

Simulated effects of racetrack material properties on the vertical loading of the equine forelimb

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Abstract

One of the factors cited as contributing to racing injuries of horses is the condition of the racetrack surface. This study examines the possible effects of different dirt racetrack surfaces by using dynamic modelling of the horse and track to quantify the vertical loading of the hoof and coffin joint. Results indicate that as the stiffness of the racetrack material increased from a weak soil to a rock surface (constant soil damping ratio of 15% of critical damping), the maximum track deflection decreased from 5.1 to 1.2 cm; stance phase duration decreased by 60%; energy dissipation decreased by 72%; maximum vertical ground reaction force and coffin joint force increased by 19% and maximum vertical rate of loading increased by 219%. Varying the soil damping ratio from 5 to 30% of critical damping had only small effects on the loading response, changing the above parameters by less than 5% for the medium soil type simulated. These results indicate that the track surface may have a profound effect on the loading conditions of the horse's limb, with the surface stiffness properties having a greater effect on loading than the surface damping properties. Design of appropriate race track surfaces may therefore be more dependent on selection of soil for structure, rather than soil amendments which have been used primarily to alter damping characteristics.

Keywords: biomechanics, dynamic modelling, ground reaction force, injury prevention, racetrack material

Introduction

Severe and catastrophic injuries at the racetrack are a major problem faced by the equine racing industry. A study involving the New York Racing Association tracks indicated that in a period between January 1986 and June 1988, 55 horses were severely injured and put down in the United States alone, while an additional 245 animals

received a less severe injury that prevented them from racing for the next six months (Mohammed *et al.* 1992). Mackay-Smith (1977) reported that the annual loss to the United States Thoroughbred industry due to lameness was in excess of US\$500 million. Owing to inflation and the growth of the sport, it is speculated that the annual loss is much higher today.

A number of factors including unsoundness, conformation, possible hereditary factors and race-track conditions may be important when the pathogenesis of severe racetrack injuries are considered (Peloso *et al.* 1994). However, the impact of the racetrack surface on the number of severe musculoskeletal injuries has been heavily debated by

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owners, trainers and racetrack officials. Mohammed *et al.* (1992) indicated that the tracks at Belmont and Saratoga posed a higher risk of severe injury than Aqueduct Main. On the other hand, the same authors reported in 1991 that Saratoga seemed to have a lower risk than Aqueduct Main, Aqueduct Inner or Belmont (Mohammed *et al.* 1991). Stover *et al.* (1992) reported no apparent differences between Californian racetracks and the number of injuries, based upon their study from February 1990 to July 1991. However, while the racetrack is commonly indicated as the cause of musculoskeletal injury, no objective data currently exists which indicates this is true.

It is estimated that the peak vertical ground reaction force (VGFR) (force between the horse's leading front hoof and the ground) at the gallop reaches a maximum of approximately 175% of the horse's bodyweight on a dirt track surface (Frederick & Henderson 1970; Clanton *et al.* 1991). The force transmitted to the cannon bone is 3–4 times greater than the force acting on the hoof due to the lever type actions of the fetlock joint (Pratt & O'Conner 1978). The complex response characteristics of different racing surfaces may alter the concussive forces which are experienced by the bones and joints of the horse's leg (Riemersma *et al.* 1996). Repeated trauma induced by the cyclic

loading of the limbs under high loads, high rate of loading or both, may accumulate to result in an injury (Nigg *et al.* 1995). While other factors may be present in varying degrees, the presence of a less suitable track surface could significantly impact the risk to all horses running on the surface.

The goal of this project was to investigate the effect of the stiffness and damping properties of the racetrack on the VGFR using dynamic modelling to simulate both the horse and dirt racetrack surface during the stance phase of the leading forelimb at gallop. Modelling provides an objective and noninvasive means of evaluating racetrack surfaces and the impact of changes on joint loading. Modelling can also produce preliminary quantifiable results to indicate the magnitude of the expected differences between track surfaces and to help focus further investigative research in the area. Further investigation will almost certainly include developing and performing more costly and time consuming experimental procedures.

Methods

A simple hoof/track impact model has been created based upon the previous work of Alexander *et al.* (1986). Alexander's model examined the role of quadrupedal foot pads during the stance phase on

