Equine Exercise Physiology 3: 97–106, 1991

Shock and Vibration during the Hoof Impact on Different Track Surfaces

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ABSTRACT. Forelimb hoof impact was studied at the trot in 8 sound horses on a number of different track surfaces. A uniaxial accelerometer, fixed on the lateral hoof wall, provided measurements for 2 seconds at a sampling rate of 2034 per second. Each horse was trotted at a mean speed of 4 m s^{-1}, on the reference surface (i.e. asphalt) and on several different track surfaces. The acceleration curves of the impacts were analysed with software which calculated measurements of shock (i.e. maximum amplitude, duration) and vibration (i.e. mean frequency, total duration, mean root square). For each track surface tested, density, and composition were measured. Results were analysed by a multivariate procedure. Impact intensity was related to density and composition of the track in synthetic and mineral materials. The damping of the track surface depended on the density, particle size distribution and rheological properties of the track materials. It was possible to predict impact characteristics such as shock acceleration, vibration frequency and power content. The results of the multivariate analysis suggested that tracks could be classified into three types of mechanical behaviour, namely dense hard surfaces, surfaces with friction damping and surfaces with structural damping.

Key words. Horses; biomechanics; concussion; acceleration; hoof; track surface.

INTRODUCTION

Force plates studies provide force/time curves of three orthogonal components of the ground reaction forces during the stance phase.[16,22,25] The vertical component usually comprises two dynamic processes;[14] high frequency forces occurring immediately after hoof impact[5,10,16,25] and low frequency forces occurring later in the stance phase. High frequency, passive, initial and impact are expressions used to describe the initial high loading forces.[15] These impact forces attain their peak and then vibrate at high frequency. The vibrations are considered to have potentially damaging effects on the locomotor system of human athletes[14,15,21] and performance horses.[20] A relationship between repeated exposure to shock and onset of chronic injuries has been established in human medicine[24] and in some animal model.[18,19] Low frequency, active, and propulsive are the terms used to describe the lower loading forces.[15] The active force has a support, decelerative and propulsive function which implicates muscular activity.

The resilience of the track surface has a great influence on the intensity of the impact forces[13,14] and amplitude of the vertical hoof force.[2,7] To minimize orthopaedic injury and to maximize sporting performance of human athletes, it has been suggested that a track should have a stiffness about three times that of the runner's stiffness.[13]

Two methods have been used to test the mechanical properties of equine tracks; the drop hammer technique[4,12,17,26] and recording of hoof acceleration of the running horse.[1,17] The purpose of this study was to compare different equestrian tracks by measuring hoof acceleration parameters in trotting horses.

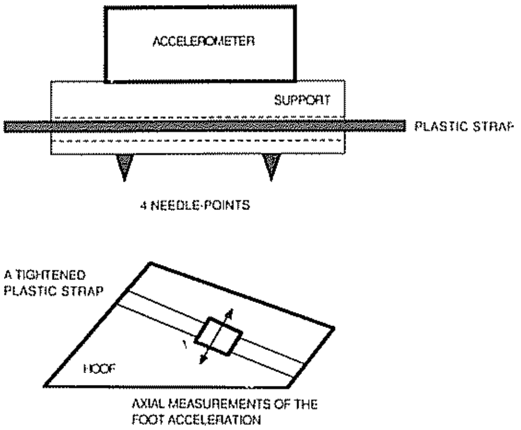

Fig 1 The location of the accelerometer fixed on the lateral wall of the left hoof. The transducer measured the acceleration along the foot axis

MATERIALS AND METHODS

Track surfaces

An asphalt road was used as the reference surface and then 8 equestrian tracks were tested. In addition, 2 horses were tested on a treadmill with a rubber belt (Säto, Sweden) (Table 1). The tracks were all located at the National Equestrian School in Saumur, France. Six tracks were outdoors and 2 tracks were indoors. All were regularly used for dressage, jumping and three-day event training and were harrowed daily. Before testing, a sample of the loose track cushion from a randomly chosen location was taken for physical analysis. Parameters calculated were: dry density (DENS), water content (WATER), percentage of organic materials (ORGA) and particles size distribution (<1 mm, 1–2 mm, 2–4 mm, >4 mm).

