Measurement of racetrack surface using instrumented horse shoes
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Characterising the interaction between the hoof and track surface in racing thoroughbred horses

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Foreword

Track surface conditions in Thoroughbred racing are known to have a significant impact upon both racing performance and the incidence of musculoskeletal injuries. However, the details of the interactions between track surface and biomechanics at racing speeds are poorly understood.

To investigate hoof impact at racing speeds, a racing shoe was modified to contain inertial transducers and a strain gauge. The shoe was capable of measuring three-dimensional accelerations and deformation due to hoof loading. This new capability will benefit racing authorities who are responsible for the welfare of horses during training and racing, as well as helping track designers and track managers. The measurement technique is equally applicable to other equine sports.

The key outcome from this research was a capability to measure track properties that relate directly to hoof impact at training and racing speeds.

Policy makers now have a direct means of addressing concerns regarding the rating of racing surfaces, including the differences between tracks of different design, as well as the variability within tracks. The methods also provide the opportunity to investigate injury and breakdown during the most stressful conditions associated with high speeds, fatigue and turning corners.

This project was partly funded by the RIRDC Horse Program, with industry partners matching the funds provided by the Australian Government. Sperero Pty Ltd funded test planning, data recording and analysis, and software development. Permission to use design information contained in the instrumented shoe was provided under an agreement with the Defence Science and Technology Organisation (DSTO). PraxSyS Pty Ltd carried out development of the Instrumented Horse shoe hardware, which was additionally funded by the University of Melbourne.

This report is an addition to RIRDC’s diverse range of over 2000 research publications and it forms part of our Horse R&D Program, which aims to see the Australian horse industry be nationally and internationally recognised for its excellence as a reputable user and supplier of quality horses, products and services, and for the industry to expand in the global market by having the requisite skills and knowledge for efficient, profitable and sustainable production.

Most of RIRDC’s publications are available for viewing, free downloading or purchasing online at www.rirdc.gov.au. Purchases can also be made by phoning 1300 634 313.

Craig Burns
Managing Director
Rural Industries Research and Development Corporation
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Particular acknowledgement is made to Melbourne University Department of Veterinary Science staff and North Melbourne Institute of Tertiary Education staff for organising and attending track trials outside of normal working hours. The assistance of Racing Victoria Limited and their track managers in Victoria who provided access to their tracks is also appreciated.
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Executive Summary

What the report is about

This report describes the development of a method for measuring the surface properties of racing and training tracks used in Thoroughbred racing. Central to this method was the use of a race-capable, rugged instrumented horseshoe. A Melbourne Innovations company developed the instrumented horseshoe, with advice from the University of Melbourne School of Veterinary Science, funded by a Research Collaboration Grant provided by the University of Melbourne. The shoe has provided the first reported measurements of hoof impact at typical racing speeds, and so enables information to be derived on the surface properties and limb loading under conditions where injury and breakdowns are known to be most prevalent. The Thoroughbred racing industry has a very strong obligation to reduce breakdown and injuries in this sport. The current knowledge of hoof-track interaction is recognised as poor, and the management of tracks as problematic. The use of the instrumented horseshoe, or similar lightweight devices used as drop-in replacements of normal shoes under racing conditions, provides a means for addressing these industry problems.

Who is the report targeted at?

The immediate target beneficiary of this research are the racing authorities, who are responsible for the welfare of horses and jockeys in racing, a topic of major importance to the future of the sport.

Where are the relevant industries located in Australia?

The Australian Racing Board (2001) found that the Australian Thoroughbred Industry employed a total of 249,000 full-time and part-time staff, equivalent to more than 77,000 full time jobs. 67% of these jobs are in non-metropolitan areas. The industry had 6,529 trainers, 87% of whom were located in non-metropolitan areas. The industry created a gross economic impact of $7.7B, of which 49% was generated in non-metropolitan regions. The distribution of employment was NSW 31.8%, Victoria 28.6%, Queensland 20.3%, SA 7.1%, WA 8.7%, Tasmania 2.2%, NT 1.2%.

Background

The instrumented horseshoe enables, for the first time, hoof impact measurements to be made under racing and training conditions.

Aims/objectives

The aim of this study was to demonstrate a method for characterising racing surfaces. The beneficiaries of this knowledge will be the racing authorities and their track designers and managers, who are responsible for providing suitable track conditions. Secondary benefits are expected to affect the trainers and owners of horses, who need to balance their aim of producing high performance results with animal welfare considerations.

