Racing Surfaces
Testing Laboratory
Orono, Maine USA

Racing Surfaces:

Current progress and future challenges to optimize consistency and performance of track surfaces for fewer horse injuries.

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White Paper

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

PREFACE

Racing surfaces have received a great deal of attention in the popular and fan coverage of horse racing (see for example Schulman 2007, Rezendes 2007, Finley 2010). Additionally, track surfaces have recently been a topic of discussion in the scientific literature. Three general areas of inquiry have emerged: (1) characterization of the interaction of the hoof and the ground, (2) in-situ testing of the surface and (3) specific characterization of the materials used in the racetrack. A general understanding of the hoof ground interaction has been facilitated by dynamic accelerometry (Dallap-Schaer 2006) and horseshoe studies (Setterbo et al. 2009) over the last decade. Some of this information is summarized in reviews of the loading of the ground and the hoof (Johnston and Back 2006, Thomason and Peterson 2008). Some work has also looked at in-situ testing of the surface (Peterson et al. 2008) including differences in types of surfaces (Setterbo et al. 2008, Thomason et al. 2007) and the effects of maintenance and weather on the track surface (Peterson and McIlwraith 2008, Peterson et al. 2010). More recent work which has emerged on the testing of the materials used in racing surfaces to both characterize the materials (Bridge et al. 2010) and to the laboratory testing of their response to loads that mimic the loading of the surface by the hoof (Bridge et al. 2010a, Bridge et al. 2011).

In these papers and in the discussion in the popular press, a common thread underlies the discussion: does a racing surface exist that combines performance and consistency with safety? Technically precise answers to this question will require that common definitions of key terminology be developed regarding the condition of the surface. A uniform vocabulary can be used to link to the epidemiological literature to descriptions of the surface, which will enable injuries to be linked to particular surfaces and conditions. Even then, however, the relationship between surfaces and equine injuries will continue to present additional specific challenges due to the differences in types of injuries and the effect of factors such as joint disease on the risk to a horse during a particular event.

Injury, in particular catastrophic injury, is a multi-factorial event that involves the complex interaction of a number of risk factors including but not limited to medication, genetics, and training. The full scope of the problem is summarized in Figure 1, in which track-surface properties are isolated as the focus of this paper from among several other known risk factors for injury. Given that the overwhelming majority of catastrophic injuries show clear evidence of preexisting disease (Norddin et al. 1998, Stover 2003), improved racing surfaces have the potential to result in an improvement in the safety of horse racing for both riders and horses. Musculoskeletal injuries have a large adverse effect on the Thoroughbred racehorse industry due to both fatal injuries that have low prevalence and milder injuries that have a high prevalence. Candidates for injury prevention that have been proposed include

- improved management practices to minimize the incidence of low hoof heel angle
- incorporation of more frequent, shorter high speed works or races in exercise regimens
- avoidance of excessive accumulation of high speed distances over short periods of time
- recognition and rehabilitation of mild injuries
- maintenance of uniformity of racing surfaces among racetracks within given environmental conditions (Riggs 2002, Stover 2003).

Another specifically documented risk for injury is when a well-trained horse changes from one type of surface to another and at the same time is expected to perform at maximum capacity, for example going from training on a soft surface to competition on a hard surface.

Other than the quality of prerace examinations, however, no risk factor has an impact on all horses racing at a particular venue on a single day greater than the quality of track surface construction and preparation. Therefore, the development of a consistent and well-characterized racing surface is an important goal of the industry. This requires that a tool exist that can objectively quantify the functional properties of surfaces, particularly those properties in the causal pathway to injury. In fact, the role of surfaces in the debate over the safety of racing is sufficiently important that it may be that many of the other challenges facing the industry will only be addressed in a systematic manner after significant progress has occurred in understanding what constitutes a safe racing surface. Thus, improved racing surfaces should be regarded as a step on the path to improved safety of the racehorse and resulting in a safer sport for the riders.

This document considers only the effect of surfaces on the risk to the horse. Even though optimization of surfaces alone will never eliminate catastrophic injuries, and may not even be a primary factor in most injuries, it is highly likely that achieving well-designed, uniform surfaces will benefit the horses, the riders and the sport. However, the absence of well-accepted characterization methods and basic science of racing surfaces is a significant obstacle to improved performance and safety. In the effort, to improve surfaces it is critical to look at the factors that control the performance of racing surfaces in the context of the relevant biomechanics, the different types of surfaces, and potential testing and maintenance strategies.

BACKGROUND

Defining the scope of the problem

A safe surface is one for which the surface properties (to be detailed later in the paper) have been designed to prevent injury. Current evidence suggests that consistency of each surface and limited variability among surfaces seen by each horse are more important than the exact values of each property. Consistency allows for the horse to adapt through training. Therefore, a greater understanding of the role of the track in the causation of injury is a prerequisite for safer track and surface design. Historically, the industry has taken a trial-and-error approach to building a safe surface, with little study into the actual causes of injury. In effect, the system so far has been to lay down a number of surfaces, test the properties, and compare frequencies of injury among surface types. Unfortunately, as a means of identifying the qualities of a safe track, this system is cumbersome and expensive, both in terms of the money spent on construction and testing and in terms of the cost to horse welfare.

A scientifically more robust approach is to aim for understanding the combinations and ranges of properties that make a surface safe and why those combinations prevent injury. This approach is complicated because there are four intervening categories – degrees of separation, if you like – between the surface properties and knowing how to prevent the many and varied injuries that occur in race horses. Figure 1 shows how optimum track surface construction and preparation must occur in context other key factors: 1) horse-hoof-track interaction, 2) loading on specific anatomical structures, 3) primary causes of injuries, and 4) the features of the injuries themselves.

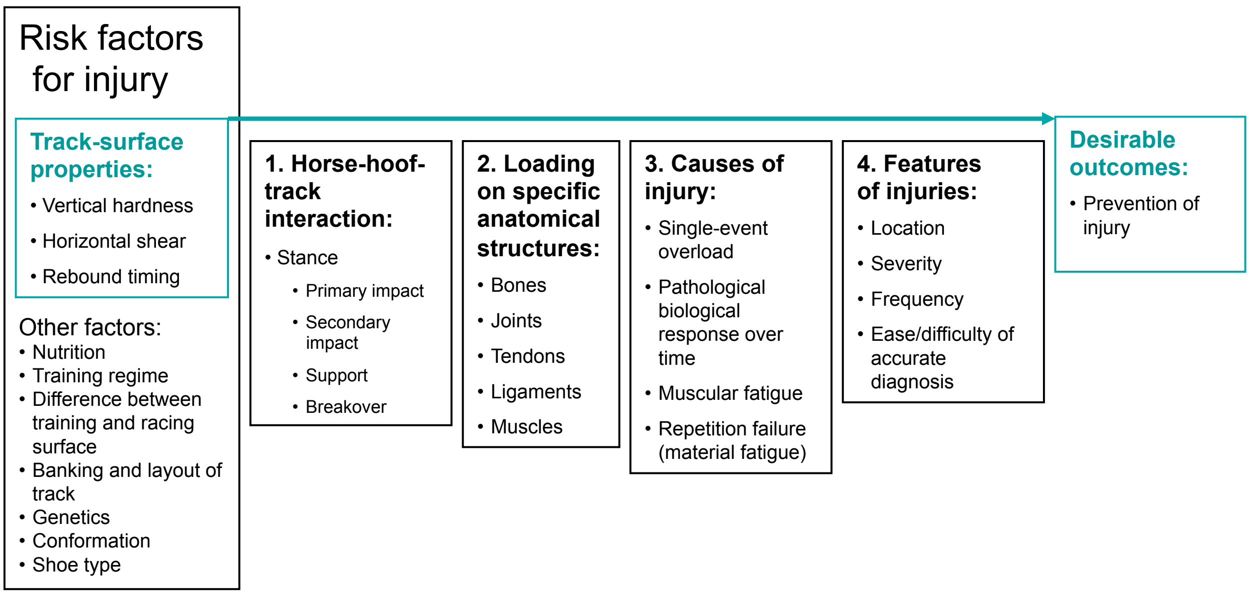

Figure 1. A pathway from track properties as a risk factor to the desirable outcome of prevention of injury, *via* the postulated mechanical underpinnings of the causes of injury, and the relevant features of injuries once they occur.

Horse-hoof-track interaction -- Energy from the shock of contact with the ground and forces owing to changing the momentum of the legs and body transfer through the hoof. The amount of energy and the magnitude of forces depend strongly on the properties of the track surface, but there are several complicating factors. First, each surface property has a different effect on the energy and forces experienced by the horse. Second, the energy and force magnitudes change throughout the footfall (stance) and swing phase. Third, shoes modify the mechanics at the hoof-track interface. Fourth, the horse's own conformation and anatomical construction contribute to the manner in which it interacts with the track, so it is important to study how the interaction varies among horses.

Loading on specific anatomical structures – The static and dynamic loads on the leg stress the materials of every anatomical structure in the leg including each bone, muscle, tendon and ligament. Each structure experiences its own resulting level of stress at any stage of the stance and swing. Injuries occur when these stresses exceed tolerable thresholds. The specific threshold limits are defined both by each specific event and by the stress history of the anatomical structure. For this reason, being able to determine the range of stress experienced by each structure is the key to understanding how injuries occur.

