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# Surface Variable Effects on the Dynamic Properties of Thoroughbred Horse Racetracks

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# SURFACE VARIABLE EFFECTS ON THE DYNAMIC PROPERTIES OF THOROUGHBRED HORSE RACETRACKS

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A DISSERTATION

Submitted in Partial Fulfillment of the

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May, 2012

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**DISSERTATION ACCEPTANCE STATEMENT**

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Michael L. Peterson, Professor of Mechanical Engineering April 26, 2012

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**SURFACE VARIABLE EFFECTS ON THE DYNAMIC PROPERTIES OF THOROUGHBRED HORSE RACETRACKS**

By Christie A. Mahaffey

Thesis Advisor: Dr. Michael L. Peterson

An Abstract of the Dissertation Presented
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Historically, equine racing surfaces have been selected and maintained without considering quantifiable data for horse biomechanics or surface mechanical properties. This approach is currently shifting in the racing industry, with an increased interest in understanding the mechanics of the hoof-surface interface to reduce injuries. This dissertation examines three components influencing the hoof-surface interface: 1) correlations between mineralogical composition of dirt tracks, track designs, and climate; 2) the effect of variable cushion depth on dynamic loading, and 3) the effects of different horseshoes on dynamic loading. The second and third pieces of this research are based on an experimental procedure designed to mimic *in-situ* performance.

In dirt racetracks, clay content is critical to moisture management and influences mechanical properties. Clay mineralogy was determined for 26 tracks representing three track designs: shallow sand, false base, and false base with a pad. Results demonstrate that shallow sand tracks occur in areas with the highest annual precipitation and have the lowest average clay content, whereas tracks with a false base and pad have the lowest annual

precipitation and the highest average clay content. Understanding moisture and clay effects in racetracks can aid in quantifying track maintenance decisions.

The next tested parameter was the effect of cushion depth on dynamic loading experienced by the horse for a range of surface conditions. The difference of 5 cm in depth significantly affects the peak load and loading rate. This effect may be reduced when a surface material is maintained at a moisture level at which maximum dry density occurs.

Finally, three horseshoes–a flat racing plate, a serrated V-grip, and a shoe with a grab and heel calks–were tested on synthetic and dirt track materials. The shoes were not significantly different barring one exception: loading rate for the V-Grip shoe on a synthetic surface was significantly less than that of the other shoes. All other statistically significant differences were due to surface variation rather than shoe type.

Understanding these variables adds to the body of knowledge needed for more quantitative decision-making on racing surfaces and also adds to the data framework necessary for robust epidemiological studies.

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## LIST OF ABBREVIATIONS

XRD: X-ray diffraction

SS: Shallow Sand

FB: False Base

FBP: False Base with a Pad

S14: Sealed surface, 14wt% moisture content

H14: Harrowed surface, 14wt% moisture content

S16: Sealed surface, 16wt% moisture content

H16: Harrowed surface, 16wt% moisture content

S18: Sealed surface, 18wt% moisture content

# 1. INTRODUCTION AND PROBLEM DESCRIPTION

## 1.1. Motivation

Thoroughbred horse racing, a multibillion dollar industry, captures hearts and raises adrenaline in fans and industry opponents alike. The racing industry captivates its audience through feats of athleticism, the aesthetics of animals that are simultaneously powerful and graceful, and gambling. While it may be difficult to quantify the emotional role of the connection with the horse in this cultural entity, the financial connection is clear. An economic impact analysis from 2005 states that horse racing has a $10,697,000,000 contribution to the US Gross Domestic Product (GDP). This represents over 25% of the GDP economic impact of the entire US horse industry, which also includes showing and recreation (The Jockey Club 2012a). An anthropologist has even studied the horse racing culture, and argues that it is indeed a unique cultural entity that has the characteristics of its own tribe (Fox 2005). This tribe, of course, is dependent on the horse. It is not surprising then, that emotions run high when faced with the bitterness of injury, death, and loss.

Injuries such as the largely publicized breakdown and 8 month attempted recovery of Barbaro in 2006–unsuccessful due to recovery complications–brought negative publicity to horse racing over the tragedy of a horse that earned household recognition across the US. Two years later, Eight Belles brought the dark side of horse racing to the public eye once again when she fractured both front legs at the fetlock and sesamoid bone. Most recently, an article making the front page of the *New York Times* portrayed the concern that the industry and the populace have over the risks and losses in horseracing (Bogdanich, Drape et al. 2012).

Unfortunately, Barbaro's and Eight Belles' fates were not isolated incidents. In 2011, Thoroughbred racing averaged 1.88 fatal injuries per 1000 starts (The Jockey Club 2012c). Injuries can result from a number of factors including genetics, nutrition, training history, medical history and drug administration, and experiences on different training and racing surfaces. Of all these factors and others not listed here, the racing surface is the one variable that all of the horses will experience on a given race day. The identification of factors that influence track consistency and safety serves two purposes: the first being improved safety of the surface, and the second benefit is that it begins the deductive procedure of eliminating secondary variables to get to other root causes of injury and suffering of the horses that are the foundation of the industry.

Proponents for Thoroughbred horse racing have recognized the need to improve safety in what is a naturally dangerous sport. Safety initiatives have included the development of the Equine Injury Database (The Jockey Club 2012b), rules regarding drug administration to mask pain and/or improve performance on race day (The Jockey Club 2012d), and efforts for increased surface testing (The Jockey Club 2009). This dissertation offers a piece toward further understanding of the hoof/surface dynamics in order to add to a growing body of knowledge for the improved safety of racing surfaces.

**1.2. Hoof/surface dynamics**

The dynamics of a horse hoof striking a track surface are an interesting junction of biomechanics and soil mechanics. This interaction is not simply modeled in part due to the complexity of fully characterizing the nonlinear mechanics of a horse's motion and biological tissue properties (Wilson, McGuigan et al. 2001; Burn 2006). As described in a review by Peterson *et al.* (2011), the gait of a galloping Thoroughbred consists of four distinct stages: primary impact, secondary impact, support, and breakover. During primary impact the hoof

contacts the ground at close to 90 degrees with the surface. At this point, the hoof is moving at a relatively high velocity towards the ground, but it does not yet bear a significant load. It is only the lower limb mass – the pastern and hoof – contributing to the mass behind the primary impact. The load and loading rate quickly increase with the secondary impact as the body, catching up to the decelerating hoof, collides with the leg causing the hoof to slide across (or through) the surface. Loading of the limb continues to increase through the support phase at which point, the vertical ground reaction force (GRF) is nearly 2.5 times the horse's body weight. Finally, the hoof rolls forward and unloads as the animal propels itself forward.

The surface side of the impact and loading also brings an interesting piece to this problem due to varying degrees of viscoelasticity in racing surfaces. Dirt and synthetic tracks (further described in Chapter 2) include granular materials (i.e. sand) at varying degrees of moisture, and in the case of synthetic surfaces, wax and fiber. These materials can behave in different ways depending on surface chemistry and moisture and thermal effects. For example, differences in surface shear strength and stiffness due to thermal variation of a synthetic surface has been shown to affect race times (Peterson, Reiser II et al. 2010). Depending on the temperature and state of the wax, it acts as a binder or a lubricant, thus significantly affecting the surface mechanics. Similarly, varying moisture levels in dirt tracks affect mechanical properties, as do the clay and fine particle ratios, which are further discussed in Chapter 2.

One strategy that has lead to much progress in quantifying the impact of a Thoroughbred horse at a gallop on different surfaces is with a biomechanical hoof tester (Peterson and McIlwraith 2008; Peterson, McIlwraith et al. 2008). This device matches the dynamics of the primary and secondary impact of the forelimb. Equipped with 3-axis load

cells and accelerometers, it provides data on ground reaction forces indicating a surface's hardness and shear strength and relates to the forces on the hoof experienced by a horse on that particular surface. Parts of the research described in the following chapters use this strategy to explore variables affecting ground reactions forces.

### 1.3. Scope of Work Presented in this Dissertation

The scope of the work presented in this dissertation addresses the effects of three components influencing the hoof-surface material interface: 1) the interplay between the mineralogical composition of dirt tracks, track designs, and climate; 2) the effect of variable cushion depth on dynamic loading of the hoof, and 3) the effects of different horseshoes on dynamic loading. The second and third pieces of this research are based on an experimental procedure designed to mimic *in-situ* testing at the tracks (see Appendix for procedural details).

This work begins by defining and characterizing the three different dirt track types in North America. It also explores possible influences on how these designs developed through trial and error in the industry in order to maintain a surface with sufficient shear strength under different climatic conditions. By defining and understanding the evolution of dirt track designs in North America, it is possible to better address maintenance concerns that tracks need to handle on a daily basis to optimize safety and operations.

The next piece of research addresses variation in cushion depth, a common concern regarding track maintenance. Racetracks are over 1 mile long, and 100 feet wide. With some tracks in particular, it can be a challenge to maintain an even cushion depth across the entire track. By developing an experimental design to model a track surface under different conditions, the magnitude of the effects of varying cushion depth are quantified.

Working up from surface characteristics to the horse for the surface/hoof interface, the next piece in this research looks at how different horseshoes affect the dynamic loading

during a gallop. There are limits to the extent that a track can be modified to handle different conditions on a race day. Therefore, Chapter 4 addresses the question of if and how much different horseshoes can affect dynamic loading in order to manipulate the surface conditions experienced by a horse.

The following three chapters are compiled from peer-reviewed papers listed below covering the topics of this dissertation.

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

Mahaffey, C. A., M. L. Peterson, L. Roepstorff. (2012 – in review). "The effects of varying cushion depth on dynamic loading in shallow sand dirt Thoroughbred racetracks."

Mahaffey, C. A., M. L. Peterson, J. J. Thomason, C. W. McIlwraith. (2012 – to be submitted). "Dynamic testing of horseshoe designs on synthetic and dirt Thoroughbred racetrack materials."

### 1.4. References


Bogdanich, W., J. Drape, et al. (2012). Mangled Horses, Maimed Jockeys. The New York Times. New York, NY.

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

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Peterson, M. L., C. W. McIlwraith, et al. (2008). "Development of a system for the in-situ characterisation of thoroughbred horse racing track surfaces." Biosystems Engineering **101**(2): 260-269.

Peterson, M. L., R. F. Reiser II, et al. (2010). "The effect of temperature on 6 furlong times on a synthetic racing surface." Equine Veterinary Journal **42**: 351-357.

Peterson, M. M., L. Roepstorff, et al. (2011). Racing Surfaces White Paper**:** 34.

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Wilson, A. M., M. P. McGuigan, et al. (2001). "Horses damp the spring in their step." Nature **414**(6866): 895-899.

# 2. ARCHETYPES IN THOROUGHBRED DIRT RACETRACKS REGARDING TRACK DESIGN, CLAY MINERALOGY, AND CLIMATE

This chapter was published in similar content by Mahaffey, C. A., Peterson, M. M., and McIlwraith, C. W. in *Sports Engineering* 15(1): 21-27, 2012.


## 2.1. Abstract

In Thoroughbred dirt racetracks, clay content plays a critical role in moisture management and influences mechanical properties. We hypothesized that different dirt track designs developed in response to the track materials used, particularly the clay content of the material. These designs are in turn a function of the local climate, in particular the amount of rainfall and the evaporation rate. X-ray diffraction (XRD) makes it possible to determine whole rock and clay mineralogy for 26 tracks that were assigned to one of three track designs: shallow sand (SS), false base (FB), or false base with a pad (FBP). Results demonstrate that SS tracks occur in areas with the highest annual precipitation and have the lowest average clay content, whereas FBP tracks have the lowest annual precipitation and the highest average clay content. FB tracks have intermediate levels of precipitation and clay relative to other track styles. Understanding the effects of clay minerals in dirt and how different racetrack designs have evolved to handle differing levels of clay and moisture can aid in quantifying track maintenance decisions.



## 2.2. Keywords

Clay mineralogy; X-Ray diffraction (XRD); dirt racetracks; Thoroughbred racing surface

## 2.3. Abbreviations

X-ray diffraction (XRD)

Shallow Sand (SS)

False Base (FB)

False Base with a Pad (FBP)

## 2.4. Introduction

Racing surfaces have received a lot of attention with the intention to improve safety to both equine and human athletes (Thomason and Peterson 2008; Setterbo, Garcia et al. 2009; Peterson, Roepstorff et al. 2011). Performance, while being an issue which is considered extensively in the popular literature, has been the subject of limited academic study. Previous research has addressed such topics as the hoof-surface interface (Ratzlaff, Wilson et al. 2005; Setterbo, Garcia et al. 2009) and *in-situ* surface testing (Peterson and McIlwraith 2008; Peterson, McIlwraith et al. 2008). However, a single optimized solution for a "safe" track does not exist. Understanding the mechanical properties of racetrack materials offers a starting point, which in itself is a dynamic issue consisting of variables including a track's design, the materials used and how the climate influences the material properties. In dirt tracks, moisture content is perhaps the most influential variable (Pratt 1985; Ratzlaff, Hyde et al. 1997), suggesting that rainfall and evaporation may be primary climatic factors.

The composition and moisture content of a soil has a large and complex effect on the stress-strain and shear strength parameters of soil (Al-Shayea 2001). The effects are sufficiently large that simple tests that can be used *in-situ*, such as cone index, are limited in their ability to measure bulk density or cohesion because of the large influence of moisture content even in homogeneous soils (Mulqueen, Stafford et al. 1977). It is thus logical that

the particle surface chemistry, which controls the interaction of the particles with water, would be a critical factor in understanding the mechanics of a dirt racetrack. Chemistry of the surface of the particles is controlled by the mineralogy of the soil particles. Given the interaction of surfaces with water, a need exists to understand the mineralogy of the clay and other track materials, as well as the chemistry of the water to understand the particle surface interaction in the racing surface (Rosenqvist 1984). More specifically, the role of different types and quantities of clays will influence the water retention or bonding between particles and water molecules and, thus, the mechanical properties of the material (Williams, Prebble et al. 1983). For example, the polarity of clay surfaces results in water adsorption, as well as agglomeration of particles in the soil (Craig 2004). The van der Waals forces and electrostatic attractions make it very difficult to dissociate the particles even when using aggressive laboratory methods (Nettleship, Cisko et al. 1997). Thus, in general, a soil with a higher clay content results in greater cohesion of the soil than does a material with little or no clay. Soil cohesion and intergranular friction are the primary mechanisms behind the shear strength of a soil. The soil cohesion will have the strongest influence on the amount of slide of the hoof during the impact phase of the gait when vertical loading is low (Thomason and Peterson 2008). Intergranular friction will, in contrast, play a greater role during the propulsive phase of the gait when the soil has higher vertical loading (Thomason and Peterson 2008; Peterson, Roepstorff et al. 2011).

