot soreness was also identified as a prevalent condition in dressage horses in addition to hind limb lameness due to suspensory ligament or tarsal joint injury (Murray et al., 2010b).

The demand on the distal limb during take-off and landing over a fence can be high and it has been recognised that weak or inexperienced jumpers increase stress on the limbs through altered biomechanics during a jumping effort (Schamhardt et al., 1993; Barrey and Galloux, 1997). Dyson

(2002) and Murray et al. (2006) reported that show jumpers were at a high risk of damage to the suspensory apparatus (and related structures) in both the fore and hind limb. Also in show jumpers the prevalence of superficial digital flexor tendon (SDFT), deep digital flexor tendon (DDFT) and suspensory ligament injuries in the forelimb will be influenced by the high strain on the SDFT of the trailing forelimb in the last approach stride to the fence (Dutto et al., 2004) and the leading and trailing forelimbs during landing (Meershoek et al., 2001a) (described in section 4.2).

3.0 Extrinsic factors

The following section considers extrinsic factors that may influence soundness and performance. The list is not exhaustive and may include any and all factors external to the horse that influence their wellbeing and ability to perform. This section highlights the main factors that have been considered to date other than the surface, which is given special attention in sections 4.0, 5.0 and 6.0.

3.1 Training regimen and competition frequency

> *'Preparation of a horse for any type of competition involves a combination of conditioning and schooling. Conditioning induces physiological and structural adaptations that maximize performance and maintain soundness; schooling develops neuromuscular coordination and mental discipline.'*
>
> Clayton (1991) pp 77.

The volume of exercise performed over a period of time depends on the intensity, duration and frequency (Clayton, 1991). Limb integrity is dictated by the volume of exercise and use of a variety of types of surface will increase limb strength and reduce likelihood of injury by providing a diverse loading environment that stimulates the musculoskeletal tissues to respond in a diverse manner. Some types of injury are judged to be sport specific (Murray et al., 2006) and the majority are regarded as repetitive use injuries that are influenced by the surfaces used for training, in addition to other variables such as the methods of training and demands of the sport.

In young horses skeletal development and health are significantly affected by exercise early in life before training begins (Firth et al., 2011; Rogers et al., 2008; van Weeren and Barneveld, 1999). Effective training protocols allow time for recovery and repair (Firth, 2006; Verheyen et al., 2006), with consideration of intensity due to the training surfaces used (Moyer and Fisher, 1991). Once in ridden work, the ability to sustain walk, trot and canter for 50 minutes should be developed gradually in young sport horses before progressing to more demanding work (Clayton, 1991). A dressage horse's training regimen will include extensive repetition of movements that are invariably conducted in an arena and will involve periods of gymnastic exercises with high levels of collection and turning. Training will develop muscle strength and proprioceptive responses (Cressey et al., 2007) both of which require these repetitive exercises however loading of the distal hind limb can increase strain and potentially damage these structures (Murray et al., 2006). Highly collected movements increase the loading of the hind limb as found in passage by Weishaupt et al. (2009) and further described in section 4.1. For show jumpers strength training is needed to develop explosive power at take-off and absorb impact shock during landing. Regular jumping is needed to strengthen the horses' bones, ligaments and tendons in a highly sport specific manner, as this cannot be achieved by other types of exercise (Clayton, 1991).

The volume of exercise in competition is another important consideration, as the intensity is likely to be greater than during training. In addition, the surface at a competition may be quite different to the training surfaces used at home. A horse should be expected to work on a variety of surfaces during training in order to condition the musculoskeletal tissues so that they are fit to perform higher intensity exercise on a competition surface. Understandably riders expect the surfaces at competition venues to be good quality, but there are currently no guidelines or grading systems. In addition, there are often disparities between the functional properties and characteristics of warm up and competition arenas even though it is considered beneficial for the warm-up arena to be the same as, or at least similar to, the arena the horse will compete on. A grading system for arenas would allow riders and trainers to select appropriate competitions with greater consideration for a horse's fitness and performance history, particularly as there is a higher risk of injury with higher intensity of exercise.

3.2 Fitness and condition

Current fitness and condition depend on many different factors, which include, but are not exclusive to, current wellness including mental and physical wellbeing, the current volume of exercise, competition frequency and diet. Most of these factors are discussed in other sections, so are not given attention here. It is merely noted that current fitness and condition should always be taken into consideration before exercise is undertaken.

3.3 Nutrition

Management of the horse during development has received considerable attention. Exercise and diet are determinants of future musculoskeletal integrity and strength (Porr et al., 1998). Optimal development of horses (particularly during growth) requires carefully balanced diets that provide sufficient energy and nutrients such as protein, minerals and vitamins. Supplementation of some nutrients beyond National Research Council recommendations may provide additional benefits. For example, Nielsen et al. (2010) suggested that bone turnover can be improved by diet and may reduce injury by enhancing repair of damaged bone in young horses. Conversely, a diet containing excess carbohydrates but insufficient nutrients may lead to orthopaedic problems resulting in lameness or poor performance (Staniar, 2010). Therefore diet plays an important role, however Nielsen and Spooner (2008) identified that small increases in exercise were more effective than changing the diet in order to increase bone mineral density.

3.4 Shoeing

The horse-hoof-ground interaction is influenced by the structure and material properties of the contacting surface of the foot. This includes the way the hoof is balanced, choice of shoes or no shoes, the type of shoe, the current condition of the shoe, the structure of the solar surface of the foot, current hoof growth, and the type, number and configuration of screw-in shoe studs or caulks (Harvey et al., 2012; Parks, 2011). As riding and sports horses are expected to compete on a variety of surfaces and under different conditions, these choices are important in order to help the horse perform to the best of its ability. Changing this interface will principally affect performance in relation to friction, traction and damping in the loading phase of the stride and then the resistance to propulsive effort in the unloading phase. Currently studies have focussed on the effect of changing the foot or shoe whilst standardizing the surface. Often the standard surface is a hard surface, such as concrete, asphalt or a rubberized runway and this limits the generalize-ability of the information to locomotion on arena surfaces that have different physical properties, as the contact area and surface deformation are quite different.

Shoeing with steel shoes was found to increase the maximal vertical force compared to barefoot (Roepstorff et al., 1999), but maximum deceleration and vibration frequency may be reduced by using light shoes made of polymers and pads made of synthetic rubber (Benoit et al., 1993). These differences may be less pronounced on surfaces with superior damping characteristics, but little information is currently available. A gradual palmar/plantar shift in the centre of pressure (COP) due to hoof growth (van Heel et al., 2006) and backwards tilting of the foot in unshod hooves (Roepstorff et al., 1999) may influence the depth of penetration of the heel into a compliant surface during loading. Long toes are also reported to prolong breakover timing and due to an increase in the length of the resistance arm, there is an increase in tension on the DDFT to initiate breakover (Clayton 1988) and toe penetration depth is likely to increase. Hoof pitch rotation during early stance due to the heel sinking into the surface has been reported (Chateau et al., 2006), but the magnitudes may vary considerably on softer surfaces. Shoes with wider heels, such as rolling reversal shoes are reported to reduce penetration into the ground at the heels and therefore DDFT extension (Denoix and Crevier-Denoix, 2007). Although this is a remedial shoe it highlights the changes in the hoof-ground interaction and limb loading patterns that can occur due to shoe design. Sports horses may be shod with a variety of shoe types or may be unshod, depending on their needs, and more studies are needed to quantify the effects of these variables when horses work on compliant surfaces.

The use of caulks or removable shoe studs may be beneficial under some circumstances and it is important that shear properties of the surface are known in order to make the most appropriate decision (Peterson et al., 2012). Caulks or shoe studs are most often used by horses that perform rapid movements and changes of direction, such as polo ponies and jumping horses (eventers and show jumpers). However there is no literature to date that reports on their effects during sport-specific movement. It is known that the use of caulks/shoe studs change the horse’s movement (Harvey et al., 2012) by altering dorso-palmar and/or medio-lateral balance (Parks, 2011) but currently there are no evidence-based recommendations for optimal type for specific surface conditions (Peterson et al., 2012). A variety of types and locations are used based on personal experience rather than evidence-based data. Unfortunately, inappropriate choices can lead to excessive concussive forces and strain on the limbs.

3.5 Equipment

A wide variety of equipment is used in training and competition with choices often being based on current market trends, anecdotal evidence or familiarity rather than scientific evidence. Some equipment and techniques have been evaluated, such as the kinematic and kinetic effects of support boots and bandages, weighted hoof boots and athletic taping, although results are somewhat conflicting. Support boots were found to reduce the magnitude and delay the timing of maximal fetlock extension (Kicker et al., 2004), whilst support bandages did not alter strain in the suspensory ligaments (Keegan et al., 1992), and athletic taping reduced swing phase fetlock flexion and peak vertical force (Ramón et al., 2004). How this alters the relative loads on different anatomical structures has not been well investigated. Adding or reducing distal limb segment mass is often used to alter the flight arc of the hoof (Willemen et al. 1994; Balch et al. 1996; Murphy et al., 2009), but it must be recognized that even small changes in distal limb mass alter metabolic costs considerably (Wickler et al., 2004). Saddle fit has been recognized as a factor in the development of back pain in horses due to uneven loading patterns and/or excessive localized pressure (Jeffcott, 1980; De Cocq et al., 2004; Fruehwirth et al., 2004; Meschan et al., 2007; von Peinen et al., 2010; Belock et al, 2012) with consequential effects on locomotion. Other tack and training devices may have positive or negative effects on performance, and should be carefully considered in relation to their use on the individual horse.

3.6 Rider Factors

As the majority of work, both in training and competition is ridden, rider factors must also be considered in relation to performance and injury risk in sports horses. Scientific studies are becoming more prevalent and are often focussed on rider symmetry and/or rider skills and ability. The skills and ability of the rider influence horse-rider harmony and, consequently, injury risk (Peham et al., 2001; Licka et al., 2004; Peham et al., 2004; Byström et al., 2009). Asymmetry in riders has been reported during symmetrical movements (Symes and Ellis, 2009), and the effects of asymmetrical activities, including rising trot (Licka et al., 2004; De Cocq et al., 2009; Roepstorff et al., 2009; De Cocq et al., 2010; Peham et al., 2010) and mounting (Geutjens et al., 2008) have also been documented. As the interaction between the horse and rider is complex these studies only begin to explore the extent of rider influences on the horse.

3.7 Age, genetic defects, conformation, current health status

Just as care must be taken not to overload young, developing horses (see section 2.1), care must also be given to older sports horses, as the strength and integrity of tissues begin to deteriorate with age. Show jumpers can compete until 15-20 years of age at a high level, and Murray et al. (2006) suggested that distal DDFT injuries in these horses may be contributed to by overuse and possible age-related deterioration. Notably, the elastic SDFT in the distal limb accumulates damage as age increases; (Dowling et al., 2000). The weight of a horse should also be given consideration, as this will influence the stresses in the limbs. Parkes et al. (2013) identified that higher body weight to height ratio in Thoroughbreds increased the risk of foot pain. Non elite show jumpers and event horses were reported to be heavier than elite competitors, which may relate to fitness, whereas non-elite dressage horses were reported to be lighter than elite dressage horses, which may relate to muscle mass and breed (Murray et al., 2006).

Limb and foot conformation can influence soundness (Marks, 2000) and competitive longevity (Ducro et al., 2009) and its significance varies according to breed and sport. There is evidence in the scientific literature of the relationship between conformation and susceptibility to injury in both racehorses (Anderson et al., 2004) and sport horses (Dyson, 2002; Ducro et al., 2009). An elite horse must have the ability to collect the stride, which is facilitated by having appropriate conformation. Although the rider and trainer are important determinants of performance, the horse's innate conformation and movement patterns have a profound effect on training and the ability to perform in competition. Holmström et al. (1990) identified attributes in elite sport horses that were necessary for soundness and balance, which are fundamental for the horse to train and compete optimally though horses can still perform well in spite of minor conformational deviations of the limb/hoof axis (Holmström et al., 1990). Hoof conformation and growth change with trimming, shoeing, wear and exercise. Foot conformation has been investigated extensively but is not the main focus of this paper. In summary the hoof-surface interaction is influenced by distal limb conformation (Marks, 2000; Parks, 2011), which influence the forces applied to the foot (Elishar et al., 2004) and consequently limb loading.

4.0 Sports analysis

Analysis of sports specific movements have been documented previously from video footage and include elite performances from Olympic competitions. These are enhanced by studies using 3-D motion analysis and force platform techniques that have addressed specific aspects of movements in groups of horses. These pioneering studies have laid the foundations of our understanding of the demands of different sports on the horses involved, but far more research is needed to quantify these demands in relation to competition level and ability of the horse. A summary of our current knowledge is given below.

4.1 Dressage

Dressage movements involve high levels of collection (passage and piaffe), extension (extended trot and canter) lateral movements (travers, renvers, half pass) and rotational movements (pirouettes). The properties of the arena surface are expected to be important to the successful execution of each movement, but to date only some measurements of elite horse-rider combinations are available.

The demands on the horse and the performance requirements of the surface are described below based on findings to date. Much work is still required in this area.

Collected movements

Collected movements require a reduction in forward motion without an alteration in cadence, elasticity or impulsion (FEI, 2011), which demands a greater reliance on static rather than dynamic equilibrium. Modifications in foot placement patterns, which enhance centre of mass (COM) stability include prolonging stance durations, increasing overlap durations, and reducing or eliminating suspension phases (Clayton, 1997). Of the collected gaits, piaffe was found to have all of these modifications and therefore considered the closest to static equilibrium (Clayton, 1997). Compared to trot, passage has a shorter airborne phase and higher flight arc, which is achieved by increasing the vertical impulse in fore and hindlimbs, but not the magnitude of peak force. There is also a shift in the load distribution to the hind limbs with greater positive dissociation between hind and forelimb foot strikes and an increased weight-bearing function (Weishaupt et al., 2009). Greater flexion is seen in the hindlimb and lumbosacral joints (Weishaupt et al., 2009), but this is not achieved by stepping further under the body with the hindlimb, as the hoof contacts the ground in a more caudal position (Holmström et al., 1995). As a result, Holmström et al. (1995) suggested that storage of elastic strain energy in the hock and pelvis may be of great importance for passage. The performance of the surface to support applied loads without large energy losses, but at lower strain rates (due to the longer stance durations) is therefore essential for collected movements.

Extended movements

Little information is currently available on the extended movements of trot and canter, which require the horse to cover as much ground as possible, in a lengthened frame, without hurrying (FEI, 2011). Elite horses were found to execute the extended trot at an average speed of 4.93 m/s with a stride length of 3.55 m and stance durations of 273 and 276 ms in fore and hindlimbs respectively. It was also suggested that for top marks a speed of 5.4 m/s and stride length of 4 m would be expected (Deuel and Park 1990).This compares to working trot at 3.61 m/s with a stride length of 2.73 m and increased stance phase durations of 341 and 339 ms in the fore and hind limbs (Clayton, 1994a). Extended canter speeds were reported to be in excess of 7.1 m/s to achieve the highest scores at the Olympic Games in 1988 (Deuel and Park, 1990) with increases in stride length, but not stride duration (Deuel and Park, 1990; Clayton, 1994b). The increase in speed and demand for a long stride combined with a decreased stance time suggest that larger peak forces must be developed but also that greater impact shock will be experienced by the limbs. Currently, the data most comparable with extended trot of dressage horses come from racing trotters performing on different sand preparations and moisture contents at comparable or faster speeds (Chateau et al., 2010; Crevier-Denoix et al., 2010). Although impact shock characteristics were increased on the firmer, wetter surface (which may be considered as detrimental), the yielding dryer surface was unable to support peak loads. So, to maintain the same speeds on the deep, dry surface the horses produced equivalent impulses by increasing limb stance times. This was achieved by reducing stride length and increasing stride frequency, which is undesirable in dressage. So for extended trot, the surface is required to support higher applied loads at higher strain rates with higher shear strength during propulsion, but with lower deceleration and vibration frequencies at impact.