Causes of injury – Injuries can principally occur in two different ways, either as a catastrophic injury due to acute overload or as degenerative changes due to repeated minor overload. Acute overload results in immediate traumatic failure, usually of a bone. Degenerative changes occur because bones and muscles are made of living tissues containing cells that are sensitive to levels of stress. Below a threshold level of stress, both types of tissue show normal, healthy adaptive responses to changes: increase the stress during exercise and bone and muscle mass increase. Even tendons and ligaments show this kind of response. However, if the threshold stress is exceeded repeatedly (for example, during every footfall at speed), the response can become maladaptive, causing pathological tissue degeneration. This inappropriate response is common in the bones and joints of racing and performance horses. The stress is not enough to cause immediate failure, but the damage caused by degeneration reduces the level of stress at which a bone will fail.

Features of injuries – Accurate diagnosis of injuries, together with information on their location, severity, and frequency of occurrence, provide valuable information in combination with the categories of data described in the preceding three subsections. Together they lead to a model for directly linking track properties with injury.

Linking track properties to injury – Achieving the goal of making a direct connection between track properties and specific injuries (not simply injuries in general) is a major step in minimizing the effect of the track on the occurrence of injury. Full understanding of the causes of specific injuries is an elusive goal. But we have the wherewithal with current technology to establish a link sufficiently well to reduce the risk of the track, i.e., make tracks as safe as possible. In concept, an appropriate program of research can be described relatively easily. However, the cost and the logistics of mounting the program would be very challenging. Simply stated, using some of the methods described below, it is relatively easy to combine the measurement of track properties with those of the hoof track interaction by direct measurement from horses on the track, at speed. If these data for a sufficiently large sample of horses are combined with the features of those injuries (accurate diagnosis, location, severity and frequency), it should be possible to find concrete links between track properties and occurrence of injury. The challenge faced by such a research program is to effectively characterize both individual variations between horses and variations in surfaces and conditions to effectively represent the risk to horses under actual racing and training conditions.

Interaction of the horse and hoof with the track

At racing speeds reaching 38 mph (17 m/s), the hoof hits the track approximately 150 times a minute, remaining on the ground in the stance phase for a sixth of a second each time. The short duration of the stance hides from our eyes several stages that are distinctive in their mechanical characteristics (Figure 2) and that have very different potential for causing injury. For the purposes of this paper, we identify four stages: Primary impact, Secondary impact, Support, and Rollover. The mechanics of each stage is dependent on the design of the track (e.g., radius of turns, angle of banking), and the properties of the track. This dependence gives us the basis for reducing injury rates by modifying track properties, because the shock energy and forces transmitted between track and hoof underlie the causes of injury to bones and soft tissues in the whole leg.

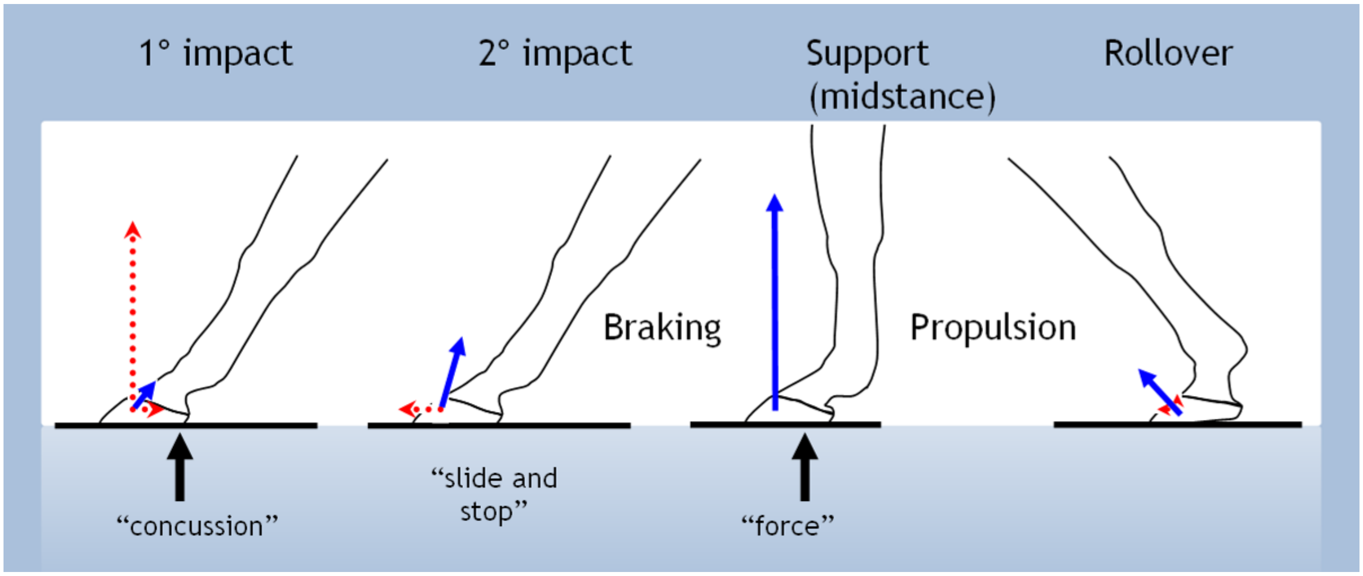

Figure 2. Stages of the stance showing the differences among the stages in acceleration (red) and ground reaction force (GRF) (blue). A tilted GRF arrow indicates that both vertical and horizontal components of GRF are present. The arrow shows the direction in which the ground is pushing the horse.

Primary impact -- When the hoof impacts the ground, it is moving downward at a high rate of speed but is moving forward relatively slowly (because the backward swing of the leg on the body almost cancels out the forward speed of the body). Essentially the hoof hits vertically, like the head of a dropped hammer. As the hoof meets the ground, it decelerates rapidly towards zero velocity (within 1-3 milliseconds on a firm surface). The rate of deceleration is of the order of 100g on racing surfaces (Dallap-Schaer et al. 2006). However, the soft tissues of the hoof dampen the shock of impact (Gustås et al. 2001), as does the track surface if it has the appropriate cushion. Forces on the foot are relatively low, because only the mass of the hoof and pastern participates in this collision. Since the mass is low, forces are usually kept within the limits of strength of the bones and soft tissues of the hoof and limb.

Magnitudes of deceleration and shock energy during primary impact are extremely sensitive to vertical hardness of the surface. Metal shoes may exacerbate the problem for certain interfaces, although there is insufficient evidence to be sure, collapsed heels, some quarter cracks, and other issues have been associated with metal shoes. This is because the shock-absorbing structures of the hoof (frog, digital cushion, heel bulbs, laminar junction) absorb 70% of the energy, based on testing on cadaver legs (Willemen et al. 1999, Lanovaz et al. 1998) and *in vivo* experiments (Gustås et al. 2001). By constraining the hoof metal shoes have may reduce the ability to absorb the energy from the impact.

Secondary impact (slide and stop) – As soon as the hoof is at rest on the surface, the body of the horse, which is still moving forward, collides with its own implanted and stationary leg (Ruina et al. 2005). The body tends to push the leg forward, forcing the hoof to slide and then stop (Pardoe et al. 2001). Forces acting on the leg now begin to rise dramatically; as the hoof pushes into the ground, the ground exerts an equal and opposite force, known as the ground reaction force or GRF, which can be broken down into vertical and horizontal components. This force is transferred back up the leg and is absorbed by the musculoskeletal system of the horse (Clayton 2004).

While the hoof is sliding and stopping, the GRF has a horizontal component that tends to retard or brake the motion of the body, as well as a rapidly rising vertical component as the animal's body weight comes to bear on the leg (Hjertén and Drevemo 1994).

Secondary impact has the potential to have a large role in causing injury. During the normal slide-stop action of the hoof that occurs in this stage, the coffin bone may be forced forward, compressing the laminar junction between itself and the capsule. This action is certainly plausible, though it has not been conclusively demonstrated. If it does occur, it might be one cause of bruising.

If the foot slips forward excessively, this action has the possibility of forcing the digital flexor muscles into rapid, unpredicted eccentric contraction, which can cause tears within a muscle. If the foot comes to too rapid a halt, it would exacerbate any forward motion of the coffin bone, as described in the preceding paragraph. Of possibly greater consequence, shortening the duration of the slide will increase the magnitude of the horizontal component of the ground reaction force, exerting larger-than-normal bending moments on the cannon bone (Pratt 1997). Even small increments in bending induce large stresses in long bones such as the cannon bone.

A key in reducing injury during this stage is matching the traction of shoes to the shear properties of the track. It is, in principle, easy to measure the grip of grabs and caulks of a range of sizes and shapes on a variety of surfaces with different shear properties. These data could potentially be made into a table so that when the shear properties of a track have been measured, the types of gripping device on a shoe that are appropriate for the track could be read from the table.

Support – This stage overlaps with secondary impact and extends through midstance and into the rollover stage. The distinctive mechanical characteristic of this stage is the rise and fall of the vertical component of the GRF, as the limb prevents the body from falling due to gravity and accelerates it upward into the next swing phase. The vertical GRF peaks around midstance, and may reach 2.4 times the body weight of the animal at a racing gallop (Witte et al. 2004).

The sheer magnitude of the forces on the foot midstance implicate this stage very strongly in causing traumatic bone fractures and tendon and ligament ruptures or strains. In addition, joint loadings at this time will exacerbate chronic joint problems. After midstance, the braking horizontal GRF changes to a propulsive force. At this time, appropriate traction between shoe and surface is critical.

Rollover – This stage is the last phase of unloading, beginning as soon as the heels leave the surface. Both vertical and horizontal GRF are falling from 30-50% of their peak values towards zero at toe off. The hoof itself unrolls then pushes off from the ground.

