Hoof landing velocity is related to track surface properties in trotting horses

Jeremy F Burn* and Steven J Usmar
Department of Anatomy, University of Bristol, Southwell Street, Bristol BS2 8EJ, UK
* Corresponding author: J.F.Burn@bris.ac.uk

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Abstract
The resistance of a track surface to deformation is known to be positively related to the magnitude of foot impact experienced during locomotion. Although passive mechanics suggests that this might be entirely due to the action of the track surface material decelerating the foot, it is also possible that the dynamics of locomotion are altered in a way that changes the landing velocity of the foot. The observed relationship between track properties and foot impact would then be due to a combination of the direct effect of the surface material and altered foot kinematics at impact. In this study we measured hoof landing velocity, stance time and limb landing angle in horses trotting over surfaces that differed significantly in their deformability. In comparison with a surface that underwent negligible deformation during stance phase, a surface that deformed 25 mm led to significantly increased stance time, significantly greater leg landing angle and significantly greater hoof landing velocity. Although the increased hoof landing velocity would act to counteract the increased shock absorption on the softer surface, we suggest that this effect is relatively small.

Keywords: impact; kinematics; compliance; gait

Introduction
The force that acts when two bodies collide is a function of the masses of the bodies, the materials from which they are made and their relative velocity at collision. During animal locomotion, the foot collides with the ground at the beginning of stance phase and an ‘impact’ force acts to decelerate the foot relative to the ground. In this context, collision velocity is the landing velocity of the hoof and the materials relevant to the collision are those comprising the track surface, the foot of the animal and the shoe if the animal is shod. The mass involved is the mass of the foot (and shoe); the mass of the ground is taken as being effectively infinite. In practice, the mass being decelerated during the collision might not only be the mass of the foot, but also include a proportion of the mass of the limb that would increase with time.

Foot impact during terrestrial locomotion has been studied in humans and horses primarily because it is widely believed that large impact forces might have a detrimental effect on the musculoskeletal system\(^1,2\), and both these animals are involved in athletic pursuits that involve locomotion. In human studies collision forces are typically measured directly using a force platform\(^3,4\). In horses, hoof impact acceleration is measured using accelerometry\(^5,6\), as commercially available force plates of suitable size do not have a fast enough response to measure impact force accurately in these animals. For a review of the mechanics and relevance of foot impact, see Whittle\(^7\).

Conditions that can lead to, or prevent, large-magnitude foot impacts during locomotion are of particular interest. Competition horses can encounter a range of track surfaces whose deformation through stance phase varies from a few millimetres to several centimetres. It has been shown that changes in track compliance of this order elicit large changes in the magnitude of hoof impact acceleration\(^8\). The mechanics of collision suggest that this might be explained by the direct effect of increased track compliance causing a reduction in peak collision acceleration, although this is not self-evident: a change in track compliance might cause a more general change in locomotion dynamics, either directly or indirectly through proprioceptive
feedback. Studies of humans both hopping and running on different track surfaces have shown that changing the stiffness of a surface can affect limb kinematics. Any alteration to locomotion dynamics that resulted in a change in foot landing velocity would imply that changes in measured hoof impact acceleration were due not only to the direct effect of altered compliance on the dynamics of collision, but also to a change in the initial conditions of the collision.

To understand the mechanism by which track compliance affects hoof impact in horses, it is therefore necessary to establish whether changes in track compliance can lead to an alteration in hoof landing velocity. The aim of the present study was to compare hoof landing velocity for horses travelling at the same speed on tracks with three different values of compliance, and to evaluate the importance of track-dependent changes in hoof velocity on the magnitude of hoof impact.

Materials and methods

Animals

Six Thoroughbred horses of body mass 526 ± 36 kg and age 11 ± 2 years (mean ± standard deviation (SD)) were used for the study. They were free from lameness and were shod with steel shoes by an experienced farrier prior to the experiment.

Track

A level horizontal trackway 40 m long and 1.5 m wide made from compressed stone was used for the experiment. Three surface conditions were created as follows. First, the track was used without a covering (T1). Under these conditions the track did not compress measurably during stance phase and the horses left no hoof-prints on the surface. The second and third conditions (T2 and T3, respectively) were created to produce 5 mm and 25 mm of plastic deformation during stance phase without penetration down to the base layer of the track. This was achieved by covering the track with sand and adding moisture evenly until the desired amount of deformation was obtained. These surfaces T1, T2 and T3 were created to approximate road, firm ground and soft ground typically experienced by horses in competition. The softest surface used in this study deformed less than the softest surfaces encountered by competition horses due to the restriction that markers on the hoof used for motion capture had to remain visible throughout stance phase.