Methods used

Measurement techniques, typical of aerospace applications, including mathematical modelling, were used to determine track surface characteristics.

Results/key findings

Four different track surfaces were measured, including grass, sand and a synthetic surface. The analysis showed significantly different characteristics between the different surfaces, as well as different levels of variability within the surfaces. In addition, the sequencing of hoof deceleration and the build up of limb load was observed to differ between the surfaces. The measurement method
provided detailed and relevant information on hoof surface impact at typical training and racing speeds. With further development and application to a broader range of surface conditions, the method has the potential to provide a standard, comprehensive, and rapid tool for use in designing, managing and rating track surfaces.

**Implications for relevant stakeholders**

This development will provide policy makers with technology that will address an important animal welfare issue within the Thoroughbred racing industry, and international leadership in an industry in which Australia is a major participant.

**Recommendations**

Because the technology used in this study was developed for use in “field conditions” it is not limited to laboratory application, but can instead be used to measure track surface interactions under training or racing scenarios. The approach uses modern electronics, instrumentation, and advanced communication and data analysis techniques.

Within the present study, we demonstrated the capability of the method to detect differences in track surfaces under a few test conditions. However, these differences represent only the metaphorical “tip of the iceberg” in terms of capability. With more data collected from different tracks, under different conditions, and using shoes worn by different horses, we would be able empirically to determine the relative importance of the differences that we are currently able to detect. We consider the current shoe design to be advanced enough to be transitioned from a prototype to a short run of manufacturing for research-only purposes. This would dramatically reduce the price of the shoe and allow a more widespread research program to be conducted, in which more conditions could be tested.

We recommend that further funding and industry initiatives should be encouraged, to develop the method as a standard means of providing data for track design and track management, and for rating track performance.
Introduction

The aim of this project was to determine whether impact measurements, made using an instrumented horseshoe, could be used to characterise and distinguish the properties of different racing and training surfaces. Previous investigations of hoof impact using accelerometers or load cells have been reported by Barrey (1990), Roepstorff and Drevemo (1993), Kai et al. (2000), Burn (2006), Setterbo et al. (2009), Schaer et al. (2010) and Moorman et al. (2012). Thomason and Peterson (2008) provided a review of the current knowledge of the hoof-track interface.

Previous studies of surface interaction have been limited by speed and instrumentation. When specially designed shoes have been used, the extra weight limited testing to speeds lower than those encountered during training or racing (Barrey 1990; Roepstorff and Drevemo 1993; Kai et al. 2000; Setterbo et al. 2009). When accelerometers have been used independently, these have generally been mounted on the hoof wall (Burn 2006; Schaer et al. 2010; Moorman et al. 2012). Hoof mounted accelerometers may measure attenuated signals due to compliance in the mounting and the hoof, rather than the true acceleration signal at the hoof-ground interface. In this study, the transducers for inertial and strain measurements were mounted in the body of a standard aluminium racing shoe. With this arrangement, measurements could be made at all speeds and in all conditions, and provided data that was representative of the interface between the hoof and surface.

Track surface conditions are known to have a significant impact upon both racing performance and the incidence of musculoskeletal injuries (Thomason and Peterson 2008). However, the details of the interactions between track surface and racing biomechanics at racing speeds are poorly understood. In the scientific literature, only the statistical correlations between performance, injury and track surface have previously been reported in any depth. The biomechanical mechanisms by which the track surface influences athletic outcomes remain largely unknown. In particular, there are currently no measurements at racing speeds, where many injuries occur.

The hoof is exposed to high accelerations and rotation rates during the flight and impact phases of the stride, and high forces during the stance phase (Thomason and Peterson 2008). The highly dynamic motion of the flight and impact phases can be reconstructed using measurements from linear accelerometers and rate gyroscopes rigidly attached to the hoof. In this study, an aluminium racing shoe was modified for this purpose. The shoe was also instrumented with a strain gauge in the toe region, to estimate the ground reaction force from the characteristic deformation of the hoof during the stance phase (Savelberg et al. 1997).

The present study was confined to an analysis of penetration and slip during impact only, to determine whether measurements from the instrumented shoe could be used to characterise racing surfaces to a level of detail that could assist surface design and maintenance. We constrained our testing to medium galloping speeds, typical of modest training exercises.