Rotational movements

The canter pirouette is performed in collected canter with the forehand moving around the haunches in a circle with a radius equal to the horse's length. A 360 degree pirouette should be completed in 6-8 strides, and should maintain the activity and clarity of the canter (FEI, 2011). To turn, the limbs on the outside of the circle need to push in the opposite direction to the horse's motion to rotate the COM around the leading hindlimb. In elite horses duration of the pirouette strides were reported to be significantly longer than collected canter strides, and there was no suspension phase, so there was overlap between leading forelimb lift off and trailing hindlimb footstrike (Burns and Clayton, 1997). As the leading hindlimb is grounded for approximately 50% of the stride (540 ms stance duration for a stride duration of 879 ms (Burns and Clayton, 1997)), and each stride covers 45 to 60 degrees of rotation, this limb may be subjected to a notable amount of torque if the surface does not allow any rotational shearing. The canter pirouette, like piaffe, is closer to static equilibrium conditions, so the surface must perform under lower strain rates, supporting an almost static load whilst allowing rotational shear for the leading hindlimb, but also resisting horizontal shear sufficiently as to allow rotation to be produced during propulsion of the other limbs.

Lateral movements

In shoulder-in, half pass, renvers, and travers the horse is evenly bent in his neck and body, but moves on more than two tracks (Dyson, 2002). To move laterally the horse must push sideways, producing larger transverse forces at the ground than those produced in a straight line (Clayton, 2002). These movements create an unusual strain on the horse's back and an additional twisting movement on the appendicular joints (Dyson, 2002). Similar to rotational movement, the shear resistance of the surface is expected to be most important to the execution of the movements and reduction of injury.

4.2 Jumping

Jumping at elite level not only demands the ability of a horse to raise its COM sufficiently to clear fences of over 1.5 m in height, but also requires superior speed and manoeuvrability. Elite horses have been recorded at approach and landing velocities of up to 8 m/s (Deuel and Park, 1991), so the surface must respond at higher loading rates than those required for dressage.

Maximum jumping capacity is fully determined by the impulse at take-off, which is a compromise between approach speed and muscle strength (Powers et al., 1999). In order to jump a fence, the COM must be redirected to a more vertical trajectory. To do this the forelimbs must produce high retardory impulses and the hindlimbs must produce larger propulsive impulses (Powers et al., 1999). This is achieved principally through rotation of the body around the trailing forelimb and positive work at the stifle, hip, hock and metatarsophalangeal joints (Dutto et al., 2004). The type of fence will influence the approach, with higher stride frequencies and shorter time intervals between hindlimb impacts at take-off associated with spread fences (Deuel and Park, 1991). In poor jumpers the ratio between fore and hindlimb force production and COM acceleration is altered, placing higher demands on individual limbs (Schamhardt et al., 1993; Barrey and Galloux, 1997). A study comparing limb placement distances relative to fences of different heights (1.10 m, 1.25 m, 1.40 m) and widths (1.10 m, 1.25 m, 1.40 m) showed that distance from the fence on the take-off side was independent of fence height or width but landing distance increased with fence height and horses landed closer to fences that had width as well as height (Clayton and Barlow, 1989). COM take-off angle and speed determine the COM trajectory over the jump; little can be done to modify these once airborne (Powers et al., 1999), though the limb positions may be adjusted to facilitate fence clearance and to adjust the angular velocity. In order to be successful in clearing a water jump, horses must take-off with a large vertical velocity whereas horizontal velocity at take-off is not a determinant of success (Clayton et al., 1995). A higher vertical velocity at take-off is correlated with a smaller distance from the leading hind hoof to the horse's centre of gravity and a more elevated trunk angle at lift off (Colborne et al., 1995).

On touching down from a 1 m fence, leading and trailing forelimbs were found to be almost completely extended with the trailing limb placed nearly vertically whilst the leading limb has a more forward placement (Meershoek et al., 2001a). Due to the vertical alignment of the trailing forelimb on landing this limb produces higher vertical and mainly propulsive forces and loads on the flexor tendons are greater in this limb (Meershoek et al., 2001a). As fence height increases stance duration for this limb reduces whilst tendon loads increase, with the greatest relative loading on the SDFT, which is probably why the prevalence of injury is higher in the this tendon (Meershoek et al., 2001b). Inexperienced horses were also found to produce higher landing forces in the trailing limb with up to twice bodyweight being recorded for one horse jumping a 1.3 m fence (Schamhardt et al., 1993). Higher total landing velocity (Hernlund et al., 2010), greater braking force, a longer stance time and an extensor joint moment in the coffin joint were found in the leading limb compared to the trailing limb (Meershoek et al., 2001a). This moment was thought to be produced by the extensor branches of the suspensory ligament and digital extensor muscles to prevent knuckling over of the hoof during deceleration. Total landing velocities were higher in the hindlimbs compared to the forelimbs (Hernlund et al., 2010), but peak forces were lower in association with their longer stance durations (Schamhardt et al., 1993). Higher velocities in jumping combined with different functional requirements of the limbs and large ground reaction forces place high demands on the surface. At elite level the surface must respond to higher strain rates, supporting higher applied loads and providing higher shear strength whilst damping unwanted impact shock on landing. To provide an equal opportunity for all riders it must also remain consistent throughout a competition.

4.3 Other Horse Sports

Sports such as barrel racing, vaulting and reining are less well described than dressage and show jumping in the scientific literature however much of these horse's exercise will be carried out in an arena. Activities that are used in these and other sports involve sharp turns, circles, rapid changes of speed and direction, including sliding stops. Studies are currently emerging that have documented aspects of locomotion on circles (Clayton and Sha, 2006; Hobbs et al., 2011; Chateau et al., 2012; Pfau et al., 2012; Starke et al., 2012) and during sharp turns (Chateau et al., 2005; Tan and Wilson, 2011). In order to turn, the horse must push outwards which results in an inwardly directed force at the ground and centripetal acceleration (Hobbs et al., 2011; Tan and Wilson, 2011). This is achieved, in part, by shifting the COM towards the inside of the turn (Clayton and Sha, 2006; Hobbs et al., 2011; Tan and Wilson, 2011), and adducting the inside forelimb through the stance phase, so that it is positioned further under the body (Chateau et al., 2005). Tan and Wilson (2011) suggested that the speed of horses during turning is limited by friction between the foot and the ground for small radius turns and by limb force for turns with larger radii. Current evidence suggests that duty factor is increased in the inside forelimb at higher speeds on 10 m circles (Hobbs et al., 2001). The inside forelimb may therefore be limited in terms of developing propulsion, due to the need to develop more inwardly directed force at the ground. Greater vertical force has also been measured in the outside forelimb on similar sized circles (Chateau et al., 2012), which supports this theory. The increase in frontal plane forces and moments when negotiating curves and turns are considered to increase injury risk, particularly in the distal joints (Denoix, 1999; Heaps et al., 2011).

Stricklin (1997) reported that strains in the suspensory ligaments of barrel racing horses are more prevalent when ground conditions are deep (due to the use of sand or wet soil). Demands on the surface to provide sufficient friction and shear resistance whilst allowing the hoof to penetrate the surface medially (so that the limb segments can remain aligned with the long axis), are therefore great, particularly for tight turns.

5.0 Biomechanical analysis

It is true to say that the majority of riders analyse their horse's performance from a qualitative perspective almost every time they ride and to some extent their perception provides a measure of the demands on their horse. This type of information has been gathered through questionnaires (Murray et al., 2010a; 2010b) to further our knowledge of rider preferences about surfaces, but since it is subjective, it can vary considerably between horse, rider and situation. To obtain objective data it is necessary to measure the horse performing on different surfaces. Research in this area is currently growing and includes the use of instrumented horseshoes to measure the forces at the ground (Ratzlaff et al., 1983; 1993; 1997; Barrey, 1990; Roland et al., 2005; Chateau et al. 2009a; Robin et al. 2009); accelerometers to measure the amplitude and frequency of impact shock and how vibration decays (Barrey et al., 1991; Hjertén and Drevemo, 1994; Schamhardt and Merkens, 1994; Gustås et al., 2001; 2004; 2006a; 2006b; Leleu et al., 2002; Burn, 2006; Dallap et al., 2006; Parsons and Wilson, 2006; Burn et al., 2007; Thomason et al., 2007; Chateau et al., 2008; Thomason and Peterson, 2008; Chateau et al., 2009b; Setterbo et al., 2009; Chateau et al., 2010); 2-D and 3-D kinematic techniques to measure differences in locomotion characteristics on different surfaces (Burn and Usmar, 2005; Chateau et al., 2006; Setterbo et al., 2008; Crevier-Denoix et al., 2010; Hernlund et al., 2010; Harvey et al., 2012; Orlande et al., 2012; Walker et al., 2012; Northrop et al., 2013) and bespoke equipment to assess the difference in forelimb SDFT loads (Crevier-Denoix et al., 2009). Some of these studies included physical and mechanical measurements of the surface with biomechanical measurements to provide additional information about the surfaces being tested. Standardized measurements of surfaces together with the quantification of the demands on the horse during equestrian activities will ultimately provide knowledge to reduce the risks of injury to the horse.

5.1 Horse-hoof-surface Interaction

The horse-hoof-surface interaction defines the response of the surface to the loads applied by the horse and the resulting effects of this response on the horse on a stride by stride basis. To date this has been described for steady state gait in a straight line, on turns and circles, on treadmills and with the use of force platforms using gaits from walk to gallop. However, there is still much to learn about locomotion in sports horses on arena surfaces. A typical horse-hoof-surface interaction can be described from these data.

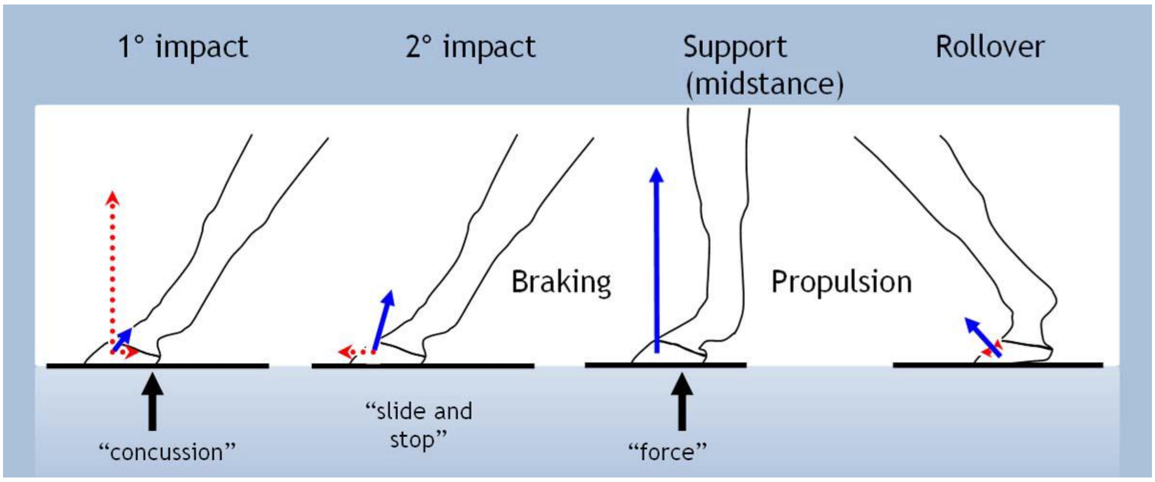

Figure 2: Stages of the stance phase showing the differences in acceleration (red) and ground reaction force (blue). When the blue arrow is tilted, it indicates that both vertical and horizontal components of the ground reaction force are present. The arrow shows the direction in which the ground is pushing the horse (Peterson et al., 2012).

The limb is loaded during the stance phase, but the demands on the horse change over the period from hoof landing to lift off. Peterson et al. (2012) divided the stance phase of limb loading into the following stages: primary impact, secondary impact, support (midstance) and rollover (or breakover) as shown in Figure 2. The swing phase can be subdivided into post breakover, midswing and pre-impact (or terminal swing). The phases of the movements and their effects on the horse are described in more detail below from pre-impact.

Pre-impact is the phase immediately before the hoof hits the ground. Following maximal protraction in the swing phase the limb is accelerated in retraction, which decreases the velocity of the hoof relative to the ground before impact. Changes in landing velocity have been recorded on different surfaces although the reasons for this are still unclear (Burn and Usmar, 2005).

Primary impact (1°) is associated with high decelerations and low forces when the hoof impacts the surface and rapidly decelerates to zero velocity (Thomason and Peterson, 2008). The vertical deceleration is higher than the horizontal deceleration during this phase due to the ratio of the forward and downward hoof movement (Gustås et al., 2006b) which differ between the fore and hind limbs (Back et al., 1995). The collision transmits shockwaves through the hoof and surrounding structures (Barrey et al., 1991; Chateau et al., 2010; Gustås et al., 2006a), which are heavily damped by the soft tissues of the hoof (Gustås et al. 2001). Forces on the foot are relatively low, because only the mass of the hoof and pastern participates in this collision (Peterson et al., 2012). The magnitudes of deceleration and shock energy during primary impact are extremely sensitive to speed of the horse, vertical hardness of the surface and the damping capabilities of the cushion (Gustås et al., 2006b; Thomason and Peterson, 2008; Peterson et al., 2012). As speed significantly influences the collision, there are likely to be sport-related differences in the characteristics of primary impact.

Secondary impact (2°) is characterised by higher forces and minimal deceleration when the mass of the horse collides with the leg that is planted on the ground (Barrey et al., 1991; Ruina et al. 2005; Thomason and Peterson, 2008). The body tends to push the leg forward, forcing the hoof to slide over the surface before coming to rest (Pardoe et al. 2001). The amount that the hoof slides and the time in which it stops sliding are important considerations and will be influenced by the surface, the landing speed of the foot, the speed of the horse and the coefficient of friction between the hoof-shoe-surface interface. Burn (2006) suggested that hoof penetration depth can affect hoof slide, due to the forces exerted on the hoof wall by the surrounding substrate. During this phase the forces decelerating the body and loading the limb begin to rise (Hjertén and Drevemo 1994; Peterson et al., 2012).

A small amount of hoof slide at impact is considered beneficial to the horse as it aids in decreasing the forces encountered during deceleration (Gustås et al., 2006; Orlande et al., 2012), although these effects are difficult to quantify. Shortening the duration of slide increases the magnitude of the horizontal component of the ground reaction force, which may exert larger-than-normal bending moments on the cannon bone at higher speeds (Pratt, 1997). Conversely, excessive hoof slide has the possibility of forcing the digital flexor muscles into rapid, unpredicted eccentric contraction, which can cause tears within a muscle (Peterson et al., 2012). As a shearing force appears in the carpus before longitudinal loading of the limb (Hjertén and Drevemo, 1994) it was surmised that this may predispose to injury under unfavourable circumstances, such as when large frictional forces are present. As such, the frictional characteristics of surfaces are important in relation to the magnitude of longitudinal force produced, but also surfaces may have an important role in damping horizontal forces.

Support (midstance) This phase overlaps with secondary impact and extends through midstance to heel lift. The weight of the body and the change in vertical velocity of the centre of mass successively load the planted limb. At midstance the limb will experience peak vertical loads and there is a transition from braking to propulsion, so the centre of mass of the horse begins to accelerate forwards (Hobbs and Clayton, 2013). The size of the forces being produced, the direction of the forces and the time that they are produced for will be specific to the movement being performed. It is expected that some movements will require additional muscular effort from the horse, whereas some will be a result of the current momentum developed in the preceding stride (where little additional effort is needed from the horse). It is important during this phase that the surface is able to carry the load being applied by the limb vertically, and provides sufficient shear resistance to allow the horse to propel its body forwards. Excessive plastic deformation of the surface would mean the reaction from the ground is smaller, so the horse must apply more muscular force to maintain the same momentum, which may lead to fatigue (Crevier-Denoix et al., 2010). For movements producing large forces, this phase is implicated very strongly in causing traumatic and chronic injuries, although more is known in relation to racing compared to sport horse injuries currently (Setterbo et al., 2009).

Rollover (or breakover) occurs when the hoof lifts at the heels and rolls from the ground during the later stage of propulsion (Reiser et al., 2000; Thomason and Peterson, 2008). Both the vertical and horizontal forces fall towards zero at toe off, so the limb is gradually unloaded. This stage is important in that altering its duration strongly affects the kinematics of the limb during the swing phase, which in turn affects the next stance phase (Peterson et al., 2012). As the grounded hoof rotates the amount of surface shear resistance will influence the amount of material that is displaced from the cushion, commonly known as kickback.

Post breakover immediately follows where the hoof and digit flex rapidly and forms the start of the swing phase (Thomason and Peterson, 2008).