The manner in which a track handles moisture is also related to climate since heavy natural rainfall can reduce the impact of the chemistry of irrigation water resulting from dissolved minerals. The material components (specifically mineralogy and particle size distribution) are also influenced by the track design or the manner in which water moves through and is retained in the layers of the track. The three typical Thoroughbred racetrack

surface structural designs used in dirt tracks in the United States are considered in this paper. Typically, soils are characterized by way of particle size distribution and composition ratios of sand, silt and clay (Craig 2004). To characterize the finer silt and clay particles (<4 μm), the hydrometer test is the accepted standard (ASTM 2007a). The hydrometer test continues to be used as a standard in spite of the consensus that the test is not accurate for characterizing the size distribution of clay particles (Nettleship, Cisko et al. 1997; Lu, Ristow et al. 2000). This, coupled with limitations on determining specific information on clay types, renders the test poorly suited for fully characterizing racetrack material (Nettleship, Cisko et al. 1997; Lu, Ristow et al. 2000). An alternative is the semi-quantitative approach of using x-ray diffraction (XRD) to determine soil mineralogy (Moore and Reynolds Jr. 1997; Hubert, Caner et al. 2009). XRD is semi-quantitative in that mineralogical components are reported as a ratio of the sample weight. Thus, if a sub-sample of the material is biased toward one component relative to the actual material, all other components of the sample will be artificially under represented. While this method is semi-quantitative, it offers valuable information for predicting how a material will behave under defined conditions.

Using XRD, we determined the mineralogy for a total of 26 tracks representing three typical track designs described below. The existence of these three types of Thoroughbred horse racing tracks is documented in order to test the hypotheses that the track design is related to clay mineralogy and climate.

**2.5. Materials and Methods**

This study compares mineralogical and climatological data for three types of Thoroughbred dirt racetracks. A "dirt racetrack" is characterized as such if it is a granular material consisting of varying ratios of sand, silt, and clay; excludes wax, oil, or synthetic fibers, which are included in "synthetic" racetrack material; and excludes a turf grass layer.

Interviews with maintenance crews and observation of tracks and maintenance operations determined the categorization of a track's design. Three design types emerged: 1) shallow sand (SS), 2) false base (FB), and 3) false base with a pad (FBP), also referred to as the "California style" (Peterson, Thomason et al. 2010; Peterson, Roepstorff et al. 2011) (Figure 2.1.). The SS tracks have a dirt cushion of 8.9 – 11.4 cm over a hard base of cement, compacted clay or other foundation material. The cushion is harrowed daily and between races. In the FB tracks, the base and cushion consist of the same dirt material over a foundation. The base is set via repeated harrowing at the same depth so that a hardpan layer develops. Fine materials (silt and clay) are washed and worked through the cushion via rain and additional watering, to create the hardpan. This hardpan is intentionally not disturbed. The FBP track style also has a base consisting of the same material as the cushion. Additionally, FBP tracks have a semi-compacted pad which is ripped and reset at a minimum of every 1-10 days to create additional compliance between the cushion and the base also referred to as heavy maintenance (Peterson, McIlwraith et al. 2008). The effect of the ripping and tilling operation reduces the peak vertical loads measured on the surface while having a limited impact on the horizontal accelerations associated with hoof slide (Peterson and McIlwraith 2008). Thus, there are three layers in the FBP racing surface. The precise maintenance protocol is not fully documented for all FBP tracks in this study since the exact protocol has to be adapted to local materials, weather and racing conditions. The FBP style track is sometimes referred to as the California style due to its prominence in California. However, not all California style tracks are in California. This research includes both those in and out of the state of California to expand and generalize the sample population. In both the FB and FBP a sub-base layer exists at an even deeper layer more than 20 cm, which

is typically composed of decomposed granite or other stable material, which is used to level the site and ensure a solid foundation prior to installing the track materials.

Samples were collected from 9 SS tracks, 7 FB tracks, and 10 FBP tracks. Twenty-two samples were from tracks within the U.S. and Canada, and four from outside this area. Samples were bored from the cushion material for SS and FB tracks and from the cushion and pad for FBP tracks using an 82 mm diameter auger (Model 77427, Forestry Suppliers, Jackson MS USA), with the holes refilled and compacted with the surrounding material. When possible, samples were taken approximately 2 meters from the rail at the 2-furlong distance marker (400 meters). However, some samples came from other parts of the track when ¼ pole (indicating ¼ mile from the finish line) samples were not available. All samples were taken within 3 meters of the inside rail.

After material was collected and mixed, samples were sent to K/T GeoServices (Gunnison, Colorado) for X-Ray diffraction (XRD), where bulk (whole rock) and clay fraction (<4 μm) XRD were performed on each sample to characterize the mineralogy of the respective tracks. Sample preparation and profile fitting of powder diffraction patterns followed methods detailed in Bish and Reynolds (1989) and Howard and Preston (1989), respectively (see also Post and Bish 1989).

XRD sample materials were first cleared of visible non-soil contaminants, and then disaggregated in a mortar and pestle. Next, samples were split into two subsamples: one to be used for whole rock XRD mounts, and the second for clay mineral XRD mounts. Distilled water was added to the whole rock sample and the slurry was then pulverized, dried, disaggregated, and packed into a sample mold to produce the whole rock mount. The second subsample was dispersed in distilled water using a sonic probe. This suspension was centrifuged to isolate clay-size (<4 μm equivalent spherical diameter) materials, which were

vacuum deposited on nylon membrane filters to produce oriented clay mineral mounts. These were attached to glass slides and exposed to ethylene glycol vapor for approximately 12 hours. Using a Siemens D500 automated powder diffractometer, samples were analyzed samples at a scan rate of 1 degree/minute, over angular range of 5-60°, 2θ for whole rock mounts, and 2-30°, 2θ for clay mounts.

The organic content was also determined for each sample in general accordance with ASTM D2974 *Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils* (ASTM 2007b).

Racetrack local climates were characterized using high, low, and mean annual temperatures (from 1971-2000), mean annual precipitation (from 1971-2000), and mean annual wind speed (from 1930-1996). These data for tracks within the U.S. were obtained from the National Climatic Data Center (National Climatic Data Center 2011; National Climatic Data Center 2011). Climate data for the four tracks outside the U.S. came from equivalent national databases, which are excluded to maintain anonymity. The use of average annual humidity was considered, however the data were determined to be too incomplete to use for statistical purposes.

MATLAB R2009b (The Mathworks, Natick, MA, USA) was used for all statistical analyses. Mineralogical and climatological data were grouped by track type. Three tracks had multiple sets of XRD data. In these cases, we used the average for each track. The average values were then added to the track type data set so that no one track was over-represented. Statistical analyses tested for mean differences between soil mineralogy and climate indices (annual precipitation, mean annual temperatures, and mean annual wind speed) between the three track designs, as these all influence the moisture content and thus mechanical properties of the different tracks and the dynamic interaction with a horse's gait.

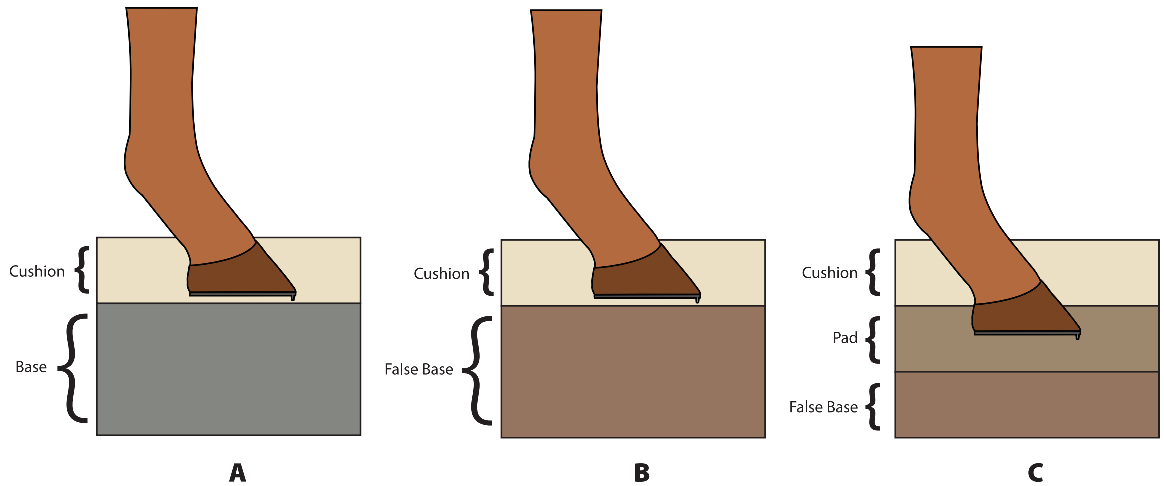


**Figure 2. 1. Track type structure**

The above images represent the vertical configuration for A) shallow sand, B) false base, and C) false base with a pad tracks. The shallow sand track (A) has a hard base with a cushion with little to no clay mixed with the sand. The false base configuration (B) has the same material in the compacted base and the cushion. The false base with pad (C) shown on the right has a partially compacted pad which is reset and maintained at intervals of one to ten days. The hoof can penetrate the pad without causing inconsistencies in the base.

**2.6. Results**

Using a boxplot, we detected outliers in two of the sample groups: one each in the SS and FB groups. Therefore, we used a Kruskal-Wallis non-parametric test to compare the three track design groups. Results yielded significant differences ($p < 0.05$) in the percentages of quartz ($p = 0.0484$), total phyllosilicates ($p = 0.0396$) (specifically illite & mica, $p = 0.0203$), organic matter ($p = 0.0109$), and mean annual precipitation ($p = 0.0034$). The two outliers were notable since they represent the two tracks included from Latin American locations. The two European surfaces included in the data set were consistent with United States and Canadian track surfaces. After removing the two outliers, an analysis of variance (ANOVA) found significant differences in quartz ($p = 0.0235$), plagioclase ($p = 0.0091$), total phyllosilicates ($p = 0.0041$), organic matter ($p = 0.0281$), and mean annual precipitation

($p = 0.0045$) between the track types (Table 2.1.). The total phyllosilicates were further differentiated into specific clay groups where the illite & mica clay component was significantly different between track types ($p = 0.0109$). There are no significant differences in any other minerals detected in the samples, or for mean annual temperatures and wind speed (Table 2.1.). All three track types had similar ratios for different types of clay within a track's clay ratio (Figure 2.2.). The Tukey-Kramer method was used for post-hoc analyses. In all cases listed above, SS and FBP tracks were significantly different in post-hoc analyses. The FB variable means were always an intermediate between the other two track styles, but not statistically different with the exception of the annual precipitation. FB tracks were significantly different than FBP tracks, and similar to SS tracks (Table 2.1.).

The FBP style tracks had more variation in clay and organic content, as indicated by the standard deviation, than the SS and FB tracks (Table 2.1.). The FB style racetrack was subjected to greater variation in the annual precipitation (Table 2.1.). Correlations between the significant mineralogical results and precipitation were also considered. Quartz and clay were negatively correlated (rho = -0.7430, $p < 0.01$). Clay was inversely proportional to precipitation (rho = -0.5043, $p = 0.0120$) (Figure 2.3.). As clay content increased, organic content did as well (rho = 0.5803, $p < 0.01$) (Figure 2.4.).

**Table 2. 1. Track type mineralogy and climate variables**

Mean and standard deviation for primary material components (%) and climatic variables. Percentages for quartz, plagioclase and clay are dependent on total mineralogy only, and are thus semi-quantitative. Organic content is the ratio of the whole, dried sample.

| | Quartz (%) mean (SD) | Plagioclase (%) mean (SD) | Clay (%) mean (SD) | Organic (%) mean (SD) | Annual precipitation (cm) mean (SD) | Annual mean temperature (°C) mean (SD) | Annual mean wind speed (m/s) mean (SD) |
|---|---|---|---|---|---|---|---|
| Shallow sand | 83.96 (12.85) *,^ | 5.81 (7.96) *,^ | 2.35 (1.02) *,^ | 0.26 (0.25) *,^ | 120.2 (28.3) *,^ | 15.9 (5.6) | 4.54 (0.79) |
| False base | 68.85 (17.64) * | 9.38 (7.78) * | 3.57 (1.53) * | 0.47 (0.35) * | 107.7 (45.2) *,‡ | 16.0 (6.4) | 4.03 (0.55) |
| False base with pad | 60.53 (18.32) *,^ | 22.98 (14.38) *,^ | 6.76 (3.60) *,^ | 2.49 (2.70) *,^ | 66.0 (25.2) *,^,‡ | 16.2 (2.3) | 3.58 (1.01) |

* ANOVA $p < 0.05$ between track types

^, ‡ Tukey–Kramer post hoc $p < 0.05$ between track types

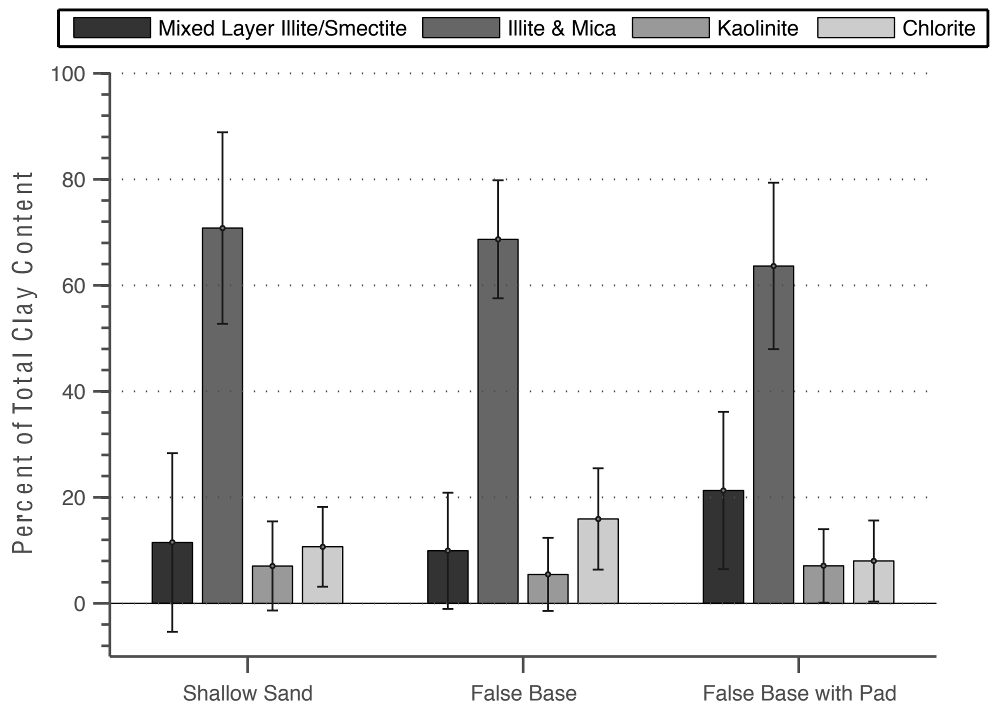


**Figure 2. 2. Track type clay ratios**

The ratios (mean ± s.d.) of different types of clays within the clay content of each track type. Although not statistically significant, we do note that the FBP style tracks have a higher ratio of a mixed layer Illite/Smectite (10%/90%), with smectite being a highly expansive clay. This is a result of a bias from two tracks. The remaining FBP tracks followed the trend demonstrated by SS and FB tracks.