In order to characterise surface properties, we used a simple mechanical model of the surface interaction during impact. The parameters of this model were tuned so that it predicted the recorded acceleration data using only the estimate of ground reaction force as an input. Thus, we condensed the time-varying acceleration history that was measured by the shoe into a set of model parameters that represented each surface. We considered this modelling approach to be superior to previous frequency domain analyses because it introduced both a mechanical explanation for observed phenomena and a predictive power that could assist greatly in track design and analysis. The variance of model parameters among strides provided a statistical measure of the variance in the results for each track. Finally, by providing controlled mechanical inputs to surfaces, independent of the horse, the model may in future be validated under laboratory conditions, and thus provide even greater confidence in the understanding of the hoof-ground interaction. None of these advantages were found to be available in a simple frequency-domain characterisation.
Objectives

The objectives of the study were:

1. to measure the hoof biomechanical parameters of Thoroughbred racehorses, including impact acceleration, ground penetration, slip distance and limb penetration load on different tracks and under varying conditions,

2. to relate the hoof biomechanical parameters to existing methods of track surface measurement,

3. to identify any parameters of hoof biomechanical performance which are not well predicted by existing methods of track surface measurement, and

4. to recommend alternative methods of track surface measurement which may better account for the variation in hoof biomechanics.
Methodology

The detailed methodology of the project is described in the following chapters. A brief summary of the methodology is presented in this section.

We constructed a novel instrumented horseshoe for this project. The instrumented horseshoe was capable of measuring linear accelerations, angular rates of rotation and an approximation of ground reaction force. The shoe was fitted to a Thoroughbred horse that was exercised on four suburban racecourses in the Melbourne region. Data were collected at a range of speeds, from walk to a moderate gallop.

Standard equations of rigid body motion allowed us to analyse the impact and stance phase data from the instrumented horseshoe. We calculated the time history of the hoof position from the measured hoof accelerations. This was used to compute basic parameters regarding the hoof kinematics and loading, including the maximum penetration of the hoof into the surface and the hoof load supported by the surface at minimum hoof velocity. We performed a statistical analysis on these simple parameters, as described below, to demonstrate that a significant difference existed between the measurements on the various surfaces.

Our main analysis technique involved a novel model of the interaction between the hoof and the track surface that took into account elastic, damping and compaction phenomena that might occur during impact and stance. The model had several parameters that characterised each surface; these being the surface non-linear stiffness, $k_e(z)$, the surface non-linear damping, $c(z)$—both of which were functions of the penetration depth, $z$—and a constant compaction coefficient, $c_c$, the details of which are described below. The model used the measured strain from the shoe to predict the penetration as a function of time. The parameters for each surface were found by tuning the model so that the predicted penetration matched the measured result.
**Instrumentation Design and Manufacture**

The instrumentation of the horseshoe is shown in Figure 1. It comprised two main parts: an instrumented horseshoe and a recording unit. The horseshoe contained a strain gauge half-bridge in the toe, located and oriented to measure the radial expansion of the shoe while minimising the influence of other bending. Due to the restricted volume available, we mounted the inertial instrumentation and signal conditioning electronics in the heel of the shoe. The inertial instrumentation consisted of three single-axis ±70g MEMs linear accelerometers and a dual-axis ±1600°/s MEMs rate gyroscope, aligned with the axis system shown in Figure 1. We selected the instruments based on their rating, analogue output, bandwidth capability, commercial availability and small package size. Signal conditioning included a power regulator, strain-bridge amplifier, single-order passive high and low filters for selected channels connected to an 8-channel, 16-bit SPI-output analogue-to-digital converter. A flying lead, for connection to the recorder, exited the shoe behind a quarter-clip, which provided mechanical protection.

The recorder contained a microprocessor, solid-state memory and battery. Prior to each test, the recorder was configured with channel selection, scan rate (up to 2 kHz), arming delay and recording period. It was then mounted on the hoof and connected to the instrumented horseshoe. Following the arming delay, the recorder captured data for the specified recording period, with an LED indicating its status. Following each test, the recorder was removed and connected to a computer for raw data transfer and post-processing.