This stage is important in that altering the duration of rollover strongly affects the kinematics of the limb during the swing phase, which in turn affects the kinetics of the next stance. Forcing a shorter or longer stance under those performance activities that induce higher loading conditions will affect the forces and stresses acting on bones and soft tissues. If more muscular control is necessary to perform the activity, muscular fatigue may become a factor in injury. If breakover and toe-off are delayed, residual tension in the deep and superficial digital flexor tendons may flick the foot back sufficiently fast that rate-dependent injury to those tendons is possible. This speculative suggestion is supported by work that shows higher magnitudes of acceleration of the hoof after toe off in galloping Thoroughbreds than the decelerations on impact with the surface (Schaer et al. 2006).

How the track influences hoof forces

The resistance of the track to the impact and loading of the hoof (Burn et al. 1997) determines the rate of loading of the leg and thus the accelerations and forces encountered in the joints of the horse (Ryan et al. 2006, Setterbo et al. 2009). Early studies on track and surface design to prevent injury in trotting horses were done in Sweden (Fredricson et al. 1975, Drevemo and Hjérten 1991). The combined loading experienced by the leg is dependent on both the vertical and horizontal response of the surface (Zebarth and Sheard 1985). These complex movements of the distal limb have been elucidated in invasive and non-invasive models that demonstrate significant differences in the loading of the distal limb as related to surfaces (Chateau et al. 2006, Spännar et al. 2004). Hence, both the horizontal and vertical components must be examined when determining the dynamic response of the surface. In the vertical direction, the track decelerates the downward traveling hoof through compaction of the loose top layer cushion on a dirt or synthetic racing surface. The profile of the top section of a turf surface, however, is more complex and may include a top layer that is either loosened mechanically or that may be covered by a surface layer of roots and organic material. As the soil or top layer of the turf compacts, it becomes stiffer and more resistant to further compaction, bringing the hoof to a stop (Thomason and Peterson 2008). Once the motion of the hoof has been slowed or has stopped, the weight of the horse is dynamically transferred to the hoof and then to the harder surface material beneath the hoof. This dynamic transfer of the weight of the horse to the hoof is the source of the acceleration, resulting in peak loads that may approach 2.5 times the bodyweight of the horse.

The hardness of the track influences how quickly the foot is decelerated and then the stiffness of the track when the load is being applied. This rate of deceleration controls the strain that is transferred to the leg, and stiffer surfaces therefore result in higher peak loads. Repeated loading to the bone can cause both micro fractures and catastrophic fractures (Radin et al. 1972). An increased hardness of the surface also increases peak loads and load rates (Goldsmith 2001). Both the acute and the repetitive impulsive and excessive loading have been proposed to be biomechanical risk factors

(Radin et al. 1972, Johnston et al. 1995). Therefore, it is reasonable to expect that above a critical strain and strain rate, there lies the potential for the propagation of cracks in the bone matrix which can result in catastrophic failure of the bones in the leg. This is a dynamic process that is not dependent strictly on the loading, but also on the degeneration and remodeling of the bone (Ehrlich and Lanyon 2002). “Hard” tracks generate a large impact force and high frequency vibrations due to the rapid deceleration of the hoof over a very short time period (Barrey et al. 1991). On a “soft” track, the deceleration occurs over a longer time, reducing the peak impact force and reducing the rate at which the strain in the hoof is applied. However, with too soft of a cushion, the soil can continue to collapse as the horse tries to push off, resulting in a loss of forward momentum and speed with the associated increase in energy expenditure and resulting fatigue (which is an important causal factor in injury). However, it is important to recall that movement and loading of the lower limb is also affected by factors such as limb conformation, shoe material and type of shoe as well as the ground surface character (Barrey et al. 1991, Willemen et al. 1999, Roepstorff et al. 1999, Pardoe et al. 2001).

The horizontal response of the surface also plays a key role in determining the loading of the leg. During the first portion of the stance phase, the hoof slides forward before coming to rest (Pratt 1985). How quickly the foot is brought to a halt and hence the peak deceleration experienced is dependent upon the horizontal shear characteristics of the surface. As in the case of the vertical loading, a rapid deceleration increases the risk of excessive strain and the rate of strain application and thus the potential injury to the leg (Johnston et al. 1994). If there is a partial shear failure of the track material as the hoof is brought to rest (i.e. there is some slippage of particles across one another), the deceleration will occur over a longer time, reducing the magnitude of the deceleration. These braking shear requirements must be balanced with those required for forward propulsion after the mid-stance point. Optimally, it is expected that the surface would allow some slide during the initial impact. However, once loaded vertically by the weight of the horse, the surface would provide adequate carrying capacity and shear resistance to support the hoof without failure during the propulsive phase (Peterson et al. 2008). If the shear resistance is low, it is sometimes referred to as a track cupping out, since the hoof will slide and elongate the hoof print during propulsion. During breakover, the surface resistance to shear determines the extent of hoof rotation (Cheney et al. 1973, Zebarth and Sheard 1985). The hoof rotates gradually into a low shear strength surface such as sand during the loading, compensating for the changing direction of force (Riemersma et al. 1996, Hood et al. 2001). The low shear strength of a sand surface thus alters the loading of the joints and tendons of the distal limb during maximal loading of these structures (Chateau et al. 2006, Spännar et al. 2004). The loading of these structures while influenced by the footing, is also highly dependent on individual biomechanics. Conformation of the horse is very important, since it will influence the angles and loads on the supporting structures. In addition, other factors such as shoeing and even training may influence joint loading.

In addition to these mechanical properties, rough, deformable surfaces increase the variance both of the vertical forces at the hoof and of the positioning of the load in the hoof (Kai et al. 1999). Therefore, it is critical to understand both the ideal surface properties and the maintenance that is required to sustain them. A properly prepared track that is uniform throughout its course should positively influence the performance and orthopaedic health of the horse.

TYPES OF RACING SURFACES

Design

To date, little formal discussion has been given to design of the racing surface. The design of racetracks has generally been the purview of experts who have developed strategies that are appropriate to particular climates and materials. However, because the approaches of different experts who have contracted for specific jobs have differed from site to site, this approach has resulted in drastically different track designs in close proximity to each other. This belies the claim that the design must adapt to local materials since very different designs are often located within close proximity. The adaptability of the horse has allowed this to continue, but ostensibly these different designs should have advantages with respect to safety, and if safety is not significantly different for these surfaces, then ease of maintenance and other considerations may result in an optimal design for a location.

Cushion and Base

Perhaps the most notable difference between types of racing surfaces is the configuration of the cushion, the pad (when applicable) and the base. Three basic configurations of a racing surface exist:

1. a shallow sand track with a solid base

2. a sand and clay track with a pad that is maintained on a regular basis

3. a track with a developed base that has a shallow sand or sand-and-clay track material laid over a base which is not disturbed on a regular basis.

These three basic designs predominate regardless of the type of material used for the track. Traditionally, the design of the cushion and base has been assumed to depend on the climate and materials of a region. However, numerous examples exist of tracks with close geographical proximity with different designs, so it is likely that the design of a given track is as dependent on the experience of the designer as it is on the climate and material used in the track.

Shallow sand tracks over a hard base are typically used with very low clay and silt content. The mechanics of the hoof interaction with this type of track are characterized by a hoof print which is in very close proximity to the base during normal usage. The cushion is typically on the order of 3 ½ to 4 ½ inches deep, and the hoof print during breakover is nearly in contact with the base. The low clay and silt content results in a track that must maintain higher moisture content in order to retain the effectiveness of the cushioning of the sand over the hard base. These shallow sand tracks are also typically very fast draining and thus can be used when heavy rainfall is common. While requiring high moisture content to retain the cushioning of the surface, the track will rapidly recover from heavy rain since the surface is permeable and the water will flow both across the top of the compacted track surface and though the permeable material toward the lower elevation at the inside rail of the track. The hard base can be composed of limestone screenings, soil cemented sand, compacted clay, porous asphalt or even concrete.

The second common design of a dirt racing surface uses the same material at a depth in the track that greatly exceeds the depth of the hoof print in normal operation. In this type of track, a material that is similar to the top surface may extend from 8 inches to as deep as 24 inches above the base material. Within this type of design, two distinct categories exist: tracks with a false base and tracks with a maintained pad. Tracks with a false base have a shallow cushion just like the shallow sand tracks that overlay a hard pan layer, which may be as compacted and difficult to penetrate as the surfaces on the shallow sand track. The hardpan layer is developed through repeated harrowing of the surface at the same depth. A very high stress area exists under the teeth of a harrow, which will compact the material below the teeth very effectively. In areas with heavy rainfall, the top surface will gradually lose fine material and will create a distinct cushion over the false base created as a hard pan layer. Repair of the uneven portions of the base can be simply handled by rototilling the material followed by repeated harrowing of the surface to recreate the hardpan layer. This is not done on a regular basis but can be done after a period when the track has not been used or when some damage to the track has occurred over time from racing and training maintenance or because a heavy rainfall has washed out the fine material in an area resulting in a portion of the track which is less resistant to hoof penetration and cannot effectively support the horse.