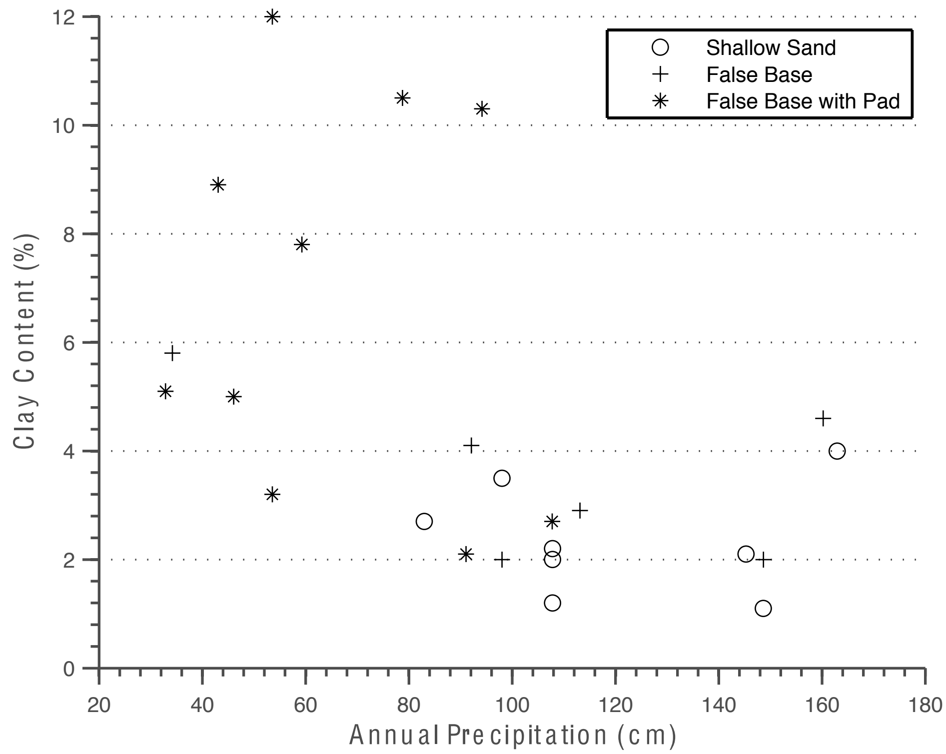


**Figure 2. 3. Annual precipitation and clay content**

Tracks in regions with higher annual precipitation typically have lower clay contents, whereas tracks in more arid regions tend towards higher clay contents. FBP tracks have greater variability in clay content.

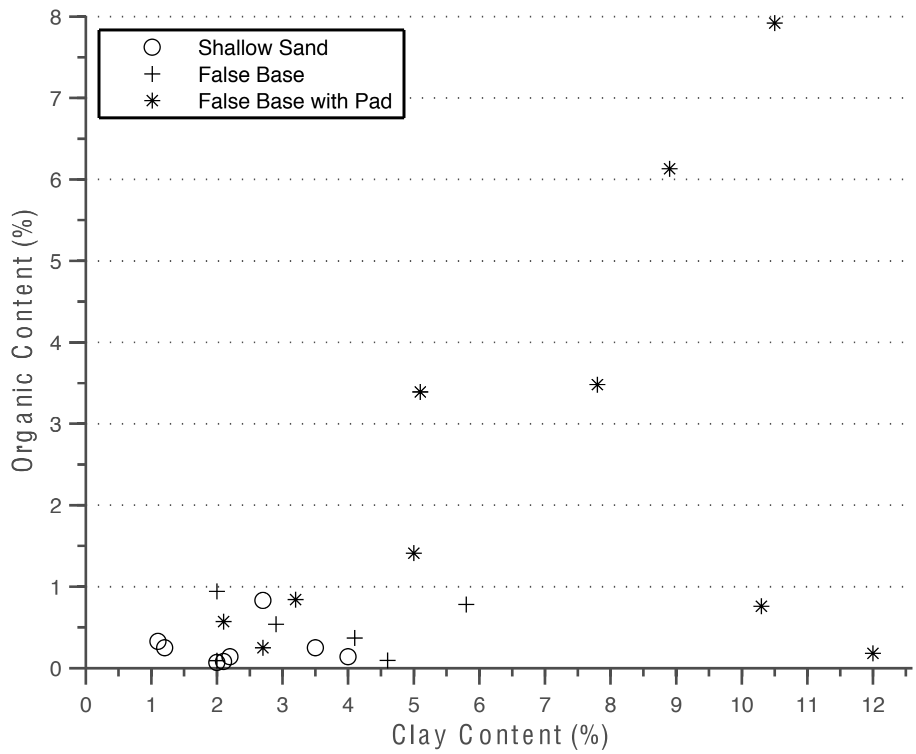


**Figure 2. 4. Clay content and organic content**

SS and FB tracks have little need for organic material due to the low clay content. FBP tracks in more arid regions, however, can use increased organic content to buffer the negative effects of using a higher clay ratio.

### 2.7. Discussion

The results indicate that the tracks which incorporate a pad (FBP tracks) tend to have higher clay contents and incorporate organic materials in the cushion. Furthermore these tracks generally are used in areas with lower rainfall. In contrast, shallow sand tracks, which use a hard base, typically have the lowest clay content, low organic content and are used in areas with much higher annual rainfall. The false base tracks represent an intermediate condition for both clay content and rainfall, although they typically have low organic content like the shallow sand tracks.

It is quite probable that these designs have developed in response to the local climate in an effort to reduce injuries to horses and through an attempt to respond to the needs of the horse trainers by the track superintendents. While extensive historical data would be required to authenticate the evolution of these designs, the creation of a culture of track design in response to climate makes sense in the context of the extensive heuristic knowledge of injuries that exists for everyone working at the racetrack. Most specifically, the same people who make decisions regarding the maintenance and design of the racetrack are almost always responsible for operating the horse ambulance. This linkage ensures that the track superintendent is aware of at least the most acute injuries experienced at the racetrack.

The results support this line of reasoning. For example, a sandy soil is useful in allowing for fast and easy drainage after a heavy rain and would therefore be more appropriate in regions with higher rainfall. Water can more easily flow through sand with less clay primarily due to greater pore size. In theory, the water can then drain along the hard base and off the track assuming a consistent grade and no other obstacles to the flow of water. Tracks with this design are at risk of losing fine particles (typically silt as there is little clay) if the water flows too quickly across the track. This design would work well in areas

with high rainfall and high humidity. Due to the high humidity, large quantities of clay are unnecessary because there is sufficient moisture to maintain appropriate shear strength. In fact a higher clay ratio would likely be a hindrance if it restricted drainage.

Conversely, the FBP style tracks require higher amounts of clay to achieve the necessary shear strength within the possible moisture limits of the regions where these tracks occur. By definition, soil shear strength increases with inter-particle cohesion and intergranular stress. Guisasola *et al.* (2010) illustrate this relationship in turf sports fields. As mentioned above, clay increases shear strength in soils with lower moisture content by increasing soil cohesion (Spoor and Godwin 1979; Al-Shayea 2001). However, increased clay content also places the surface at risk of getting too hard via compaction with repeated wetting and drying (Awadhwal and Thierstein 1985; Al-Shayea 2001). Clay being the finest grain-size (<4 μm) in a soil particle size profile fills gaps within the soil and acts cohesively with the larger-sized particles, such as sand. Over time, the finer particles move down through the vertical profile of the harrowed cushion leading to a heterogeneous distribution in the absence of intervention by way of working the surface sufficiently to redistribute the finer grains. This process of clay particles working down in the track results in the formation of a hardpan. It is assumed that horses that experience a higher impact when running on a hard surface may be at risk for increased hard tissue injuries (Thomason and Peterson 2008; Setterbo, Garcia et al. 2009). While this hypothesis has not been fully tested, some characteristics of the racetrack have been associated with higher injury rates which could be reduced by redesigning the track (Oikawa, Ueda et al. 1994).

One possibility to prevent a track from getting too hard, may be for maintenance crews to rip and till an intermediate layer – the pad – on a regular basis, as seen in the FBP style racetracks. This breaks up hard formations resulting from the clay, while gaining the

necessary shear strength at lower moisture levels with the clay. Additionally, this allows for more forgiveness for hoof penetration. In the SS and FB tracks, too much hoof penetration leads to an inconsistent base (or false base). Therefore, it is likely that the culture of people working at the tracks implemented an action, maintaining an intermediate pad, to maintain a consistent base without having a too-deep cushion. This compromise is an adaptation to weather and is generally driven by a need to protect the safety of horses and riders.

The false base style is an intermediate design typically with less clay than in the FBP style tracks. The pad is not necessary as there is not as much clay in the cushion and base layers, and less risk of the surface getting too hard when it does dry out.

FBP tracks have more variance in clay content when compared to the other two track styles, suggesting that historically tracks used local materials independent of an awareness of or interest in clay content, or that the optimal clay content may be hard to control and may also suffer from the availability of adequate assessment tools. What is implied is that the potential exists for a quantitative strategy to be used for setting up a track with higher clay content, thus increased shear strength at lower moisture levels that ideally is not too hard when the pad is maintained. The effect of surfaces on the forces experienced by the horse has been considered for comparisons of types of surfaces such as turf, synthetic and dirt (Setterbo, Garcia et al. 2009). However, the significant differences that are evident in soils research suggest that the effects of types of soils may be just as significant.

One way to handle the effects of using different ratios of clay is to add organic content to the track material (Hamza and Anderson 2005). Organic matter is more of a second-tier effect in that the addition of it on a track is a response to increased clay, which we have found to be correlated to annual precipitation. Organic content is often added to high-clay materials in order to reduce compaction and stabilize soil structure (Hamza and

Anderson 2005), and it is a sufficiently common additive to horse racing tracks that commercial vendors of the products have emerged to formulate these materials for the specific market (i.e. Stabilizer, Stabilizer Solutions, Phoenix, AZ, USA). It is another area in which tracks can manipulate the mechanical properties of the dirt in a manner appropriate to the climate. As such, it is not surprising that organic content is significantly correlated to clay content.

These results suggest the recognition by track designers and/or track managers of needing to address shear strength and moisture content for tracks in different climates. This exercise aims to optimize these variables through consideration for a track's climate, the surface material and the track design. Traditionally, the problem has not been discussed in quantifiable terms increasing the risk of inappropriate design decisions when climatic demands are not appropriately assessed.

Two factors that are not addressed in this paper are those of track watering and evaporation rates. These are two critical factors, that when combined with local weather data, can offer a complete array of quantifiable information relevant to track material selection. Additionally, maintenance records regarding surface disruption (i.e. harrowing) will influence evaporation and moisture content of the soil (Sillon, Richard et al. 2003). These can then also be assessed along with epidemiological data on horse injuries to optimize track safety.

### 2.8. Acknowledgements

XRD samples were separated at the Racing Surfaces Testing Laboratory with analysis and surface sample preparation by James P. Talbot, K/T GeoServices, Inc. Funding was provided by the Grayson-Jockey Club Research Foundation, the founding sponsors of the

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# 3. THE EFFECTS OF VARYING CUSHION DEPTH ON DYNAMIC LOADING IN SHALLOW SAND DIRT THOROUGHBRED RACETRACKS

This chapter is currently under review in similar content by Mahaffey, C. A., Peterson, M. L., and Roepstorff, L.

## 3.1. Abstract

Surface consistency is an important factor for the safety of Thoroughbred racing surfaces. Factors that influence the consistency in dirt tracks include homogeneity of surface material composition, moisture content, and cushion depth. This paper addresses the influence of cushion depth on the dynamic load and accelerations experienced by the horse at a range of moisture levels typical to operating conditions (14%, 16%, and 18% gravimetric for the material tested in this work), and surface maintenance conditions (sealed and harrowed). A biomechanical hoof tester designed to simulate the forelimb impact of a galloping Thoroughbred horse was repeatedly dropped on five different surface conditions, each at two cushion depths (10 cm and 15 cm). The difference of 5 cm, a depth range often found within a single track had a statistically significant effect on the peak load and the secondary phase loading rate experienced by a horse, particularly under the outlying moisture content conditions (relatively dry or moisture saturated). The tested material behaved more similarly at the two cushion depths under moisture conditions at which maximum dry density occurred (16%). Peak loads and loading rates were significantly different between the two depths for harrowed, 14% moisture conditions, and sealed, 18% moisture conditions. These cushion depths and surface material moisture levels are within normal operating conditions for Thoroughbred race meets on shallow sand tracks and therefore may influence the development of musculoskeletal disease and the safety of horses and jockeys.

### 3.2. Keywords

Thoroughbred racing surface; dirt racetrack; cushion; dynamic load

### 3.3. Highlights

- Cushion depth and moisture content affect dynamic loading experienced by horses.
- Cushion depth ranges common to shallow sand tracks affect peak load and load rate.
- Cushion depth uniformity can increase mechanics consistency and potentially safety.

### 3.4. Abbreviations

Sealed surface, 14wt% moisture content (S14)

Harrowed surface, 14wt% moisture content (H14)

Sealed surface, 16wt% moisture content (S16)

Harrowed surface, 16wt% moisture content (H16)

Sealed surface, 18wt% moisture content (S18)

### 3.5. Introduction

Surfaces in Thoroughbred horse racing are one of few variables consistently experienced by all horses in an event. Current thinking in the industry follows that a consistent track (material composition and performance indicators such as shear strength) is a safer track (Kai, Takahashi et al. 1999). This is based on the assumption that although horses may adapt to different surface dynamics by modifying leg stiffness, as seen in humans (Ferris and Farley 1997; Kerdok, Biewener et al. 2002), stride-to-stride modifications in muscle stiffness at a gallop may not occur fast enough. A horse's misstep not only endangers the animal, but also its rider and the other horses and jockeys on the track due to

the high speeds and close proximities of horses during a race. Thus variation within a track could be a potential safety risk to both the horse and jockey during a race.

One factor influencing track variation is cushion depth. All three types of Thoroughbred racetracks - shallow sand, false base and false base with a pad (Peterson, Thomason et al. 2010; Mahaffey, Peterson et al. 2012) - have a topmost cushion layer. This upper layer of the granular structure absorbs the majority of the impact force. Soil composition and moisture content affect the range, or depth, over which the force is distributed (Soehne 1958). Therefore, if a cushion is not sufficiently deep to fully absorb the impact on a given soil type and moisture content, the hoof loading will be influenced by the harder track base (or false base), resulting in greater peak loads and load rates, and a faster track. This effect has been described using drop hammer data (Pratt 1985). Also, a simplified model of a trotting horse has demonstrated differences in dynamic properties due to cushion depth (Setterbo, Yamaguchi et al. 2011). However, this work does not account for racing speeds at a gallop, or the secondary impact caused by a slide and stop of the hoof (Johnston and Back 2006; Peterson, Roepstorff et al. 2011).