Relative collision dynamics for the three surfaces were assessed with a simple drop-hammer test. A small metal cylinder of diameter 5 cm and height 8 cm was instrumented with a piezoelectric accelerometer oriented so that its sensitive axis was aligned with the axis of the cylinder and vertical to the ground surface. The base of the cylinder was covered with 3 mm thick plastic disc of 5 cm diameter. The mass was dropped five times onto each surface from a height of 5.0 cm. Acceleration was recorded at 40 000 samples s\(^{-1}\) on a personal computer fitted with an analogue-to-digital converter card. The bandwidth of the analogue stages of the measurement system was 10 kHz. The peak deceleration for each drop was extracted from the time series and averaged for each surface condition.

Test protocol

Circular reflective markers of diameter 2 cm were placed on the lateral surface of the left forelimb in the following locations:

- lateral hoof wall at the approximate location of the centre of rotation (COR) of the distal interphalangeal joint (M1);
- lateral hoof wall distal to the coronary band and immediately palmar to the widest point of the hoof (M2);
- COR of the metacarpo-phalangeal joint (M3);
- lateral tuberosity of the proximal radius (M4);
- tuberosity of the scapular spine (M5); and
- trunk lateral to the base of the dorsal spinous process of the fifth thoracic vertebra (M6).

The vertical position of the surface of the track was recorded before and after experimental measurements were made for each horse. A rectangular piece of plywood 500 mm × 1000 mm × 18 mm, with four spherical motion-capture markers positioned at the corners of the upper surface, was laid on the surface such that its longest dimension was in line with the direction of the track. Positions of the markers were recorded using the optical motion-capture system, and the position of the surface calculated from the diameter of the markers and the thickness of the board.

For each horse, the vertical position and length of the base of the hoof were determined as follows. The horse was stood on a non-deforming surface and two small blocks of wood, on which reflective markers were mounted laterally, were placed on the ground immediately dorsal to the toe and immediately palmar to the left (lateral) heel of the hoof. The limb and the blocks were filmed using the optical motion-capture system. The dimensions of the blocks and their markers were used to calculate the position of a line in the median plane of the limb, from the base of the hoof at the toe to the heel. The position of this line was related to the positions of the two markers, M1 and M2, on the hoof in order that the position...
of the base of the hoof could be calculated from these two hoof markers.

Horses were trotted along the track at constant speed in a straight line while kinematic data were recorded at 200 frames s\(^{-1}\) using a three-dimensional motion-capture system (ProReflex; Qualisys Medical AB, Gothenburg, Sweden). The horses were trained to use the handler as a speed reference for their locomotion, and the handler maintained a speed of 3 m s\(^{-1}\) on each surface. Data collection was performed in the middle of the runs after the horses had established a constant speed and before they began to decelerate. Eight runs for which the speed was within the range 2.8–3.2 m s\(^{-1}\) were collected for each horse on each track surface condition. After each run on the sand surfaces, hoof prints were filled with sand and the surface levelled. Depth of the surface was monitored using an improvised penetrometer consisting of a 0.5 cm diameter metal rod marked at 1 cm intervals along its length.

**Data analysis**

Data processing was performed using software supplied with the motion-capture system and custom functions written in Matlab. Positional data were smoothed using a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz, and differenced to obtain velocity. Speed of travel during each run was obtained from marker M5.

The level of the track surface and the position of the base of the hoof were used to identify stance phase as follows. The start of stance phase was defined as the time during swing phase when any part of the line defining the position of the base of the hoof first went below the level of the track surface. The end of stance phase was defined as the time during stance phase when all of the line representing the position of the base of the hoof had moved above the position of the line at mid-stance. The location of mid-stance was determined approximately as the time when the marker on the proximal radius (M4) was vertically above the COR of the metacarpo-phalangeal joint (M3).