6.0 Arena Surface Attributes

It is fair to say that the complex demands on the surface sometimes lead to contradictory needs to accommodate the range of loading and conditions for usage. For example the canter pirouette requires that the frictional characteristics and/or material shear strength is sufficiently low that excess loading does not occur from a fixed foot and rotating limb. In contrast the same arena may need to provide sufficient shear strength for stable turns and jumps. However it is reasonable to assume that an uncertain or inconsistent surface is undesirable and may be more likely to lead to injury. In addition we hypothesize that while a horse is able to adapt to a range of surfaces, training and competing on dramatically different surfaces may negatively impact performance and may be associated with injury. Therefore, based on the biomechanics of the hoof surface interaction we consider a range of tests which may provide a basis for insight into the development of a safe high performance arena surface.

Several aspects of arena surfaces influence the surface dynamics experienced by the horse. While many competitors and vendors of footing materials tend to focus on the mechanical and physical characteristics of the surface material, a number of other factors must be considered including the arena base, the drainage system, the maintenance procedures, environmental factors (i.e. temperature for wax surfaces and moisture content for sand surfaces), the age of the surface and how much it is used (Barrett et al., 1997; Burn, 2006; Burn and Usmar, 2005; Ford et al., 2006; Peterson et al., 2012). These factors interact in a complex system in which several different combinations may result in the qualities desired for performance and safety of a surface.

It is generally believed that a surface with optimal performance is associated with a greater risk of injury whereas a surface that has shock absorbing properties will be detrimental to performance (Chateau et al., 2010; Dura et al., 1999). The trade-off between high performance and low injury rate is not a given in human biomechanics where improved performance has been linked to much lower injury rates in at least one study (McMahon and Greene, 1979.). The absence of a link between injury and performance has not yet been shown to be true in equestrian events. In addition, the optimum surface for a specific sport is yet to be determined but has been described by Barrey et al. (1991) as needing to minimise concussion through energy absorption, whilst still returning suitable power to aid performance. There is also a need to optimize shear strength, where optimization is likely dependent on the event. This is an area that requires further research. As the balance between safety and performance is highly dependent upon the functional properties and characteristics of the surface, it is important to understand the characteristics and performance of the individual parts of the system as well as having standard measures that can be taken *in-situ*.

6.1 Functional properties and characteristics

The functional properties and characteristics of arena surfaces are influenced by a surface's material, the layout and design of the arena, and maintenance of the surface material. The combination of these factors affects how a surface performs and how it feels to a horse and rider. The following section defines these properties and characteristics as they relate to commonly accepted surface descriptions in the sport horse industry. In general however the conditions of loading are either vertical or horizontal which is consistent with human loading (Nigg and Yeadon, 1987) but with important aspects of both rotational and sliding motions in the horizontal axis. In all cases however this loading is sensitive to the loading rate which is consistent with the literature on human biomechanics (Nigg and Yeadon, 1987) as well as the literature on soils (Santucci De Magistris et al., 1999).

However, the goal is to understand the loading on the leg of the horse not to simply characterize the material used in arena surfaces. Therefore in addition to understanding the surface material, the effect of a wide range of inputs including water and maintenance must be understood as well as the spatial context of the surface material (i.e. the cross sectional area and depth of material under load). Thus not only is some degree of *in situ* testing required but the conditions of the surface must be controlled during the testing period and fully documented. In addition, even the most advanced *in-situ* measurements also have inherent limitations in capturing all mechanical behaviours of interest. To further exacerbate the complexity of quantifying surfaces, terminology common to the sport industry often describes multiple properties and characteristics at once (Figure 3), whereas basic laboratory testing does not necessarily capture this complexity. However, standardized equipment can provide consistent comparisons between surfaces leading to long-term studies on quantifying desirable and undesirable functional properties and characteristics. These tests may not fully capture the demands of the horse on the footing, but they can capture important properties and characteristics of interest. In contrast, laboratory based tests of component parts of the surface may provide more information on material properties, but cannot provide complete information on the characteristics and performance of individual surfaces due to the absence of the underlying materials and loading conditions which are less representative of the actual loading of the surface material by a horse. Therefore because of the needs to more completely characterize these surfaces a summary of the methods currently used to measure each functional property or characteristic are given along with further detail on test equipment in Section 6.3. In addition, relevant standard test methods and the potential effects of that functional property or characteristic on the horse are provided. Section 6.2 defines the functional properties and characteristics from a rider perspective.

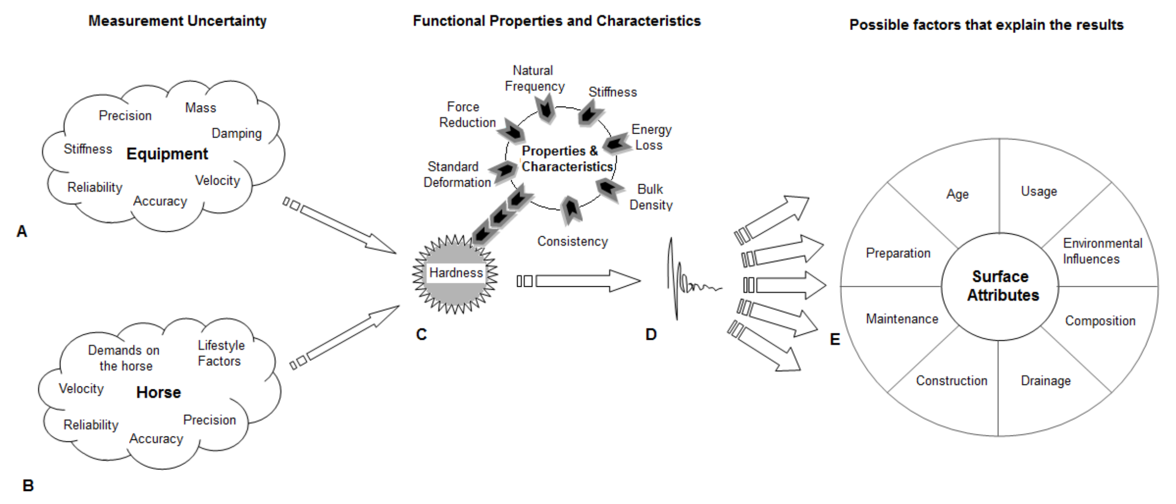

Figure 3: The uncertainty in measuring one functional property, for example hardness (commonly known as firmness), independently of others. A) The difference in design of the mechanical equipment used to test the surface will provide different results. B) The horses used to test the surface will not necessarily represent the population of horses that would use the surface. C) Hardness (or firmness) is influenced by all of the other functional properties and characteristics of a surface. In addition, the variability in measurements from different parts of the arena will be influenced by consistency. D) The measurements obtained from the equipment. E) The analysis of the measurements obtained must take into consideration all surface attributes.

Force reduction (shock absorption or damping)

Force reduction is a standard measurement that compares the maximal force produced on the surface being tested to the maximal force produced on a rigid surface (usually concrete), expressed as a percentage reduction. In equine research it is known more commonly as shock absorption, damping or cushioning and comparisons are usually made between different arena surfaces rather than comparing with concrete.

Force reduction or shock absorption has been measured using horses equipped with force measuring devices (Barrey et al., 1990; Ratzlaff et al., 1983; 1993; 1997; Chateau et al., 2009a, Robin et al., 2009; Chateau et al., 2010; Crevier-Denoix et al., 2010;) and with mechanical test devices (Cheney et al., 1973; Pratt, 1984; Zebarth and Sheard, 1985; Drevemo and Hjertén, 1991; Ratzlaff et al., 1997; Peterson et al., 2008; Setterbo et al., 2011). For horses it is important to control speed and load as well as factors that may influence force production, such as warm up, fatigue and shoeing. For mechanical equipment it is important that standard set ups are used, such as mass, drop height and spring constants. Mechanical impact tests with standardized equipment intended to represent impacts produced by the lower extremities of an athlete during landing events are used to measure force reduction by sports surfaces (ASTM F2569; BS EN 14808:2005). Currently only one design that represents impacts produced by a horse's limb during landing events has been standardized for equine arena surface testing (Peterson et al., 2008), which is in use by collaborating researchers in Europe and North America.

Shock absorption was classified by Barrey et al. (1991) as either frictional where damping is achieved by the displacement of particles, or structural where damping is achieved by deformation of viscoelastic particles. Shock absorption may be beneficial in that it reduces the magnitude of peak force during the support phase, thereby reducing the peak stress experienced by the horse. It may also be detrimental to the horse, as more muscular effort may be required to produce the same movement. Greater shock absorption was measured from horses trotting on an all-weather waxed track compared to a crushed sand track (Robin et al., 2009; Crevier Denoix et al., 2010). Maximum forces, load rates, maximum accelerations, and tendon forces were also lower for synthetic racing surfaces than traditional dirt surfaces, indicating that engineered surfaces have potential for injury reduction (Setterbo et al., 2009; 2011). However, the mechanical properties of these surfaces are temperature dependent (Bridge et al., 2010; Peterson et al., 2010), and behave differently under various operating conditions. Similarly, surfaces that are dependent on water, i.e. dirt surfaces, provide varying degrees of shock absorption and shear strength with different levels of moisture. Shock absorption is also highly dependent on the material composition of the surface.

Standard deformation

Standard deformation is defined as the maximum surface deflection during a standardized test. Both vertical and horizontal components may be measured (ASTM F2157; EN 14809; BS EN 14809). Arena surfaces may deform elastically, plastically or viscoelastically depending on the composition and would usually be categorized as point elastic, due to their pliability and low bending strength (Nigg and Yeadon, 1987). An elastically deforming surface describes a surface that would deflect when a load is applied, but then recover completely to its original shape as the load is removed. A plastically deforming surface describes a surface that deforms under load and no recovery is made as the load is removed. A viscoelastic surface is a surface that has some elastic elements, but the surface will also deform due to viscous flow, which is not recovered as the load is removed. Viscoelastic surfaces are also strain rate dependant, so the time that the foot is in contact with the ground and, consequently, the speed with which the limb is loaded will influence the surface deformation characteristics. The amount of vertical deformation reflects the resistance of the surface to compressive stress, which is also known as hardness, whereas the amount of horizontal deformation reflects the resistance of the surface to shear stress (shear resistance). The combination of standard deformation and force reduction can provide a measure of surface stiffness and, with more information about the volume of material under load, the modulus of the surface could be estimated *in situ*. Although the tangent modulus can be measured under laboratory conditions, the *in situ* measurements offer much more information because the standard deformation and force reduction are also dependent on the base (unpublished data from Greenwich Park, 2012).

Hardness

Hardness is defined as the resistance of a material against penetration of a defined object under a defined pressure (Nigg and Yeadon, 1987). Hardness is a material property. The hardness of a surface is also a function of a number of physical properties including stiffness and resilience (Baker and Canaway, 1993). In an engineering context hardness is measured by examining the size of an indentation made by an indenter (ASTM E18-11; EN ISO 14577-2). In the context of surfaces, standards are available for sports surfaces (EN 1516; BS EN 14954), but hardness is difficult to measure accurately on arena surfaces, as standardized equipment is not representative of the mass of a horse.

For sports surfaces hardness is often quantified using a Clegg hammer (Brosnan et al., 2009), where the maximum vertical deceleration upon impact is measured using a known mass and drop height. Maximum vertical deceleration has also been quantified using other mechanical devices, such as drop hammers (Drevemo and Hjérten, 1991; Ratzlaff et al., 1997; Peterson et al., 2008; Setterbo et al., 2011) and using accelerometers attached to the hoof (see section 5.0). For mechanical equipment, consideration of the mass of the device is essential, as the first drop of a small mass will measure the hardness of the cushion and not the whole surface (Peterson et al., 2012). In the context of measuring peak impact deceleration, a hard surface will increase the magnitude of impact shock and as such is a risk factor for injury (Barrey et al., 1991; Malmgren et al., 1994; Ratzlaff et al., 1997; Chateau et al., 2009b; Setterbo et al., 2009). Conversely, a soft surface that deforms considerably can increase physical demands of work (Sloet van Oldruitenborgh et al., 1991) and induce an earlier onset of fatigue. Modifications to the surface influence hoof landing velocity (Burn and Usmar, 2005) and impact deceleration (Peterson and McIlwraith, 2008; Tranquille et al., 2012;

Walker et al., 2012), so maintenance and surface preparation are particularly important to this property.

Shear resistance

Shear resistance relates to the frictional forces that are generated in the horizontal plane whilst the hoof is in contact with the surface. Friction has been described by Medoff (1995) as a combination of mechanical interlocking and adhesion between two interfaces, and these may vary in translation compared to rotation (Nigg and Yeadon, 1987). Friction is generated between the hoof-surface interface, but also between the particles within, and layers of the surface. Standards are available for the measurement of slip resistance on sports surfaces (BS EN 14877), but mechanical devices that measure shear resistance in an equine context are less common and little is currently known about rotational shear. Under laboratory conditions, the shear strength of the cushion material can be quantified using a modified triaxial shear strength test (modified from ASTM D4767). The material must be drained and tested at low confining pressures to better represent conditions on a horse racetrack, which is similarly appropriate for testing arena materials (Bridge et al., 2010).

Shear resistance during impact will mainly involve the hoof/shoe-cushion interface and possibly the cushion-sub-surface interface which is quantified as the amount of hoof slide (Gustas et al., 2006; Orlande et al., 2012). It is difficult to define a desirable amount of shear resistance, however, as propulsion requires a minimum shear strength that is sufficient to ensure efficiency of locomotion (Crevier-Denoix et al., 2009) and the secondary impact phase requires an optimized shear strength window that allows the hoof to slide through the cushion.

Response time or natural frequency

The timing between deformation of the surface during loading and the timing of any elastic recovery (sometimes referred to as tuning) is critical to the demands on the horse. This response time is related to the natural frequency of the limb, the surface and the gait frequency. If elastic recovery occurs too soon, it will impose additional forces that must be dissipated by the limbs (Ratzlaff et al., 1997), whereas if it is well timed it may reduce the energy input required from the horse to maintain momentum. This has been demonstrated in human running tracks (McMahon and Greene, 1979), but more work in the equine field is needed to develop a better understanding of the horse-hoof-surface response, as horses also modify locomotion in response to functional properties (Walker et al., 2012; Northrop et al., 2013).

Stiffness

Stiffness is defined as the ratio of applied force to deflection (Nigg and Yeadon, 1987), so it defines a surface's resistance to deformation under an applied load. Although stiffness is a ratio of force and deformation it is important to consider this changing relationship during the application of force, as stiffness is likely to vary from primary impact through support on arena surfaces. During impact stiffness will be influenced by the surface cushion, but then as more force is applied stiffness will reflect the entire surface composition, including the base materials. Like surfaces used for human athletic events some arenas have a compliant base layer which results in deformation of an area that is larger than the area of the applied force. Since stiffness also varies with the magnitude and rate of force application, loads should be applied at a rate consistent with the biomechanical loading of the surface. For most equine surface materials, the resulting relationship between applied load and displacement, or the modulus of the material, is then not linear and should be reported for the conditions under which it will be installed. While it is possible to determine the tangent modulus under static loading in a laboratory test based on ASTM E111-04 (Bridge et al., 2010), this test is limited to describing the surfacing materials in a comparative manner.

Loss of energy

When a hoof impacts a surface an amount of energy involved in the collision is lost. The largest single loss of energy is due to inelastic compaction of the top layer of the surface, which also reduces peak load on the limb due to its effect on the rate at which the load is applied. The alteration in the load rate has a significant effect in bone remodelling (Goodship et al., 1979). Additionally, other mechanisms are associated with loss of energy including particle friction and material damping or hysteresis (both resulting in a conversion to heat), and viscous flow of the tissues within the hoof and limb. Secondary effects include energy losses in the form of kinetic energy particularly if the hoof impacts a very hard surface (from the limb vibrating) and acoustic energy. All of these mechanisms contribute to energy loss during the collision between the hoof and the arena surface. These losses may be measured with mechanical devices by knowing the energy prior to impact and comparing that to the area under a force-deformation curve.

To minimise locomotor stresses on the horse, it has been suggested that the surface properties should generate low impact forces and accelerations in the horizontal and vertical directions and that a relatively low amount of energy should be lost on impact (Ratzlaff et al., 1997). The fact that energy loss is generally negatively correlated with surface hardness presents a challenge in surface selection. It has been reported by Setterbo et al. (2011) that an ideal, safe surface should have a relatively low energy loss along with low hardness, which is difficult to achieve. The idea of a tuned surface is a step towards achieving this combination of effects; however differences in locomotor speed also influence behaviour of the surface. Therefore, a surface that is ideal for some uses might be inappropriate for other activities. In general, mechanisms that result in a loss of energy associated with reducing peak load and loading rate are responsible for the perception that high performance and injury reduction are conflicting objectives.