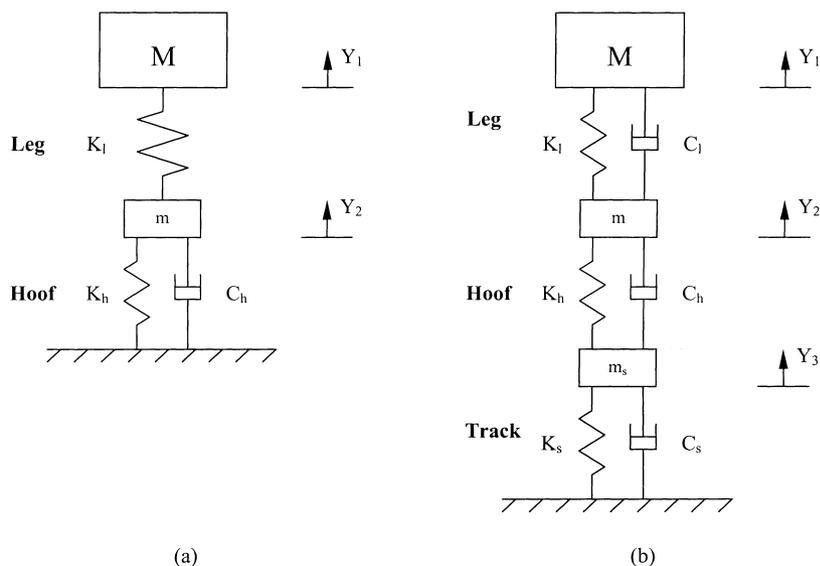


Figure 1 (a) Vertical impact model proposed by Alexander *et al.* (1986). (b) Modified model used in this study including damped leg and compressible track material. The models include the size and mass of the hoof (m), the mass of the horse (M), the mass of displaced soil (m_s), the stiffness (K_1) and damping qualities of the limb (C_1), the stiffness (K_h) and damping qualities of the hoof (C_h), the stiffness (K_s) and damping qualities of the track material (C_s) and the displacements of the horse (Y_1), hoof (Y_2) and soil (Y_3) relative to their location at first contact with the surface.

an incompressible surface [Fig. 1(a)]. That model has been expanded to include a damped leg and compliant dirt track material surface [Fig. 1(b)]. The magnitude and time varying characteristics of the VGRF are dependent on several factors including: the size and mass of the hoof (m), the mass of the horse (M), the mass of displaced soil (m_s), the velocity of the hoof and horse at impact, the stiffness (K_l) and damping qualities (C_l) of the limb, the stiffness (K_h) and damping qualities (C_h) of the hoof and the stiffness (K_s) and damping qualities (C_s) of the track material.

The stiffness of the limb, hoof and track material may be modelled by springs with appropriate response characteristics and spring constants. The damping qualities of the leg, hoof and track material can be modelled with equivalent viscous dashpots. A linear spring is used to represent the horse's leg and track material while the hoof is modelled as a nonlinear spring with a stiffness that is proportional to the sum of the distance compressed plus the distance compressed to the fourth power (Alexander *et al.* 1986). Under this type of nonlinear spring stiffness, when displacements are small the exponential term in spring stiffness has little effect; however, as the compression increases the stiffness also increases. The additional exponential term prevents the hoof from compressing beyond realistic limits.

While the dynamic characteristics of a particular hoof and leg do not change with track conditions, the mechanical characteristics of the track material are expected to differ significantly (Cheney *et al.* 1973; Pratt 1985; Barry *et al.* 1991). The spring stiffness and damping coefficient of the track material will vary depending on the granular structure, moisture content, amount of organic material and density of the track material (Barry *et al.* 1991). In addition, since racetracks have a loose and scarified top layer followed by a relatively hard and dense under layer, the change in these properties with track depth must be accounted for when accurately modelling the response characteristics of the racetrack under loads (Cheney *et al.* 1973). The track material model also includes compaction. The track material is twice as stiff on unloading as it is on loading and does not

return to its original height (Vyalov 1986), effectively leaving a footprint (Fig. 2).

The model was created assuming that only one hoof is in contact with the ground at any one time. The leading forelimb carries the full weight of the horse for all but the first tenth of its stance (Leach 1989). Since the trailing forelimb is virtually unloaded when the leading forelimb strikes (Ratzlaff *et al.* 1993), the effect of the opposing forelimb was assumed to be negligible. The equations of motion for this new model relative to the vertical displacement of the horse's centre of mass (Y_1), hoof (Y_2), and soil (Y_3) at impact are as follows (one superior dot refers to velocity and two superior dots refer to acceleration, g = acceleration due to gravity):

While the hoof is in contact with the ground, the spring mass system has the form

$$M \cdot \ddot{Y}_1 = -K_l \cdot (Y_1 - Y_2) - C_l \cdot (\dot{Y}_1 - \dot{Y}_2) - M \cdot g$$

$$m \cdot \ddot{Y}_2 = -K_h \cdot \left((Y_2 - Y_3) - 100^3 \cdot (Y_2 - Y_3)^4 \right) - C_h \cdot (\dot{Y}_2 - \dot{Y}_3) + K_l \cdot (Y_1 - Y_2) + C_l \cdot (\dot{Y}_1 - \dot{Y}_2) - m \cdot g$$

$$m_s \cdot \ddot{Y}_3 = K_h \cdot \left((Y_2 - Y_3) - 100^3 \cdot (Y_2 - Y_3)^4 \right) + C_h \cdot (\dot{Y}_2 - \dot{Y}_3) - K_s \cdot Y_3 - C_s \cdot \dot{Y}_3 - m_s \cdot g$$

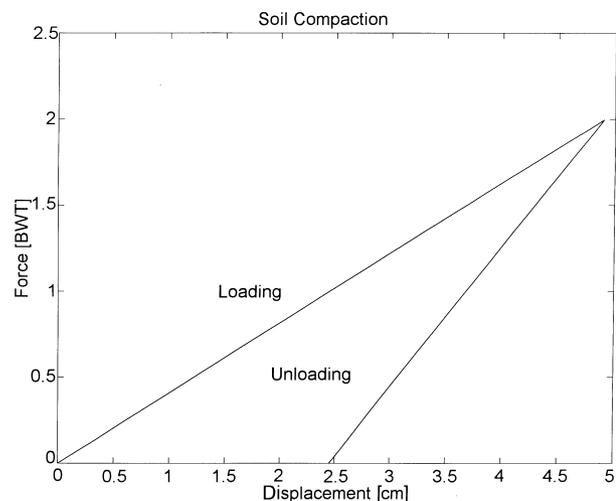


Figure 2 Loading and unloading track displacement for a maximum force of twice bodyweight on a weak soil surface. After unloading, the displacement at zero force is the depth of the footprint (~2.5 cm).