Shallow sand tracks may be most susceptible to this phenomenon based on the design conditions. Shallow sand tracks typically have a hard, permanent base with a dirt cushion with low clay and silt content (Mahaffey, Peterson et al. 2012). The hard base can be composed of limestone screenings, soil cemented sand, compacted clay or even concrete. The sand cushion is typically, although not always consistently, 10-15 cm deep and the toe of the hoof print during propulsion and breakover (described in Chapter 1) is often nearly in contact with the base. This suggests that the full impact is not entirely absorbed by the cushion. Due to the low clay and silt content in this type of track, a higher moisture content relative to materials used in other dirt racetrack designs (i.e. False Base and False Base with a

Pad described in Chapter 2) is required to maintain sufficient shear strength of the sand over the hard base during different phases of the gait. This is consistent with the common use of this track design in areas with high rainfall (Mahaffey, Peterson et al. 2012). Lower moisture contents of the material used on these tracks results in too-low shear strengths during loading of the hoof on primary and secondary impact (described in Chapter 1) resulting in the hoof sliding down to and across the hard base.

This research tests the effect of varying cushion depth on the loading of a horse hoof. Using a biomechanical hoof tester (Peterson, McIlwraith et al. 2008), we quantified the dynamic load and accelerations resulting from a standardized impact representative of a gallop hoof-strike on varying cushion depths. We hypothesized that the variation in dynamic loading between a cushion depth of 10 cm and 15 cm would be significantly different at different moisture contents that are typical for shallow sand tracks.

### 3.6. Materials and Methods

This research compares dynamic loads for different cushion depths using a biomechanical hoof tester developed by Peterson *et al.* (2008) and used in other work including onsite testing of track maintenance (Peterson and McIlwraith 2008). The design specifications of this machine result in an impact event that simulates the impact phase of the front foot for a Thoroughbred at a gallop. The biomechanical hoof was dropped on a 2 meter square plot of racetrack material with predefined boundary conditions in order to quantify the effect of varying track depths for harrowed and sealed surfaces at three different moisture contents. Visits to 60 Thoroughbred racetracks found that typical cushion depths in shallow sand tracks, as defined by Mahaffey et al. (2012), ranged from 10-15 cm with a harrowed depth of 6-10 cm. This range in depth is found not only between tracks, but can also occur within any one racetrack and in some cases can exceed 20 cm (Figure 3.1.),

including the track from which the sample for this experiment was collected. This range dictated the selection of tested cushion depths of 10 cm and 15 cm.

The track material used in this study was collected from a dirt stockpile which was going to be used for renovation of a surface at a Thoroughbred racetrack in the southern US and dried in general accordance to ASTM D 2216 (ASTM 2005). Prior to the biomechanical hoof tester experiment described below, samples were characterized using the following standard lab tests: bulk density (ASTM D698; (ASTM 2007b)), particle-size distribution (ASTM D422 (ASTM 2007a)), and consolidated undrained triaxial compression tests (ASTM D4767 *Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils* (ASTM 2004)), modified to be drained to better approximate the behavior of the material *in situ* for a racetrack (Bridge, Peterson et al. 2010).

Dried samples were rehydrated with distilled water to three moisture contents (14%, 16% and 18% by weight) representative of typical conditions on the track from which the track material sample was obtained, where approximately 16wt% was the mean moisture level for track operations. After the sample was dried and rehydrated to one of the three assigned moisture contents, it was sealed and left to settle overnight.

The following day, the material was packed into a latex film-lined, 30.5 cm diameter mold to a prescribed height of 10 cm or 15 cm following the protocol detailed in the Appendix. The mold was centered in a 2 $m^2$, 20 cm deep box constructed on a base composed of approximately 6 cm of compacted gravel and asphalt over a clay foundation. Low-dust silica sand at 13% volumetric moisture surrounded the sample mold for support and to provide a consistent lateral boundary condition (Figure 3.2.). A 1.27mm thick latex film (Shore A durometer = 40, McMaster-Carr, Santa Fe Springs, CA, USA) prevented contamination of the sample with the surrounding silica sand. The constraining effect of the

latex film was minimal since the modulus of the material is less than the expected value of the compacted track material. This assumption was tested and confirmed by comparing the dynamic load of the biomechanical hoof tester on the silica sand with and without the latex film (see Appendix). Within the mold, the sample material was tamped 18 times with a 5.7 kg mass in 2 or 3 lifts of 5 cm of compacted material for a total of 10 or 15 cm depths, respectively. This resulted in a total compaction effort of 55 kJ $m^{-3}$. Following compaction, the surface was either left untouched to simulate a sealed track, or raked with six strokes of a garden rake with three 7.6 cm tines (2 strokes in opposite directions over 3 paths to cover the entire surface) to represent the softer cushion of a harrowed surface. The 18wt% sample was too wet to maintain a "harrowed" cushion and therefore excluded from "harrowed" testing. At this moisture content, a track surface would normally remain sealed in use. The resulting variable combinations were as follow:

14wt% moisture content, sealed (S14)

14wt% moisture content, harrowed (H14)

16wt% moisture content, sealed (S16)

16wt% moisture content, harrowed (H16)

18wt% moisture content, sealed (S18).

The biomechanical hoof was dropped once per prepared sample. Post-impact, the sample was removed, remixed, and replaced to ensure homogenous particle size distribution between each trial per set of independent variables. This was repeated 10 times per variable set, with the exception of the H14 and S14 groups, which had eight and seven repetitions, respectively. The biomechanical hoof was equipped with a 3-axis accelerometer and a single-axis load cell aligned with the vertical axis with respect to the hoof (Peterson, McIlwraith et al. 2008).

Filtering was performed on the load cell data. Each signal was Fourier transformed to verify the frequency band of interest in the data. A relatively large peak at the high frequencies for the transformed data resulted from noise and a low-pass finite impulse response filter was then used to remove noise. Acceleration data were not filtered. In addition to the vertical load and 3-axes of acceleration, displacement was calculated via double integration of the vertical acceleration. This was compared to the displacement measured by a string potentiometer. Reliability issues with the string potentiometer precluded use of duplicate data for all of the trials. Based on a comparison, the double integration data provided a good estimate of the compaction depth during the peak loading where the last peak of the double integrated vertical accelerations corresponds with the maximum compaction depth determined by the string potentiometer. However, the potentiometer data indicate that displacements early in the loading were not fully captured by the vertical accelerometer signal. Therefore, we limit these analyses to time rates, which closely match the available displacement data.

A three-way analysis of variance (ANOVA) compared peak load, primary and secondary peak load rates, and maximum vertical and horizontal accelerations for the three-tiers of independent variables (two cushion depths at three moisture contents under sealed or harrowed conditions). All of the signal processing and statistical analyses were performed using Matlab R2009b (The Mathworks, Natick, MA, USA).

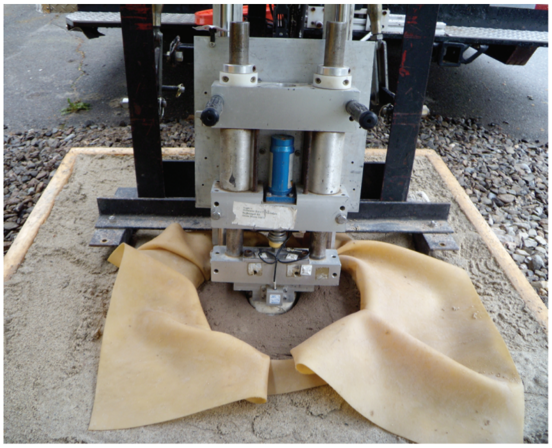
A

B

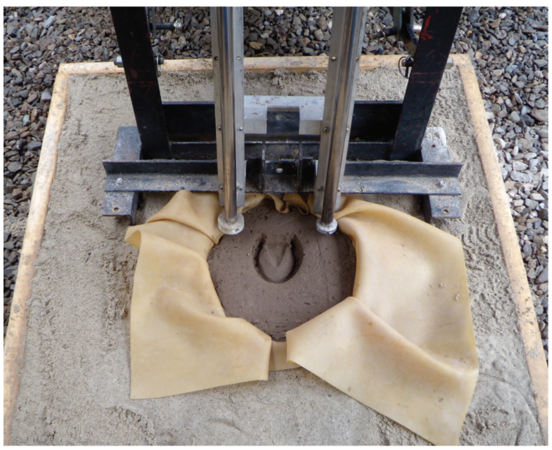
C

**Figure 3. 1. Cushion depth examples**

(A, B) An 82mm diameter auger (Model 77427, Forestry Suppliers, Jackson MS USA) demonstrates the difference in cushion depth on a single Thoroughbred dirt racetrack (A: 25-cm depth, B: 10-cm depth). (C) Training and races will still take place on saturated surfaces after sealing, or "floating," the surface to squeeze out water as well as minimize additional permeation.



A



B

**Figure 3. 2. Biomechanical hoof tester with sample box**

(A) The biomechanical hoof tester was dropped once per sample preparation (in a "sealed" state in the above example). The latex film prevented contamination of the dirt sample with the surrounding silica sand. (B) The impact surface is a racing shoe screwed onto a mold from a Thoroughbred horse, resulting in the imprint seen in the second image above.

### 3.7. Results & Discussion

Following standard sieve and hydrometer protocols, the material was determined to consist of approximately 81% sand, 13% silt and 6% clay. The clay content determined via hydrometer testing was higher than expected for the material; therefore we validated results via X-ray diffraction (XRD) completed by K/T GeoServices (Gunnison, Colorado). XRD determined the clay content to be 3.4%, which is typical for most other shallow sand racetracks (Mahaffey, Peterson et al. 2012). The discrepancy between hydrometer and XRD testing is common and suggests that small, angular particles with mineralogy other than phyllosilicates were behaving like clay as they fell through the water column for the hydrometer test. The highest ratio of material is retained in sieve number 100 with an intermediate particle size of 0.152-0.251 mm. XRD indicates the majority of this material is quartz (77.3%).

Dry density testing indicated that 16.5wt% is the moisture content at which maximum material density occurs for this particular material. Thus, the mean moisture content at which the track operates, is approximately the moisture content for maximum compaction for a given compaction force on this material. It also follows that the selected 14wt% moisture content for this study represents relatively dry conditions for the track material, and the 18wt% moisture content represents a material in a wet, or "sloppy" track as it is known in the horse racing industry. The wet condition indicates that the water overfills the soil's pore space. Consequently, the material was water saturated at 18wt% moisture so that it would not maintain a harrowed cushion. The saturated sand material at the higher moisture content flowed to fill in the harrow tooth pattern.

The dry density data are supported by the triaxial shear strength results. In a drained triaxial test at low confining pressures (Bridge, Peterson et al. 2010) the greatest particle

cohesion occurs at 16% forming moisture (Figure 3.3.), indicating that maximum capillary pressure occurs at or near this moisture. The maximum shear strength at 14% forming moisture indicates that when compacted, the sand and silt particles more easily lock into a position without the lubricating effect of additional water. Finally, the lowest shear strength is at 18wt% moisture content, at which the material was saturated. The low shear strength at this moisture content is expected due to water saturation between particles sufficient for increased pore space and hydrodynamic lubrication, thereby reducing the load necessary for failure. While the compaction conditions for the dry density and triaxial shear strength testing do not match the compaction of a track's surface, these data do offer information on the behavior of the track material during compaction via the hoof impact under different moisture conditions. The varying water contents relate to pore space and thus performance under dynamic loading. Water content, which is easily measured for tracks, is thereby used as an accessible proxy to describe strength at different dry densities.

A three-way ANOVA of the biomechanical hoof tester data with independent variables of surface treatment, moisture content, and cushion depth yielded significant results ($p \leq 0.05$) between cushion depths for peak load, primary and secondary maximum load rates, and maximum vertical and horizontal accelerations (Table 3.1.). Moisture content and surface treatment also significantly affected these variables with the exception of the secondary maximum load rate, for which moisture content did not have a statistically significant effect.

The initial slopes, or primary loading rate, of the loading curves (Figure 3.4.) are similar for the paired cushion depths in each variable set with the exception of the S14 and S16. The difference in the later tests suggests that density achieved at different moisture levels and surface treatment are primary variables for the initial loading rate, and likely

stiffness, of a given material. The higher primary loading rate in the shallow cushion depth for the S14 and S16 is due to dynamic effects from the hard base. In the harrowed samples and saturated sample (S18), low compaction of loose dirt would normalize the early loading rate, thus making it more dependent on the surface treatment. However, in comparing the soil compression behavior calculated from the double integration of the vertical acceleration with string potentiometer data, we observe that the initial compression during loading is underestimated by the double integration and that differences in the full behavior of the stiffness for varying cushion depths cannot be ruled out. The available string potentiometer data were insufficient to statistically evaluate this effect.

After the primary loading in the H14 and H16 trials, a secondary load slope occurs. The primary loading corresponds to compression of the track material, which is why the drier sealed samples (S14 and S16) have a different loading pattern. This can be observed in the vertical accelerations (Figure 3.5.). After the initial material compression, the biomechanical hoof is able to slide as does a galloping horse (Thomason and Peterson 2008), which is indicated by the first horizontal acceleration peak (Figure 3.6.). As the hoof slides, it continues to compress material in the vertical direction through the primary loading. The maximum horizontal acceleration marks the beginning of the secondary loading phase with the cessation of the slide and the continuation of vertical loading. The similarities in the maximum forward accelerations indicate that the forward acceleration is more heavily influenced by the moisture content affecting the material (dry) density than cushion depth. This effect is less evident in the higher dry density (achieved at low moisture contents), sealed samples, because the more compacted material has a greater shear strength due to interlocking particles. There is naturally more slip in the harrowed samples; therefore, there is less influence of the cushion depth.

During this phase, the secondary load rate, prior to the peak load, is significantly lower in the 15 cm cushion than the 10 cm cushion (Table 3.1., Figure 3.4.) for the H14. This suggests that after the initial compression under the front hoof, the effects of the stiffer base layer are more prominent in shallower areas of a shallow sand track. The S18 trials demonstrate a similar effect, but the primary load rate takes place only briefly with water displacement. This is followed by a brief rebound and then loading of the dirt material (secondary loading). The secondary load rate is significantly lower in the deeper cushion depth (15 cm).