Bulk Density

The maximum bulk density of a surface is a property of the material. Material with a wide range of particle sizes and low organic content in general will compact to a higher peak density. The maximum bulk density is also a function of moisture content with either high or low moisture content being associated with reduced maximum bulk density or compaction. Compaction increases the bulk density of a surface by reducing the amount of air between the surface particles and it is usually achieved mechanically, that is by applying a compressive force to the surface. Generally maintenance is used to reduce the compaction of the top surface of an arena and additives such as rubber are used to limit the compaction of the material that has not been maintained. By using a higher proportion of sand with the same particle size the ability of the material to fill all of the voids is also reduced. Compaction generally increases surface stiffness, shear strength and hardness and reduces the magnitude of standard deformation. The maximum bulk density of a surface material can be measured in a laboratory setting following established standards (i.e. ASTM D698, small proctor ref). This testing also provides information on the water content needed to achieve the maximum bulk density for a defined amount of compactive effort. In some arena surfaces the design goal is a highly compacted surface over a compliant base. This type of elastic surface is also used in playing fields (Nigg and Yeadon, 1987). Maintenance, which is discussed in section 6.8, can reduce the compaction of a surface. However selection of sand and the addition of fibres, rubber and other materials can alter both the maximum bulk density and the resistance to compaction with use.

Consistency

Consistency is defined as conforming to an unchanging pattern (Oxford English Dictionary, 1994) and in the context of arena surfaces this would be consistency around the arena and changes in consistency from one time point to the next. All of the functional properties listed above will influence the consistency of a surface. Therefore, to measure consistency, it is necessary to quantify functional properties, particularly those most likely to vary, over an appropriate spatial and temporal range. Spatially it is necessary to map the surface sufficiently well to reflect variability due to the base construction including drainage, habitual usage (traffic), typical maintenance and preparation routines and any other relevant activities/influences. This approach, which is used for racetrack testing (Peterson and McIlwraith, 2008), has more recently been applied to arena surface testing (Blundell, 2010; Tranquille et al., 2012) and was used at Greenwich Park for the 2012 Olympic Games. Temporal data is currently sparse, as this requires longitudinal data collections. More studies are needed in this area, as surface degradation (which is likely to occur over time) has a large influence on consistency.

The single largest variable in surface consistency of a sand arena surface is moisture. While effects from cushion depth and maintenance equipment are important, based on results from racing these effects are secondary to the effect of moisture on consistency (Mahaffey et al., 2013). This is one of the primary reasons for the development of wax and poymer coatings for sand used in arenas. By applying a hydrophobic coating to the sand and ensuring that the pores do not become filled with fine material, the permability of the material is enhanced and the effect of mositure is reduced.

While moisture may be a larger effect, working on a surface that is inconsistent due to variation in depth is believed to increase the risk of lameness in dressage horses due to the horse becoming unbalanced, producing an uneven gait and early fatigue (Dyson, 2002). An inconsistent surface will reduce the horse's confidence in the footing and has been suggested as increasing the incidence of tripping and slipping and loss of balance (Murray et al., 2010a). If proprioception is a limiting factor, horses are likely to have greater confidence in the surface if it is consistent and similar to what they are accustomed to. Functional properties that maintain consistency are favourable for competitions since all horses have an equal opportunity and the need to maintain the surface during a competition is reduced. Blundell et al. (2010) investigated changes in mechanical properties of a surface during dressage competitions and found that a synthetic surface became significantly harder as the competition progressed.

6.2 Rider terms

Many terms are used by riders to define a surface, usually based on how their horse performs. The trouble with these definitions is that they often describe multiple functional properties and characteristics and consequently their meaning is interpreted differently by different riders. As such, the definitions of popular rider terms are given below together with the functional properties and characteristics that can be used to measure them.

Impact firmness

The shock experienced by the horse and rider when the hoof contacts the surface.

Impact firmness relates to the hardness of the very top surface and the initial stiffness during primary impact, so higher peak acceleration would be measured on a hard surface such as concrete. If a covering of sand of a few centimetres was put on top of tarmac, such as covering a road on race days, the impact firmness would be considerably reduced, but the surface would still provide a large amount of support to the horse. Conversely, if wooden boards were laid on top of a waterlogged part of a field to protect it from the horses' feet from sinking into the soft earth, then the impact firmness would be higher, but the surface would still give under the horse.

Cushioning

How much a surface is supportive compared to how much it gives when riding on it.

Cushioning relates to how the whole of the surface reacts to the forces produced by the horse during locomotion. This encompasses the amount of force reduction or damping and the stiffness of the surface during the support phase of the stride, specifically maximal load at midstance, and will be influenced by the amount of elastic compared to the amount of plastic deformation. A compacted surface with no cushioning would produce high peak forces during the support phase, so the amount of deformation would be very small. This would mean the horse could perform very well, but may be injured much more quickly because it is also very stiff.

Responsiveness

How active or springy the surface feels to the rider.

Responsiveness relates to the natural frequency or tuning of a surface. If a surface responds well to the locomotion of the horse it will feel springy or active, as the timing of the way it moves helps to return energy to the horse. Responsiveness is also influenced by the stiffness of the surface, so is closely related to cushioning. However, a very compacted surface that produces high peak forces may rebound too quickly to return energy to the horse, so it would feel stiff, but also dead. A surface that responds too slowly, such as a deep surface, would also feel dead.

Grip

How much the horses' foot slides during landing, turning and pushing off.

Grip relates to the interaction between the horse hoof surface interface, as well as the interaction between the materials that interlock and hold the surface together. If the interaction between the hoof and the surface is stronger, perhaps due to shoe studs, then the surface may shear at a depth below this interface, such as pulling off the top layer of turf during a jump landing. The angle that the limb lands and the speed of the horse is important to how much grip there will be.

Uniformity

How regular the surface feels when the horse moves across it.

Uniformity relates to how much the functional properties and characteristics of a surface change across the whole of an arena. A surface can be even, so it looks level, but as you ride across it the impact firmness, cushioning, responsiveness and grip change. If these changes are quite small and gradual the horse may adapt to them easily and the rider may not feel any difference in performance across the arena. If they are larger and occur more frequently the horse may find it much more difficult to adapt to, and are more likely to trip or have an irregular gait pattern. Arenas where there are obvious differences from one end to another, such as a wet end and a dry end, may cause some disturbances in locomotion during the transition between the wet and dry ends, but then the horse may perform consistently within, but differently between the wet and dry ends. Some surfaces may also be unlevel in the sense that they are not flat and these surfaces are also likely to be very variable in terms of their functional properties and characteristics.

Consistency over time

How much the surface changes with time and use.

Consistency over time relates to how much the functional properties and characteristics change due to the way they are used, the environmental conditions they are subjected to and the way they are prepared and maintained. This may be how well the surface holds up between the start and the end of a competition. Equally, it may be how much difference there is between summer and winter riding on an outdoor arena or changes due to the amount of use and frequency of maintenance. An ideal surface would provide the horse and rider with a sound footing every day regardless of weather and use and would hold up to the rigors of competition while providing a safe secure and high performance surface for every rider.

6.3 In-situ test equipment

There are two perspectives from which to measure the response of a surface: one being repeatable measures via mechanical testing equipment, and the second being measures obtained via sensors on a horse. The challenge with the former is to be able to closely approximate and be able to quantify the combination of factors experienced by a horse. However, the advantage is that one gains repeatability in testing multiple surfaces. Equipping a horse with sensors introduces several challenges including but not limited to minimization of gait alterations due to equipment and/or surface properties, and inconsistency between animals on different surfaces. However, even if measurements of the surface are performed using mechanical testing equipment, it is critical to understand the loading of the horse on the surface. Therefore, at best a hybrid approach is required in order to provide the required repeatability as well to understand the biomechanical demands on the surface.

Mechanical Test Equipment

Mechanical test equipment allows for a standardized approach, and therefore comparison of data between studies is possible provided procedures are carried out in the same way. Currently the range of equipment available to measure arena surfaces is limited, so in some studies equipment designed to represent human locomotion is used as an alternative. The advantages are that larger data sets are available for comparison, the disadvantages are that these devices do not provide collisions equivalent to those of a horse. This is because they are usually much smaller so the energy of the collision is correspondingly smaller.

Perhaps one of the simplest devices is the Clegg hammer, which measures the hardness and compactability of a surface and the base. Since compaction is related to material properties, including moisture content, it is important to always include descriptive data about the material at the time of measurement. The limitation of the Clegg hammer is that it only characterizes compaction upon vertical impact and the magnitude of the impact is typically much smaller than that of the horse. Several vertical drop hammers have been used that provide larger collisions due to increased mass (Drevemo and Hjérten, 1991; Ratzlaff et al., 1997; Setterbo et al., 2011) and they tend to be instrumented with multiple sensors, so that more than one functional property can be measured simultaneously. They are limited to the description of vertical properties and do not replicate the speed and geometry of the equine gait.

The Orono Biomechanical Surface Tester was developed to capture performance measures on horse racetracks (Peterson and McIlwraith, 2008). The machine design includes an angled rail allowing a dropped mass with linear bearings in line with a spring and damper system to replicate the vertical loading of a horse’s limb while simultaneously sliding across the surface. Aligning the dropped mass on a second axis that is perpendicular to the surface allows for the slide upon impact. The hoof tester is instrumented with a three-axis load cell, three-axis accelerometer and string potentiometer, so it is possible to measure multiple functional properties of a surface simultaneously, whilst replicating the speed and impact of a realistic horse-hoof-surface collision. As identified in section 6.1, this is currently the only design and it has been shared by Prof. Mick Peterson with collaborating groups in Europe. In order to test equine arena surfaces, the drop height has been reduced from the height that was used to test racetracks. There is a growing database of comparable measurements made with this equipment using the standardized values for arena testing.

Equine Test Equipment

Studies using horses instrumented with devices to quantitatively compare different surfaces are identified in section 5.0. Both off the shelf and bespoke equipment and techniques have been used to quantify aspects of the horse-hoof-surface interaction. As off the shelf equipment is often adapted or customized to collect data from horses it is essential that the measurement accuracy and reliability are known, as with bespoke equipment. Valuable data may then be obtained, particularly when combined with mechanical equipment tests. It must be recognized that lifestyle factors and demands on the horse will influence the results though, which limits the comparison of data between studies. In addition, validation of the equipment and documentation of the speeds used in the study are important when reporting absolute data.

6.4 Surface composition

In recent years there has been an increasing trend towards the use of artificial and synthetic surfaces rather than grass surfaces for training and competition arenas. Factors associated with this increase potentially include climate (Riggs, 2010), greater demand for all year round use, ease of maintenance, planning considerations and taxes levied on buildings (particularly related to the construction of indoor arenas), greater rider awareness of performance and injury risks, the emergence of surfaces composed of silica sand and other materials, and an increase in the number of manufacturers and suppliers of these products. Nevertheless, grass arenas are still used worldwide where the climate is favourable and they are also used at elite level competitions on established sites.

There are many different types of artificial surfaces on the market for the various equestrian sports, which can be sold as individual components or mixed with additives according to the requirements of the buyer and the intended use of the arena (van Weeren, 2010). To date however, the manufacture and selection of materials have been based largely on empirical evidence and marketing factors (Setterbo et al., 2009). The surfaces used most commonly in training arenas by dressage riders in the UK are sand and rubber, sand, woodchip, and sand and polyvinylchloride (PVC) (Murray et al., 2010a). The additives can include synthetic or natural fibres of varying lengths, rubber, cloth or felt strips. A polymer or wax coating is applied to a number of the commercial surfaces; it serves as a binder between the particles and, depending on the coating material, can create a hydrophobic coating layer. The surface is then usually supported on an engineered foundation or drainage system. The geographical location of the arena may affect the ability to source certain materials and it may only be feasible to utilise surfaces that are locally available, which may influence quality control of the materials.

Grass based

Historically high level competitions on established sites used a turf surface, but the difficulty in maintenance and days lost due to bad weather alongside the development of synthetic surfaces has meant there has been a shift towards other solutions. Some venues have opted for all weather surfaces, which are usually based on sand and fibre mixes whilst others have invested in ‘all weather’ turf, such as Hickstead in the UK that hosts the Hickstead Derby and the Royal International Horse Show (Hickstead, 2012). A ‘second generation gravel carpet’ that enhanced the drainage and base layer thus increasing the ability to manage consistency regardless of environmental conditions was installed at Hickstead (Sportsturf Research Institute, 2012). Grass based surfaces are suggested to provide the horse with what is often described as a more natural footing, but the functional properties will be highly dependent on the quality of the root structure and the moisture content. Poorer quality or overly wet turf surfaces can lack shear resistance and the use of shoe studs or caulks may be necessary (Boswell et al., 2011; Harvey et al., 2012). Conversely, compaction of grass based surfaces can occur over time which increases bulk density and hardness (Brosnan et al., 2009; Saffih-Hdadi et al., 2009). The presence of organic matter has been found to strongly influence bulk density and consequently the ability of the soil to compact (Baker et al., 1998; Saffih-Hdadi et al., 2009).

Rubber and Woodchip

Rubber and woodchip based surfaces are commonly used and are usually cheaper to buy than premium sand-based surfaces (Murray *et al.*, 2010a). Two forms of rubber additives can be used in arena surfaces although alternative forms may also be found; 1) rubber crumb which consists of regular particles of 2-5 mm in diameter and 2) larger rubber pieces which are 25-40 mm in diameter. Rubber crumb is mixed into sand surfaces whereas rubber pieces are laid (to a depth of 50 mm) over rolled sand subsurface. The rubber source material is usually either new rubber, usually EPDM (Ethylene propylene diene monomer) or 'alternative' rubber (Li et al., 2009) such as shredded carpet backing and tubing, or processed tyre or belting rubber. Processing removes the steel reinforcement belts and foreign objects from tyre waste, leaving pieces of rubber and any associated fibre backing or reinforcement. Tyre rubber is available in high volumes (at a low cost) and as such represents a preferential raw material for economic surface production. The rubber is effective in reducing compaction of either a sand or woodchip surface because rubber compresses with almost no change in volume and so opens up pores in the surfaces when pressure is applied.

Injury risk may be increased on woodchip and rubber surfaces where routine maintenance is not carried out due to a lack of consistency. Woodchip used as a primary surface is also reported to increase the occurrence of slipping in horses (Murray *et al.*, 2010a). In contrast, a woodchip layer below the primary surface is reported to provide more cushioning by significantly reducing hardness and increasing shock absorbency (Drevemo and Hjertén, 1991). Degradation of these materials can affect the functional properties so the rate of degradation should be monitored and the surface should be refreshed when needed.

Sand with additives

Some arena manufacturers recommend using very fine angular or sub-angular silica sand with up to 15% clay or silt content (<63 µm diameter) to provide a firm surface of approximately 15cm in depth (Andrews Bowen, 2012). In more traditional wax coated arenas sub-rounded sand with high quartz content is used to ensure durability of the sand and to maintain vertical drainage. The sand particles themselves have a high modulus of elasticity. The addition of polymer or natural fibres and rubber particles adds elastic recovery from impact and reduces compaction (Baker and Richards, 1995; Setterbo et al., 2011). If sand with a narrow particle size distribution is used, it is usually beneficial to add a binder such as wax to produce sufficient shear strength and some level of cohesion to avoid creating deep hoof prints and to provide lateral support when turning. The way the sand responds to any of the added materials depends on particle size distribution of the grains, which affects the bulk density, compaction, water retention and dustiness of a surface (Barrey et al., 1991). The use of fibres in a sand based surface appears to have many advantages, as they are thought to create a root-like structure and are reported to increase the stability and drainage of games pitches (Baker and Richards, 1995). At higher confining pressures the mechanics of fibre reinforcement of sand is well established (for example Gray and Ohashi, 1983; Sadek et al., 2010). However, high quality fibres that are dust-free are expensive. In the UK sand based surfaces appear to be most popular for dressage riders, as Murray et al. (2010a) found at least 77% of British Dressage riders responding to a survey had a sand based surface.