While the hoof is in the air the equations of motion take the form

$$\begin{aligned} M \cdot \ddot{Y}_1 &= -K_1 \cdot (Y_1 - Y_2) - C_1 \cdot (\dot{Y}_1 - \dot{Y}_2) - M \cdot g \\ m \cdot \ddot{Y}_2 &= K_1 \cdot (Y_1 - Y_2) + C_1 \cdot (\dot{Y}_1 - \dot{Y}_2) - m \cdot g \\ m_s \cdot \ddot{Y}_3 &= -K_s \cdot Y_3 - C_s \cdot \dot{Y}_3 - m_s \cdot g \end{aligned}$$

The equations are solved using finite difference methods with a time step of 100 μ s. When the hoof is in contact with the track, the VGRF is equal to the sum of the forces exerted by the spring and dashpot of the hoof:

$$\begin{aligned} \text{VGRF} &= -K_h \cdot \left((Y_2 - Y_3) - 100^3 \cdot (Y_2 - Y_3)^4 \right) \\ &\quad - C_h \cdot (\dot{Y}_2 - \dot{Y}_3) \end{aligned}$$

The vertical reaction force at the coffin joint (VCJF) is equal to the force exerted by the spring and dashpot modelling the leg:

$$\text{VCJF} = -K_1 \cdot (Y_1 - Y_2) - C_1 \cdot (\dot{Y}_1 - \dot{Y}_2)$$

The rate of loading is then calculated by applying a second order central differences equation to the VGRF.

The mass of the horse was set to 500 kg, the hoof (including shoe) to 1.1 kg, and the mass of involved track material is estimated to be 1 kg. The mass of the horse was based on an estimated average value for a Thoroughbred, while the mass of the hoof was obtained by weighing a cadaveric hoof from a Quarter horse. The spring and dashpot constants for the leg were set to produce a stance phase of 0.1 s on an rock surface ($K_1 = 1500 \text{ kN m}^{-1}$, $C_1 = 16.4 \text{ kNs m}^{-1}$). This corresponds to the stance phase of the leading forelimb of a horse galloping at a velocity of 15 m s^{-1} (Leach 1989). Since both stiffness and damping have a large influence on the stance-phase duration, leg stiffness was first set by extrapolating an undamped value from the data presented by Alexander *et al.* (1986). The leg damping coefficient was then set to 30% of critical damping (Greene & McMahon 1984) and the leg stiffness reduced accordingly to bring the stance phase back to 0.1 s.

The stiffness and damping properties of the hoof were also based upon the data presented by Alexander *et al.* (1986). It was assumed that a horse's hoof is 50% stiffer than the paw pads of most mammals (due to the large quantity of bone in the hoof compared to paws of mammals tested in that study). The damping properties of the hoof were assumed to be similar to those of paw pads ($K_h = 28\,500 \text{ kN m}^{-1}$, $C_h = 1.5 \text{ kNs m}^{-1}$).

Independent verification of the leg, hoof and soil properties was not possible. However, their values should not alter the relative levels of force resulting from track surface variation. To test the sensitivity of the models to the mass of the hoof, mass of displaced soil and surface area of the hoof (discussed later), these values were independently altered by $\pm 50\%$ of the above values and the results computed for one of the intermediate surfaces (medium soil with damping ratio of 15% of critical damping).

The initial vertical velocity of the horse's centre of mass was set at -0.4 m s^{-1} to produce a peak force similar to that which has been estimated in the literature [approximately 2 times bodyweight (BWT) (Frederick & Henderson 1970; Clanton *et al.* 1991)]. An initial downward velocity of 0.4 m s^{-1} is likely to be quite accurate since the other three limbs have already completed their stance phases and have reduced the initial downward velocity. Additionally, the horse keeps its centre of mass from travelling more than one-third of a metre in the vertical direction during a complete stride (Stillman 1881). However, no data have been found to confirm this initial velocity for the centre of mass. The initial vertical velocity of the hoof of a galloping horse was set at -1.0 m s^{-1} based on the estimates by Frederick & Henderson (1970).

It was not possible to examine all racetrack surface parameter combinations, so four distinct track materials were selected to encompass a broad range. The materials include surface types that may not be practical for a race track in order to assess the magnitude of variation. The soil data used were derived from soil engineering studies (Das 1983). Soils are categorised as: weak

(stiffness = 20 000[kN m⁻³] * Area[m²]), medium strength (40 000 * Area), or strong soils (75 000 * Area) and rocks (100 000 * Area). Weak soil includes clay and silty clays with sand in a plastic state; clayey and silty sands; also soils with laminae of organic silts and of peat. Medium strength soils include clays and silty clays with sand close to the plastic limit, and sand. Strong soils include: clays and silty clays with sand of hard consistency, gravels and gravelly sands, and loess and loessial soils.