![Analysis Axes](image)

**Figure 1** Instrumentation and hoof mounted data recorder.

To construct the instrumented shoe, we machined an existing cast aluminium racing shoe on a vertical mill, creating interconnected pockets that were suitable to house the instrumentation. The pockets extended only part of the way through the thickness of the shoe, so that some of the shoe remained below each pocket to protect the instrumentation from the ground. The tops of the instruments were mechanically protected during trials by the solar surface of the hoof. We installed miniaturised printed circuit boards, a strain gauge and connecting wires in the appropriate pockets and sealed them in place using a potting compound. The completed instrumented shoe was a similar weight to the original aluminium racing shoe.
Data Collection

A single, fit Thoroughbred horse was used for all trials. An experienced farrier fitted the horse for an aluminium racing shoe. The shoe was modified over a period of several weeks to add instrumentation (described above) and then attached by the farrier in a traditional fashion with nails prior to each exercise session. The contralateral limb was fitted with a similar shoe, without instrumentation, to retain symmetry. The horse was ridden at a range of speeds, from walk to a gallop, on four different training and racing tracks. In addition, measurements were made on a range of other surfaces, including bitumen, in order to provide a check of the data processing algorithms.

The racing track surfaces chosen for the study are shown in Table 1.

Table 1  The racing track surfaces used for the study. The dates indicate when trials were conducted.

<table>
<thead>
<tr>
<th>Track Type</th>
<th>Racecourse</th>
<th>Date</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>Werribee</td>
<td>27 Mar 2012</td>
<td>GRASS1</td>
</tr>
<tr>
<td>Synthetic</td>
<td>Geelong</td>
<td>4 Jun 2012</td>
<td>SYNTH</td>
</tr>
<tr>
<td>Grass</td>
<td>Cranbourne</td>
<td>24 Nov 2012</td>
<td>GRASS2</td>
</tr>
<tr>
<td>Sand</td>
<td>Cranbourne</td>
<td>24 Nov 2012</td>
<td>SAND</td>
</tr>
</tbody>
</table>

The speed of the horse was not measured directly, but was estimated using the stride duration (see, for example, Parsons et al. 2008), with data interpolated from the values shown in Table 2.

Table 2  Stride duration vs. speed, determined on a treadmill. These values were interpolated to compute the speed of the horse during trials.

<table>
<thead>
<tr>
<th>Stride Duration (ms)</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>581</td>
<td>1.67</td>
</tr>
<tr>
<td>211</td>
<td>4.03</td>
</tr>
<tr>
<td>110</td>
<td>7.06</td>
</tr>
<tr>
<td>90</td>
<td>8.33</td>
</tr>
<tr>
<td>63</td>
<td>18.06</td>
</tr>
</tbody>
</table>

Figure 2 shows some example data acquired by the shoe at the Werribee Racecourse (GRASS1). This data was recorded at 2 kHz, over a period of 15s, during which the horse accelerated through a transition into gallop. Increases in peak toe strain, impact acceleration and roll rate are visible. The figure also shows the detail from a single stride, in which the main stride events and the features of the recording are visible. Figure 2 does not show the other channels (2 accelerations and 2 rotation rates), although these were also recorded simultaneously.
Figure 2  Example of raw data acquired by the instrumented horseshoe during a transition to gallop on the Werribee Racecourse (GRASS1). The bottom inset figure shows the detail of an individual stride. Data were recorded at a rate of 2 kHz.
Data Processing

Heuristic Stride Phase Identification

We identified phases of the stride using heuristic algorithms, developed during the project to be reliable across a range of gaits, speeds and surfaces. These algorithms detected the timing of the following events for each stride (see Figure 2 for an illustration of the event timing):

- **Impact start**: the time at which the hoof first contacted the surface
- **Impact end**: the time at which the strain signal was maximum
- **Breakover**: the time at which the hoof began to rotate at the end of stance

From these data, the stance duration, flight duration and stride frequency were computed.

Inertial Instrument Calibration and Drift Error Correction

The accelerometers and rate gyroscope MEMs devices that we used to instrument the horseshoe are known to suffer from small systematic errors (see, for example, Rehbinder and Hu 2004, for a discussion of these issues). These errors often have a dependence upon temperature. They have a special importance when the inertial measurements are used to compute position data, as we did during this study. The small errors, when integrated to obtain position signals, result in a “drift error”, causing the computed position and orientation to drift gradually from the true values due to the integration of small constant offsets. The drift magnitude has a dependence upon time, and will become worse when signals are integrated over longer periods of time. In order to account for this drift, we selected points during the stance phase at which we could perform a signal re-calibration.