The third design is a variation of the second design of surface. As in the second design, the material is consistent to a depth much greater than the penetration of the hoof, even during breakover. This design, however, uses a regularly maintained pad under the cushion of the track. The pad is a partially compacted layer that is typically mixed one or more times per week to maintain a level of compliance in the layer below the cushion. Typically this partially compacted layer is 2 to 4 inches thick. The hardpan layer that develops below the harrow teeth is intentionally disturbed during a weekly maintenance procedure consisting of breaking and mixing of the layers. The composition of this type of dirt track is different from that of other dirt tracks, since it typically has clay or other cohesive material. Most of the wax-based synthetic racing surfaces are also maintained in this fashion. The high clay content dirt tracks are most common in drier climates where the track can be operated with lower moisture content, while retaining the support required for the propulsive phase of the gait.

The distinctions between the types of track are less clear in turf tracks. Because of the need to maintain a growing medium throughout the root zone, a turf track is generally homogeneous throughout the entire depth of the portion of the track that the hoof contacts. A turf track also uses aeration and other mechanical means to maintain a softer top layer and to open up the surface to increase permeability to the root zone and to help maintain the compliant top surface which is needed to reduce the peak load on the leg of the horse. The turf foliage and thatch layers are biomechanically analogous to the harrowed cushion on a dirt track. This surface and its associated root structure overlays the soil, which will be relatively homogeneous due to the maintenance needs associated with a healthy turf layer. A primary distinction between turf tracks and types of turf will be the degree of compaction of the growing medium and the strength of the associated root system, which will affect both the hardness and the shear strength of the soil. In general though, choice of materials that resist compaction and the use of mechanical methods to reduce compaction will result in surfaces that closely resemble the dirt tracks with a pad in their mechanical performance. The consistency of the maintenance protocol for this type of surface can be clearly seen from the condition of the turf growth.

Below the maintained layers of sand, or sand and clay, or turf, the primary function of the base is to create a consistent level surface. The role of a base that is more than 12 inches below the top surface of the track is less critical. In those cases, maintenance of the pad or false base is of primary importance. However, a consistent base is still an important factor, since it can be important for drainage and can provide a stable layer for installation and heavy maintenance of the track. For shallow sand tracks, the base is critical to maintaining a safe surface. Since the toe of the shoe will be close to the base, and the base provides a significant percentage of the support required for the hoof during the loading phase.

Geometrical Configuration

While there has been little comparative research on the different designs of surfaces of racetracks, slightly more consideration has been given to the geometrical configuration of a racing surface. However, most of the rigorous and systematic work has been done with trotting horses rather than with Thoroughbreds. Understanding the methods of describing the geometry of a racetrack is critical to understanding risk to the horse and rider. Typical areas of interest include the slope and possible existence of a crown on the straights; the length of the straights relative to the turns; the banking or super-elevation of the turns; and the radius of the turns and whether the radius of the turn is constant or varies through the turn.

On dirt or other surfaces where water is shed across the surface, even straight sections of the track will slope toward the inside rail. While some tracks have as little as 1% grade, the typical grade toward the inside rail is more than 2%. This allows the top surface of the track to be compacted with a float so that rain will drain to the inside rail. On wider tracks, a crown is used so that the outside one quarter or one third of the track will drain to the outside rail. While harder to maintain, this crowning of the track reduces the amount of water that must be managed on the inside rail and, depending on the track material, can reduce loss of fine material on the inside rail. The biomechanical impact of running on a sloped surface has not been studied systematically. The common asymmetry of the riding position (acey-deucy) with the left stirrup lower than the right, which is typically used for racing Thoroughbreds, further exacerbates asymmetry of loading on the animal. In contrast, most synthetic racing surfaces depend on vertical drainage and may have flat straight sections and more flexibility in the banking used in the corners. The impact of the banking in turns has been the subject of a large amount of discussion but only a small amount of systematic evaluation. The best understanding of the issues to be considered is in some articles outside of the scientific literature (Coons 1981). However, this work is based on engineering concepts used in road building rather than biomechanics. In this and other articles, the definitions and concepts that are well established from road and railroad building are applied to horse racing. In particular, the spiral turn is defined and the applicability to horse racing is discussed. Developing true spiral turns in the current race tracks would be quite difficult because of the required changes in the geometry of the track and the limited space surrounding most racetracks.

While Thoroughbred racing has been the subject of discussion of the issues to be considered, previous work with banking has never linked this to loading on the legs. This is a complex issue for thoroughbreds because the horse has an ability to lean into the corner and the asymmetric riding position of the jockey reduces lateral loading on the legs in the turns, while increasing lateral loading in the straights. These factors combine to make banking optimization specific to not only the speed and radius, but also to the positioning of the jockey and the gait of the horse. The most important work linked to the biomechanics of the gait and risk to the horse has been done with trotting horses, and it specifically links banking with injuries (Fredricson et al. 1975). This work has been repeated in other racing jurisdictions, but also with Standardbred horses (Evans and Walsh 1997). No comparable study has been performed with Thoroughbred horses with the differences in loading and gait, which makes extrapolation of the results from Standardbred horses problematic. There is, therefore, a need to understand the optimal design of a racetrack and to understand the implications of the current design for the health of the horse.

Composition and Design

No other aspect of racing is as firmly established as characterizing the use of basic composition measurements. At least a basic composition test is used at nearly all racing venues and is a key aspect of management of the surface. Less well understood is the interaction of track design and composition. The type of measurements, frequency and locations for sampling are different for a shallow sand track laid over a hard base than for the other track designs. In contrast, surfaces that can be effectively compacted are well suited to base materials and for use in tracks that have a false base of compacted material. Better quantitative methods of characterizing track material are needed. In addition, new developments from synthetic track material characterization must be extended to the testing of dirt and turf track materials, and these characteristics must be linked to the climate and design of particular tracks.

TESTING OF RACING SURFACES

Surface Material Characterization

The characterization of the racing surface materials is the best understood and most common type of racing surface monitoring. While important to the overall performance of the surface, material is just one aspect of developing an appropriate racing or training surface. Many of the discussions which revolve around the surface material, are really issues associated with weather or maintenance. However, without consistent and appropriate material, it can be difficult if not impossible to have a good racing surface.

Composition Testing

Most tracks use simple sieve and hydrometer testing (ASTM D422, 2007) to determine the sand particles size and percentage of clay and silt. The best-established characteristic of the sieve data is the correlation between broad particle size distribution and the compactability of the material. However, a number of other characteristics of the sieve and hydrometer data are less well established, such as relative percentages of clay and silt and the effect of fine material mixed in with coarser sand. Serious concerns have also arisen regarding the suitability of the traditional hydrometer testing for the determination of clay content (Lu et al. 2000), which is a critical factor in the design of tracks in more arid regions. In addition, the introduction of synthetic surfaces in North America was not initially accompanied by extensive new methods, but some parts of the industry have worked to develop these methods as the surfaces have been in use over time. In general, composition testing is useful for maintaining desirable properties of a surface that has been found to work. The simple composition tests must in the case of traditional dirt surfaces be supplemented with tests such as clay mineralogy, and in the case of synthetic surfaces, full thermo-mechanical and chemical characterization of the wax is required to maintain the properties of the surface. However, beyond the details of sieve and gas chromatography is the big picture of material response.

Perhaps the most important characteristic of all the cushion surfaces is the shear strength of the material. Shear strength is a function of the cohesion of the material and the shear. The cohesion of the material is a result of bonding between the sand particles, which is typically influenced by clay in dirt surfaces (Al-Shayea 2001) and wax in synthetic surfaces (Bridge et al. 2010a). In addition, friction between particles can be enhanced by the presence of fibers or roots that can further increase the shear strength. The frictional portion of the shear strength increases as the load on the material increases. Therefore, in order to understand a change in the shear strength of a surface, it is necessary to understand the details of the shape and size of the sand, as well as to understand the exact nature of the components that increase the shear and cohesion, such as fiber content, clay mineralogy and wax chemistry. The basic tests for dirt and synthetic surfaces are shown below:

Dirt Tracks

- Sieve separation
- Hydrometer tests of clay and silt
- Organic content
- Bulk density (as a function of moisture)
- Salt content
- X-ray diffraction for clay mineralogy
- Sand microscopy

Synthetic Tracks

- Wax percentage
- Fiber and rubber separation
- Gas chromatography of wax
- Differential scanning calorimetry of wax
- Oil content measurement
- Bulk density (as a function of moisture)
- Sand weight percentage
- Sand particle size distribution
- Moisture holding capability

Laboratory Performance Testing

Composition testing has the distinct limitation that it only describes the material, not the results which occur from the composition of the material. For surfaces that may have unique local sand or clay, this is particularly problematic, since the performance of the track may not be consistent with other sand and clay tracks. As a result, laboratory performance testing is needed both to evaluate the performance of the components of the track material and to determine if the composition produces values similar to other racing surfaces. In addition, in-situ performance testing should be used to describe the overall performance of the material when combined with the design of the track.

Shear Strength: The shear strength of the cushion material is the most fundamental characteristic of the performance of the track. A material with high cohesion will reduce the slide during the impact phase of the gait; low shear strength will keep the track from supporting the hoof during the propulsion phase of the gait resulting in cupping out. Finally, during breakover on many materials, the toe of the hoof will penetrate into the track, which is also characterized by the shear strength of the material. Figure 3 shows the configuration of the test cell used for the shear strength testing which is based on a standard test method (ASTM D4767, 2004). In the case of traditional materials, the testing is done at a range of moisture contents, whereas the track material temperature is controlled for the synthetic materials.