Below the maximum dry density moisture level (achieved at 16.5wt%), where shear strength is the highest, the sealed samples at both depths (S14 and S16) respond with two load peaks (indicating a bounce), and higher loading rates compared to all other variable combinations (Table 3.1., Figure 3.4.). The maximum load was highest in the S14, followed by the S16. This result is not surprising as the material was compact and had little water acting as a lubricant. The compacted cushion material behaved similar to a compacted base material; therefore there was little difference in loading between the 10 cm and 15 cm depths. However, as this material is accurately perceived to be a hard track by track employees, Thoroughbred races are unlikely to be run on sealed, compacted conditions below saturated moisture conditions. This is the reason that track managers harrow the cushion. These results clearly indicate the critical nature of this decision on the track hardness. For the case of a drying track, the decision to harrow may be made in the middle of a race day. It is, however, important not to assume that a softer track is a safer track. Lower loading is not necessarily better. For example, studies on beach running highlight increased fatigue and injuries are associated with running on softer, dry sand versus wet, compacted sand (Barrett, Neal et al. 1998).

The different loading rates that occur for varying cushion depths are relevant not only to assumed gait consistency, but also bone remodeling. In reviews of bone adaptation research, dynamic loading has a clear effect on bone mass and remodeling as demonstrated through both modeling and *in-vivo* research (Ehrlich and Lanyon 2002; Torcasio, van Lenthe et al. 2008). Additionally, previous work with human running mass-spring models suggests that a surface could be optimized to improve speed and reduce injuries with a surface that matches a runner's leg stiffness, and has a relatively high horizontal stiffness, effectively maximizing energy return and minimizing fatigue (McMahon and Greene 1979). Further, an equine forelimb model demonstrated that surface stiffness would have a significant effect on the dynamic loading of a horse's limb (Reiser II, Peterson et al. 2000). Similar models adapted for equine gait and anatomy, as well as an improved understanding of dynamic limb stiffness in horses and optimized dynamic loading for training and racing Thoroughbreds could offer insight for improved equine health and therefore safer racing conditions.

The fact that several shallow sand tracks operate at a moisture content at which maximum dry density occurs, which minimizes the dynamic load variation due to cushion depth, suggests an intuitive or learned pattern by track managers for improved racing and safety at these conditions. However, this strategy is lost when weather patterns cause a track to operate outside preferred conditions. Further, inexperienced managers may not understand or recognize the effects of seemingly small changes in operation conditions.

**Table 3. 1. Cushion depth results**

Mean (s.d.) for peak load, primary and secondary peak load rates, and maximum vertical and horizontal accelerations. The p-value indicates statistical significance for cushion depth in a 3-way ANOVA with surface treatment and moisture content (both of which were also statistically significant for all variables with the exception of moisture content for secondary peak load rate).

| Moisture content (gravimetric) | | 14% | | 16% | | 18% |
|---|---|---|---|---|---|---|
| Surface treatment | | Harrowed | Sealed | Harrowed | Sealed | Sealed |
| Peak load (kN) | 10cm | 5.40 (0.23) | 7.73 (0.50) | 5.02 (0.18) | 5.93 (0.36) | 5.11 (0.14) |
| | 15cm | 4.27 (0.31) | 7.18 (0.41) | 4.28 (0.30) | 5.64 (0.39) | 3.77 (0.20) |
| | p < 0.05 | * | * | * | | * |
| Primary peak load rate (kN/ms) | 10cm | 1.27 (0.13) | 5.32 (0.57) | 0.70 (0.10) | 3.53 (0.39) | 0.74 (0.09) |
| | 15cm | 1.14 (0.28) | 4.74 (0.23) | 0.70 (0.05) | 2.62 (0.73) | 0.42 (0.11) |
| | p < 0.05 | | * | | * | |
| Secondary peak load rate (kN/ms) | 10cm | 0.55 (0.08) | 0.41 (0.07) | 0.55 (0.06) | 0.43 (0.11) | 0.46 (0.07) |
| | 15cm | 0.39 (0.12) | 0.33 (0.03) | 0.42 (0.09) | 0.29 (0.12) | 0.30 (0.12) |
| | p < 0.05 | * | | | | * |
| Max. vertical acceleration (g) | 10cm | 38.57 (1.84) | 74.54 (12.69) | 35.10 (2.41) | 61.08 (16.44) | 27.35 (4.42) |
| | 15cm | 31.92 (3.17) | 65.71 (8.90) | 30.44 (2.77) | 54.90 (18.77) | 19.22 (3.92) |
| | p < 0.05 | | | | | |
| Max. horizontal acceleration (g) | 10cm | 12.49 (2.00) | 29.35 (6.36) | 7.87 (1.72) | 48.59 (14.29) | 11.23 (1.14) |
| | 15cm | 13.13 (2.50) | 32.84 (9.75) | 7.91 (1.39) | 30.53 (13.25) | 9.38 (2.20) |
| | p = 0.05 | | | | * | |

* Cushion depth post-hoc (Tukey-Kramer) statistical significance (p<0.05) for the surface treatment and moisture content variable set.

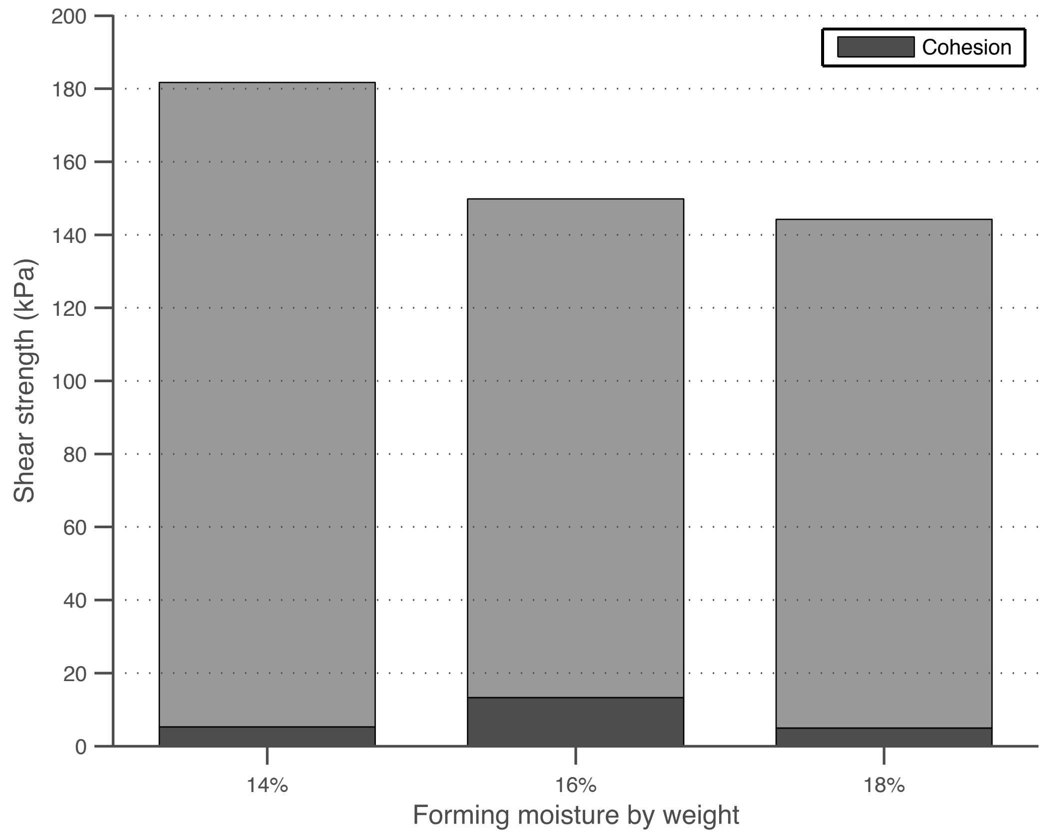



**Figure 3. 3. Shear strength of dirt used in cushion depth experiment**

Drained consolidated triaxial results at three forming moistures. The maximum dry density occurred at approximately 16% forming moisture, corresponding to the maximum cohesion at 103kPa confining pressure (following methods to test Thoroughbred racetrack materials (Bridge, Peterson et al. 2010)). The total shear strength of the material is highest at 14% gravimetric moisture.

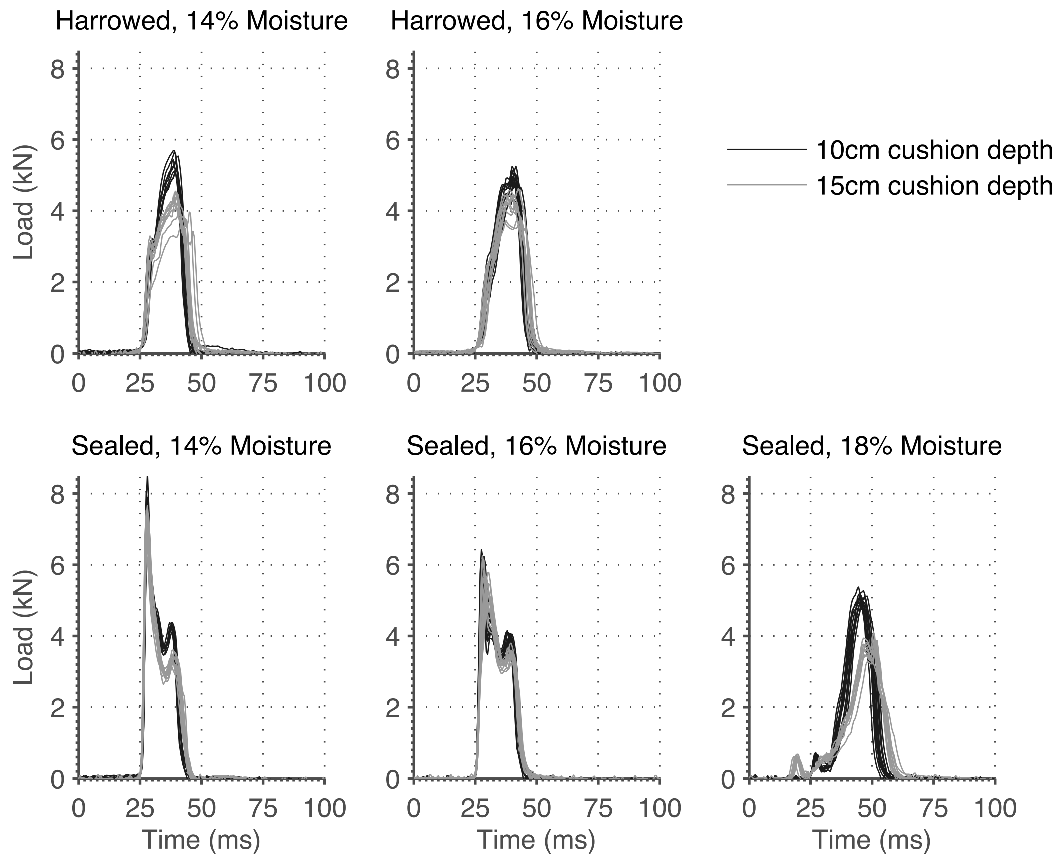



**Figure 3. 4. Cushion depth loads**

Peak loads are consistently higher for the shallow cushion depth (10 cm), with the exception of the S16 treatment. The slopes of the lines represent the loading rate. Primary peak load rates are calculated from the initial loading phase. Secondary load rates are also included.

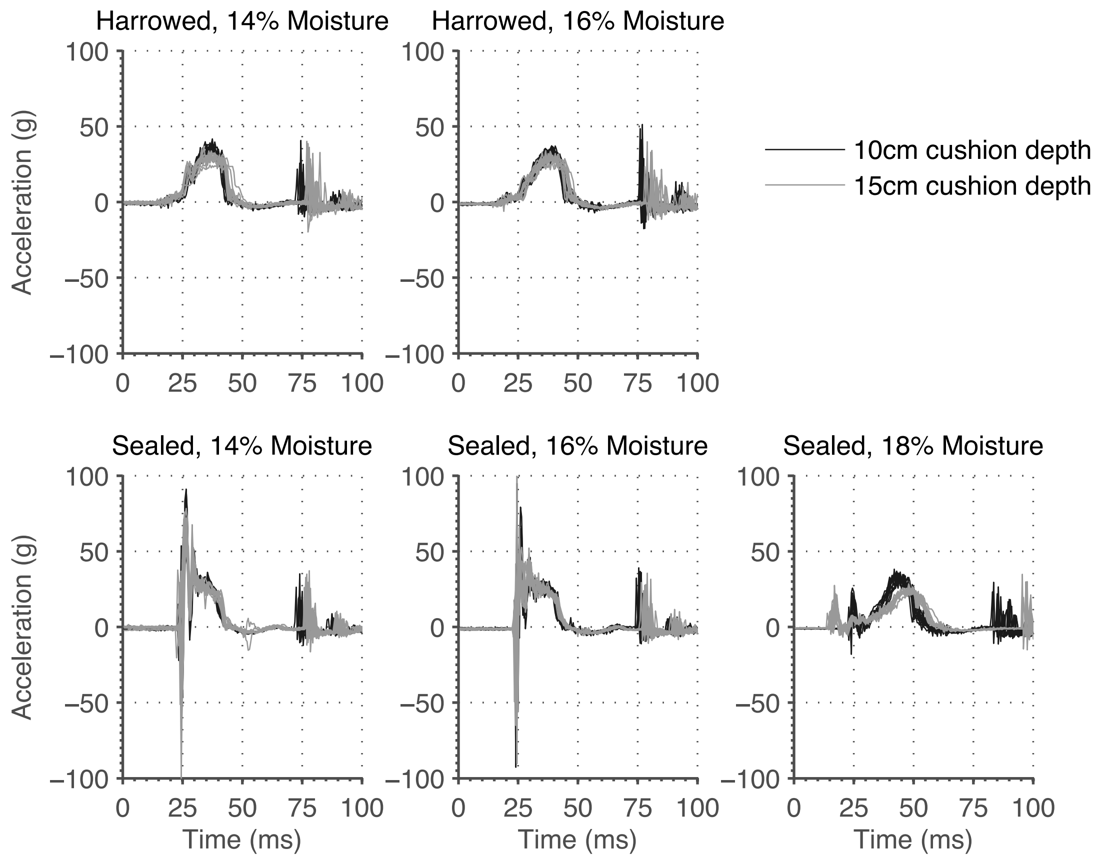



**Figure 3. 5. Cushion depth vertical accelerations**

Vertical accelerations match the general trends determined by the single-axis load cell. The last peaks in the signal depicted represent the rebound. The drops on the shallow cushion depth (10 cm) rebounded faster than on the deeper cushion depth (15 cm).