During the central part of the stance phase, the vertical linear velocity and angular velocities were assumed to be zero. These boundary-condition states allowed the correction of any bias error on a stride-by-stride basis. Additionally, during this part of the stride, we performed a simple 1g check on the accelerometers to confirm the manufacturer’s calibration of the instruments.

We did not perform independent “bench test” calibrations, because the large accelerations and rotations experienced by the hoof could not be replicated reliably using available equipment. In this comparative study of track surfaces, calibration errors would apply equally to all surfaces and so should not alter the comparisons. In future, bench-test calibrations could be performed using high-speed multi-axis robots, capable of replicating the combinations of acceleration and rotation experienced by the hoof.

Estimation of Ground Reaction Force Magnitude from Strain

The signal from the strain gauge in the toe of the shoe was assumed to be directly proportional to the ground reaction force magnitude. This signal was not calibrated against force plate or pressure mat measurements. However, careful preliminary testing confirmed that it provided a good indication of the stance phase, and that its shape closely matched previous reported measurements of ground reaction force magnitude during walking and trotting.

Any errors arising from the assumed relationship between strain and ground reaction force magnitude would apply to all surfaces used in the study, and so should not alter comparisons.

Importantly, the units of compaction model parameters (see below) are likely to be affected by any inaccuracies in this measurement. Hence, the assumption of a proportional relationship between toe strain and ground reaction force magnitude should be considered when interpreting the accuracy of compaction model parameters.
Impact Peak Reconstruction

Two competing factors determined the acceptable range of the accelerometers that were used in the horseshoe: range and resolution. Accelerometers with a high range (i.e. those able to measure greater magnitudes of acceleration) had a decreased resolution. We selected accelerometers with a range that was suitable to measure most of the signal. These were rated to ±70g, with a non-linear measurement up to 100g. However, these accelerometers were unable to measure some of the very high peaks in vertical acceleration that occurred transiently during impact, which we estimated to reach over 100g. The very high peaks occurred over a very short period of time—approximately 5ms, or around 1% of the stride duration—and thus their contribution to the integrated position signal was small despite their large magnitude.

The missing peaks were reconstructed by matching the rising and falling curve slopes at an 85g level. This technique was tested at 40g, and resulted in an error of approximately ±5g in the reconstructed peak magnitude of known impacts.

Motion Reconstruction

The accelerometers and rate gyroscopes were rigidly attached and aligned along orthogonal axes within the horseshoe (see Figure 1). We were able to compute the time histories of the shoe velocity, displacement and orientation by solving the standard six degree-of-freedom equations for the motion of a rigid body, taken together with the boundary conditions described above.

During later analysis, we focused only on the stance phase. For the purpose of the compaction model (described below), only the vertical acceleration was considered. We ignored any rotation of the shoe for the compaction model analysis, assuming it to be oriented horizontally at all times. We also computed slip distance by integrating the motion in the cranio-caudal (y) direction of the shoe following impact.

Compaction Model

A single degree-of-freedom model was formulated to characterise the different track surfaces. This model was unlikely to provide a comprehensive physical description of surface properties, but was intended to capture the key surface reaction parameters that might be necessary to distinguish different surfaces.

Thomason and Peterson (2008) described hoof impact as having two phases. In the first phase, the hoof was regarded as an unconnected mass decelerated from some initial velocity. In the second phase, the dynamic load associated with the mass of the horse’s body was supported by the surface through the limb.

For the initial “free mass” impact phase, our model represented the initial velocity of the hoof by imparting an initial velocity to the displacement state variable that described the position of the hoof mass. For the second phase, in which the limb began to support the mass of the limb, we introduced an additional load to the hoof mass that was proportional to the strain gauge measurement. We did not model a change in participating mass between the impact and support phases.

Our model was derived from the second-order non-linear spring-mass-damper system shown in Figure 3. The system in Figure 3 consisted of a non-linear elastic spring element (stiffness $k_s(z)$) in series with a non-linear plastic spring ($k_p(z)$), the latter corresponding to a permanent, unrecoverable deformation. A non-linear damper (coefficient $c(z)$) provided a velocity-dependent force during compression only. The impacting hoof was represented by a connected mass $m$. An external force, $P$, represented the dynamic mass of the body acting on the hoof, as measured by the strain signal. The system in Figure 3 had two displacement state variables ($z$ and $z_p$), but was simplified as described below by considering penetration and rebound as two separate phases.
Our compaction model distinguished the penetration phase by the velocity of the $z$ displacement, so that penetration occurred when $\dot{z} > 0$ and rebound occurred when $\dot{z} < 0$. We did not include the plastic displacement, $z_p$, as a state variable when solving for the system, because we approximated the motion by these two phases only (i.e. there was no periodic oscillation between penetration and rebound). The equation of motion of our compaction model was thus:

$$m\ddot{z} = \begin{cases} P + c(z)\dot{z} + z(k_e^{-1}(z) + k_p^{-1}(z))^{-1}, & \dot{z} > 0 \text{ (penetration)} \\ P + zk_e(z), & \dot{z} < 0 \text{ (rebound)} \end{cases}$$

We related the non-linear elastic stiffness, $k_e(z)$, to the non-linear plastic stiffness, $k_p(z)$, through the use of a constant compaction coefficient, $c_c$, defined as:

$$c_c = \frac{z_p}{z}$$

so that:

$$k_p(z) = k_e(z)\left(\frac{1}{c_c} - 1\right)$$

We made the assumption that energy was absorbed by the surface through material compaction, particle displacement and surface elasticity. Burn (2006) described compaction as the process of increasing the density of soil by packing the particles together, with a reduction in the volume of air. Standard tests are available for assessing compaction, but these tests specify a large number of repeated blows. Little information exists on single impact compaction, or the energy absorbed by compaction. Water content is also known to alter compaction values. In the absence of further data, we made the simplifying approximation that a constant ratio, $c_c$, would be used to specify the proportion of permanent plastic displacement ($z_p$) relative to the total displacement ($z$).
The key parameters of the compaction model that characterised a surface were therefore:

- Surface non-linear elastic stiffness, $k_e(z)$, from initial impact to rebound,
- Surface non-linear damping, $c(z)$, during initial impact only, and
- Compaction coefficient, $c_c$, important for determining rebound characteristics.

**Compaction Model Parameter Fitting**

The determination of the parameters of the compaction model for each surface involved three stages: estimation of state variables, identification of model parameters and verification of the identified model.

**Step 1: Calculation of State Variables for Impact and Slip**

In the compaction model, we assumed that hoof placement was horizontal and that during the calculation of surface penetration and slip, all angular rotations were zero. At the time of maximum ground reaction force magnitude, which was determined from the strain measurements, we assumed that the linear velocity and the two horizontal accelerations were all zero. Only the vertical acceleration was non-zero at mid-stance, adjusted to match the surface rebound characteristic.

With these assumptions, the velocity and displacement profiles in all three orthogonal directions, known as the model state variables, were estimated by simple integration.

The calculation of displacement involved integrating large accelerations over short impact periods. This process was sensitive to the time at which hoof contact was first detected. As a measure of the sensitivity, the identified impact time was varied through a small range and the effect of this variation on the maximum penetration depth was computed. During typical strides, we found that an error in the identified impact time of ±1 data point (±0.5ms) introduced an error in penetration depth of ±2mm. Further, a measurement error in acceleration of ±1g introduced an error in maximum penetration of ±0.08mm. As a practical check of the penetration estimation, we conducted tests on a bitumen surface at a slow speed, since bitumen was likely to undergo minimal if any measurable deformation.

**Step 2: Estimation of Model Parameters**

A manual optimisation of model parameters was performed to minimise the error between the model output and measurements, as shown in Figure 4. A unique set of surface parameters ($k_e(z)$, $c(z)$ and $c_c$) were found over a random selection of strides for a given track.

![Figure 4](image-url)  
**Figure 4**  
Illustration of the optimisation process used to find compaction model parameters for each track surface. In this report, manual tuning of model parameters was used.
as the optimisation method. A random selection of strides from each track was chosen for model identification purposes.

**Step 3: Model Validation**

To verify the integrity of the model, predictions were made of the impact response of other strides that were *not* used in the identification process. These model predictions used only the strain signal of each stride as the input. Some of the differences between predicted and measured response could be explained by variability among strides, while some variations likely occurred because of modelling limitations and the assumptions discussed above.

**Non-Model Surface Characterisation**

In addition to the compaction model surface parameters, we obtained two additional values for each stride to compare the surfaces:

- Maximum penetration depth \( z_{\text{max}} \), and
- Percentage of maximum limb load applied at minimum hoof velocity \( P_{vm_{\text{in}}} \).