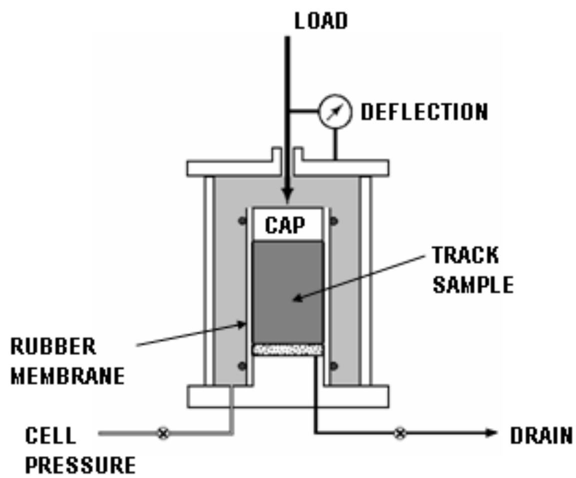

Figure 3: Configuration of the triaxial test cell used for the determining the triaxial shear strength of track cushion materials

In the triaxial shear, the test is performed using a cylinder of the test material that is surrounded by a pressurized fluid. The top of the cylindrical test specimen is loaded, and the deflection of the sample is measured. The point at which the sample begins to fail is the shear strength at a particular confining pressure. The test is repeated for a range of confining pressures to evaluate the cohesion (the strength with zero load) as well as to determine the relationship between increased loading and the shear strength of the material. Typically, twelve to 15 tests are performed to understand the effect of moisture or temperature on the cohesion and the frictional components of the shear strength. The link between these measurements and key aspects of the wax composition has been demonstrated for materials from a number of different synthetic racing surfaces (Bridge et al. 2010, Bridge et al. 2010a).

Compaction: The compactability of the surface material determines both the effect of horse traffic between maintenance of the material as well as the ability of a material to form a solid base under the track. These two goals are somewhat contradictory for a track where the top material and the base are the same composition. For example, the ideal track would have limited differences in the surface regardless of the amount of horse traffic that had passed across it. However, a good base material should be easy to compact. This is addressed in shallow sand tracks by using a different material for the base and the cushion. However, this means that under some circumstances the horses may end up running on a very hard surface, so maintenance of the base becomes critical. If a partially compacted pad is used, then a balance should be maintained between consistency of the surface and providing cushioning for the hoof. The compaction of the surface is a function of the moisture content of the material with maximum compaction occurring at particular moisture content. A modification of a standard test is used that allows a reasonable amount of material to be used for testing (ASTM D698 2007, Dı´az-Zorita et al. 2001). From the tests, a graphical curve relating moisture content versus bulk density is produced. This information provides guidance regarding the optimal amount of moisture to be added to the base material to allow it to be effectively compacted. The compaction curve also helps in understanding the effects of moisture on the track when the cushion is sealed prior to rain or otherwise maintaining the track.

Impact Absorption and Energy Return: The manner in which energy is absorbed in the track material has not been previously investigated and must be better understood to develop a system that tracks both the safety and speed of surfaces. In general, from the human literature it is known that deep and absorbing surfaces are tiring and may be associated with particular types of injuries (Kerdok et al. 2002, Barrett et al. 1997).   At the same time, it is clear that the proper tuning of a surface for humans can result in both a fast and a safe surface (McMahon and Greene, 1979). Understanding these dynamics for horse racing can be done to a certain degree with lab tests but is likely to also involve the design of the surface and thus will probably require in-situ measurements. The impact absorption during the initial impact stage is a function of the dynamic response of the hoof or the hardness of the impactor, as well as the modulus of the surface (referred to as the target in impact mechanics) (Abrate 1994, Goldsmith 2001). This same effect has been clearly observed in measurements on horses where the effect of surfaces is related in a complex fashion to the anatomy of the hoof (Burn, 2006). At this time no standard test is available, but the potential exists for tests developed for other purposes to be used to characterize the energy return and the impact absorption of the surfaces (ASTM D3763, 2010). However, as with the triaxial and other tests, the test will need to be run with careful control of the moisture content and temperature for dirt and synthetic surfaces respectively. Like most of the laboratory performance tests, these tests are poorly suited to turf tracks and are primarily applicable to dirt and synthetic surfaces.

Moisture Sensitivity: For both dirt and turf surfaces there is a need to understand the relationship between the water content and the surface performance. For these surfaces, moisture is the single most important variable in the maintenance of the surface. For shallow sand surfaces, aspects of the track design such as the type and consistency of the drainage along the inside rail is also important. For turf surfaces, the wetability of the material and the design and maintenance of the irrigation system are critical issues. As synthetic surfaces wear, it is also likely that the sensitivity to moisture will increase as the hydrophobic coating is lost from the surface. The relationship between moisture content and shear strength is well established (Al-Shayea, 2001), even for materials similar to those used in racing surfaces (Ratzlaff et al. 1997). In general, the shear strength, like the compactability, reaches a maximum at a particular water content with lower shear strength at both lower and higher moisture contents. However, the percentage of moisture at which the maximum occurs is highly dependent on the material. Further, the sensitivity of the moisture content around the peak is also highly material dependent. These characteristics must be developed for each material and then monitored for change over time. The use of the triaxial shear test as a function of moisture content is useful for dirt track material much as it has been used for synthetic surface materials (Bridge et al. 2010).

Permeability must also be considered if the flow of water though the surface is an important aspect of the design of the surface. Again, the permeability can be measured using standard test methods (ASTM D5856, 2007). For synthetic racing surfaces and turf tracks, the water must be able to penetrate the surface for drainage and for turf health. Most sand tracks do not have significant permeability through the depth. However, on these surfaces a portion of the drainage toward the rail may occur within the track surface, and a more permeable track will quickly recover from rain and will be more difficult to keep wet during dry periods. Generally, with the exception of the drainage toward the rail for shallow sand tracks, permeability of the surface is not a major factor for dirt racing tracks, since the surface is sealed before rain, and the primary flow of water is across the top of the track toward the rail.

In-Situ Testing

Regardless of the utility of the laboratory tests, these tests are essentially limited to ensuring that a track stays the same over time. In addition to these laboratory measurements, the consistency of the track is determined by how the design is implemented and by how effective the maintenance is in keeping a consistent surface that is within the original design parameters. However, even these measurements are not a complete picture of the track. The complex interaction of climate, maintenance, usage, and design occurs only at the racetrack where all aspects of the surface interact to provide a racing surface for the horses. Understanding a complete interaction of these factors requires in-situ performance measurements that do not presuppose a particular track design. In-situ performance measurements can be quite complex. Furthermore, it is clear from looking at different designs in different locations, that a single solution is not possible and that a track design which works in one location may not be ideal in all applications. Therefore, eventually only performance measurements that do not presuppose the design of the surface can be used for evaluating the characteristics of a racing surface.

Operational Measurements

Basic operational measurements of the surface depend on the design of the surface and the climate. Very few racetracks have a systematic approach to these measurements, even though they are critical to maintaining a consistent surface. These basic measurements have the potential to significantly improve the consistency of racing surfaces at those tracks that do not currently perform these measurements. Care must be taken to make the measurements in a manner consistent with the type of surface.

Moisture Content: The single most important variable on dirt or turf surfaces is moisture content. For turf surfaces, the moisture content of the surface both controls health of the turf and the mechanical properties of the surface. For dirt surfaces, the mechanical properties are a function of the moisture content and can vary dramatically with even small changes in moisture content, depending on the material. Moisture is challenging since it can change dramatically over a short time. In a shallow sand track, the biggest challenge is getting enough water on the track during a dry period, since many of these tracks can take a lot of rainfall and will shed the water very effectively. On tracks that are capable of operating effectively during dry periods, the challenge is to keep enough water on the track to maintain the shear strength and to manage the track during periods of rain. Two separate factors need to be addressed: variation of moisture over the total track between days, and variation in the moisture content around the track or, more formally, the temporal and spatial variation of the moisture content of the track.

In order to complete a spatial map to monitor the variation in moisture content around the track, a simple, fast reading probe is needed. This is not simple for a racetrack because racing surfaces operate over a wider range of moisture contents than seen in most types of agriculture. Also, on a track which experiences heavy rain, the salt and clay composition can change over time as water passes through the surface. Both salt and clay composition will affect the moisture readings from most moisture probes. The best probe for the conditions of the racing surface is a Time Domain Reflectometry (TDR) probe. The TDR probe is affected by both salt and clay but can be calibrated, and it effectively averages through the depth of the cushion of the track. Several devices are available, and a number of companies sell the same unit. These units are also available in a configuration that allows them to be used with a low cost commercial GPS system. Currently the communication to the GPS is not reliable and is not worth the bother until the communication with the GPS becomes more reliable. Without the GPS, data can be either written down or downloaded to a computer and manually mapped.

Typically it is best if the moisture content of the track is mapped after training and after racing. This gives an idea of wet and dry spots and can be shared with the maintenance team to identify approaches that can be used to avoid wet and dry spots. In particular, attention can be brought to issues with track drainage, shading of the track from foliage and the grandstand, and overwatering the inside of the turns due to the shorter distance traveled by the inside nozzle on the truck.

Temporal moisture measurement is more difficult because the weather can change during training and racing, and this should be considered in the water application and other maintenance such as floating of the track. Most experienced superintendents are good at observing these changes and responding in real time especially to rainfall. Evaporation is much more difficult. In some cases, the evaporation rate is evident from the color of the track, but a light spray of water on the top can mask a gradually drying track. In precision framing this is handled with evapo-transpiration models. These are models that describe the loss of water from the leaves and soil in farming. Using a specially designed weather station, these evapo-transpiration models can guide farmers in the irrigation of crops. While horseracing is similar, the models do not work for the main track. Since the track is harrowed between races and does not have crop cover, the evaporation rate for the dirt is much higher. While academic work has addressed some of the issues with evaporation from harrowed dirt surfaces, these models have not been implemented for the unique conditions of horse racing (Stroosnijder 1987, Mutziger et al. 2005). Factors such as the depth of the harrow need to be added to the model for the racing surface weather station. These models do not currently exist, but weather stations that have been developed for precision agriculture can be adapted for use on the racetrack.