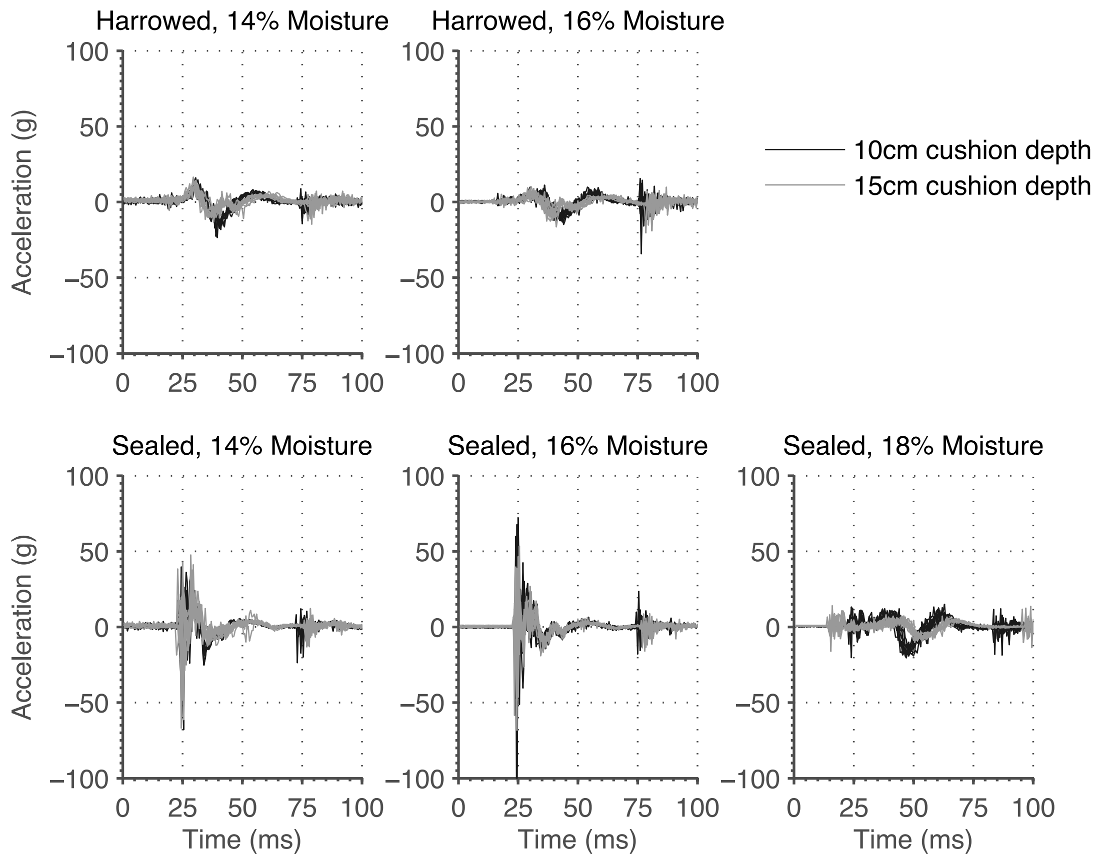



**Figure 3. 6. Cushion depth horizontal accelerations**

Horizontal accelerations are more similar between the two tested depths for each variable set than the vertical accelerations. However, the peak horizontal acceleration in the 10 cm S16 is significantly greater than in the 15 cm S16 suggesting a reduction in slide due to the base material.

### 3.8. Conclusions

The performance measures considered in this work indicate that track cushion variation is most significant at the extremes of typical performance moisture conditions in shallow sand tracks. For tracks that operate outside of the moisture content at which maximum dry density occurs, consistency in cushion depth may be even more important to maintaining consistent mechanical track surface conditions.

It is important to harrow tracks once the moisture content drops to or below that at which the maximum dry density occurs for the material described in this paper. If a track remains sealed at a relatively low moisture content, the load rate, the peak load, and maximum vertical and horizontal accelerations significantly increase. This could result to an increase in hard tissue injuries.

The shallower cushion depth (10 cm) demonstrates more consistency between harrowed material at lower moisture contents and the sealed high moisture content. While this consistency could be a benefit to the safety of racing, it also suggests that the base is having a large affect on the loading of the hoof and the peak load and load rate will be higher, which may be associated with increased hard tissue injuries.

### 3.9. Acknowledgements

XRD samples were separated at the Racing Surfaces Testing Laboratory with analysis and surface sample preparation by James P. Talbot, K/T GeoServices, Inc. Funding was provided by the Grayson-Jockey Club Research Foundation, the founding sponsors of the Racing Surfaces Testing Laboratory and the Churchill Downs Incorporated Safety from Start to Finish Initiative.

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# 4. DYNAMIC TESTING OF HORSESHOE DESIGNS ON SYNTHETIC AND DIRT THOROUGHBRED RACETRACK MATERIALS

This chapter is currently in preparation for submission in similar content by Mahaffey, C. A., Peterson, M. L., Thomason, J. J., and McIlwraith, C. W.


## 4.1. Abstract

Different horseshoe designs have been developed in an attempt to optimize footing for equine athletes. The performance of these horseshoes is dependent on the surface and the gait associated with the event. The objective of this work is to quantify the dynamic loading for three aluminum racing shoe designs. A flat racing plate, a serrated V-grip, and a shoe with a 6 mm toe grab and 10 mm heel calks were tested on two Thoroughbred racetrack surface materials using a biomechanical hoof tester equipped with a triaxial load cell. Three shoes were tested on a synthetic and a dirt surface at typical operating conditions (temperature and moisture content) for the respective material samples. Samples were compacted into a latex-lined mold and surrounded by low-dust silica sand for representative boundary conditions. Using this methodology, the dynamics of different shoes are characterized for a forelimb impact of a galloping horse on these surface materials. Maximum load and loading rate were not significantly different between shoe types with the exception of loading rate for the V-Grip shoe on the synthetic surface. All other statistical significance was related to the surface, and shoe type did not have an effect. However, uneven localized loading of the shoe attachment points with the hoof may still have important differences on the stresses and strains experienced by the horse. Therefore, while shoeing does not have a significant effect on the impact with the surface in most cases, it may still have an effect on the performance and safety of the horse.

### 4.2. Keywords

Horseshoe; Equine sports; Surface material; Dynamic loading

### 4.3. Introduction

Safety concerns in horse racing are often focused on surfaces and other variables at the track surface-hoof interface (Peterson, Roepstorff et al. 2011). One way that trainers can attempt to control the surface-hoof interface is to use different kinds of horseshoes for various track surfaces and conditions. Accordingly, different horseshoe designs have been developed in an attempt to optimize footing for equine athletes. For example, toe grabs and heel calks at varying heights are used in order to manipulate traction. Other shoes are also available such as the V-Grip shoe available through Victory Racing Plates (Baltimore, Maryland, USA), intended to affect slide and traction in a horse's gait. The performance of these horseshoes is dependent on the surface and the gait associated with the event.

Research behind these claims is limited, but some work supports the feasibility of a horseshoe design affecting the damping (Benoit, Barrey et al. 1993) and loading experienced by the horse, primarily with respect to treating injuries and gait maladaptation (Scheffer and Back 2001). Other studies warn that toe grabs in particular may increase the risk of injury, although some of the statistical support behind these claims is limited (Hill, Stover et al. 2001; Gross, Stover et al. 2004; Hernandez, Scollay et al. 2005; Anthenill, Stover et al. 2007). As many injuries are related to loading, more specifically loading rates (Barrett, Neal et al. 1998; Ehrlich and Lanyon 2002; Torcasio, van Lenthe et al. 2008; Kulin, Jiang et al. 2011), increased control on the horse's biomechanics by farriers could be beneficial – even more so if different shoes could be tuned and selected for different racing surfaces.

The objective of the research presented here is to quantify the dorsoventral and craniocaudal dynamic loading for three horseshoe designs in a controlled laboratory setting. The three shoes were tested on common racetrack surface materials using a biomechanical hoof tester simulating the forelimb impact during a gallop. By doing so, we could characterize how different shoes affect dynamic loading, which may influence a horse's gait on these surface materials.

### 4.4. Materials and Methods

Three different aluminum racing horseshoe designs were tested with a biomechanical hoof tester developed by Peterson *et al.* (2008) and used in other work including *in situ* testing of track maintenance (Peterson and McIlwraith 2008) and offsite testing for track materials (Mahaffey, Peterson et al. 2012 - in review). The horseshoe designs (all from Victory Racing Plate Company, Baltimore, MD, USA) included a standard flat racing plate with a low toe, a shoe with serrated sides (V-Grip), and a shoe with both a high toe grab (6mm) and heel calks (10mm) (Figure 4.1.).

**Figure 4. 1. Horseshoes used in study**

The three aluminum shoes used in this study are a flat racing plate, a serrated V-Grip (middle), and a shoe with a 6mm grab and 10mm calks (right). All shoes were a size 5.

Two different types of racetrack surface material samples were used for the testing. A dirt sample with high sand and low clay content was used (80.7% sand by mass) from a location in the southern United States and a synthetic racing material. Synthetic racing surfaces have been used since 2005 when Turfway Park racetrack in Kentucky installed a Polytrack® brand surface to replace its dirt track. The synthetic granular material differs from dirt used in conventional tracks in that it contains silica sand (>70%), polymer fibers (<5%) and rubber particles (0-15%) all coated with a paraffin-based, high-oil content wax (Cushion Track 2010; Polytrack® 2010). Both samples were dried according to soil standards (ASTM 2005)—modified to a lower temperature and increased time for the synthetic sample— and brought to a predefined moisture content replicating typical operating conditions for the material: 4% moisture by weight for the synthetic sample and 16% for the dirt sample to represent medium track conditions for that particular dirt sample. After rehydration, samples were sealed and settled 8-12 hours. Due to the relationship between shear strength and temperature (Bridge, Peterson et al. 2010; Peterson, Reiser II et al. 2010), the synthetic material was tested at 7ºC and 20ºC. The dirt material was tested at 16% moisture by weight, at which the maximum dry density was achieved (ASTM 2007), and represented standard operating conditions for the track from which the material came. The dirt track material sample used in this study was collected from a dirt stockpile which was going to be used for renovation of a surface at a Thoroughbred racetrack in the southern US. The synthetic track material used in this experiment is one that is also used by several Thoroughbred racetracks in North America. The wax content was 6.2% by weight, within the range of typical North American synthetic tracks. Additional information for the composition of the synthetic and the dirt samples are also reported here (Table 4.1.).

**Table 4. 1. Composition of materials used in horseshoe experiment**

Composition of the synthetic and dirt samples. In both samples, the highest ratio of sand had an intermediate particle size O 0.152-0.251 mm.

| | | |
|---|---|---|
| **Synthetic** | | |
| Composition | *Wax* | 6.2% |
| | *Sand and fiber* | 93.8% |
| | *Sand (> 0.075 mm)* | 99.8% |
| | *Silt/clay (< 0.075 mm)* | 0.2% |
| Differential Scanning Calorimetry | *Onset temp (ºC)* | -0.6 |
| | *Peak temp (ºC)* | 29.3 |
| | *End temp (ºC)* | 69.6 |
| **Dirt** | | |
| Composition | *Sand (> 0.075 mm)* | 80.7% |
| | *Silt (< 0.075 mm, > 0.04mm)* | 12.9% |
| | *Clay-sized fraction (< 0.04 mm)* | 6.3% |
| Mineralogy | *Quartz* | 77.3% |
| | *Clay* | 3.4% |
| | *Other* | 19.3% |
| Maximum dry density | *(kg/m$^3$)* | 1320 |
| | *Moisture content (wt%) to achieve max. dry density* | 16.5% |

Following methods described by Mahaffey *et al.* (2012 - in review), samples were then compacted into a 30.5 cm diameter mold lined with 1.27 mm thick latex film, in three 50 mm lifts to total height of 150mm. Dirt samples were compacted in three lifts followed by raking with six strokes of a garden rake with three 76 mm tines (2 strokes in opposite directions over 3 paths to cover the entire surface) to represent a harrowed surface. The

synthetic material was compacted in 2 compacted lifts followed by a third uncompacted layer added to achieve a total height of 150 mm to represent typical track conditions. The 2 $m^2$ frame contained low-dust silica sand on top of a 12.7 mm thick rubber mat (Shore A durometer = 60, McMaster-Carr, Santa Fe Springs, CA, USA) on a 50 mm thick concrete base. The rubber mat provided thermal insulation to control thermal effects on the synthetic material behavior. The latex film prevented contamination of the sample with silica sand while having a low stiffness relative to the sample and supporting materials.

The biomechanical hoof was equipped with a 3-axis load cell aligned with the mechanical hoof in order to quantify maximum loads and load rates. The load and load rates were used because the load cell offered the greater consistency between measurements over accelerometers. The relationship between the modulus, which is a property of the surface material, and the acceleration may also be of value in understanding the loading on the leg. However a comparison between shoes should be as closely related to the physiological parameter of interest as possible, which are the peak load and the loading rate and the influence of the shoeing on these parameters (Fung 1993).

Data were obtained from the 3-axis load cell with a sampling rate of 2 kHz. Low pass filtering was performed on the load cell data after analysis of the signal content to ensure sufficiently high frequencies were included to capture the signal rise. Each signal was Fourier transformed to verify the frequency band of interest in the data. Several sources of mechanical and electrical noise were identified at higher frequencies, which were above the highest frequency of interest required to capture the rise of the load signal. A 10th-order low-pass finite impulse response filter with a 400 Hz cut off was then used to remove noise from the load signal.

Prior to the biomechanical hoof tester experiment described above, the shear strength of the samples was characterized using a standard lab test for consolidated undrained triaxial compression (ASTM 2004) modified to be drained to better approximate the behavior of the material *in situ* for a racetrack (Bridge, Peterson et al. 2010).

A two-way analysis of variance (ANOVA) compared peak load and peak load rates for the dorsoventral and craniocaudal directions, as well as the ratio of craniocaudal to dorsoventral loading, for the two-tiers of independent variables (three horseshoes on different surfaces). All of the signal processing and statistical analyses were performed using Matlab R2009b (The Mathworks, Natick, MA, USA).

### 4.5. Results

The 7°C synthetic material sample had a higher shear strength and lower cohesion than the 20°C sample under compacted conditions for drained triaxial testing (Table 4.2.). While the dirt shear strength is reported at the maximum stress, the synthetic shear strength is reported at 10% stress because the material does not have a clear failure as does the dirt. The highest cohesion for the compacted dirt material occurred at 16% moisture (by weight) at which moisture content the dirt surface sample also achieved the maximum dry density. The 14% moisture content resulted in the greatest total shear strength in the dirt (further described in Chapter 3).