Landing velocity was calculated as the magnitude of the velocity of M1 in the frame immediately prior to the beginning of stance phase. Stance time was calculated as the time elapsed between the beginning and end of stance phase. Leg landing angle was calculated as the angle to the horizontal of a line connecting M1 and M5 in the frame identified as the start of stance phase. For each dependent variable, the presence of a difference due to the change in surface was tested using repeated-measures analysis of variance at a significance of 0.05. Pair-wise comparisons between T1–T2 and T1–T3 were performed to identify which contrast in surface compliance produced a difference in the dependent variables. Bonferroni correction was applied to the significance of individual tests in order to keep the overall significance for the paired tests at 0.05.

**Results**

All six horses completed the experiment successfully. The angle between the base of the hoof and the horizontal at the onset of stance did not vary by more than ±3° for any of the horses on any surface. The drop-hammer test gave a value of 720 g (SD 8 g) for the compressed stone surface, 23 g (SD 0.8 g) for the first sand surface and 4 g (SD 0.5 g) for the second sand surface (1 g = 9.81 m s\(^{-2}\)).

The results for each horse are given in Table 1. With the exception of horse 2, hoof landing velocity increased between T1 and T3. Track surface significantly altered landing velocity (\(P < 0.05\)). Landing velocity increased significantly between T1 and T3 (\(P = 0.02\)). Although mean landing velocity increased between T1 and T2, this was not significant (\(P = 0.35\)). The mean percentage increase in landing velocity between T1 and T3 was 8%.

<table>
<thead>
<tr>
<th>Horse</th>
<th>Hoof landing velocity (m s(^{-1}))</th>
<th>Stance time (s)</th>
<th>Limb landing angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1</td>
<td>T2</td>
<td>T3</td>
</tr>
<tr>
<td>1</td>
<td>1.72</td>
<td>1.75</td>
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<tr>
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<td>2.06</td>
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<tr>
<td>4</td>
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<td>2.44</td>
<td>2.61</td>
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<tr>
<td>6</td>
<td>1.43</td>
<td>1.71</td>
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<tr>
<td>Mean</td>
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<td>1.90</td>
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</tr>
<tr>
<td>SD</td>
<td>0.38</td>
<td>0.32</td>
<td>0.37</td>
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</tbody>
</table>

SD – standard deviation.
The angle of the limb at the beginning of stance phase increased as the surface became more deformable. The change in angle with track surface was significant ($P < 0.05$). The increase in angle was not significant between T1 and T2 ($P = 0.04$) but highly significant between T1 and T3 ($P = 0.0023$). The mean value for all horses also showed a monotonic increase with deformability of the track. Stance time was significantly altered by track surface ($P < 0.05$). It increased significantly between T1 and T3 ($P = 0.014$) but not between T1 and T2 ($P = 0.14$). Mean stance time increased monotonically with surface deformability.

Interactions between the three kinematic parameters were investigated using scatter plots and correlation. There was a clear relationship between hoof landing velocity and stance time ($r = 0.9$), but no strong relationships were evident between other pairs of parameters ($r < 0.5$).

**Discussion**

Drop-hammer tests have been used previously to evaluate the shock-absorbing properties of tracks for equestrian use$^{12,15}$. The results of the drop-hammer test performed in this study indicated that collision with the surfaces T1, T2 and T3 under identical dynamic conditions would elicit a large variation in collision acceleration magnitude. The difference between firm sand and compressed stone is deceptively large; the difference in deformability between the two materials is several hundred per cent owing to the extremely small deformation of compressed stone under the applied load. Consequently, peak impact acceleration can vary by several orders of magnitude between surfaces that appear to be not too dissimilar. Similarly, the compliance that can be designed into horse shoes is limited by practical considerations, although the range of materials used for horseshoes has a significant effect on hoof impact acceleration magnitude$^5$. The mass of the drop hammer was chosen to be of the order of the mass of an equine foot$^{14}$ and the drop height was calculated to give a landing velocity of approximately the magnitude of hoof landing velocity. We do not imply that the test is a simulation of *in vitro* loading; our aim was simply to perform a dynamic test in which reasonable attention has been paid to the dynamics of the living system.