The spring constant for each of these track material categories is obtained by multiplying the reported elastic subgrade modulus by the area under impact (Das 1983). An area of 0.01 m² was selected based on an approximately circular hoof with radius of 0.06 m landing flat to the surface. It is anticipated that the loose topsoil deforms sufficiently under loading so that more than just the shoe is in contact with the track. Damping ratios for soils range from approximately 0.1 to just under 0.3 (Hardin & Drnevich 1972). The soil damping ratio (ζ) is related to the soil damping coefficient (C_s) in the following manner:

$$\zeta = \frac{C_s}{\sqrt{4 \cdot m_s \cdot K_s}}$$

When the damping ratio is multiplied by 100 it describes the damping as a percentage of critical damping. This formula also holds for calculating hoof and leg damping coefficient values from percent critical damping information.

Results

The model was run multiple times to examine the effect of track material properties on the loading of the hoof and coffin joint. Typical horse, hoof and track surface deflection, VGRF, VCJF and rate of VGRF loading ($dVGRF/dt$) were plotted (Fig. 3). From the deflection data, the time during which contact between the hoof and ground was sustained, the time at the end of the stance phase, the duration of maintained hoof contact with the ground and the maximum track material displacement were extracted. The kinetic parameters of maximum VGRF, rate of VGRF and energy dissipated have also been tabulated. Due to the extreme similarities in the

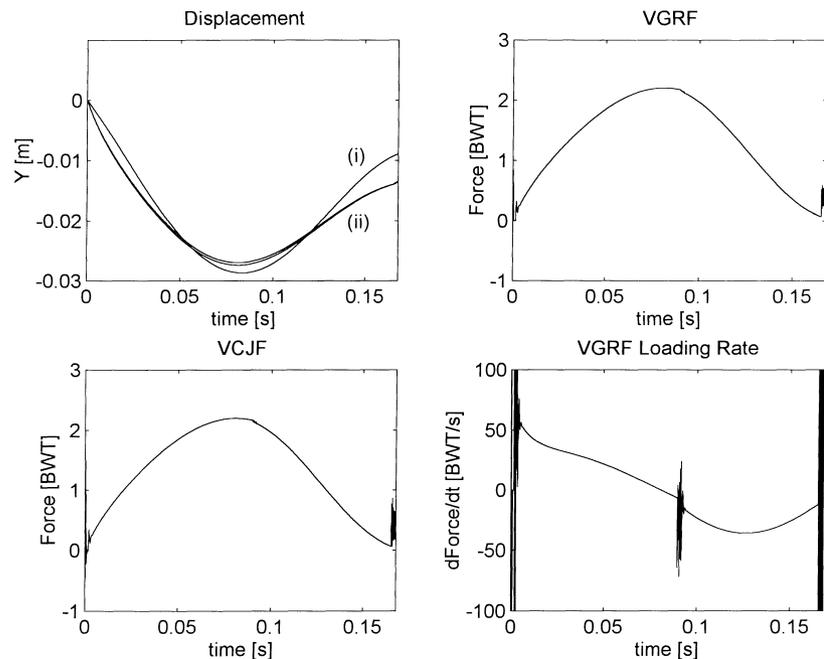


Figure 3 Typical hoof/track impact model results. Plotted are the results for a medium strength soil with damping ratio of 15% of critical damping. In Displacement diagram: (i) horse centre of mass (ii) hoof and track surface with respect to their position at first hoof contact with the surface. VGRF and VCJF refer to Vertical Ground Reaction Force and Vertical Coffin Joint Force, respectively. VGRF Loading Rate is the slope of the VGRF curve.

maximum VGRF and VCJF, the maximum VCJF was not reported. In addition, since the rate of VGRF was extremely sensitive to fluctuations in the VGRF, the rate of VGRF reported in the tables is computed by dividing the maximum VGRF by the time of sustained contact from the initial contact to maximum VGRF.

After initial contact of the hoof with the track surface, the hoof and surface generally break contact several times before maintaining contact for the remainder of the stance phase (Fig. 3: VGRF). These breaks in contact [termed 'chattering' by Alexander *et al.* (1986)] are caused by the initial reaction to loading of the springs modelling the compressibility of the hoof and surface. While chattering is taking place, the mass of the horse continues to drop, with no VGRF to oppose its fall. The time when chattering ceases is then necessary to compute a correct value of the stance duration and VGRF loading rate. The time at the end of stance phase was the time from initial impact until the loading rate dropped to zero, not when the VGRF went to zero. The VGRF may not drop to zero at the end of stance because no energy is added to the system during the stance, only dissipated through the hoof and track material. Energy must be added to the system during stance to simulate the muscular contractions of the leg in order to ensure that the hoof and racetrack break contact at the end of stance.

The energy dissipated is the difference in the kinetic and potential energies in the horse's centre of mass and leg from just prior to impact and the end of stance. The maximum VGRF and VCJF were measured after the hoof maintained continuous contact with the track so that peaks due to initial impact were not used as maximum values.