**Table 4. 2. Shear strength of materials used in horseshoe experiment**

Shear strength of the synthetic and dirt samples. The synthetic track materials do not have a clearly defined maximum shear strength as do dirt track materials. Therefore, the shear strength is reported at 10% stress for the synthetic sample.

| | Friction Angle (deg) | Cohesion (kPa) | Shear Strength (kPa) | Q-C (kPa) |
|---|---|---|---|---|
| Dirt 14% | 38.0 | 5.5 | 176.5 | 171.0 |
| Dirt 16% | 31.4 | 13.1 | 136.5 | 122.7 |
| Dirt 18% | 33.8 | 4.8 | 139.3 | 133.8 |
| | | | | |
| Synthetic 4%, 7°C | 35.6 | 2.1 | 148.9 | 146.2 |
| Synthetic 4%, 20°C | 28.6 | 17.2 | 124.1 | 106.9 |

* "16%" denotes 16% (wt) forming moisture
** Shear strength is reported for confining pressure of 103.4 kPa (15 psi)

For the performance testing with the biomechanical hoof tester, the maximum dorsoventral and craniocaudal loads for the synthetic material at 7ºC and 20ºC and the dirt material were significantly different ($p<0.05$) in a two-way ANOVA, as well as individual post-hoc (Tukey-Kramer) testing. The synthetic surface at 20ºC had the highest peak load in both the dorsoventral and craniocaudal directions, followed by the synthetic at 7ºC and then the dirt with the lowest peak dorsoventral and craniocaudal loads. Despite having the highest peak load in the dorsoventral direction, the 20ºC synthetic also had the highest ratio of maximum craniocaudal to maximum dorsoventral loads, which is characterized by the angle of the resultant load (Table 4.3.). The different horseshoes did not significantly affect loading in either direction, or the angle of the resultant load.

**Table 4. 3. Horseshoe experiment results**

Mean ± s.d. for maximum loads, the ratio of craniocaudal to dorsoventral maximum loading, and maximum load rates.

| | Surface material | Flat | V-grip | Grab & Calks |
|---|---|---|---|---|
| Dorsoventral peak load (kN)† | Synthetic 7ºC | 1.71 ± 0.06 | 1.67 ± 0.09 | 1.67 ± 0.08 |
| | Synthetic 20ºC | 1.77 ± 0.07 | 1.85 ± 0.07 | 1.77 ± 0.12 |
| | Dirt | 1.25 ± 0.08 | 1.04 ± 0.15 | 1.06 ± 0.12 |
| Craniocaudal peak load (kN)† | Synthetic 7ºC | 0.35 ± 0.04 | 0.34 ± 0.06 | 0.37 ± 0.03 |
| | Synthetic 20ºC | 0.43 ± 0.05 | 0.49 ± 0.06 | 0.44 ± 0.06 |
| | Dirt | 0.19 ± 0.02 | 0.17 ± 0.04 | 0.20 ± 0.03 |
| Resultant force angle from dorsoventral axis (deg)† | Synthetic 7ºC | 11.69 ± 1.42 | 11.51 ± 2.38 | 12.57 ± 1.09 |
| | Synthetic 20ºC | 13.78 ± 1.60 | 14.81 ± 1.78 | 13.92 ± 1.18 |
| | Dirt | 8.64 ± 0.79 | 9.24 ± 1.13 | 10.46 ± 0.58 |
| Dorsoventral peak load rate (kN/s)† | Synthetic 7ºC | 205 ± 14 | 222 ± 18 | 203 ± 14 |
| | Synthetic 20ºC | 224 ± 16 | 247 ± 21 | 225 ± 30 |
| | Dirt | 157 ± 17 | 138 ± 12 | 151 ± 14 |
| Craniocaudal peak load rate (kN/s)†‡ | Synthetic 7ºC | 134 ± 3 | **119 ± 6*** | 133 ± 9 |
| | Synthetic 20ºC | 127 ± 11 | **110 ± 7*** | 121 ± 12 |
| | Dirt | 68 ± 7 | 67 ± 7 | 77 ± 6 |

† $p<0.05$ between surface materials for ANOVA and all post-hoc comparisons
‡ $p<0.05$ between shoes for ANOVA
* $p<0.05$ statistical significance in post-hoc comparison for shoe type

The peak dorsoventral and craniocaudal load rates were also significantly different between the three surfaces. The different shoes did not significantly affect the peak dorsoventral load rate. However, the V-grip shoe did have a significantly lower craniocaudal load rate for the synthetic surfaces at both 7ºC and 20ºC than did the flat racing plate and

the grab and calks shoe. The maximum load rate of these two surfaces was still higher than that of the dirt surface for all of the shoe types.

The laboratory testing demonstrated strong repeatability (Figure 4.2.). The synthetic material at both 7ºC and 20ºC in particular responded consistently to the controlled loading. The dirt had more variation between repeated tests than the synthetic samples at the two temperatures.

**4.6. Discussion**

Under the controlled laboratory conditions for a synthetic and a dirt Thoroughbred racetrack material, horseshoe design did not significantly affect performance indicators. These results support that a track's surface material has a much greater effect on loading during the primary and secondary impact in a gallop than do horseshoes – the primary impact occurring at the peak dorsoventral load, and the secondary impact occurring at the peak craniocaudal load (Peterson, Roepstorff et al. 2011). Moisture content (affecting dry density and thus shear strength) and temperature are documented as having significant effects on the loading of dirt (Ratzlaff, Hyde et al. 1997) and synthetic materials (Bridge, Peterson et al. 2010), respectively. Therefore, we conclude that these material properties are of greater consequence to loading than shoeing. The magnitudes of the loading and the load rate are greater than those on the scale of seeing differences in shoeing. For example, the difference between the loading (both dorsoventral and craniocaudal) of the synthetic at the two temperatures is greater than any differences between the three shoe types.

However, the reduction in the maximum craniocaudal peak load rate for the V-grip versus the flat and grab and calks shoe indicates that the V-grip shoe performs as intended. This shoe was developed in order to increase the slide upon impact (Steffanus 2003), thus reducing the craniocaudal peak load rate. At the same time, the dorsoventral loading is not

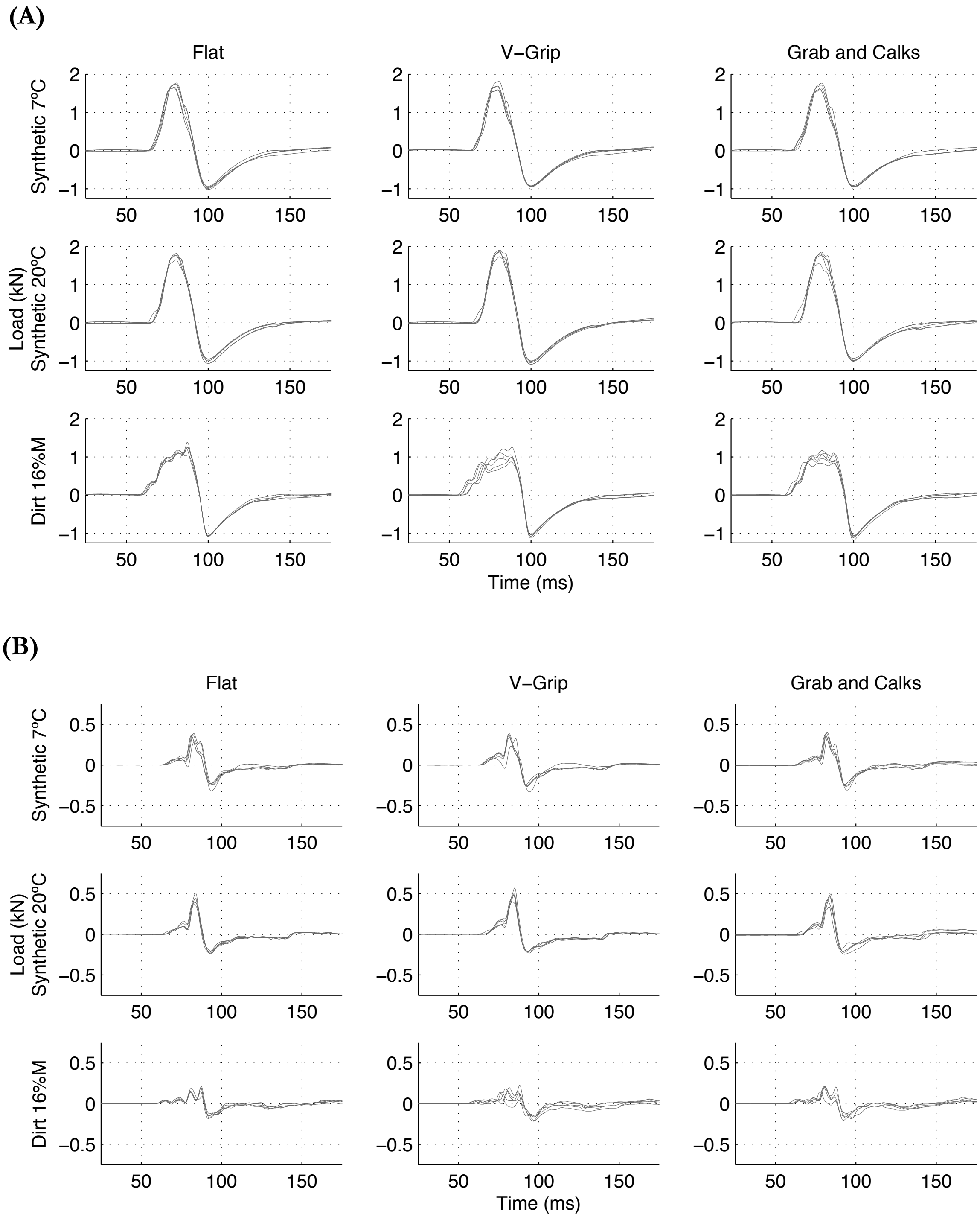


**Figure 4. 2. Dorsoventral and craniocaudal loading in horseshoe experiment**

Loading in the dorsoventral (A) and craniocaudal (B) directions for the mechanical hoof tester. The steepest part of the slope is the maximum load rate. Individual trials are overlaid in each plot. The dirt surface had more variation between trials than did the synthetic surfaces.

affected. While these effects are less than those observed between surfaces, it implies that shoeing should not be dismissed from the discussion of safety. In fact concerns that have been expressed in the popular press about a lack of slide on the synthetic surfaces (Duckworth 2007) are directly addressed by the design of the V-grip shoe. The high shear strength of the synthetic surface supports this concern and possible, albeit minimal, mitigation.

This work also demonstrates that synthetic surfaces can be as stiff, and stiffer, than dirt surfaces, contrary to other findings (Setterbo, Garcia et al. 2009). This supports the contention that the composition of surfaces—both dirt and synthetic—and maintenance can have a very significant effect on a track's performance (Setterbo, Yamaguchi et al. 2011; Mahaffey, Peterson et al. 2012 - in review). The stiffness depends on the material composition, moisture and temperature, and the maintenance of the material. Horses, like humans, seem to adapt to different surfaces, likely by changing limb stiffness (Ferris and Farley 1997; Kerdok, Biewener et al. 2002; Pfau, Witte et al. 2006), which is why tracks with different kinds of material (i.e. dirt or synthetic) and different mechanical properties (i.e. shear strength and stiffness) can simultaneously have low injury rates. However, irregularities within a track during a race or training may be problematic if the horse cannot sense and/or respond in time to avoid injury. Even under constrained conditions, the dirt surface material had greater variability than did the two synthetic materials (Figure 4.2.). This may in part explain the lower the injury rate seen on synthetic tracks compared to dirt tracks in the most recent update from the Equine Injury Database (The Jockey Club 2012). A possible explanation for the increased variation observed with the dirt surfaces versus the synthetic surfaces is that the dirt surfaces may be more susceptible to localized effects while the synthetic surfaces are more uniform and/or are affected by a larger area, thus averaging

any heterogeneity. However risk is multi-factorial (Parkin 2007) and the best of the dirt surfaces are comparable to synthetic surfaces, which may represent better control of key variables such as moisture content.

While this study indicates that shoeing has little effect on the dynamic loading during the impact gait phase, especially when compared to the effects caused by different surface properties, shoes may still have significant effects on localized biomechanics, specifically to strains and strain rates on the hoof and lower limb (i.e. strains and crack propagation through hoof). In a study comparing flat racing shoes to shoes with toe grabs, Schaer et al. (2006) found that the two shoe types did not have consistent differences across the horse subjects. Rather, all variation was dependent on the individual horse and how it changed its gait with the different shoes. This present study does not address the value of shoeing choices for individual horses. Individual shoeing choices are likely valuable to addressing imperfections with conformation of the hoof or to treat preexisting injuries. For example, shoeing choices may be based on preexisting injuries and can affect the loading angles of the hoof and fetlock (Scheffer and Back 2001). That work also found that the type of surface had a greater affect on kinematics at a walk and trot than did different shoe types, although the shoe types did have an effect. The center of pressure can also be shifted using different horseshoes (Colahan, Leach et al. 1991) in order to relieve pressure from the rear of the hoof, possibly during injury recovery. However, these treatments would not necessarily be used for actively racing horses.

Another area in which horseshoes may impact a horse's biomechanics more so than is presented in this dataset is during the propulsive gait phase. Friction to grip the surface can be a limiting factor to speed (Tan and Wilson 2011). Thus, shoes with varying grab

lengths have been developed, as well as shoes like the V-grip. Future work should include horseshoe comparisons for the propulsive phase of the gait.

## 4.7. Conclusions

Different aluminum racing shoes for Thoroughbred horses do not have a significant impact on loading and loading rate with the exception of the V-grip shoe on a synthetic surface. Although the V-grip may reduce craniocaudal peak load rates in a sticky synthetic material (i.e. having a relatively high wax content), the reduction in load rate is still less than the difference found between materials.

## 4.8. Acknowledgements

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# 5. SUMMARY AND CONCLUSIONS

The three parts of this research provide new data for understanding the effects of variables on footing consistency for Thoroughbred horseracing. The development of a material testing plot is an idealized system for evaluating effects. The test plot allows track surface testing to be performed in a laboratory setting where temperature, moisture content, material depth, compaction, harrowing, and other variables can all be carefully controlled. This, however, does not replace the benefit of *in-situ* testing where irregularities in a particular track can be determined. Instead, the track testing allows the relative importance of different factors to be tested under controlled conditions. Additional information on the laboratory testing box procedure is available in the Appendix.

## 5.1. Archetypes in Thoroughbred Dirt Racetracks for Surface Consistency in Different Climates

Chapter 2 illustrates different strategies to achieve the objective of optimized shear strength in racing surfaces. A key goal is to obtain the right amount of slide during the secondary impact phase of the gait. The combination of track design and material allow for different options on how to handle geographical variation in water availability. Since water content is a primary influence on dirt track performance, the management of water is the determining factor in track design. When limited moisture is a factor due to low rainfall and/or a high evaporation rate, increased clay mineralogy helps to buffer moisture content in the dirt and it can increase the shear strength of the dirt. The tradeoff is that increased clay content can also increase the surface shear strength and compaction without constant maintenance intervention. Thus, track managers developed the strategy of having an intermediate layer, the pad, to control surface stiffness.

False base and shallow sand tracks are typically used in areas with higher rainfall, and make use of material with lower mineralogical clay content. An interesting perspective on this is that these tracks may well have started with material with higher clay contents when originally constructed. However, due to the nature of being in an area with greater precipitation, it is likely that the fines (i.e. silt and clay) are regularly washed out. Thus, the mineralogy of these tracks is correlated to the climate, but it not necessarily, that the original construction of these tracks prescribed lower clay content in the cushion when installed.