Depth: Depth of the cushion is a critical and relatively straightforward measurement on shallow sand track surfaces. Requiring nothing more than a marked probe, the surface on a shallow sand track can be probed regularly at evenly spaced intervals to ensure that a consistent amount of cushion covers the hard base. This can also be done at more closely spaced intervals and with higher accuracy using ground penetrating radar. The best case is a combination of regular probing of areas with known issues and periodic evaluation with radar to ensure that the overall surface consistency is good.

For tracks with a pad or false base design, the depth is a more complex characteristic. For surfaces with a false base, the depth of the cushion usually is referenced to the top of the track, and as long as the base is firm can be measured in the same manner as with a shallow sand track. However, if the base is not well developed or if a pad is used, judgment is required to determine if the cushion is the same depth. In that case, the relevant depth is based on the depth of the material after periodic rototilling and on an assumption of accurate grades on the surfaces of the track. Alternatively, ground penetrating radar can in many cases be used to show the depth of the cushion and the depth of the pad if the difference in the density of the material is sufficient.

Material Consistency: One of the continuing challenges for surfaces is differences in wear and movement of material in the surface. For a turf track, this is mitigated by moving the inside rail on the track and spreading out the wear on the surface. However, for dirt and synthetic surfaces this is not done. Several factors will alter the material composition across the width of the track, including heavy horse traffic along the rail, loss of fine material along the rail to the drainage system, drainage from chutes across the main oval of the track, and physical movement of material due to the banking of the turns. Around the track variation in the composition can also occur due to movement of equipment and horses onto the track, more heavily trafficked portion of the track from the 6 furlong pole to the wire, and traffic on the track unrelated to racing. In both cases measurements are needed that can be used to compare the track on the inside rail with material further out from the racing surface. Sampling protocols for laboratory testing can include samples from locations that are two distances out from the rail as well as sampling from locations with known issues such as the close to the rail on the track where water from the chute will flow toward the drainage system. The most basic sampling protocol used is for material to be taken from the track at the ⅛, ½ and ¾ poles at a location 2 meters from the rail, along with two samples at the wire and the ¼ pole taken at distances of 1 meter and 3 meters from the rail. This sampling method gives insight into the variation of the material at two distances from the rail as well as proving insight into any variability around the track.

Temperature: For synthetic surfaces that operate with minimal maintenance and have not worn significantly, temperature essentially takes the place of moisture for turf and dirt tracks in the discussion of key variables for the surface. With proper maintenance, this effect can be moderated if not completely eliminated. Like the effect of moisture, the effect of temperature is not simply linear but will result in maximum values for the shear strength as well as other effects such as high cohesion of the material leading up to balling of the material in the frog. Monitoring the effect of temperature on the surface allows the use of maintenance methods such as harrow depth variation and the addition of water to reduce these effects.

Geometry: As discussed above, the geometry of the racetrack including the radius of the turns, banking, and transitions from the straight to the banked turns have been demonstrated to be important in Standardbred racing. While scientific evidence does not exist to demonstrate the optimal design of the turn for a Thoroughbred, logic suggests that the transitions should be smooth and consistent. Epidemiological work suggests that the geometry of the turns would be considered as a possible source of risk for the horse. Thus it is important to consistently measure the banking and to ensure that the transitions are maintained. This can be done with laser or GPS, and the positions can be either programmed directly into a GPS controlled grader or can be based on monuments placed on the perimeter of the track for reference purposes. This technology is well established; however, the precision required for horse racing surfaces is much higher than that of many applications and thus suggests that care be taken when using off-the-shelf technology.

In-situ Performance Testing

Regardless of how carefully the various aspects of racetrack design and maintenance are performed, these factors must be combined in the real world to produce consistent results. These results can only be measured in-situ so that the combined aspects of the surface characteristics can be understood. The ideal measurement method would replicate the horse moving on the surface. Direct measurements of people or horses are not typically used to characterize the surface because of individual variation in gait and other factors such as fatigue or injury (Shorten, 2008). In addition, testing the interaction of specific horses with specific tract configurations can be complex and expensive for an animal the size and speed of a racehorse. Therefore, the other options for in-situ testing of tracks should also be considered.

Simple In-Situ Testing Devices: Several simple devices have been proposed for the testing of racing surfaces and some of these devices are currently in use, such as the Clegg hammer, the dynamic penetrometer, and the agricultural penetrometer. However, with one exception, these devices have been adapted from other applications and typically require a significant amount of technique in order to produce repeatable results. The long term goal should be to develop monitoring methods that can be consistently applied and which cannot be easily influenced by the operator.

The Clegg Hammer is probably the most commonly used measure of surface performance in North America. The Clegg Hammer was developed primarily for looking at the compaction of base course layers for roadways. Because of the initial use of analog electronics in the early system, only the peak acceleration was displayed on the unit. The peak acceleration after four impacts of the mass on the surface was used in this unit to replicate the effect of equipment used to compact surfaces over which a roadway would be constructed. A significant body of work exists in the literature that related the Clegg hammer readings to parameters of interest, including some more recent work that even proposes the replacement of the nuclear density meter for some applications (Farrag 2006). The Clegg hammer has been shown in this work as well as other efforts to be capable of measuring the compactability of a surface if the moisture content is also measured. Clearly, however, the compactability requires that the moisture content be measured as well, since the moisture content has a first order effect on the compaction of materials (Al-Shayea 2001, Ohu et al. 1989, and others).

This type of measurement is useful for racing surfaces for the evaluation of the condition of the base and in measurements that match those that are relevant to road building. If the maximum compactability of a surface is important, such as with those surfaces that depend on a false base or hardpan layer to support the cushion, then the Clegg hammer is a useful tool for determination of this characteristic of the surface. In this application the cushion should be scraped away from an area of the track and the pad or false base should be tested. By using the average and maximum values the current and potential compaction of the pad or false base can be determined. The Clegg hammer, however, does not provide useful information regarding the peak load on the hoof because of the small weight and the repeated impact on a surface. The repeated impact of the surface with the Clegg hammer, which is necessary for influencing the surface below the top cushion, eliminates the influence of the top harrowed layer on the loading of the hoof. If the initial drop is evaluated, the measurement does not include anything except the top cushion layer. The standard Clegg hammer is 2.25 kg, which means that at the modest height from which it is dropped, it underestimates the loading on the surface from a running human or a canine. Ultimately, the Clegg hammer may have limited uses outside of compactability measurements for civil engineering applications, as relevant studies in ball sports and human athletics have recently begun to cast doubt on the simple analysis used with the Clegg hammer electronics for characterizing sports surfaces (Carré and Haake 2004). Indeed the Clegg hammer measurement is not a part of the standards used for tennis, soccer, or other sports. Instead, systems of measurement that are more closely based on the biomechanical motion of interest are preferred over a simple test like the Clegg Hammer, which is easy to perform, but which yields one-dimensional data. (Barry and Milburn 2000 and Cawley et al. 2003).

The dynamic penetrometer is the most widely used tool for the characterizing of racing surfaces. This device is made by Gill Engineering in Australia among other companies. Unlike the blunt weight of the Clegg hammer, this device penetrates the surface with a small tool surface that measures the depth of penetration into the surface. The dynamic penetrometer has been used primarily in areas where turf racing overwhelmingly predominates. This is because this type of device presupposes that to the depth of penetration into the surface, the surface is homogeneous. The strong layering common in any type of dirt and most synthetic surfaces will mean that the characteristics of recent maintenance will control the depth of penetration. However, for the types of homogeneous surfaces that are preferred for turf health and for certain aspects of surface design, this is a well-established tool, which is supported in the literature (Murphy et al. 1996). However, it is necessary to correct these measurements for soil type and moisture in order to create useful data that will help to provide an understanding of the performance of a horse on a surface. The weight of the device is small and the measurement probably relates most closely to the response of the surface to the hoof during breakover. Modeling of the surface interaction of the penetrometer makes it possible to create a general rating of turf conditions that can be compared between locations (Thomas et al. 1996).

The primary limitations to the dynamic penetrometer are the inability to deal effectively with a layered surface, such as most dirt and synthetic racing surfaces. Little discussion has also occurred regarding the applicability of the tool to some warm weather grasses that can create a layered root zone. The existence of a horizontal root system and perhaps even the existence of reinforcing fibers or grids in the surface can result in erroneous and highly variable readings from the penetrometer. In general, the characteristic length of any of the constituent materials in the surface should be several times smaller than the measurement device. For example, turf grids that are of the same size as the penetrating probe of the penetrometer will result in a measurement of the existence or absence of a turf grid under the probe, not a measurement of the strength of the soil. However, recognizing the limitations of the measurement and assuming proper calibration of the penetrometer to the soil type, along with simultaneous measurement of moisture, the dynamic penetrometer is a good tool for in-situ measurement of turf surfaces and is one of the few methods with solid support in the published literature. If the penetrometer data acquisition process were be automated to eliminate the operator judgment that is currently required, and if the collected data were linked to GPS coordinates, the resulting dynamic penetrometer system would provide a very promising tool for characterizing turf racing surfaces.