As expected, the leg, hoof and racetrack all exhibit downward displacement followed by a return towards, but not equal to, their original location during the stance phase (Fig. 3: Displacement). The horse's centre of mass (i) compresses the most due to the leg stiffness being lower than both that of the hoof and racetrack. However, damping in the leg reduces the magnitude of the displacement. The displacement of the hoof is

virtually identical to that of the track material (ii). This occurs because the hoof is much stiffer than both the track material and leg. As the racetrack compresses, the hoof displaces with the surface material. The slight difference between the hoof and racetrack displacement is due to the small amount of compression of the hoof.

Rapid fluctuations were noticeable in the VGRF and VCJF due to the high accelerations of the hoof at impact and chattering. However, the magnitude of the displacements caused by the chattering were small and are not visible on the plot (Fig. 3: Displacement). The displacement curves quickly descend and then begin to rebound, but none of these three parameters return to their original displacements due to the compaction of the racetrack material and loss of energy through damping in the leg, hoof and racetrack.

The VGRF patterns predicted by the model are very similar to those in the literature (Ratzlaff *et al.* 1989, 1993; Merkens *et al.* 1991, 1993; Schamhardt *et al.* 1991; Hjerten & Drevemo 1994). At first contact there are sharp peaks due to the high accelerations of the hoof at impact (the first peak is indistinguishable from the vertical axis at time equals zero). The VGRF then stabilizes and increases to its maximum value as the fall of the centre of mass is stopped by the leg. After maximum displacement of the centre of mass, the VGRF then starts to decline and continues to fall until it levels out at the end of the stance phase.

Owing to the compressibility and damping characteristics of the hoof, the sharp peaks in the VGRF at first contact with the racetrack are not transferred to the coffin joint with the same magnitude (Fig. 3: VCJF). The large initial peaks in the VGRF are attenuated into relatively small initial peaks in the VCJF. Thus, much less 'shock' is felt by the horse than would be expected by analysing the VGRF patterns alone. After the initial 'shock' of impact and the cessation of chattering, the coffin joint force is virtually identical to the VGRF due to the high stiffness and low mass of the hoof. A discontinuity is visible just after maximum VGRF and VCJF due to the change in soil stiffness on unloading.

Since the VGRF loading rate is the slope of the VGRF curve, the profile is very unstable at first contact with the racetrack due to the rapid fluctuations in force (Fig. 3: VGRF Loading Rate). When the VGRF becomes stable, the loading rate also stabilises. The loading rate is initially high, dropping to zero at maximum VGRF, and then negative during unloading where it eventually returns to zero indicating the end of the stance phase. Owing to the discontinuity produced by the change in soil stiffness on unloading, the VGRF Loading Rate is very unstable near this point.

As the stiffness and damping characteristics of the racetrack material change from soil type to soil type, the general patterns of the displacement, VGRF, VCJF and VGRF loading rate do not change. However, the maxima, minima and the duration of events do change (Tables 1 and 2). As the stiffness of the racetrack material increased from a weak soil to a rock soil surface, the duration of chattering decreased by 66%, stance phase duration and time at end of stance both decreased by 60%, the maximum track deflection decreased from 5.1 to 1.2 cm, energy dissipated decreased by 72%, maximum VGRF and VCJF increased by 19% and maximum vertical rate of loading increased by 219% (Table 1).

The range of track material damping ratios does not seem to affect the track material loading response as much as altering the racetrack stiffness (Table 2). Increasing the damping ratio from 5 to 30% of the critical value on the medium soil surface decreased the chatter time by 50%, increased the end of stance time by 1%, increased the stance duration by 2%, did not change the maximum track deflection, maximum VGRF, VCJF and vertical rate of loading and only increased the energy dissipated by 2%.

Varying the mass of displaced soil by $\pm 50\%$ of the mass used for all other simulations does not alter any of the reported values by more than 5% except for the duration of chatter, which was increased by 100% from the lesser to greater mass (Table 3). Varying the hoof mass by $\pm 50\%$ of the mass used for all other simulations does not alter any of the reported values by more than 3% except

Table 1 Hoof/Surface material loading results (constant damping ratio = 0.15)

Soil type	Chatter time (ms)	End of stance (ms)	Stance duration (ms)	Max Track deflection (cm)	Max VGRF (BWT)	Loading Rate (BWT s ⁻¹)	Energy Dissipated (J)
Weak	3	243	240	5.1	2.1	17	121
Medium	2	168	166	2.7	2.2	28	63
Strong	1	123	122	1.6	2.4	44	39
Rock	1	98	97	1.2	2.5	55	34
%Change	-66	-60	-60	-76	19	219	-72

%Change = $100 * (\text{Rock Value} - \text{Weak Soil Value}) / \text{Weak Soil Value}$

Table 2 Hoof/surface material loading effects (constant stiffness, medium soil)