Wax

Wax coated sand and fibre surfaces are also offered on the equine market however, this is usually at a premium because the properties allow for long term performance under a variety of conditions (Bridge et al., 2010). Paraffinic and microcrystalline wax is commonly used as a binding polymer. This material in the form of a relatively unrefined slack wax has cohesive properties and has a high oil content. The unrefined nature of the material requires blending to obtain the phase transition points and viscosity required (Bridge et al., 2010). More recently there has been a lot of activity in coatings that are more selectively tailored to applications that can make use of a polymer combined with a solvent for coating of the particles. Permanent competition centres or arenas in high use often provide waxed surfaces, as better longevity with less maintenance has been reported (Murray et al., 2010a). It could be considered that these surfaces are more uniform at a wide range of moisture content and are thus less sensitive to weather with the exception of large shifts in temperature. When compared to sand and woodchip surfaces, the incidence of lameness and injuries is reduced (Murray et al., 2010a). This is supported by data from a waxed track, which showed a significant reduction in impact shock related variables during trotting compared to a crushed sand track (Chateau et al., 2009; Crevier Denoix et al., 2009; Robin et al., 2009).

Other surface materials

Other combinations of surface materials are used in different geographical locations according to cost, local availability of materials and environmental considerations. Often these surfaces incorporate cheaper natural or recycled materials, which include but are not limited to carpet strips, rubber from tyres, plastic coatings from wire and dirt.

6.5 Construction of the base and drainage

The construction of a uniform, level base and the installation of an adequate drainage system are essential parts of the arena. Traditionally a rigid base is used, such as limestone, crushed concrete or porous tarmac (asphalt). A base formed from screened limestone is preferred over crushed concrete in relation to uniformity (Murray et al., 2010a). In areas with lower rainfall a clay base can be used to retain moisture more effectively in the surface. Perforated pipes dug further into the ground are commonly used beneath the surface with a geotextile membrane or porous tarmac covering the pipes to aid in drainage while ensuring that a consistent base is provided. Woodchip or rubber layers beneath the top surface are also used and are thought to provide additional shock absorption (Barrey et al. 1991; Drevemo and Hjertén, 1991) or increase elastic recovery. More scientific evidence is needed to assess the functional properties of these surfaces for equine applications, although area compliant surfaces of this type are common in playing fields (Nigg and Yeadon, 1987).

The surface type and drainage system installed play a large role in the water holding capacity, where maintaining the correct distribution of air-fill and capillary porosity is essential. An effective system will prevent excess water from gathering and encourage hydraulic conductivity of the substrate, which is the ability of the surface to transmit water and therefore drain (Adams and Gibbs, 1994). Adequate drainage must be installed to ensure the surface recovers quickly from rainfall. However, a surface that is too permeable may have a reduced moisture retaining ability during dry periods. The geographical location of the arena is also an important consideration when choosing a drainage system due to the different amounts of rainfall and evaporation rates.

Specialised drainage systems are a recent development and include the Equaflow™ system (Andrews Bowen, 2012) and the Ebb and Flow system (Strathoof Managebodems, 2012). These designs allow water to be removed and added to the surface with the use of a storage tank and automatic pump to regulate and maintain the moisture content. The newer drainage systems are not widely used at present, but the Equaflow™ system was used under the footing at the 2012 Olympic Games which may advance its use throughout the industry. It is critical in the design of these systems that the open porous structure of the arena is maintained. Therefore the formation of a layer of impermeable material (or hard pan) will render these subsurface watering systems ineffective. In order to avoid these problems both proper maintenance and durable sand with a high silica content are required.

6.6 Environmental influences

The largest environmental influence on the functional properties of an arena surface and how they change over time is expected to be the geographical location and therefore the effects of climate. Whether the arena is outdoor or indoor will also have a large effect on surface moisture content, degradation and material losses. In general, outdoor surfaces are more likely to encounter a larger range of moisture and temperature differences, whereas indoor surfaces are more likely to suffer from reduced ventilation (Wheeler et al., 2005).

Moisture content is considered to be the most important physical property to measure because it strongly influences the functional properties of a surface (Goodall et al., 2005; Peterson et al., 2008). Some authors have stated that an increase in moisture content improves particle adherence and consequently shear resistance which provides more stability (Ratzlaff et al., 1997; Chateau et al., 2010; Murray et al., 2010a). This is true until the material is saturated, at which point the shear strength again drops. The moisture content at which sand has maximum shear strength is normally between 8% and 17% (Barrey et al., 1991; Ratzlaff et al., 1997). The optimal moisture content may differ according to surface type and sport. For example maximum shear strength of the arena surface would not be desirable for the spin in a reining horse since it would increase the loading on the limb by reducing the ability for the hoof to rotate on the surface. As a result the surface should be slightly drier for these types of actions to reduce the likelihood of injury. Ratzlaff et al. (1997) reported that low (4%) and high (12%) moisture contents produced higher peak forces on a sand/silt racetrack surface compared to moderate (8%) moisture content. This result is probably due to the existence of a hard layer under the top cushion of the racetrack and indicates that at the gallop the hoof has penetrated to the base. A different outcome would be expected with other racetrack designs, e.g. false base and pad designs (Mahaffey et al., 2012). An increase in surface hardness was associated with a reduction in moisture content and an increase in compaction on non-turfed base path plots (Brosnan et al., 2009). High hardness at low moisture content could be explained by an increase in compaction reducing surface porosity and increasing particle strength, which decreases soil water infiltration and holding capacity (Saffih-Hdadi et al., 2009). A small variation (5.5%) in moisture content between two sand tracks that were used in a study by Chateau et al. (2010) was sufficient to cause a significant difference in peak vertical deceleration at the onset of the stance phase. More information is required on the effects of moisture content on properties, in particular taking into consideration the surface type. The findings would also inform arena construction and management practices. Factors that control the sensitivity to moisture content include not only particle size and the resulting pore sizes, but also the type of sand which can alter the surface chemistry and thus the attraction of water to the sand particles.

Recent work indicated that airborne particle distribution in stables varies according to season, time of day, management and stable design (Millerick-May et al., 2011) but there has been minimal research with respect to airborne particles polluting the air in equestrian arenas and on racetracks. It is known organic dust particulates affect prevalence of inflammatory respiratory disease (Pirie et al., 2003) and performance is thought to be negatively modified by increased mucus in the trachea (Holcombe et al., 2006) due to airway obstruction and reduced oxygen availability. Horses working intensively are more susceptible to inhaled particles due to dilated airways and increased ventilation.

Housing environments can be considered to affect respiratory tract health due to dust found in bedding and feed material and it is likely that some indoor arena surface materials can also influence air quality (Mazan and Hoffman, 2006) and have the potential to be inhaled by the trainer, rider and horse during exercise (Kollar et al., 2005). Rapp et al. (1992) assessed 29 riding track surfaces and reported that all surfaces will ultimately cause some air pollution, though the level of dust particles present in arenas appears to be lower than in a stable environment (Wheeler et al., 2005).

Ventilation is a significant factor in air quality (Millerick-May et al., 2001) and it is expected that working in an indoor arena would pose greater risk of dust inhalation than working outside where there is enhanced airflow. Additionally humidity and ambient temperature can influence airborne dust particles and warrant some consideration. Wheeler et al. (2005) investigated two indoor arenas where an inorganic surface (predominantly sand-based) demonstrated significantly higher levels of total dust than the organic surface (predominantly sawdust and bedding). The differences may have been related to specific surface composition though differences between pollutant inorganic and organic material may be relevant. Inorganic dust fractions are made up of silicates and are derived from the sand or soil component of a surface; drier, finer surfaces are likely to result in greater exposure (Malikides and Hodgson, 2003). The organic dust fraction originates from biological material such as organic fibres, excreta and plant and insect matter. Both inorganic and organic materials have been associated with human respiratory disorders (ATS, 1998). There is evidence that further work is necessary to understand the impacts that specific surface components have on the respiratory health of the horse, trainer and rider under different conditions.

6.7 Usage

The usage of an arena is an important consideration for choice of surface, maintenance regime and expected lifetime to refurbishment or renewal. Arena surfaces used for training and competition are likely to have very different requirements in terms of functional properties, depending on the level of training and competition undertaken on the surface. Permanent competition venues often have commercial pressures to fully book their venues with a range of activities throughout the year. These include equine, canine and other events that will affect the surface in different ways due to different types of loading in different areas of the arenas. Training arenas and riding schools may suffer from more habitual and/or routine use of particular parts of the arenas, such as the track around the outside or frequent jump locations. It has been suggested that surfaces owned privately are least likely to be a risk to lameness in dressage horses (Murray et al., 2010a), possibly due to a reduced number of horses working on the surface in between maintenance procedures.

6.8 Preparation and maintenance

In the context of this article, preparation of a surface involves watering, harrowing, levelling, rolling and/or grading a surface to make it ready for a specific activity or competition. Maintenance includes routine work, which may include a regular programme of preparation as above and in some cases may involve deeper harrowing or work in specific areas of high usage, the upkeep of drainage systems, the addition of materials and, but not limited to, the removal of faeces and other contaminants. The large variation in base construction, drainage, surface materials, environment and usage means that methods of preparation and maintenance will be different for each surface type. Some surfaces, such as dirt are also more dependent on maintenance procedures compared to the synthetic surfaces for keeping the surface properties consistent (Kai et al., 1999; Setterbo et al., 2011).

The outstanding reasons for preparing and maintaining an arena surface correctly are to reduce compaction and to improve or maintain consistency around the arena. Uneven surfaces with varying moisture content, compaction and composition result in inconsistent forces acting upon the horse (Kai et al., 1999; Murray et al., 2010a; Ratzlaff et al., 1997; Riggs, 2010). Conversely, reduced maintenance contributes to a more uneven surface and is associated with a higher risk of injury (Kai et al., 1999; Williams et al., 2001; Peterson and McIlwraith, 2008; Murray et al., 2010b).

Emerging evidence suggests that horses modify their gait patterns based on even small changes in surface preparation (Walker et al., 2012; Northrop et al., 2013). Regularly altering surface preparation to provide different daily functional properties that stimulate different gait patterns may be beneficial for training and conditioning programmes. Conversely, older horses or horses with chronic injuries may benefit from being restricted to exercising on surfaces prepared to limit the development of further degenerative changes.

Knowledge of the most effective maintenance and preparation methods appears to be limited, partly due to the lack of industry based guidelines that can inform both arena owners and surface contractors, and partly due to the limited knowledge we have in this area of research. Both immediate and long term effects of preparation and maintenance procedures on functional properties for a wide range of surfaces and locations would be of great benefit to the industry.

6.9 Size

The size of an arena will influence its usage and, therefore, the amount of compaction around the arena (see sections 6.1; 6.6; 6.7). This should be taken into consideration when designing the maintenance programme and also when taking *in situ* measurements from it (see sections 6.1; 6.2; 6.7).

6.10 Age

It is well known anecdotally that arena surfaces are subject to degradation, compaction, loss of material and contamination over time and wear and tear inevitably affects their functional properties. Older synthetic racetrack surfaces are often replaced completely, whereas older arena surfaces are often topped up. Conversely, temporary sites often lay surfaces for a competition and remove them at the end of the competition, which also influences functional properties (such as the arena surfaces laid for Greenwich 2012). Despite this, little information is currently available on the extent to which properties are altered over time. This is an area of research that requires considerable investment.

6.11 Environmental impact

The environmental impact of equestrian surfaces has not been fully established in technical and scientific literature but it is an aspect that warrants consideration as the number of artificial arenas increases. Synthetic surfaces consist of a variety of substances that are highly heterogeneous and the potential impacts of the individual components will be reviewed.

Sand

Direct impacts such as runoff and leaching are minimal from arena sands. The majority of surface manufacturers utilise pre-washed sands and therefore avoid issues such as silt displacement and deposition. Several sources of sand in the UK, continental Europe and the Midwestern region of the United States have become quite common for high quality arena construction. These sands typically have more than 99% silica content which enhances its durability. However, when fine materials are included to increase the cohesion of the surface the exact type of clay is critical to the performance of the surface. Direct extraction of sand as the raw material does have some significant environmental impacts either from marine sands (van Dalfsen et al, 2000; Vanaverbeke et al, 2007) or as a quarried resource. The quantities of sand used in arena surface production are however small in comparison with its use by the construction industry.

Rubber and Polymers

A range of organic compounds and metals are associated with tyre rubber usage although zinc, poly aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and benzothiazole (BT) constitute the most well-documented leachate emissions (Li et al, 2010; Wik and Dave, 2009). Reported concentrations of these emissions vary depending on particle size (Nelson et al, 1994; Abernethy et al, 1996), pH (Gualtieri et al, 2005), water salinity (Stone, 1975) and age and composition of the rubber particles (Li et al, 2010). Despite these apparent variations, most report significant emissions.

Airborne rubber particulates are deemed to be low in the context of an equine arena. Studies examining airborne rubber particulates have focussed on emissions from roads (e.g. Fauser et al; 2002), which are not totally comparable. Generally, however, rubber particulate concentrations were higher in close proximity to the source, so care should be taken to minimise particulate-release through wetting.

Processing of tyres produces a low density, porous material through which air may percolate. The total surface area can therefore be large compared to the occupied volume. This combination of air-permeability and high exposed surface area means that rubber crumb has the potential to demonstrate high temperature rises (Beyler, 2006), particularly in areas where the rubber crumb has been allowed to mound. There are concerns associated with the use of rubber crumb on synthetic turf fields where high temperatures have been recorded (Williams and Pulley, 2002). Higher temperatures can accelerate the off-gassing of VOCs alongside an increase in decomposition rate. There is a possibility of large temperature rises on equine surfaces with rubber additives but regular mixing through harrowing and watering should diminish these issues.

Evidence of significant toxicity to organisms, particularly aquatic species is widespread (Wik and Dave, 2009). Severity of toxic effects is related to particle size and the parts of the tyre being used. Toxicity assessment of whole tyres has generally resulted in low (or negligible) effects. Fine particles however derived from the tyre treads constitute the most significant toxic effects. This is associated with the relative surface area and the differing formulations used in specific areas of the tyre (Wik and Dave, 2009). Acute toxicity to aquatic organisms is apparent in a majority of studies (e.g. Hartwell et al, 2000; Day et al; 1993). High degrees of differences in toxicity levels are apparent where toxicity has been assessed. The exception to this is where examination of leaching from whole tyres has taken place.

In terms of equine surfaces, age is a significant factor in influencing leachate emissions (Birkholz et al, 2003). Newly produced (<6 months) rubber additives have higher levels of emissions than their older counterparts (Li et al, 2010). It may therefore be prudent to consider ‘ageing’ the rubber additives in controlled conditions before integration into a surface mixture. Since local conditions and standards vary among countries, it would be prudent to control the drainage from any equine arena that contains rubber additives due to the evidence of pollution as described above.

Some arena surfaces have made extensive use of copper wire insulation. These materials produce a high quality surface but can result in leaching of copper into the groundwater. This has limited the use of these materials in some coastal applications (Pugmire, 2013).

Disposal

Disposal of synthetic arena surfaces poses a significant problem for arena owners and operators. These surfaces consist of a significant volume of sand-based material which will not re-integrate into the environment without some pre-treatment or qualification of its components prior to disposal. The preferred disposal route depends on a number of factors, primarily cost and environmental considerations. The primary ‘disposal’ route is to re-use and repair a surface. This route emphasises using construction materials which can be manipulated and which do not degrade; this stresses use of sand and artificial fibre surfaces over organic ones such as woodchip.

Options (after complete removal and disposal) require examination of the surface’s endpoint. Re-use as another substrate (applied to agricultural land, used as a surface constituent in construction or as a groundwork material for building paths, etc.) is a realistic endpoint usage for these surfaces.

The surface constituents have a significant influence on the potential endpoints, however, and non-organic additives (such as rubber) may hinder this process.

The sole credible ‘complete-disposal’ route for an equine arena surface is sending it to landfill. Disposal through this means however can be highly costly. In a number of countries (particularly the EU) sending waste to landfill can incur a fee (per tonne) for disposal. In the United Kingdom for example, the fee is £72 (≈US$110/€84) (in April 2013) per tonne. This cost may alter if (after a WAC (Waste Acceptance Criteria) test) the surface material is deemed to be inert.

7.0 Future Directions

This paper has attempted to capture our current knowledge of the effects of arena surface footing on the horse-hoof-surface interaction and on the risks for the horse. In doing so, it has highlighted the complexity of this interaction and also the uncertainty in factors that influence the measurements we make.