In several gait studies, the method used to delimit stance phase involves recognizing the effect of mechanical interaction with the surface. This might, for example, involve detecting a rise in ground-reaction force$^{15}$ or an associated change in limb kinematics$^{16,17}$. On soft surfaces, it is difficult to identify precisely the start of stance phase because the mechanical interaction with the surface builds up gradually. The technique used here provides an accurate time at which the foot physically contacts the surface provided sufficient care is taken to ensure the position of the surface is known accurately. The end of stance phase on a plastically deforming surface is also difficult to identify from kinematic data because the point at which the hoof leaves the surface is not clear. Here we worked on the assumption that the surface deformed entirely plastically, and maximum deformation occurred at mid-stance corresponding to peak vertical ground-reaction force. The plastic nature of the sand surface was confirmed independently by pushing objects into the surface, measuring their depth of penetration, and measuring the depth of the hole left after their removal. For the purposes of this study, therefore, the technique used to delimit stance provided a repeatable and reasonably accurate method for identifying the end of stance. It should be noted, however, that the same technique could not be used without modification on surfaces with an elastic component.

Hoof landing velocity was affected by changing the properties of the surface such that the more deformable surface elicited a higher hoof landing velocity. This is interesting because the direction of the change implies that it would act to increase impact magnitude, counteracting the direct effect of the change in material properties that would act to reduce impact acceleration. It is possible to estimate the relative importance of these two effects if we assume that the kinetic energy of the foot at landing is lost as a result of the foot doing work on the track surface. We can say that:

$$Fs = 0.5mv^2,$$

where $m$ is the mass of the foot, $v$ is the landing velocity of the foot, $s$ is the deformation of the surface during the collision and $F$ is the impact force. In this simple formulation of the equation, it is assumed that the force applied to the surface and the mass of the foot are constant. In reality, both are likely to vary. Although this is not likely to be an accurate representation of the force time history during the collision, it is sufficient to illustrate the relationship between the measured changes in hoof landing velocity and changes in track deformation. Given that it is hoof acceleration ($a$) that is measured as an index of impact in horses, we could re-arrange the equation as follows:

$$a = \frac{F}{m} = 0.5v^2/s.$$

It can be seen from this representation that, to keep impact acceleration constant, track deformability would have to vary inversely proportional to the square of velocity. Although statistically significant, the mean variation in hoof landing velocity between
Hoof landing velocity and track surface properties

T1 and T3 was only 8% in comparison with an order of magnitude difference between the deformation of T1 and T3. This suggests that the direct effect of changing track material properties is much larger than the indirect effect of changes in hoof landing velocity on measured impact.

Significant changes were also observed in stance time and limb landing angle. The reason for examination of these two parameters, apart from their role as important parameters describing the dynamics of gait, was to investigate whether increased limb landing velocity might be due to the limb landing relatively earlier during swing phase. Following limb protraction the limb is accelerated in retraction, which decreases the velocity of the hoof relative to the ground prior to ground contact. A change in landing velocity might be explained by contacting the ground relatively earlier or later during swing phase without any change to swing phase dynamics. Here we found that, overall, increased landing velocity occurred concomitant with increased limb landing angle, although these variables were not strongly correlated ($r = 0.46$). Stance time also increased on the softer surfaces and was strongly related to hoof landing velocity ($r = 0.9$). It is difficult to construct a strong case for a direct causal relationship between these two parameters.

Clearly the dynamics of equine locomotion were altered by the different surfaces used in this study. While this is interesting, it is not possible to establish the underlying reasons for the changes observed on the basis of this study. We have described the difference between track surfaces as being in their compliance. While this might be a convenient term, we accept that it is not ideal as the term is used correctly (along with stiffness) to describe elastic deformation. The surfaces T2 and T3 used in this study deformed plastically, and so it would be more correct to describe them in terms of their deformation under a given load. The changes in dynamics observed here could be due to the fact that the surfaces deformed by different amounts, or that the deformation was plastic and therefore non-recoverable work was done on the surface during locomotion.

In conclusion, it appears that surfaces typical of those used for equestrian competition affect the dynamics of locomotion including hoof landing velocity. Although these changes are statistically significant and oppose the direct effect of the surface material in reducing impact acceleration, their effect is likely to be considerably smaller. In studies of track surfaces, the method used to identify stance phase should be considered carefully. If surfaces undergo considerable deformation under small loads, physical contact with the surface might occur some time before the mechanical interaction is sufficient to be detectable in kinematic data.

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References