### 5.2. Uniform Cushion Depth for Consistent Dynamic Loading on a Track

By defining and understanding the evolution of dirt track designs in North America, it is possible to better address concerns that tracks deal with on a daily basis to optimize safety and operations. The second section of this research addresses a common concern: consistent cushion depth. Cushion depth variation that is within current normal operating limits for some US tracks (i.e. a 10-15 cm range of cushion depth as tested for this research) does indeed affect the dynamic loading experienced by the horse. While track consistency is often cited to be important, this work is a first step in quantifying the relative importance of this factor. The material that was tested demonstrated the least variation between the tested depths when that material was at the moisture content at which maximum dry density was achieved (ASTM 2007). If tracks can determine and maintain an appropriate moisture content matching the occurrence of maximum dry density, it may reduce dangerous effects of variation in the track's cushion depth. However, due to the higher loading on the leg and the difficulty of controlling moisture content, consistent grading of the track becomes a high priority for the racing surface. Determination of parameters for individual tracks is critical to this approach because previous work (Soehne 1958; Soane, Blackwell et al. 1980) demonstrates that different soils (depending on compaction, moisture, and other

composition parameters) transfer vertical loads to different depths. This is where again onsite characterization and testing with the biomechanical hoof tester (Peterson and McIlwraith 2008; Peterson, McIlwraith et al. 2008) is useful to achieve a benchmark. From there, the constraints can be replicated in the laboratory test box with only 5 gallons of material (see Appendix for details on test box setup).

### 5.3. Horseshoe Influences on Dynamic Loading

Returning to a greater emphasis on the horse, the next section of the dissertation looks at how different horseshoes affect the dynamic loading at impact at a gallop. Under a controlled setting accounting for moisture, temperature, and impact energy and angle, three horseshoe designs–including the extreme example of one with a 6 mm grab and 10 mm calks–did not have a significant effect on loading dynamics. The one exception was a V-grip shoe on a synthetic surface that reduced the load rate on the craniocaudal axis. While horseshoes have a lesser degree of effect on dynamic loading compared to material composition, track maintenance, and cushion depth, in some cases they, too, can play a role in manipulating loading to achieve consistency for the horse. It is more likely, however, that any effect would be related to influencing an individual horse's gait.

### 5.4. Future Work

The data presented here are a beginning of a list of work to be pursued for the continued interest in improving safety at Thoroughbred racetracks. As demonstrated in Chapter 2, because of variation in climate, track design, track use and maintenance strategies, it is clear that there is no one universal answer to the problem of track optimization. That said, trends have emerged that can direct track stakeholders down a path from which track-specific answers can begin to surface. For example, track design and associated maintenance

strategies, moisture content, and clay mineralogy are three pieces to understanding how to balance shear strength and track stiffness in different climates. Also, as suggested in previous work (Bridge, Peterson et al. 2010) and the horseshoe study in Chapter 4, synthetic materials may offer consistency at a constant temperature, but this does not guarantee optimization of mechanical properties such as stiffness. On a more immediate note, there is a need for future research on the stresses and strains on the hoof under loading of different horseshoes. Although the GRF may not significantly change with the use of different horseshoes, the shoes may have significant effects on localized loading of the hoof and hoof wall.

All of the factors considered in this work are based on the perspective of the primary and secondary impact loading. Future research priorities should also include development for mechanical testing that matches forces during the propulsive phase of the gait. This may be an area where differences in shoeing, in particular, has a significant effect on a horse's performance and safety.

Mechanical testing, such as the work presented here and proposed above, offers a methodical way to understand the physics of the problem. However, to truly achieve increased safety for the horseracing industry, in-depth epidemiological studies must be coupled with the dynamics data. This is critical in order to understand how to apply mechanical findings to improved safety to the horse. This moves forward beyond the important, but early goal of consistency.

Along these lines, another area for future work is the continuation of cooperation between tracks and with research scientists and engineers. This kind of work may be best supported by documentation of both surface maintenance and animal care decisions. The Jockey Club's Equine Injury Database is a good example of the start of this process (The

Jockey Club 2012). However, the work really should be extended to include decisions leading up to the day of a race, including training and veterinary practices for every animal. This industry is meticulous about maintaining breeding and financial records for individual horses. For the purposes of welfare and safety, this approach should be extended to these other realms of the animal lives on which the industry depends. The compilation of these proposed datasets alongside maintenance data and continued track surface analyses creates an opportunity for a robust epidemiological study.

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# APPENDIX: LABORATORY TESTING BOX PROCEDURE AND VALIDATION

The laboratory testing box procedure provides an idealized system for evaluating surface material effects under different conditions. This appendix documents the procedure's steps and validation through comparisons with *in situ* data.

## Sample preparation

1. Samples are first dried at 110ºC (40ºC for synthetic samples), rehydrated to a predefined moisture content, sealed, and left to settle overnight as per ASTM D2216 *Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass* (ASTM 2005).

2. The test area is 2 $m^2$ containing enough low-dust silica sand with an predominant size range of 0.2 – 0.6 mm, to fill the test box to the desired testing depth (i.e. 10 cm or 15 cm). This creates a lateral boundary layer for tested samples.

3. Next, a space is dug out of the low-dust silica sand to fit a 30.48 cm (12 in) diameter mold (form tube) cut to the desired sample depth (i.e. 10 cm or 15 cm). The mold is placed in the hollow area followed by further removal sand until all of the sand is cleared from the mold (Figure A.1.).

**Figure A. 1. Inserting the mold**

The test box before and after inserting the mold tube (left and right, respectively).

4. Leaving the mold in place, a 1.27 mm thick latex film (Shore A durometer = 40, McMaster-Carr, Santa Fe Springs, CA, USA) is draped in the hollowed space ensuring that the latex will not be stretched, which would add lateral compression, once the lined mold is filled with the sample material (Figure A.2.).

**Figure A. 2. Latex-lined sample mold**

Comparisons of biomechanical hoof testing on silica sand compacted in the mold with and without the latex liner demonstrate that the liner does not have a significant effect on the loading of the sample material (Table A.1.).

**Table A. 1. Validation of using latex liner**

Comparison of dynamic loading and accelerations for hoof tester drops in silica sand with and without the latex liner. There was no statistical difference with the use of the latex film liner.

| | No Liner (n = 4) | Latex Liner (n = 4) | Statistical significance ($p < 0.05$) |
|---|---|---|---|
| Max. Load (kN) | 4.89 ± 0.85 | 4.33 ± 1.06 | NS |
| Max. Load rate (kN/ms) | 3.40 ± 0.73 | 2.85 ± 0.84 | NS |
| Max. Vertical Acceleration (g) | 34.33 ± 8.88 | 34.04 ± 6.43 | NS |
| Max. Horizontal Acceleration (g) | 17.09 ± 4.00 | 19.96 ± 4.66 | NS |

5. The material sample is added in 5 cm (2 in) lifts compacted using 18 drops of a 5.7 N rammer per lift until achieving the desired depth (Figure A.3.).

The standardized compaction effort based on the following equation:

$$CE = \frac{mgh}{(1000 \times \pi r^2 \times depth)} \times \frac{18\ drops}{5\ cm\ layer} \times No.layers$$

Compaction effort (CE) = 55 kJ/m$^3$

Rammer weight (mg) = 5.7 N (12.5 lb)

Rammer drop height (h) = 0.2032 m (8 in)

Mold area ($\pi r^2$) = $0.15^2\pi$ m$^2$ ($6^2\pi$ in$^2$)

Depth of prepared sample = 10 cm or 15 cm (4 in or 6 in)

No. layers = 2 and 3, for 10 cm and 15 cm final depth, respectively

**Figure A. 3. Compaction layering**

Layers are added and compacted in 5 cm sections until reaching the desired depth.

The total compaction effort of 55 kJ/m$^3$ is approximately 10% of the compaction effort used in the ASTM D698 *Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))* (ASTM 2007). This strategy offers over 75% percent relative compaction for a material, which is primarily sand (Selig and Waters 2000). Racetracks do not typically operate at maximum compaction through the full depth profile, as would a roadbed, for example. Therefore it is undesirable to reach full compaction. This is supported via a comparison of the laboratory sample preparation described here with *in situ* biomechanical hoof testing at the track from which the material

sample came. The peak loading and load rate achieved on samples following the laboratory preparation protocol are similar to values achieved at the track from which the material came (Table A.2., Figure A.4.).

**Table A. 2. Sample preparation validation results**

Comparison of maximum peak values for loading and accelerations using the laboratory sample preparation and *in situ* testing. The cushion depth for the laboratory values is 15 cm and the cushion depth for the onsite testing ranges from 27 - 72 cm.

| Moisture content (gravimetric) | 14% | | 16% | | 10-16% |
|---|---|---|---|---|---|
| Surface treatment | Laboratory Harrowed (n = 10) | Laboratory Sealed (n = 10) | Laboratory Harrowed (n = 10) | Laboratory Sealed (n = 10) | *In situ* (n = 24) |
| Max. load (kN) | 4.27 ± 0.31 | 7.18 ± 0.41 | 4.28 ± 0.3 | 5.64 ± 0.39 | 5.94 ± 1.1 |
| Max. load rate (kN/ms) | 1.14 ± 0.28 | 4.74 ± 0.23 | 0.7 ± 0.05 | 2.62 ± 0.73 | 4.15 ± 1.63 |
| Max. vertical acceleration (g) | 31.92 ± 3.17 | 65.71 ± 8.9 | 30.44 ± 2.77 | 54.9 ± 18.77 | 63.98 ± 18.19 |
| Max. horizontal acceleration (g) | 13.13 ± 2.5 | 32.84 ± 9.75 | 7.91 ± 1.39 | 30.53 ± 13.25 | 30 ± 14.12 |

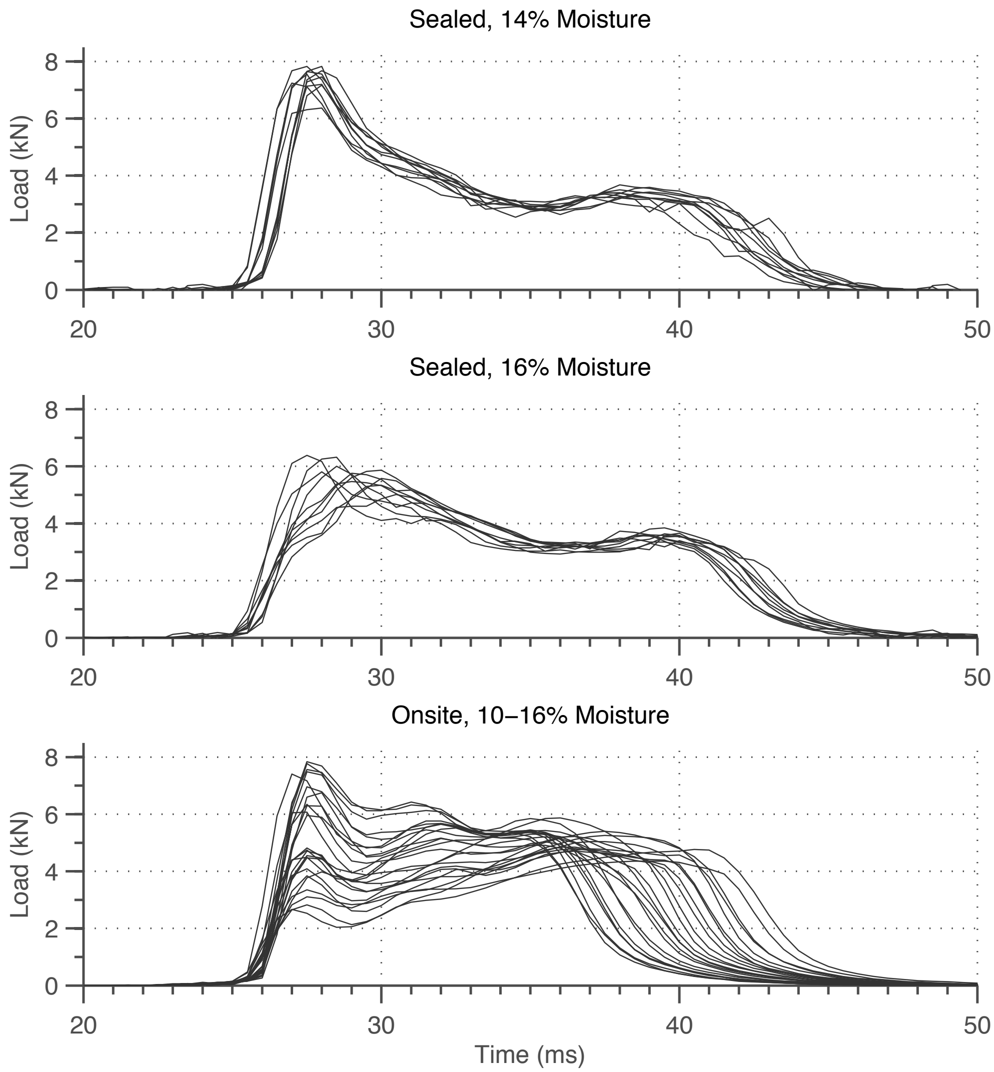


**Figure A. 4. Loading of laboratory prepared sample and onsite at a track**

Loading of a prepared sample (15 cm cushion depth, sealed surface) at 14% and 16% (top and middle, respectively), and loading of the same material at the track (27-72 cm cushion depth, sealed surface).

The lower compaction effort relative to the ASTM standard also reduces abrasion wear on material samples undergoing multiple trials of compaction preparation and biomechanical hoof impact testing (Compton and Strohm Jr. 1968). ASTM D698 requires

that material not be previously compacted (ASTM 2007), however, this procedure does allow for re-compaction due to the reduced compaction effort. To control for any minor wear of the material during testing, independent variables (i.e. cushion depth or horseshoe type) are tested in a random order of clustered repetitions representing no more than half of the total repetitions per set.

6. After adding and compacting the material to the desired height, the sample is left compacted to represent a sealed track, or harrowed with six strokes of a garden rake with three 7.6 cm tines spaced 10.0 cm on center using two strokes in opposing directions over three paths to cover the entire surface (Figure A.5.).

**Figure A. 5. Surface treatments**

The sample can represent a sealed (left) or harrowed (right) state.

7. When the sample preparation is complete, the edges of the latex liner are carefully draped over the surface, and, using pliers, the mold is slowly removed by lifting straight up (Figure A.6.). The surrounding sand is allowed to gradually fill in the space previously occupied by the mold. After the mold is removed, the level of the surrounding sand is checked to match

the level of the sample and carefully compacted by hand without disturbing the sample. This lateral boundary condition allows for loading that matches *in situ* results (Table A.2. and Figure A.4.). The latex is then spread out again and the sample is ready for testing (Figure A.7.).

**Figure A. 6. Mold removal**


**Figure A. 7. Completed surface preparation and removed mold**

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