It is suggested that the way forward should focus on standardizing as much as possible our mechanical measurement techniques and using them alongside biomechanical measurements and information on the physical attributes of the arena to capture the breadth of data needed to identify the effects of each factor. To fully understand the risks to horses it is also necessary to carry out further epidemiological studies on lifestyle factors, arena types, the activities they are used for and the maintenance and preparation practices employed. The challenge would then be to link acute and chronic injuries to undesirable factors.

To compare between research groups, standard terminology is needed together with methods of data normalization (Karvanen 2003). This then must be linked to terminology that is already in place in the industry. Figure 4 illustrates an approach that could be used to standardize results. This diagram depicts rider terms that can be described by functional properties. The normal line describes a pooled mean from data collected worldwide, the red mean line shows how far the arena tested differs from that mean and then the variability is shown by the blue bars and error bars. With additional knowledge the risks associated with each term will become more explicit.

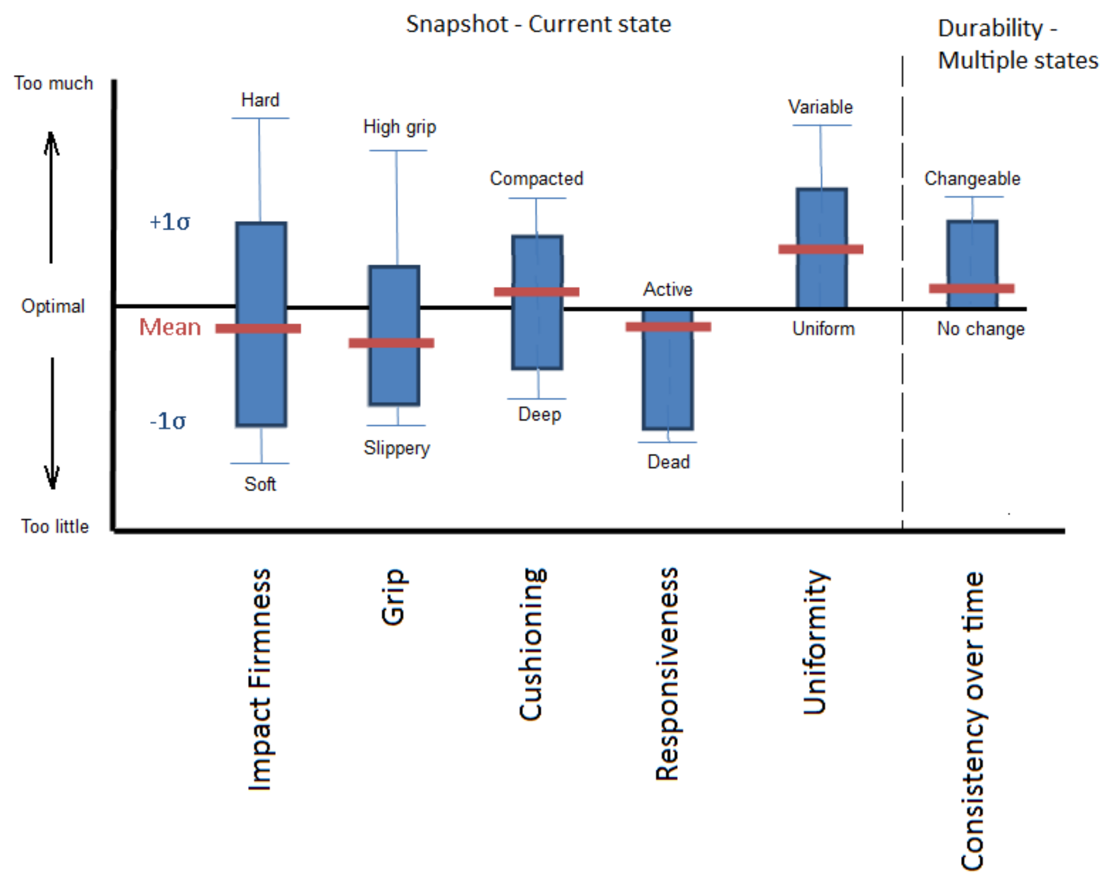

Figure 4: A method of standardization for arena surfaces

This method could also be employed at competition venues either in its current or in a simplified form to inform trainers and riders about the footing.

Our knowledge of aging and degradation of arenas is also somewhat limited, which requires a longitudinal approach to data collection. These studies are vital to inform us of the changes in functional properties over time and the effects of degradation on the environment. A similar approach is required as that described above, but with additional consideration of contamination of land, water courses and the atmosphere.

Monitoring, measuring, and influencing soundness and performance are a shared responsibility between everyone involved in equestrianism, be they owners, trainers, veterinarians, farriers, scientists, surface providers, practitioners, venue owners or other equine industry professionals. As scientists we must promote the approach described here, but practitioners and the industry alike must adopt a similar approach to their responsibilities to truly benefit the horse.

8.0 References

Abernethy, S., Montemayor, B.P., Penders, J.W., (1996) The *Aquatic Toxicity of Scrap Automobile Tires*. Ministry of Environment and Energy, Ontario, Canada.

Adams, W.A. and Gibbs, R.J. (1994). Natural turf for sport and amenity. CAB International.

Andrews Bowen Limited (2012) Installation. Accessed via http://www.andrewsbowen.co.uk/Installation.asp

Anderson, T. M., McIlwraith, C. W., Douay, P. (2004) The role of conformation in musculoskeletal problems in the racing Thoroughbred. *Equine Veterinary Journal,* 36 (7): 571-575.

Back, W., Schamhardt, H.C., Hartman, W., and Barneveld, A. (1995) Kinematic differences between the distal portions of the forelimbs and hind limbs of horses at the trot. *American Journal of Veterinary Research* 56: 1522-1528.

Bailey, C. J., Reid, S. W. J., Hodgson, D. R., Bourke, J. M. and Rose, R. J. (1998) Flat, hurdle and steeple racing: risk factors for musculoskeletal injury. *Equine Veterinary Journal,* 30 (6): 498-503.

Baker, S. W. and Canaway, P. M. (1993) Concepts of playing quality: Criteria and measurement. *International Turfgrass Society Research Journal* Chapter 20: 172-181.

Baker, S. W. and Richards, C. W. (1995) The effect of fibre-reinforcement on the quality of sand rootzones used for winter games pitches. *Journal of Sports Turf Research Institute*, 71: 107-117.

Baker, S. W., Cook, A. and Binns, D. J. (1998) The effect of soil type and profile construction on the performance of cricket pitches. I. Soil properties and grass cover during the first season of use. *Journal of Turfgrass Science,* 74: 80-92.

Balch, O.K., Clayton, HM. and Lanovaz, J.L. (1996) Weight- and length-induced changes in limb kinematics in trotting horses. *Proceedings of the American Association of Equine Practitioners*, 42, 218-219.

Barrett, R. S., Neal, R. J. and Roberts, L. J. (1997) The dynamic loading responses of surfaces encountered in beach running. *Journal of Science and Medicine in Sport,* 1 (1): 1-11.

Barrey, E. (1990). Investigation of the vertical hoof force distribution in the equine forelimb with an instrumented horseboot. *Equine Veterinary Journal,* 22 (S9): 35–38.

Barrey. E., Landjerit, B and Walter, R. (1991) Shock and vibration during hoof impact on different surfaces. *Equine Exercise Physiology*, 3: 97-106.

Barrey, E. and Galloux, P. (1997) Analysis of the equine jump technique by accelerometry. *Equine Veterinary Journal Supplement,* 23: 45-49.

Belock, B., Kaiser, L. J., Lavagnino, M. and Clayton, H. M. (2012) Comparison of pressure distribution under a conventional saddle and a treeless saddle at sitting trot. *The Veterinary Journal,* 193 (1): 87–91.

Benoit, P., Barrey, E., Regnault, J.C. and Brochet, J.L. (1993) Comparison of the damping effect of different shoeing by the measurement of hoof acceleration. *Acta Anatomica* 146: 109-113.

Beyler, C. (2006) Self-heating properties of styrene-butadiene rubber. *Fire and Materials* 30: 215–221.

Birkholz, D.A., Belton, K.L., Guidotti, T.L., (2003) Toxicological evaluation for the hazard assessment of tire crumb for use in public playgrounds. *Journal of Air & Water Management Association,* 53 (7): 903-907.

Blundell, E. L, Northrop, A. J., Owen A. G. and Lumsden, P. J. (2010) The Short and Long-term changes in Mechanical Properties of a Synthetic Equestrian Surface. *International Society of Equitation Science Annual Conference*. Uppsala, Sweden, 31st July – 2nd August 2010.

Boswell, R. P., Mitchell, R. D., Ober, T. R., Benoit, P. H., Miller, K. B. and Dyson, S. J. (2011) Lameness in the show hunter and show jumper In: *Diagnosis and Management of Lameness in the Horse*, Second Ed. Elsevier, St Louis, Missouri, USA pp. 1096-1111.

Boyde, A. (2003) The real response to bone. *Journal of Anatomy,* 203: 173-189.

Bridge, J. W., Peterson, M. L., Radford, D. W. and McIlwraith, C.W. (2010) Thermal transitions in high oil content petroleum-based wax blends used in granular sports surfaces. *Thermochimica Acta*, 498: 106-111.

Brosnan, J. T. and McNitt, A. S. (2008) Surface condition of highly maintained baseball fields in the Northeastern United States: Part 1, non-turfed basepaths. *Online Applied Turfgrass Science.*

Brosnan, J. T., McNitt, A. S. and Serensits, T. J. (2009) Effects of varying surface characteristics on the hardness and traction of baseball field playing surfaces. *International Turfgrass Society Research Journal*, 11: 1-13.

Burn, J. F. (2006) Time domain characteristics of hoof-ground interaction at the onset of stance phase. *Equine Veterinary Journal*, 38 (7): 657-663.

Burns, T. E. and Clayton, H. M. (1997) Comparison of the temporal kinematics of the canter pirouette and collected canter. *Equine Veterinary Journal,* 23: 58-61.

Burn, J. F., and Usmar, S. J. (2005) Hoof landing velocity is related to track surface properties in trotting horses. *Equine and Comparative Exercise Physiology,* 2 (1): 37-41.

Burn, J.F., Wilson, A. and Nason, G.P. (2007). Impact during equine locomotion: techniques for measurement and analysis. *Equine Veterinary Journal,* 29 (S23): 9-12.

Byström, A., Rhodin, M., Von Peinen, K., Weishaupt, M. A. and Roepstorff, L. (2009) Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. *Equine Veterinary Journal,* 41 (3): 280–284.

Chateau, H., Degueurce, C. and Denoix, J.-M. (2005). Three-dimensional kinematics of the equine distal forelimb: effects of a sharp turn at the walk. *Equine Veterinary Journal,* 37 (1): 12-8.

Chateau, H., Degueurce, C. and Denoix, J.-M. (2006) Effects of egg-bar shoes on the 3-dimensional kinematics of the distal forelimb in horses walking on a sand track. *Equine Veterinary Journal. Supplement,* 36: 377-382.

Chateau, H., Robin, D., Veniard, N. Falala, S., Pourcelot, P., Valette, J.-P., Ravery, B., Denoix, J-M. and Crevier-Denoix, N.(2008). Reliability and sensitivity of an accelerometric device to discriminate between the biomechanical effects of different racetracks in the horse trotting at high speed. *Computer Methods in Biomechanics and Biomedical Engineering,* 11 (1): 57-58.

Chateau, H., Robin, D., Simonelli, T., Pacquet, L., Pourcelot, P., Falala, S., Denoix, J.-M. and Crevier-Denoix, N.(2009a). Design and validation of a dynamometric horseshoe for the measurement of three-dimensional ground reaction force on a moving horse. *Journal of Biomechanics,* 42 (3): 336-340.

Chateau, H., Robin, D., Falala, S., Pourcelot, P., Valette, J-P., Ravary, B., Denoix, J.-M. and Crevier-Denoix, N. (2009b) Effects of a synthetic all-weather waxed track versus a crushed sand track on 3D acceleration of the front hoof in three horses trotting at high speed. *Equine Veterinary Journal,* 41 (3): 247-251.

Chateau, H., Holden, L., Robin, D., Falala, S., Pourcelot, P., Estoup. P., Denoix, J.-M. and Crevier-Denoix, N. (2010) Biomechanical analysis of hoof landing and stride parameters in harness trotter horses running on different tracks of a sand beach (from wet to dry) and on an asphalt road. *Equine Veterinary Journal,* 42 (38): 488-495.

Chateau, H., Camus, M., Holden, L., Falala, S., Ravery, B., Vergari, C., Denoix, J.-M., Pourcelot, P. and Crevier-Denoix, N. (2012). Ground reaction force and moments around the hoof axis during circling on different ground surfaces at trot. *7th International Conference on Equine and Canine Locomotion, Strömsholm*, Sweden, 25-28th June, 2012.

Cheney, J.A., Shen, C.K. and Wheat, J.D. (1973) Relationship of racetrack surfaces to lameness in the Thoroughbred racehorse. *American Journal of Veterinary Research,* 34: 1285-1289.

Clayton, H.M. (1988). Comparison of the stride of trotting horses trimmed with a normal and a broken back hoof-pastern axis. In: *Proceedings of the American Association of Equine Practitioners,* 33: 289-298.

Clayton, H.M. (1991). Conditioning principles. In: Conditioning Sports Horses. Sport Horse Publications, MI, USA. pp 77-94.

Clayton, H. M. (1994a) Comparison of the stride kinematics of the collected, working, medium and extended trot in horses. *Equine Veterinary Journal,* 26 (3): 230-234.

Clayton, H.M. (1994b) Comparison of the collected, working, medium and extended canters. *Equine Veterinary Journal Supplement,* 17: 16-19.

Clayton, H. M. (1997) Classification of collected trot, passage and piaffe based on temporal variables. *Equine Veterinary Journal Supplement,* 23: 54-57.

Clayton, H.M. (2002) *Walk this way*. [online]. USDF Connection, 39-42.

Clayton, H.M. and Barlow, D.A. (1989) The effect of fence height and width on the limb placements of show jumping horses. J Equine Vet Sci 9, 179 185.

Clayton, H.M. and Sha, D.H. (2006) Head and body centre of mass movement in horses trotting on a circular path. *Equine Veterinary Journal Supplement*, 38 (S36): 462-467.

Clayton, H.M., Colborne, R.G. and Burns, T. (1995) Kinematic analysis of successful and unsuccessful attempts to clear a water jump. Equine Vet J Supplement 18, 166-169.

Colborne, R.G., Clayton, H.M. and Lanovaz, J. (1995) Factors that influence the generation of vertical velocity during take off in horses jumping a water jump. Equine Vet J Supplement 18, 138-140.

Cressey, E. M., West, C. A., Tiberio, D. P., Kraemer, W. J. and Maresh, C. M. (2007) The effects of ten weeks of lower-body unstable surface training on markers of athletic performance. *Journal of Strength and Conditioning Research,* 21 (2): 561-567.

Crevier-Denoix, N., Pourcelot, P., Ravary, B., Robin, D., Falala, S., Uzel, S., Grison, A., Valtte, J-P., Denoix, J. M. and Chateau, H. (2009) Influence of track surface on the equine superficial digital flexor tendon loading in two horses at high speed trot. *Equine Veterinary Journal,* 41 (3): 257-261.

Crevier-Denoix, N., Robin, D., Pourcelot, P., Falala, S., Holden, L., Estoup. P., Desquilbet. L., Denoix, J.-M. and Chateau, H. (2010) Ground reaction force and kinematic analysis of limb loading on two different beach sand tracks in harness trotters. *Equine Veterinary Journal Supplement,* 38: 544-551.

Dahlgren, L. A. (2007) Pathobiology of tendon and ligament injuries. *Clinical Techniques in Equine Practice,* 6: 168-173.

Day, K.E., Holtze, K.E., Metcalfe-Smith, J.L., Bishop, C.T., Dutka, B.J. (1993) Toxicity of leachate from automobile tires to aquatic biota. *Chemosphere,* 27: 665–675.

De Cocq, P., Van Weeren, P. R. and Back, W. (2004) Effects of girth, saddle and weight on movements of the horse. *Equine Veterinary Journal,* 36 (8): 758–763.

De Cocq, P., Prinsen, H., Springer, N. C. N., van Weeren, P. R., Schreuder, M., Muller, M. and van Leeuwen, J. L. (2009) The effect of rising and sitting trot on back movements and head-neck position of the horse. *Equine Veterinary Journal* 41 (5): 423–427.