We took the maximum penetration depth, \( z_{\text{max}} \), to be an overall measure of surface compliance, independent of the compaction model and all other parameters. We obtained it from motion reconstruction, as the maximum value of the displacement state variable, \( z \).

We found the percentage of maximum limb load applied at minimum hoof velocity, \( P_{vm_{\text{in}}} \), by taking the strain signal at the minimum hoof velocity and dividing it by the maximum strain signal for that stride. We then expressed this quantity as a percentage. This measure was an indication of how rapidly the surface was able to support the limb during the onset of loading in the stance phase.

We chose these two additional parameters to compare different surfaces because of their simplicity and ease of use in a statistical analysis. However, we did not believe that either parameter provided as much physical insight into surface properties as those obtained from the compaction model. These parameters did not enable a meaningful predictive ability, in the sense that they could not be related to the overall time-history of the hoof-ground interaction. Instead, they were essentially a “snap-shot” of the hoof state at particular points in time.
Statistical Analysis

We performed a one-way Kruskall-Wallis ANOVA on both the maximum penetration ($z_{max}$) and percentage of maximum limb load at minimum velocity ($P_{vmin}$) parameters using the R Statistical Computing Language (R Development Core Team 2008). For the statistical analysis, N=8 non-consecutive strides were chosen randomly from the gallop data of the trial conducted on each surface. Based upon the stride duration versus speed table (Table 2), the strides were chosen from periods in which the horse was galloping at 6.7–7.2 m/s because we had the most representative data at these speeds across all trials. The strides were treated as independent measurements for the purposes of statistical analysis, since their timing within each trial was random.

Following the ANOVA, which revealed differences in means, we performed a post-hoc Tukey “Honestly Significant Difference” test to examine individual differences in means for $z_{max}$ and $P_{vmin}$ on each surface (R Development Core Team 2008). Significance at the 5% level ($p < 0.05$) was considered adequate for statistical comparison purposes.

It should be emphasized that we did not perform a statistical analysis of the results of the compaction model. Although it is possible to produce scalar values from this model that may be suitable for the purposes of statistical comparison, we considered it premature to do so given the limited data presently available and the possibility of more thorough experimental tests in the near future. The statistical comparison of the two more direct measurements of surface behaviour ($z_{max}$ and $P_{vmin}$), more closely related to the raw data obtained from the shoe, was considered to be sufficient to demonstrate that a simple, clear difference between tracks was evident.
Results

Motion Reconstruction

Figure 5 shows an example of reconstructed hoof position from vertical acceleration by double integration, after boundary conditions were imposed. The figure shows the typical features of hoof penetration into a surface that were observed during this project. The entire stance phase is shown. This motion reconstruction was performed for all strides that were analysed.

The vertical acceleration illustrates the patterns typical of impact during early stance (0 to 20ms), during which rapid oscillations were observed. At mid-stance, the vertical acceleration was set to zero by the boundary conditions (as described above).

Integrated vertical velocity exhibited rapid changes in early stance, from a high initial value of 4 m/s, with some oscillation, down to zero at mid-stance. The vertical velocity was also set to zero at mid-stance (as described above) to comply with boundary conditions.

The integrated displacement had a pattern that indicated that the hoof sank into the surface somewhat during the very earliest stages of impact, but its main penetration occurred later, around mid-stance, when the main body weight was supported by the limb.

![Figure 5](image)

**Figure 5** Vertical acceleration (top) was measured by the instrumented shoe. Vertical velocity and displacement (middle and bottom) were obtained by integration of the acceleration signal after boundary conditions were imposed. The time period shown is the entire stance phase.

Surface Stiffness and Damping Profiles

Figure 6 and Figure 7 show the fitted surface stiffness and damping profiles for all of the surfaces that were measured. Due to the manual adjustment that was used to optimise the model parameters, a standardised damping profile was fitted, but the stiffness profiles showed clear differences among the surfaces. Compared with the natural surfaces, the synthetic surface had a very low stiffness at low
penetration, but rapidly increased in stiffness at greater depths. By contrast, the stiffness of the grass surfaces increased in a much more even fashion with depth.

Figure 6  Stiffness profiles (stiffness as a function of depth, \( k_e(z) \)) obtained by the compaction model for all track surfaces.

Figure 7  Standardised damping profile (damping as a function of depth, \( c(z) \)) that was used for all track surfaces in the compaction model.