In North America, the term penetrometer is generally used to refer to a pointed probe that is pressed into the soil while the penetration force is measured. For agricultural applications, this is an important measurement, since crop yield is related to the compaction of the soil in the root zone, and the profile of the soil compaction can be measured. Depending on the crop to be grown in a soil, the allowable compaction or penetration resistance at a depth may be well characterized. Because the speed of penetration is not controlled, in damp soil the operator must take great care to ensure that the speed of the probe is sufficiently slow that the proper measurement of penetration which is relevant for roots is obtained. Like the Clegg hammer, the agricultural penetrometer is a useful tool for its intended purpose. In the case of the agricultural penetrometer, the quasi-static penetration resistance of soil may be related to the penetration resistance of a hoof on a surface, or it may be independent. Certainly, at the high speeds at which a hoof penetrates the surface, the moisture content and thus the dynamic properties are of critical importance. Like the Clegg hammer, the penetrometer can also make it possible to determine if a false base type surface has set up sufficiently, or if a track which uses a pad has set up excessively. While both of these measurements may be useful for daily maintenance support for the track surface and for identifying intervals at which the track should be have deeper maintenance, these measurement tools are not likely to be well suited for predicting either the performance or the risk to the horse.

The Going Stick: At an intermediate level of complexity for in-situ characterization of racing surfaces is the Going Stick (TurfTrax Ltd, Cambridgeshire, UK). This device has two load cells and is used manually in a combined two axes of motion to measure the racing surfaces. The systems are best suited for use on the turf, which is consistent with the origins of the device in the UK where most racing is held on turf. Like the dynamic penetrometer, the Going Stick assumes that the track consists of a homogenous top layer. Unlike the dynamic penetrometer, the Going Stick measures the force required to penetrate a flat blade into the surface. However, after the blade is placed in the surface, the top of the Going Stick is then rotated about the base so that the handle is at a 45-degree angle to the vertical. By measuring the peak force in a two axis load cell, information about not only the penetration resistance but the shear strength of the surface is obtained. From a biomechanical perspective this measurement has some characteristics in common with the breakover and propulsion phase of the gait. While this may not be the most critical measurement with respect to injury to the horse, the propulsive phase is very important for the performance of the horse. As a result of the origins of this device as a tool for providing data for the public, the interpretation of the measurement physics of the Going Stick seems consistent with the goals of the device. While a narrowly focused study was published on the efficacy of some of the related hardware for determining horse position (Spence et al. 2008), in general, the Going Stick is not supported by any data that is published in the open literature. In spite of the absence of any scientific support for their approach, of all the relatively simple devices for characterizing a surface, the Going Stick is the device with the greatest potential.

However, several caveats exist with the Going Stick. While the penetrating probe is larger than the dynamic penetrometer, it is still much smaller than the foot of the horse. As such, any component of the track that may be on the same scale as the probe can be a problem. For example, root structures in warm weather grasses and the rubber particles in some synthetic surfaces are as large as the width of the probe. Furthermore, the device is inserted manually into the ground. Speed of insertion is critical since soil is strain rate dependent especially at the higher moisture contents seen in many damp surfaces. This makes the operator technique very critical to the proper use of this tool. In the future, use of this tool has very good potential for use with turf surfaces, especially for cool weather grasses. For some types of synthetic surfaces it may also be useful. Additional work is needed to understand the use of the measurement and to support any association with risk to the horse.

Biomechanical Hoof Tester: The Biomechanical Hoof Tester is a system that has been developed more recently primarily in response to the limitations of the other testing methods described above. With the Biomechanical Hoof Tester, it is possible to load the track at the rate and loads that are applied by a horse at a gallop (Peterson et al. 2008). This system mimics the point at which the fore limb contacts the track and the weight of the horse is transferred to the hoof. This is the period of the gait during which both the highest vertical loads and the highest shear loads are applied to the soil (Biewener, 2003). The device that has been developed is a two axis drop tower type of apparatus which impacts a synthetic hoof at an angle to the soil surface (Figure 3). Two non-orthogonal axes of motion allow acceleration due to the sliding of the hoof in contact to be measured, as well as vertical loads and vertical acceleration.

In Figure 3, the two axes can be seen as a long set of rails and a shorter linear bearing apparatus that is attached to the hoof. With gravity acting on the first axis (the long rails on which the hoof and instrumentation slides), the force is generated by accelerating this mass down the rails. The total mass of the portion of the system that drops on the long rails is 30 kg, which provides energy at impact of approximately 540 J. This impact energy accounts for the energy of the hoof impacting the surface as well as the partial weight of the animal and associated musculature. A second set of shorter linear rails moves down as a part of the mass attached to the slide. This second axis is preloaded by a gas spring and only moves once the hoof is in contact with the soil. The difference in the angle between the first and second axes (5 degrees from the long rail angle) forces the hoof to slide forward towards the toe as it impacts the soil and the second preloaded axis is compressed. The angle at which the hoof impacts the soil is adjusted to match the published biomechanical data for initial impact of the hoof (Ratzlaff et al. 1993). A total of five data channels at a 4 kHz sampling rate are recorded during the testing. Attached to a stiff mass above the hoof is a three-axis 100 g accelerometer. Load is transferred into the gas spring from the hoof mass using a dynamic load cell with a 0 Hz (DC) to 36 kHz bandwidth. Redundant data from the acceleration and the position measurement is used to estimate the penetration into the soil and to verify the velocity of the hoof at impact. The angle of the hoof with respect to the soil is adjusted to seven degrees from the vertical to match treadmill data from horses at a gallop.

The two parameters that have been used from the Biomechanical Hoof Tester are the peak load and the accelerations in the horizontal and vertical planes. However, the entire data set consisting of loads and accelerations on the hoof are acquired which provides opportunities to consider other parameters that may be better suited to characterizing the performance of the surface, including impact injury scores (Dallap et al. 2010) and total energy return (Nigg 1995), among other measures. One particularly important parameter that has not been considered is the effect of the tuning of the track on the energy return. As previously mentioned in the discussion of laboratory performance tests, the potential exists based on experience with human athletes to produce a surface that can be fast as well as safe, through the tuning of the natural frequency of the surface to the stride frequency of the athlete (McMahon and Greene 1979). Some data is currently available from the Biomechanical Hoof Tester; however, it remains to be shown that the dynamic response is correlated with the response of the horse at a gallop.

Although the machine is large and somewhat complex, unlike the other tools, the biomechanical hoof tester replicates the speed and impact of one of the most critical phases of the gait for risk to the horse. While the two measured characteristics, shear and impact force, are expected to be related to performance of the horse, it is even more likely that these parameters measured with the full load and speed of the hoof landing represent the risk to the horse of catastrophic injury to the forelimb. The biomechanical hoof tester has been shown to be capable of measuring the effect of typical maintenance on a surface (Peterson and McIlwraith 2008). A sufficiently large study has not yet been done that makes it possible to link these measurements to risk to the horse. The immediate effect of the availability of this tool is to be able to characterize those aspects of the surface that pose the greatest risk of catastrophic and career ending injury. Even in the absence of a large epidemiological study, methods that are likely to result in more consistent surfaces will move racing toward the goal of providing a safer surface. It is also likely that data will be available that can also be used to predict performance of the horse on a surface. This less ambitious goal creates a potential for the testing to provide information to the public, which can help to support the need to do continued testing, which in turn will provide the data that eventually can be used to estimate the risk to a horse.

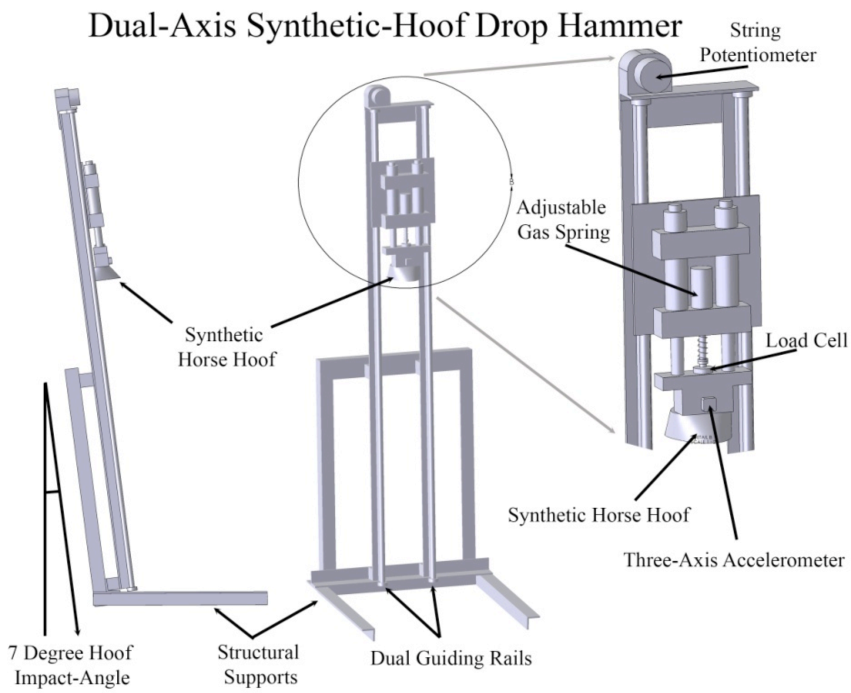

Figure 3: Biomechanical hoof tester used to replicate the speed and loading by the hoof on the racing surface.