De Cocq, P., Duncker, A. M., Clayton, H. M., Bobbert, M. F., Mullera, M. and van Leeuwena, J. L. (2010) Vertical forces on the horse's back in sitting and rising trot. *Journal of Biomechanics* 43 (4): 627–631.

Denoix, J.-M. (1999) Functional anatomy of the equine interphalangeal joints. *Proceedings of the American Association of Equine Practitioners,* 45: 174-177.

Denoix, J.-M. and Crevier-Denoix, N. (2007) Corrective shoeing of equine foot injuries. In: 10th Geneva *Congress of Equine Medicine and Surgery*, Geneva, 11-13 December 2007.

Dowling, B.A., Dart, A.J., Hodgson, D.R. and Smith, R.K.W. (2000) Superficial digital flexor tendonitis in the horse. Equine Vet J 32, 369-378.

Drevemo, S. and Hjérten, G. (1991) Evaluation of a shock absorbing woodchip layer on a harness racetrack surface. In *Equine Exercise Physiology* 3: 107-112.

Ducro, B. J., Gorissen, B., van Eldik, P. and Back, W. (2009) Influence of foot conformation on duration of competitive life in a Dutch Warmblood horse population. *Equine Veterinary Journal,* 41 (2): 144-148.

Deuel, N.R. and Park, J.-J. (1990) The gait patterns of Olympic dressage horses. *International Journal of Sports Biomechanics.* 6: 198-226.

Deuel N.R. and Park J.-J. (1991) Kinematic analysis of jumping sequences of Olympic Show Jumping horses. *Equine Exercise Physiology 3*: 158-166.

Durá, J. V., Hoyos, J. V., Lozano, L. and Martínez, A. (1999) The effect of shock absorbing sports surfaces in jumping. *Sports Engineering,* 2: 103-108.

Dutto, D. J., Hoyt, D. F., Cogger, E. A. and Wickler, S. J. (2004) Ground reaction forces in horses trotting up an incline and on the level over a range of speeds. *The Journal of Experimental Biology*, 207, 3507-3514.

Dyson, S. (2002) Lameness and poor performance in the sport horse: dressage, show jumping and horse trials. *Veterinary Review,* 22 (4): 145-150.

Elishar, E., McGuigan, M. P. (2004) Relationship of foot conformation and force applied to the navicular bone of sound horses at the trot. *Equine Veterinary Journal,* 36 (5): 431-435.

Fauser, P., Tjell, J.C., Mosbaek, H., Pilegaard, K., (2002) Tire-tread and bitumen particle concentrations in aerosol and soil samples. *Petroleum Science and Technology,* 20: 127–141.

Fédération Equestre Internationale (2011) *FEI regulations for equestrian events at the Olympic games.* Accessed via http://www.britishdressage.co.uk/uploads/File/FEI%202012%20Olympic%20Rule%20Book.pdf

Firth, E. C. (2006) The response of bone, articular cartilage and tendon to exercise in the horse. *Journal of Anatomy,* 208: 513-526.

Firth, E. C., Rogers, C. W., van Weeran, R., Barneveld, A., McIllwraith, C. W., Kawcak, C. E., Goodship, A. E. and Smith, R. K. W. (2011) Mild exercise early in life produces changes in bone size and strength but not density in proximal phalangeal, third metacarpal and third metacarpal bones of foals. *The Veterinary Journal,* 190: 383-389.

Firth, E. C., Rogers, C. W., van Weeran, R., Barneveld, A., McIllwraith, C. W., Kawcak, C. E., Goodship, A. E. and Smith, R. K. W. (2012) The effect of previous conditioning exercise on diphyseal and metaphyseal bone to imposition and withdrawal of training in young Thoroughbred horses. *The Veterinary Journal,* 192: 34-40.

Ford, K. R., Manson, N. A., Evans, B. J., Myers, G. D., Gwin, R. C., Heidt Jr., R. S. and Hewett, T. E. (2006) Comparison of in-shoe foot loading patterns on natural grass and synthetic turf. *Journal of Science and Medicine in Sport*, 9: 443-440.

Fruehwirth, B., Peham, C., Scheidl, M. and Schobesberger, H. (2004) Evaluation of pressure distribution under an English saddle at walk, trot and canter. *Equine Veterinary Journal*, 36 (8): 754–757.

Geutjens, C. A., Clayton, H. M. and Kaiser, L. J. (2008) Forces and pressures beneath the saddle during mounting from the ground and from a raised mounting platform. *The Veterinary Journal*, 175 (3): 332–337.

Gibson, K.T., Snyder, J.R. and Spier, S.J. (2002) Ultrasonographic diagnosis of soft tissue injuries in horses competing at the Sydney 2000 Olympic Games. *Equine Veterinary Education,* 14: 149–156.

Goodall, S. A., Guillard, K., Dest, W. M. and Demars, K. R. (2005) Ball response and traction of skinned infields amended with calcined clay at varying soil moisture contents. *International Turfgrass Society Research Journal*, 10: 1085-1093.

Goodship, A. E., Lanyon, L. E. and McFie, M. (1979) Functional adaptation of bone to increased stress. *Journal of Bone Joint. Surgery*, 61A: 539-546.

Gray, D. and Ohashi, H. (1983) Mechanics of fiber reinforcement in sand. Journal of Geotechnical Engineering, 109 (3): 335–353.

Gualtieri, M., Andrioletti, M., Vismara, C., Milani, M., Camatini, M., (2005) Toxicity of tire debris leachates. *Environment International,* 31: 723–730.

Gustås, P., Johnston, C., U., Roepstorff, L. and Drevemo, S. (2001) *In vivo* transmission of impact shock waves in the distal forelimb of the horse. *Equine Veterinary Journal Supplement*, 33: 11-15.

Gustås, P., Johnston, C., U., Roepstorff, L., Drevemo, S. and Lanshammar, H. (2004) Relationships between fore- and hindlimb ground reaction force and hoof deceleration patterns in trotting horses. *Equine Veterinary Journal*, 36 (8): 737–742.

Gustås, P., Johnston, C., and Drevemo, S. (2006a) Ground reaction force of hoof deceleration patterns on two different surfaces at the trot. *Equine and Comparative Exercise Physiology,* 3 (4): 209-216.

Gustås, P., Johnston, C., Hedenstrom, U., Roepstorff, L. and Drevemo, S. (2006b) A field study on hoof deceleration at impact in Standardbred totters at various speeds. *Equine and Comparative Exercise Physiology,* 3 (3): 161-168.

Hartwell, S.I., Jordahl, D.M., Dawson, E.O., (2000) The effect of salinity on tire leachate toxicity. *Water, Air and Soil Pollution,* 121: 119–131.

Harvey, A. M., Williams, S. B. and Singer, E. R. (2012) The effect of lateral heel studs on the kinematics of the equine digit while cantering on grass. *The Veterinary Journal,* 192: 217-221.

Heaps, L.A., Franklin, S.H. and Colbourne, G.R. (2011) Horizontal moment around the hoof centre of pressure during walking on right and left circles. *Equine Veterinary Journal*, 43 2: 190-195.

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

Hickstead (2012) *Horseshows* Accessed via http://www.hickstead.co.uk/horse-shows.aspx

Hjertén, G. and Drevemo, S. (1994) Semi-quantitative analysis of hoof-strike in the horse. *Journal of Biomechanics,* 27: 997-1004.

Hobbs, S.J. and Clayton, H.M. (2013). Sagittal plane ground reaction forces, centre of pressure and centre of mass in trotting horses. *The Veterinary Journal*. DOI: 10.1016/j.tvjl.2013.09.027

Hobbs, S.J., Licka, T. and Polman, R. (2011) The difference in kinematics of horses walking, trotting and cantering on a flat and banked 10 m circle. *Equine Veterinary Journal*, 43 (6): 686–694.

Holcombe, S. J., Robinson, N. E., Derksen, F. J., Berthold, B., Genovese, R., Miller, R., De Feiter Rupp, H., Carr, E. A., Eberhart, S. W., Boruta, D. and Kaneene, J. B. (2006) Effect of tracheal mucus and tracheal cytology on racing performance in Thoroughbred racehorses. *Equine Veterinary Journal,* 38 (4): 300-304.

Holmström, M., Fredericson, I. and Drevemo, S. (1995) Biokinematic effects of collection on the trotting gaits in the elite dressage horse. *Equine Veterinary Journal,* 27: 281-287.

Holmström, M., Magnusson, L.-E. and Phillipsson, J. (1990) Variation in conformation of Swedish Warmblood horses and conformational characteristics of elite sport horses. *Equine Veterinary Journal,* 22 (3): 186-193.

Jeffcott, J.B. (1980) Disorders of the thoracolumbar spine of the horse – a survey of 443 cases. *Equine Veterinary Journal*, 12 (4): 197-210.

Kai, M., Takahashi, T., Aoki, O. and Oki, H. (1999) Influence of rough track surfaces on components of vertical forces in cantering thoroughbred horses. *Equine Veterinary Journal Supplement,* 30: 214-217.

Karvanen, J. (2003) The statistical basis of laboratory normalization. *Drug Information Journal*, 37, 101–107.

Kasashima, Y., Smith, R. K. W., Birch, T., Takahashi, K., Kusano. K. and Goodship, A. E. (2002) Exercise-induced tendon hypertrophy: cross-sectional area changes during growth are influenced by exercise. *Equine Veterinary Journal Supplement,* 34: 264-268.

Keegan, K.G., Baker, G.J., Boero, M.J., Pijanowski, G.J. and Phillips, J.W. (1992). Evaluation of support bandaging during measurement of proximal sesamoidean ligament strain in horses by use of a mercury strain gauge. *American Journal of Veterinary Research*, 53: 1203-1208.

Kicker CJ, Peham C, Girtler D, Licka T.(2004) Influence of support boots on fetlock joint angle of the forelimb of the horse at walk and trot. *Equine Veterinary Journal,* 36 (8): 796-771.

Kollar, J. L. (2005) Dust exposure and respiratory disorders in equine instructors. *The Professional Animal Scientist,* 21: 128-132.

Leleu, C., Gloria, E., Renault, G. and Barrey, E. (2002) Analysis of trotter gait on the track by accelerometry and image analysis. *Equine Veterinary Journal*, 34 (S34): 344–348.

Li, X., Berger, W., Musante, C., Incorvia, M., (2010) Characterization of substances released from crumb rubber material used on artificial turf fields. *Chemosphere,* 80: 279–285.

Licka, T., Kapaun, M. and Peham, C. (2004) Influence of rider on lameness in trotting horses. *Equine Veterinary Journal*, 36 (8): 734–736.

Mahaffey, C. A.,, Peterson, M. and Roepstorff, L. (2013) The effects of varying cushion depth on dynamic loading in shallow sand dirt thoroughbred horse racetracks, *Biosystems Engineering,* 114: 178-186.

Mahaffey, C. A., Peterson, M. and McIlwraith, C. W. (2012) Archetypes in Thoroughbred dirt racetracks regarding track design, clay mineralogy, and climate *Sports Engineering* 15 (1): 21-27.

Malikides, N. and Hodgson, J. L. (2003) Inflammatory airway disease in young Thoroughbred racehorses. *Rural Industries Research and Development Corporation* US.

Malmgren, R., Shideler, R. K., Butler, K. D. and Anderson, E. W. (1994) The effect of polymer and rubber particles on arena soil characteristics. *Journal of Equine Veterinary Science,* 14 (1): 38-42.

Marks, D. (2000) Conformation and soundness. *Proceedings of the American Association of Equine Practitioners,* 46: 39-45.

Mazan, M. R. and Hoffman, A. M. (2006) How to do air quality testing in the equine barn. *American Association of Equine Practitioners Proceedings,* 52: 81-86.

McMahon, T. A. and Greene, P. R. (1979) The influence of track running compliance. *Journal of Biomechanics,* 12: 893-904.

Medoff, H. (1995) Problems in defining and measuring friction on natural and artificial playing surfaces. *Proceedings of the 1995 Fourteenth Southern Biomedical Engineering Conference,* Louisiana pp. 171-174.

Meershoek, L. S., Roepstorff, L., Schamhardt, H. C., Johnston, C. and Bobbert, M. F. (2001a) Joint moments in the distal forelimbs of jumping horses during landing. *Equine Veterinary Journal,* 33 (4): 410-415.

Meershoek, L. S., Schamhardt, H. C., Roepstorff, L. and Johnston (2001b) Forelimb tendon loading during jump landings and the influence of fence height. *Equine Veterinary Journal Supplement,* 33: 6-10

Meschan, E. M., Peham, C., Schobesberger, H. and Licka, T. F. (2007) The influence of the width of the saddle tree on the forces and the pressure distribution under the saddle. *The Veterinary Journal,* 173 (3): 578–584.

Millerick-May, M. L., Karmaus, W., Derksen, F. J., Berthold, B., Holcombe, S. J. and Robinson, N. E. (2011) Particle mapping in stables at an American Thoroughbred racetrack. *Equine Veterinary Journal,* 43 (5): 599-607.

Moyer, W and Fisher, J.R.S. (1991) Bucked Shins: Effects of differing track surfaces and proposed training regimens. *Proceedings of the 37th Annual Convention of the American Association of Equine Practitioners.* San Francisco, California, USA, December 1-4 1991. pp 541-547.

Murphy, J. (2009) Weighted boots influence performance in show-jumping horses. *The Veterinary Journal* 181, 74-76.

Murray, R. C., Dyson, S. J., Tranquille, C. and Adams, V. (2006) Association of type of sport and performance level with anatomical site of orthopaedic injury diagnosis. *Equine Veterinary Journal Supplement,* 36: 411-416.

Murray, R. C., Walters, J., Snart, H., Dyson, S. and Parkin, T. (2010a) How do features of dressage arenas influence training surface properties which are potentially associated with lameness? *The Veterinary Journal*, 186: 172-179.

Murray, R. C., Walters, J., Snart, H., Dyson, S. and Parkin, T. (2010b) Identification of risk factors for lameness in dressage horses. *The Veterinary Journal*, 184: 27-36.

Nelson, S.M., Mueller, G., Hemphill, D.C., (1994) Identification of tire leachate toxicants and a risk assessment of water quality effects using tire reefs in canals. *Bulletin of Environmental Contamination and Toxicology,* 52: 574–581.

Nielsen, B. D. and Spooner, H. S. (2008) Small changes in exercise, not nutrition, often result in measurable changes in bone. Comparative Exercise Physiology, 5 (1): 15-20.

Nielsen, B. D., Potter, G. D., Greene, L. W., Morris, E. L., Murray-Gerzik, M., Smith, W. B. and Martin, M. T. (1998) Characterization of changes related to mineral balance and bone metabolism in the young racing Quarter horse. *Journal of Equine Veterinary Science,* 18 (3): 190-200.

Nielsen, B. D., Cate, R. E. and O'Connor-Robison, C. I. (2010) A marine mineral supplement alters markers of bone metabolism in yearling Arabians. *Journal of Equine Veterinary Science,* 30 (8): 419-424.

Nigg, B. M. and Yeadon, M. R. (1987) Biomechanical aspects of playing surfaces. *Journal of Sports Sciences*, 5: 117-145.

Northrop, A J., Dagg, L-A., Martin, J H., Brigden, C, Owen, A G., Blundell' E. Peterson, M L. and Hobbs, S. J. (2013) The Effect of Two Preparation Procedures on an Equine Arena Surface in Relation to Motion of the Hoof and Metacarpophalangeal Joint *The Veterinary Journal.* DOI: 10.1016/j.tvjl.2013.09.048

Orlande, O., Hobbs, S. J., Martin, J. H., Owen, A. G. and Northrop, A. J. (2012) Measuring hoof slip of the leading limb on jump landing over two different equine arena surfaces. *Comparative Exercise Physiology*, 8 (1): 33-39.

Orsini, J. A. (2012) A fresh look at the process of arriving at a clinical prognosis Part 4: fractures *Journal of Equine Veterinary Science,* 32: 129-138.

Oxford English Dictionary (1994) 4th Edn. Ed; Pollard, E. and Liebeck, H. Oxford University Press, Kent, UK.

Pardoe, C.H., McGuigan, M.P., Rogers, K.M., Rowe, L.L., and Wilson, A.M.. (2001) The effect of shoe material on the kinetics and kinematics of foot slip at impact on concrete. *Equine Veterinary Journal Supplement,* 33: 70-73.