Damping Ratio	Chatter Time (ms)	End of Stance (ms)	Stance Duration (ms)	Max Track Deflection (cm)	Max VGRF (BWT)	Loading Rate (BWT s ⁻¹)	Energy Dissipated (J)
0.05	2	168	166	2.7	2.2	28	63
0.10	2	168	166	2.7	2.2	28	63
0.15	2	168	166	2.7	2.2	28	63
0.20	2	169	167	2.7	2.2	28	63
0.25	1	169	168	2.7	2.2	28	64
0.30	1	169	168	2.7	2.2	28	64
%Change	-50	1	2	0	0	0	2

%Change = $100 * (0.30 \text{ Damping Value} - 0.05 \text{ Damping Value}) / 0.05 \text{ Damping Value}$

for the rate of loading and energy dissipated, which were decreased and increased by 10%, respectively (Table 3). Varying the area of hoof by $\pm 50\%$ of the area used for all other simulations has a dramatic effect on all parameters (from between 10 and 124%) (Table 3). This is expected since the hoof area is multiplied by the soil's elastic subgrade modulus to determine its stiffness. A 50% change in the hoof area changes the soil stiffness by 50%.

Discussion

Results from the preliminary modelling suggest that factors other than soil damping may be most important for prediction of soil response. However, significant expansion of these results will be necessary to allow more complete conclusions to be drawn. A brief discussion of these results will be followed by proposed extensions to the model.

Table 3 Sensitivity Analysis

Property	Chatter Time (ms)	End of Stance (ms)	Stance Duration (ms)	Max Track Deflection (cm)	Max VGRF (BWT)	Loading Rate (BWT/s)	Energy Dissipated (J)
Soil Mass							
50% Less	1	165	164	2.7	2.2	28	64
50% More	2	172	170	2.7	2.2	28	62
%Change	100	4	4	0	0	0	-23
Hoof Mass							
50% Less	2	166	164	2.7	2.2	30	60
50% More	2	171	169	2.7	2.2	27	66
%Change	0	3	3	0	0	-10	10
Hoof Area							
50% Less	3	243	240	5.1	2.1	17	121
50% More	1	137	136	1.9	2.3	38	45
%Change	-66	-43	-43	-63	10	124	-63

%Change = $100 * (50\% \text{ More Value} - 50\% \text{ Less Value}) / 50\% \text{ Less Value}$

Perhaps the most significant observation from the model is the subtle impact of damping on the VGRF loading rate, energy dissipation and stance phase duration. Alterations in surface stiffness or hoof contact area appear to be more important in determining the level of these loading factors. It is, however, necessary to verify that the damping ratios of racetrack surface materials do not vary over a greater range than that used in this study. The results do suggest that racetrack material amendments which primarily alter surface damping may not be particularly important in avoiding racetrack breakdown.

More significant than damping effects are results in which racetrack surface stiffness is altered. The hoof area in contact with the surface plays a major role in the loading response. A 50% change in the hoof area has the effect of making the surface respond with a stiffness characteristic of a different soil type. It is not expected that the hoof areas of racing Thoroughbreds differ from each other by more than 10%, but even this small variation may have a significant impact on the bone and joint loading rates of the horse. This suggests conformation characteristics which should be considered for injury avoidance. The sensitivity analysis does show that altering the hoof area does not change the characteristic pattern of the ground reaction force. As a result, no matter what the contact area of the hoof, different surface material properties of

the racetrack will alter the loading on the bones and joints of a particular horse. Further research should be conducted to quantify these input parameters for the model. Better understanding of these values will make it possible to accurately predict the loading response under different racetrack conditions.

In addition, the size of the hoof has an influence on the depth of foot print, since this is dependent on soil stiffness. The foot print depths obtained from this analysis are somewhat lower than those measured on racetrack surfaces. A typical footprint at a track with moderate soil conditions may appear to be as deep as 10 cm (Larry Bramlage, personal communication, December 1999). However, many racetrack surfaces have a loose surface layer that does not contribute significantly to the load carrying. The surface layer is simply punched through by the hoof at first contact. A large crater with upraised edges then results. The more dense, lightly compacted layer underneath the top surface provides the reaction to the hoof and results in a footprint of the order of those found in the model. This is also similar to measured results from harder arena surfaces.

This modelling effort has shown that consistent quantitative measurements of the racetrack surface response to loading are needed. Previous track material studies have been performed to quantify the dynamic response of track surfaces to loads in

the vertical direction (Barry *et al.* 1991; Cheney *et al.* 1973; Pratt 1985; Zebarth & Sheard 1985; Clanton *et al.* 1991). However, the results from these methods have been shown to be poorly correlated with the loading of the limb (Nigg 1990). The lack of correlation may result from incomplete vertical characterisation; in particular, material properties may not be measured to a sufficient depth or at a sufficient load. However, the lack of correlation may have more complicated implications regarding the relative lack of importance of the variation in the vertical loading component. Future work should also consider horizontal loading components in the racetrack surface evaluation.

While significant potential exists for extensions to the model, prioritization of efforts may be considered based on the results presented. While extensive kinematic data could be obtained to verify the centre of mass and hoof velocities at impact, the second order characteristics of the mass of hoof suggest that the error introduced by the current approach on the loading will be limited. One exception would be if the gait of the horse is significantly altered by the racing surface. To determine if gait is altered, kinematic data must be collected on various surfaces to confirm that centre of mass and hoof velocities remain relatively constant regardless of surface stiffness. If the kinematics vary significantly between different surfaces these effects should be accounted for in the model.