UNDERSTANDING RACING SURFACE SAFETY

Beyond the tools needed for monitoring of racing surfaces, there is a need to understand what is done to the surface and how these surfaces are used. The condition of a racing or training surface is a result of maintenance, material, weather and usage. A complete understanding of the surface can only be obtained if these factors are all included to understand the outcome in terms of the resulting surface performance. The performance can then be measured relative to these inputs. In at least three cases this has already been done: the speed of a synthetic surface relative to the material temperature (Peterson et al. 2008), the effect of moisture on performance (Murphy et al. 1996) and the effect of maintenance on the measurements made with the biomechanical hoof tester (Peterson and McIlwraith 2008). These studies also show the correlation of inputs on the surface on the performance, which makes it clear that control and measurement of inputs has the potential both to create a more consistent surface and to understand the effect on the material of various environmental and other external characteristics.

Climate and Design

The first aspect of a large-scale project is to understand the interaction of climate and track surface design. While to a certain extent the design of a track surface is a response to local materials and tradition, it is primarily a response to the local climate. In arid regions, the retention of moisture and the ability to operate with a drier track have been dominant in the design of tracks. Conversely, in areas with frequent heavy rainfall, the priority is on a quick draining track that can retain the integrity of the surface even after a heavy rainfall. The first step in the project is to achieve a more comprehensive approach to mapping the use of different track designs and to understanding what other confounding risk factors may exist, such as turn radius and banking, as well as the design of the surface drainage around the track. In order to be done properly, the turns will have to be surveyed to understand the as-built and as-maintained geometry. This along with the climate of the area is the critical baseline information for understanding the decisions being made with a racing or training surface.

Monitoring of the Racing Surface

Once the track design is known, a protocol for monitoring can be developed. Aspects of the track that are crucial for some designs are less important for other designs. For example, cushion depth must be carefully monitored and measured for shallow sand tracks used in areas with heavy rainfall. In contrast, tracks which are maintained with a pad under the cushion have few issues with the cushion depth but can have a pad that either compacts excessively or does not compact sufficiently to provide the required support for the hoof of the horse during propulsion. These surfaces require that density and compaction of the surface be monitored on a regular basis.

Composition

Over a shorter time interval, movement of the material and the vertical segregation of the material due to water and maintenance can be an issue. Spatial variation in track composition is a key source of track inconsistency. Identifying the existence of variable track composition and the resulting differences in track performance provides an understanding of allowable tolerance for the separation of the material. This information can only be developed based on data from the track that shows the degree of material segregation and associated variability in surface performance. Similarly, other factors in the track composition such salinity or clay mineralogy must also be better understood prior to developing a complete understanding of the racing surface and allowable variability. Therefore, the track material must be characterized as fully as possible at regular and frequent intervals so that variation can be tracked and laboratory testing of the resulting materials variability can be fully understood.

Maintenance

Unlike material composition of the track, the resolution of the maintenance monitoring that is required is well understood. Maintenance must take place daily, and the frequency as well as the type of maintenance is always critical. Comprehensive monitoring of a racing surface requires that all of the track maintenance procedures must be monitored constantly and that the maintenance must be performed in a consistent manner. The only way that the effect of maintenance on the track surface can be understood is for all of the maintenance to be logged, including type of equipment, depth, speed and number of passes. These factors combine to describe the operation of the equipment and create the surface the horses run on.

Weather and Usage

Finally, the other two critical inputs are the usage of the track and the weather. Heavy usage will create a more inconsistent surface, which will require additional maintenance. Similarly, weather defines both the frequency and type of maintenance. Heavy rain requires that a dirt track be compacted, while dry periods and conditions of rapid evaporation require frequent water application and changes in maintenance that will reduce the track evaporation rate. These two input factors and the resulting response create a more or less consistent surface for racing and training.

Performance

A combination of factors: weather, usage, maintenance, composition, and design result in a surface that is harder or softer, faster or slower, and more or less consistent. To the extent that these factors can combine in a positive manner, the racing surface will perform better or worse and will be either safer or more prone to injury. The goal of the performance measurement is likely to be narrower, focusing on the result of uncontrolled inputs on the surface, weather, and usage and on understanding the effects of the responses to these inputs, water, and maintenance and material modifications. While the most direct method of understanding the surface performance is to measure it directly, the complexity and cost of having consistent monitoring may be prohibitive. Therefore, if the performance effect of each of the possible additives is known, then simply tracking the addition of materials to the surface may be sufficient. This type of indirect measurement is certainly reasonable, but it presents significant additional challenges for the research.

SAFETY AND THE EPIDEMIOLOGICAL LITERATURE

Epidemiological studies on Thoroughbred race horses suggest that differences in injury risk exist based on training and shifts between surfaces. However, the large number of factors involved indicates that a need exists for more work in this area, not only to link the surface properties to risk, but also to clearly separate other risk factors. As a result, an understanding of other equestrian surfaces may provide some guidance in spite of the differences in loading and conditions.

The most common reason for lameness in sport horses is injury to the distal limb. As with racing, the interaction between the horse (distal limb/hoof/shoe) and supporting surface is often considered to be an important factor in mechanisms of injury. For instance, the surface and shoeing practices in show jumping during the recent Olympic Games (2004 in Athens, Greece) has been a great source of speculation in the causes of acute tendon injuries of three jumping horses competing. Review of the scientific literature reveals meager support for the understanding of the interaction of the horse and common surfaces. In a recent literature review on track surface injuries, the conclusion was that an understanding of the risk factors for musculoskeletal injuries is emerging, while information to produce guidelines for the design and management of safer racetrack surfaces is insufficient (Stubbs et al. 2004). However, guidance for design of racing surfaces from arena design is unlikely. A review of scientific databases reveals essentially no scientific basis for the arena surface design for non-racing horses. In a popular text on arena surfaces, suggestions are derived from trial and error and even include parallels from racetrack surface experiences in spite of the differences in design and gait (Malmgren 1999). The need for objective information and methods to evaluate the relationships between the distal limb-surface and injury is fundamental for the development of safe surfaces in training and competition in all uses of horses.

Therefore, the Thoroughbred epidemiological database remains the most valuable existing collection of work. Correlations between injury types and surfaces have been established for both training and racing surfaces. Recent studies have demonstrated differences between training practices, surfaces, and risk for injury that are independent of other known risk factors such as nutrition, conformation, and genetic predisposition (Rossdale et al. 1985, Robinson et al. 1988, Pool and Meagher 1990, Kobluk et al. 1991, Mohammed et al. 1991, Moyer and Fisher 1992, Stover et al. 1992, Johnson et al. 1994, Oikawa et al. 1994, Peloso et al. 1994, Bailey et al. 1998, Estberg et al. 1998, Cohen et al. 1999, Nunamaker 2000, Hernandez et al. 2001, Hill et al. 2001, Verheyen et al. 2005ab, Parkin et al. 2005). While a comprehensive review of this literature is outside of the scope of this paper, the critical nature of the epidemiological work to link surface properties to the health of the horse cannot be overemphasized. Once the measurement methods exist to characterize surfaces, then data sets such as the Equine Injury Database can be used to link safety of the horse and rider to objective surface measurements. While the consistency and fairness of the surfaces can be improved by developing measurement tools, actual linkage to health and safety will require broad and high quality data sets to develop surfaces that are engineered for safety of the horse and jockey.

ENGINEERED RACING SURFACES

At various stages during their development, synthetic racing surfaces have been referred to as “engineered surfaces” rather than “synthetic” or even “advanced” racing surfaces. Regardless of the terminology used to describe the surfaces, for the most part the people developing the materials were not materials engineers, geotechnical engineers or biomechanical engineers. The surfaces were developed by people with a commitment to equestrian sports and racing with significant experience with installation of arenas, racing and training surfaces. A need thus remains to apply engineering principles to the design and maintenance of synthetic and traditional dirt and turf surfaces. With proper monitoring, these surfaces can then be tracked over time to determine the characteristics of surfaces that will result in safe, high performance footings.

The initial set of design requirements for engineered racing surfaces should consist of the modulus of the surface material, shear strength of the surface material, and the rebound or coefficient of restitution of the material. In the absence of knowledge about the optimal values for these parameters, the objective of an engineered surface should be to match surfaces that are acknowledged to have desirable performance characteristics, and thus to have the measured values within the range of a typical racing surface. Determination of the optimal values will only come after large-scale epidemiological studies have provided the required direction for reduced injury rates. This material must then be used in a track design that is based both on geometry and a physical design that is optimized for maintenance, and to the extent possible, that uses best practices for track surface design. For example, nearly all current racetracks do not transition the radius of the turn properly to allow a spiral turn design to be used. While it is certainly important to have the proper amount of banking in the turns, it is currently impossible to have smooth and appropriate transitions if turns of a constant radius are used for the track designs (AASHTO 2004). The idea of changing turn radius in a spiral turn like those used in highway design is applicable to Thoroughbred racing; however, the degree of banking used in highway design is not applicable because of the compliance and adaptation of the horse and rider. It is unrealistic to expect the change in turn radius to be made to existing tracks; however, the discussion of optimal banking in horseracing is often lost in more well-established issues, and this type of proper geometry is a key element of an engineered racing surface.

The final element of a truly engineered racing surface is the development of preventative and well-defined maintenance protocols. Synthetic surfaces have in the last two years begun to approach this ideal as closely as any type of surface. As a result of extensive work on the wax thermal chemistry and resulting mechanical behavior, it is becoming more realistic to expect that the synthetic surfaces can be more consistent with temperature and that the degradation of the surface safety over time can be reversed. The greater variability and complex chemistry of natural materials makes this a longer-term effort for dirt surfaces.

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