Parkin, T. D. H., Clegg, P. D., French, N. P., Proudman, C. J., Riggs, C. M., Singer, E. R., Webbon, P. M. and Morgan, K. L. (2004) Race- and course-level risk factors for fatal distal limb fracture in racing Thoroughbreds. *Equine Veterinary Journal*, 36 (6): 521-526.

Parkes, R. S., Newton, J. R. and Dyson, S. J. (2013) An investigation of risk factors for foot-related lameness in a United Kingdom referral population of horses. *The Veterinary Journal,* 196 (2): 218-225.

Parks, A. H. (2011) The foot and shoeing In: *Diagnosis and Management of Lameness in the Horse*, Second Ed. Elsevier, St Louis, Missouri, USA pp.282-308.

Parsons, K.J. and Wilson, A.M. (2006) The use of MP3 recorders to log data from equine hoof mounted accelerometers. *Equine Veterinary Journal*, 38 (7): 675–680.

Peham, C., Licka, T., Kapaun, M. and Scheidl. M. (2001) A new method to quantify harmony of the horse–rider system in dressage. *Sports Engineering*, 4 (2): 95–101.

Peham, C., Licka, T., Schobesberger, H. and Meschan, E. (2004) Influence of the rider on the variability of the equine gait. *Human Movement Science*, 23 (5): 663–671.

Peham, C., Kotschwar, A.B., Borkenhagen, B., Kuhnke, S., Molsner, J. and Baltacis J. (2010) A comparison of forces acting on the horse's back and the stability of the rider's seat in different positions at the trot. *The Veterinary Journal* 184, 56-59.

Peterson, M. L. and McIlwraith, C. W. (2008) Effect of track maintenance on mechanical properties of a dirt racetrack: A preliminary study. *Equine Veterinary Journal*, 40 (6): 602-605.

Peterson, M. L., McIlwraith, C. W. and Reiser, R. F. (2008) Development of a system for the in-situ characterisation of thoroughbred horse racing track surfaces. *Biosysytems Engineering*, 101: 260-269.

Peterson, M. L., Reiser, R. F., Kuo, P.-H., Radford, D. W. and McIlwraith, C. W. (2010) Effect of temperature on race times on a synthetic surface. *Equine Veterinary Journal*, 42 (4): 351-357.

Peterson, M. L., Roepstorff, L., Thomason, J. J., Mahaffey, C. and McIlwraith, C. W. (2012) *Racing Surfaces. White Paper*. Accessed via http://www.racingsurfaces.org/bulletins. html

Pfau, T., Stubbs, N.C., Kaiser, L., Brown, L. and Clayton, H.M. (2012) The effect of trotting speed and circle radius on movement symmetry in horses during lunging on a soft surface. *American Journal of Veterinary Research* 73: 1890-1899.

Pirie, R. S., Collie, D. D. S., Dixon, P. M. and McGorum, B. C. (2003) Inhaled endotoxin and organic dust particulates have synergistic proinflammatory effects in equine heaves (organic dust-induced asthma). *Clinical Experimental Allergy,* 33: 676-683.

Porr, C. A., Kronfeld, D. S., Lawrence, L. A., Pleasant, R. S. and Harris, P. A. (1998) Deconditioning reduces mineral content of the third metacarpal bone in horses. *Journal of Animal Science,* 76: 1875-1879.

Powers, P. N. R. and Harrison, A. J. (1999) Models for biomechanical analysis of jumping horses. *Journal of Equine Veterinary Science,* 19 (12): 799-806.

Pratt, G.W. (1984). Racing surface – A survey of mechanical behaviour. *Proceedings of the American Association of Equine Practitioners* pp. 321-331.

Pratt, G.W. (1997). Model for injury to the foreleg of the Thoroughbred racehorse. *Equine Veterinary Journal*, 29: 30–32. doi: 10.1111/j.2042-3306.1997.tb05048.x

Pugmire, L. (2013). Del Mar's new surface has uneven track record, July 18, 2007, *Los Angeles Times*, accessed March 18, 2013 at http://articles.latimes.com/2007/jul/18/sports/sp-turf18)

Radin, E. L., Parker, H. G., Pugh, J. W., Steinberg, R. S., Paul, I. L. and Rose, R. M. (1973) Response of joints to impact loading – relationship between trabecular microfractures and cartilage degeneration. *Journal of Biomechanics*, 6: 51-57.

Ramón T, Prades M, Armengou L, Lanovaz JL, Mullineaux DR, Clayton HM. (2004) Effects of athletic taping of the fetlock on distal limb mechanics. *Equine Veterinary Journal,* 36 (8): 764-8.

Rapp, H. J., Bockisch, F., Heiss, K., Becker, M., Stechele, M. and Heisse, K. (1992) Riding arenas and different riding track surfaces in relation to the airway contamination in horses. Laboratory studies on riding surfaces. *Tierärztliche Praxis Supplement,* 20 (5): 503-508.

Ratzlaff, M.H., Grant, B.D., Frame, J.M. and Hyde, M.L. (1983) Locomotor forces in galloping horses. *Equine Exercise Physiology*, 2: 574-586.

Ratzlaff, M.H., Wilson, P.D., Hyde, M.L., Balch, O.K., and Grant, B.D. (1993) Relationships between Locomotor Forces, Hoof Position and Joint Motion during the Support Phase of the Stride of Galloping Horses. *Acta Anatomica,* 146:200-204.

Ratzlaff, M.H., Hyde, M.L., Hutton, D.V., Rathgeber, R.A. and Balch, O.K. (1997) Interrelationships between moisture content of the track, dynamic properties of the track and the locomotor forces exerted by galloping horses. *Journal of Equine Veterinary Science,* 17: 35-42.

Reed, S. R., Jackson, B. F., McIlwraith, W. C., Wright, I. M., Pilsworth, R., Knapp, S., Wood, J. L. N., Price, J. S. and Verheyen, K. L. P. (2012) Descriptive epidemiology of joint injuries in Thoroughbred racehorses in training. *Equine Veterinary Journal,* 44 (1): 13-19*.*

Reiser, R. F., Peterson, M. L., McIlwraith, C. W. and Woodward, B. (2000) Simulated effects of racetrack material properties on the vertical loading of the equine forelimb. *Sports Engineering*, 3 (1): 1-11.

Riggs, C. (2010) Clinical problems in dressage horses: Identifying the issues and comparing them with knowledge from racing. *The Veterinary Journal*, 184 (1): 1-2.

Robin, D., Chateau, H., Pacquet, L., Falala, S., Valette, P., Poureclot, B., Denoix, J._M. and Crevier Denoix, N. (2009) Use of a 3D dynamometric horseshoe to assess the effects of an all-weather waxed track and a crushed sand track at high speed trot: Preliminary study. *Equine Veterinary Journal,* 41, (3): 253-256.

Roepstorff, L., Johnston, C. and Drevemo, S. (1999) The effect of shoeing on kinetics and kinematics during the stance phase. *Equine Veterinary Journal Supplement,* 30: 279–285.

Roepstorff, L., Egenvall, A., Rhodin, M., Byström, A., Johnston, C., van Weeren, P. R. and Weishaupt, M. (2009) Kinetics and kinematics of the horse comparing left and right rising trot. *Equine Veterinary Journal,* 41: (3) 292–296.

Rogers, C. W., Firth, E. C., McIlwraith, C. W., Barneveld, A., Goodship, A. E., Kawcak, C. E., Smith, R. K. W. and vanWeeren, P. R. (2008) Evaluation of a new strategy to modulate skeletal development in racehorses by imposing track-based exercise during growth: The effects on 2 and 3 year old racing careers. *Equine Veterinary Journal*, 40 (2): 119-127.

Roland, E. S., Hull, M. L. and Stover, S. M. (2005) Design and demonstration of a dynamometric horseshoe for measuring ground reaction loads of horses during racing conditions. *Journal of Biomechanics*, 38: 2102-2112.

Ruina, A., Bertram, J., and Srinivasan, M. (2005) A collisional model of the energetic cost of support work qualitatively explains leg-sequencing in walking and galloping, pseudo-elastic leg behavior in running and the walk-to-run transition. *Journal of Theoretical Biology* 14: 170–192.

Sadek, S., Najjar, S. and Freiha, F. (2010) Shear strength of fiber-reinforced sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 136 (3): 490–499.

Santucci De Magistris F., Koseki, J. and Amaya M. (1999) A triaxial testing system to evaluate stress-strain behaviour of soils for wide range of strain and strain rate. ASTM *Geotechnical Testing Journal*, 22 (1): 44-60.

Saffih-Hdadi, K., Défossez, P., Richard, G., Cui, Y.–J., Tang, A.–M. and Chaplain, V. (2009) A method for predicting soil susceptibility to the compaction of surface layers as a function of water content and bulk density. *Soil and Tillage Research*, 105: 96-103.

Schamhardt, H.C. and Merkens, H.W. (1994) Objective determination of ground contact of equine limbs at the walk and trot: comparison between ground reaction forces, accelerometer data and kinematics. *Equine Veterinary Journal*, 26 (S17): 75–79.

Schamhardt, H.C., Merkens, H.W., Vogel, V. and Willekens, C. (1993) External loads on the limbs of jumping horses at take-off and landing. *American Journal of Veterinary Research* 54: 675-680.

Setterbo, J. J., Garcia, T. C., Campbell, I. P., Kim, S. Y., Hubbard, M. and Stover, S. M. (2008) Forelimb Kinematics of Galloping Thoroughbred Racehorses Measured on Dirt, Synthetic, and Turf Track Surfaces. In: *The Engineering of Sport 7*. Springer Paris. pp. 437-446.

Setterbo, J. J., Garcia, T. C., Campbell, I. P., Reese, J. L., Morgan, J. M., Kim, S. Y., Hubbard, M. and Stover, S. M. (2009) Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces. *American Journal of Veterinary Research,* 70: (10) 1220-1229.

Setterbo, J. J., Yamaguchi, A., Hubbard, M., Upadhyaya, S. K. and Stover, S. M. (2011) Effects of equine racetrack surface type, depth, boundary area, and harrowing on dynamic surface properties measured using a track-testing device in a laboratory setting. *Sports Engineering*. 14: 119-137.

Singer, E. R., Barnes, J., Saxby, F. and Murray, J. K. (2008) Injuries in the event horse: training versus competition. *The Veterinary Journal,* 175: 76-81.

Sloet van Oldruitenborgh-Oosterbaan, M. M., Wensing, T. H., Barneveld, A. and Breukink, H. J. (1991) Work-load in the horse during vaulting competition. *Equine Exercise Physiology 3:* 331-336.

Sportsturf Research Institute (2012) *STRI Equestrian*. Accessed via http://www.stri.co.uk/case-studies/hickstead-arena/

Staniar, W. B. (2010) Linking dietary energy and skeletal development in the horse. *Revista Brasileira de Zootecnia,* 39: 138-144.

Starke, S.D., Willems, E., Ma,y .S.A, Pfau, T. (2012) Vertical head and trunk movement adaptations of sound horses trotting in a circle on a hard surface. *The Veterinary Journal* 193: 73-80.

Stone, R. B., Coston, L. C., Hoss, D. E., Cross, F. A. (1975) Experiments on some possible effects of tire reefs on pinfish (*Lagodon rhomboides*) and Black Sea Bass (*Centropristis striata*). *Marine Fisheries Review*, 37: 18-20.

Strathoof Managebodems (2012) *Building an ebb and flow arena*. Accessed via http://straathofmanegebodems.nl/eb-en-vloed/

Stricklin, J. B. (1997) Barrel racing. In *Proceedings of the American Association of Equine Practitioners* 43: 37-39.

Symes, D. and Ellis, R. (2009) A preliminary study into rider asymmetry within equitation. *The Veterinary Journal,* 181 (1): 34-37.

Tan, H. and Wilson, A.M. (2011) Grip and limb force limits to turning in horses. *Proceedings of the Royal Society B*, 278: 2105–2111.

Thomason, J. J*,* Cruz A.M.*,* Bignell W.*,* Redman, D., and Jackson, S. (2007). *In*-situ strain measurement *on the* equine hoof*. In* Proceedings *SEM Annual Conference and Exposition on Experimental and Applied Mechanics - Experimental Mechanics Applied to Advanced Materials and Systems;* 1636–1642.

Thomason, J. J. and Peterson, M. L. (2008) Biomechanical and mechanical investigations of the hoof-track interface in racing horses. *Veterinary Clinics of North America: Equine Practice*, 24 (1): 53-77.

Tranquille, C. A., Walker, V. A., Roepstorff, L., Hernlund, E. and Murray, R. C. (2012) Does harrowing have an effect on the mechanical properties of waxed sand with rubber or waxed sand with fibre surfaces? *In Proceedings: BEVA Congress*: September, 2012, Birmingham, pp. 158.

Vanaverbeke, J., Deprez, T., Vincx,. M. (2007) Changes in nematode communities at the long-term sand extraction site of the Kwintebank (Southern Bight of the North Sea). *Marine Pollution Bulletin*, 54 (9): 1351-1360.

van Dalfsen, J.A., Essink, K., Madsen, H.T., Birklund, J., Romero, J., Manzanera, M. (2000) Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean*. ICES Journal of Marine Science,* 57: 1439-1445.

van Heel, M.C.V., van Weeren, P.R., Back, W. (2006) Compensation for changes in hoof conformation between shoeing sessions through the adaptation of angular kinematics of the distal segments of the limbs of horses. *American Journal of Veterinary Research*, 67 (7): 1199-1203.

van Weeren, P. R. (2010) On surfaces and soreness, guest editorial. *The Veterinary Journal*, 186: 129-130.

van Weeren, P. R. and Barneveld, A. (1999) Introduction: Study design to evaluate the influence of exercise on the development of the musculoskeletal system of foals up to age 11 months. *Equine Veterinary Journal*, 31 (S31): 4-8.

Verheyen, K. Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone,* 39: 1322-1330.

von Peinen, K., Wiestner, T., Von Rechenberg, B. and Weishaupt, M. A. (2010) Relationship between saddle pressure measurements and clinical signs of saddle soreness at the withers. *Equine Veterinary Journal Supplement,* 42: (s38) 650–653.

Walker, V. A., Tranquille, C. A., Roepstorff, L., Landolt, C., Brandham, J. and Murray, R. C. (2012) The effect of harrowing and watering on arena surface characteristics and kinematics of the working trot. *In Proceedings: BEVA Congress*: September, 2012, Birmingham, pp. 159.

Weishaupt, M. A., Byström, A., von Peinen, K., Wiestner, T., Meyer, H., Waldren, N., Johnston, C., van Weeren, R. and Roepstorff, L. (2009) Kinetics and kinematics of the passage *Equine Veterinary Journal,* 41 (3): 263-267.

Wheeler, E. F., Diehl, N.K., Zajaczkowski, J. L. and Brown, D. (2005) Horse Riding Arena Dust Measurements *Proceedings of the Seventh International Livestock Environment Symposium*. Beijing, China. ASAE St. Joseph, MI. pp. 171-178.

Wickler, S. J., Hoyt, D. F., Clayton, H. M., Mullineaux, D., Coggert, E. A., Sandovalt, E., McGuiret, R. and Lopez, C. (2004) Energetic and kinematic consequences of weighting the distal limb. *Equine Veterinary Journal*, 36 (8): 772-777.

Wik, A. and Dave, G. (2009) Occurrence and effects of tire wear particles in the environment – a critical review and an initial risk assessment. *Environmental Pollution,* 157: 1–11.

Willardson, J. M. (2007) Core stability training: applications to sports conditioning programs *Journal of Strength and Conditioning Research,* 21 (3): 979-985.

Willemen, M.A., Savelberg, H.C.C.M., Bruin, G. and Barneveld, A. The effect of toe weights on linear and temporal stride characteristics of Standardbred trotters. *Veterinary Quarterly*, 16: S97-100.

Williams, F. C. and Pulley, G. E. (2002) *Synthetic Heat Studies*. Brigham Young University. (http://aces.nmsu.edu/programs/turf/documents/brigham-young-study.pdf).

Williams, R. B., Harkins, L. S., Hammond, C. J. and Wood, J. L. N. (2001) Racehorse injuries, clinical problems and fatalities recorded on British racecourses from flat racing and national hunt racing during 1996, 1997, 1998. *Equine Veterinary Journal,* 33 (5): 478-486.

Zebarth, B.H. and Sheard, R.W. (1985) Impact and shear resistance of turf grass racing surfaces for Thoroughbreds. *American Journal of Veterinary Research*, 46: 778-784.