One important extension to the model includes the addition of muscular contractions of the leg. The spring and dashpot representing the leg and its musculature does a reasonable job of representing the response during stance; initially absorbing the load during the first half of the stance phase and then extending to return energy during the second half of stance. However, no additional energy can be introduced beyond that which was originally contained in the system when a simple spring representation of the leg is used. Additional energy must be supplied in order for the hoof to leave the soil at the end of stance. Supplying additional energy during the second half of the stance phase,

however, would have no effect on the loading rates during the first half of the stance phase or on the maximum VGRF. To the extent that loading rates and maximum VGRF are correlated to the racetrack breakdown, the current model may be sufficient.

Another extension which would result in the hoof leaving the surface at the end of stance is to add the horizontal motion of the centre of mass of the horse. This will serve to reduce the contact time of the hoof with the track because one component of the inertia will pull the leg in the direction of motion after the centre of mass passes over the hoof. This motion will make the stance duration times more realistic for all racetrack surfaces. However, the inertia of the horse is not expected to alter the relative differences in the loading rates of the surfaces during the first half of the stance phase. As with adding energy to the system, the effects of horizontal motion will be apparent in the second half of the stance phase. Affected horizontal motion is also unlikely to alter the peak loading and, probably, racetrack breakdown.

Perhaps more important are the horizontal displacements and forces of the hoof. The hoof has horizontal displacements, velocities, accelerations and forces which are nonzero and could be added to the model to make it more realistic. The hoof has initial horizontal motion which first causes braking forces (to resist sliding) at initial impact and then propulsive forces in the cranial/caudal direction as the horse moves forward. These horizontal motions and ground reaction forces are expected to be significantly affected by the racetrack material properties and therefore may contribute to the safety and performance of horses. Additional horizontal motion occurs during cornering which subjects the leg to lateral forces. As the horse leans into the curve, a vertical component of the cornering force will also be evident. The racetrack material properties will clearly play a role in how the horse is affected by cornering.

One more extension to the model which may be important is the inclusion of rotation of the hoof during the stance phase (Ratzlaff *et al.* 1993). The rotation of the hoof, coupled with the horizontal and vertical ground reaction forces, can cause the

racetrack material to break loose at the end of the stance (termed 'cupping'). Cupping may be injurious to the horse due to the dramatic force changes and subsequent motions of the hoof and leg when traction is lost. The point at which cupping occurs is clearly dependent on the material properties of the racetrack surface. In order to consider the effect of cupping, the shear strength of the soil must be known as well as the resultant of the shear forces due to cornering and propulsion. Consideration of the horizontal loads and soil characteristics suggest additional racetrack testing as well as modelling may be needed in order to understand racetrack breakdowns.

In addition to cupping, rotation of the hoof alters the surface area of the hoof which is in contact with the racetrack. Change in the surface area will alter the surface stiffness which may significantly impact the loading on the hoof and limb. At the beginning of stance, the surface area would be smaller than presently modelled because the hoof does not contact the racetrack as a flat surface. The smaller surface area would reduce the effective stiffness of the soil and therefore reduce the initial 'shock' on the hoof at first contact as well as reducing the amount of chattering. As the stance phase continues, the hoof flattens out mid-stance and then continues to rotate through the second half of the stance phase. The surface area/effective stiffness of the racetrack thus first increases and then decreases through the stance phase. Measurements of the hoof have indicated that contact with the surface occurs at an angle of 15°. The hoof then leaves the surface with an angle of -30°, rotating a full 45° during the complete stance phase (Ratzlaff *et al.* 1993). While the rotation of the hoof will play a role at the beginning (reducing chatter) and end of the stance (promoting cupping) it is not expected to alter the maximum VGRF or maximum VGRF loading rate which occur between these two events temporally.

Conclusions

These preliminary results indicate that the track material characteristics may have a profound effect

on the loading rate of the limb and have possible implications for injury as well as performance. While it is premature to make definitive comments due to modelling assumptions and lack of knowledge relating to the exact causes of racetrack breakdown, it appears that the loading rate is significantly affected by the track surface. Notably, soil damping does not appear to be a significant factor in either the maximum VGRF or loading rate. This indicates that soil modifications, such as the addition of organic material, which primarily alter damping rather than stiffness or strength of the soil may not have a significant impact on racetrack breakdown.

With further research, the model can be expanded to include the horizontal contributions to the loading response. Further experimental testing of both horse and racetrack parameters can also reduce the number of assumptions resulting in a better understanding of the role of the racetrack surface on racetrack breakdown. The work presented is a first step in the modelling and reinforces the significance of the racetrack surface on the total loading of the forelimb.