Compaction Model Validation

Appendix A contains plots showing the compaction model validation. These plots show both the measured displacement and the displacement predicted by the model using only the strain signal as input. Good agreement was achieved between the predicted and actual vertical displacement in most strides.
Maximum Penetration

Figure 8 shows a box-plot of maximum penetration ($z_{\text{max}}$) on the different surfaces (N=8 strides from fast gallop). The sand track showed significantly greater maximum penetration than the grass tracks ($p < 0.05$). The synthetic track also appeared to have a somewhat greater penetration than the grass tracks, but this did not reach a level of statistical significance in our dataset.

![Box-plot showing maximum penetration ($z_{\text{max}}$) of the hoof on different surfaces. Surfaces with different statistical designation letters (shown as A, B above the boxes) had significantly different means ($p < 0.05$).](image)

Percentage of Maximum Limb Load Applied at Minimum Hoof Velocity

Figure 9 shows a box-plot of the percentage of maximum limb load applied at minimum hoof velocity ($P_{\text{vmin}}$), which indicated the rate at which limb support load increased following impact. The sand and synthetic tracks were both significantly different from the grass tracks ($p < 0.05$), supporting less of the peak limb load than the grass tracks by the time that the hoof had been decelerated following impact.

These $P_{\text{vmin}}$ results agreed intuitively with the results of the compaction model (see above). The compaction model found that both the sand and synthetic surfaces had lower stiffness at lower levels of penetration. Hence, we expected to observe lower $P_{\text{vmin}}$ values on these two surfaces, since the hoof had not penetrated far and was not yet bearing a significant proportion of the total body mass by the time it had been decelerated.
Figure 9  Box-plot showing limb load at minimum hoof velocity as a percentage of peak load \( (P_{\text{min}}) \) on different surfaces. Surfaces with different statistical designation letters (shown as A, B above the boxes) had significantly different means \( (p < 0.05) \).
Implications

The direct importance of the technology for measuring surface impact properties is the provision of data for use in track design and track management, leading to reduced injury and breakdown of horses in training and racing. This information would also allow better decision making on training regimes and recovery from injury. The broader implications for the investigation of causes of racing injuries could depend on public attitudes to animal welfare. Reducing training and race breakdowns would improve the image of the sport management and ensure the industry remains a key regional employer.
Recommendations

The technology used in this study was developed for use in “field conditions”. Instead of being restricted to laboratory use, it directly measured the conditions that apply in training and racing. Consideration should be given to further development of the process and its application to a wider range of track conditions. This will provide important information for track design and management. Consideration should also be given to developing the technique to provide a rapid and comprehensive method for providing overall track ratings. The approach used modern electronics and instrumentation, and advanced communication and data analysis techniques. The adoption of these technologies would improve track and training conditions and the standards of animal welfare in thoroughbred training and racing in Australia.
Appendix A: Plots of Compaction Model Validation

Figure 10  GRASS1 (Werribee Grass) model validation set 1 of 2.
Figure 11  GRASS1 (Werribee Grass) model validation set 2 of 2.
Figure 12  GRASS2 (Cranbourne Grass) model validation set 1 of 2.
Figure 13  GRASS2 (Cranbourne Grass) model validation set 2 of 2.
Figure 14  SAND (Cranbourne Sand) model validation set 1 of 2.
Figure 15  SAND (Cranbourne Sand) model validation set 2 of 2.
Figure 16  SYNTH (Geelong Synthetic) model validation set 1 of 2.
Figure 17  SYNT (Geelong Synthetic) model validation set 2 of 2.
References


Kai, M, Aoki, O, Hiraga, A, Oki, H & Tokuriki, M 2000, ‘Use of an instrument sandwiched between the hoof and shoe to measure vertical ground reaction forces and three-dimensional accelerations at the walk, trot, and canter in horses’, American Journal of Veterinary Research, vol. 61, issue 8, pp. 979–985.


Measurement of racetrack surface using instrumented horse shoes

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This report describes the development of a method for measuring the surface properties of racing and training tracks used in Thoroughbred racing. Central to this method was the use of a race-capable, rugged instrumented horseshoe. The instrumented horseshoe enables, for the first time, hoof impact measurements to be made under racing and training conditions.

The immediate target beneficiary of this research are the racing authorities, who are responsible for the welfare of horses and jockeys in racing, a topic of major importance to the future of the sport.

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