References

- Alexander, R.M., Bennett, M.B. & Ker, R.F. (1986) Mechanical properties and function of paw pads of some mammals. *Journal of Zoology (London)*, **209**, 405–419.
- Barry, E., Landjert, B. & Wolter, R. (1991) Shock and vibration during the hoof impact on different track surfaces. *Equine Exercise Physiology*, **3**, 97–106.
- Cheney, J.A., Shen, C.K. & Wheat, J.D. (1973) Relationship of racetrack surface to lameness in the Thoroughbred racehorse. *American Journal of Veterinary Research*, **34**, 1285–1289.
- Clanton, C., Kobluk, C. & Robinson, R.A. (1991) Monitoring surface conditions of a Thoroughbred racetrack. *Journal of the Veterinary Medicine Association*, **198**, 613–620.
- Das, B.M. (1983) Analysis of Foundation Vibration. *Fundamentals of Soil Dynamics*. Elsevier. New York, pp. 185–223.
- Frederick, F.H. & Henderson, J.M. (1970) Impact force measurement using preloaded transducers. *American Journal of Veterinary Research*, **31**, 2279–2283.
- Greene, P.R. & McMahon, T.A. (1984) Reflex stiffness of man's anti-gravity muscles during knee bends while

- carrying extra weights. *Sport Shoes and Playing Surfaces: Biomechanical Properties* (E.C. Frederick, ed.). Human Kinetics Publishers, Inc., Champaign, Illinois, USA, pp. 119–137.
- Hardin, B.O. & Drnevich, V.P. (1972) Shear modulus and damping in soils: measurement and parameter effects. *Journal of Soil Mechanics & Foundations Division*, **98** (SM6), 603–624.
- Hjerten, G. & Drevemo, S. (1994) Semi-quantitative analysis of hoof-strike in the horse. *Journal of Biomechanics*, **27**, 997–1004.
- Leach, D. (1989) Locomotion of the athletic horse. *Equine Exercise Physiology*, **1**, 516–535.
- Mackay-Smith, M.P. (1977) Report-committee to study the prevention of lameness in racehorses. Report to the American Association of Equine Practitioners Executive Board. *American Association of Equine Practitioners Newsletter*, **1**, 33–38.
- Merkens, H.W., Schamhardt, H.C., van Osch, G.J.V.M. & van den Bogert, A.J. (1991) GRF analysis of Dutch Warmblood horses at canter and jumping. *Equine Exercise Physiology*, **3**, 128–135.
- Merkens, H.W., Schamhardt, H.C., van Osch, G.J.V.M. & van den Bogert, A.J. (1993) GRF patterns of Dutch Warmblood horses at normal trot. *Equine Vet Journal*, **25**, 134–137.
- Mohammed, H.O., Hill, T. & Lowe, J. (1991) Risk factors associated with injuries in Thoroughbred horses. *Equine Vet Journal*, **23**, 445–448.
- Mohammed, H.O., Hill, T. & Lowe, J. (1992) Risk of severity of limb injuries in racing Thoroughbred horses. *Cornell Veterinarian*, **82**, 331–341.
- Nigg, B.M. (1990) The validity and relevance of tests used for the assessment of sports surfaces. *Medicine & Science in Sports & Exercise*, **22**, 131–139.
- Nigg, B.M., Cole, G.K. & Bruggemann, G.P. (1995) Impact forces during heel-toe running. *Journal of Applied Biomechanics*, **11**, 407–432.
- Peloso, J.G., Mundy, G.D. & Cohen, N.D. (1994) Prevalence and factors associated with musculoskeletal racing injuries of Thoroughbreds. *Journal of the American Veterinary Medicine Association*, **204**, 620–626.
- Pratt, G.W. (1985) Racing surfaces – a survey of mechanical behavior. *Proceedings of the American Association of Equine Practitioners 30th Annual Conference*, 321–331.
- Pratt, G.W. & O’Conner, J.T. Jr (1978) A relationship between gait and breakdown in the horse. *American Journal of Veterinary Research*, **39**, 249–253.
- Ratzlaff, M.H., Grant, B.D., Frame, J.M. & Hyde, M.L. (1989) Locomotor forces of galloping horses. *Equine Exercise Physiology*, **1**, 574–586.
- Ratzlaff, M.H., Wilson, P.D., Hyde, M.L., Balch, O.K. & Grant, B.D. (1993) Relationships between locomotor forces, hoof position, and joint motion during the support phase of the stride of galloping horses. *Acta Anatomica*, **146**, 200–204.
- Riemersma, D.J., van den Bogert, A.J., Jansen, M.O. & Schamhardt, H.C. (1996) Tendon strain in the forelimbs as a function of gait and ground characteristics and *in vitro* limb loading in ponies. *Equine Veterinary Journal*, **28**, 133–138.
- Schamhardt, H.C., Merkens, H.W. & van Osch, G.J.V.M. (1991) GRF analysis of horses ridden at the walk and trot. *Equine Exercise Physiology*, **3**, 120–127.
- Stillman, J.D.B. (1881) *The Horse in Motion*. James R. Osgood, Boston, MA, USA.
- Stover, S.M., Johnson, B.J. & Daft, B.M. (1992) An association between complete and incomplete fractures of the humerus in racehorses. *Equine Veterinary Journal*, **24**, 260–263.
- Vyalov, S.S. (1986) Elasticity, plasticity and viscosity. *Rheological Fundamentals of Soil Mechanics*. Elsevier. New York, NY, USA.
- Zebarth, B.J. & Sheard, R.W. (1985) Impact and shear resistance of turfgrass racing surfaces for Thoroughbreds. *American Journal of Veterinary Research*, **46**, 778–784.