Measuring method

The measuring system consisted of an accelerometer fixed to the hoof and a data acquisition system (Fig. 1). The accelerometer provided continuous measurements of the axial acceleration of the hoof. The accelerometer (Egasy-250D-FR, Entran sarl, France) was selected to record shocks and vibrations of the hoof impact which require both large amplitude scale ($\pm 2\,500$ m s^{-2}) and high natural frequency (2000 Hz). The accelerometer was fixed on the lateral wall of the left hoof on the widest transverse axis to ensure that it was the same relative location for each horse.

The data acquisition system consisted of an amplifier, an analog-digital interface (Kap 303, KAP sarl, Paris) and a portable microcomputer (Canon X-07). Wires were

Table 1. *Track surfaces tested and their physical characteristics*

			Particle size distribution					
Track composition	Type of track	Density (g cm^{-3})	<1 mm (%)	1–2 mm (%)	2–4 mm (%)	>4 mm (%)	Organic (%)	Water (%)
Asphalt	Road	2.7	–	–	–	100	–	–
Gravel + sand	Jumping	1.31	49.5	33.5	15.6	1.4	2.5	4.3
Wood fibers	Training	0.28	49.8	17.0	20.0	13.2	70.3	48.1
Sand	Training	1.38	94.6	3.6	1.3	0.5	1.5	0.6
Sand	Steeple	1.33	89.9	5.5	2.3	2.3	4.1	5.6
Gravel + sand	Dressage	1.40	53.2	26.8	15.1	4.9	2.9	4.5
Sawdust + sand	Manege	0.64	50.4	31.2	15.5	2.9	24.6	28.3
Wood chips	Manege	0.21	33.7	19.4	23.6	23.6	70.5	41.1
Gravel	Pathway	1.40	25.0	10.0	60.0	5.0	1.0	20.0
Rubber belt	Treadmill	1.19	–	–	–	100	–	–

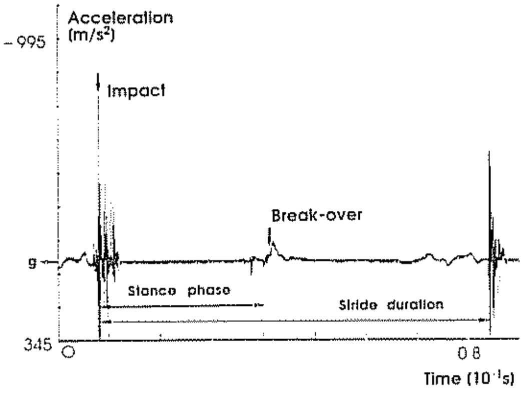

Fig. 2. Hoof acceleration/time curve of a trotting stride on the asphalt road (G = gravity acceleration).

taped to the limb and connected to the amplifier attached to the saddle. A person moving beside the horse carried the microcomputer-A/D interface pack wired to the amplifier with a cable 10 m long. During each trial, the person could start the recording and the data acquisition occurred at the rate of 2034 per second over 2 seconds. After transferring the data to another microcomputer the acceleration/time curves were analyzed with software which calculated kinematic and stride parameters.

Track-testing

Each surface was tested with several horses to minimize individual effect on the results. Seven sound saddle horses shod with standard steel shoes were ridden for track testing by the same rider (70 kg). Data acquisition was performd at the trot in a straight line as soon as the gait reached a regular cadence. The acceleration measurements were collected over 2 or 3 strides. The horses trotted at the average speed of 4 m s^{-1} (±0.54). The velocity was determined by measuring the time required to trot 20 m. A total of 31 track tests were performed on the reference surface (asphalt), and the 8 equestrian tracks and 2 tests on the treadmill belt (Table 2).

Kinematic parameters

A computer program provided quantitative information about shock, vibration and the temporal stride parameters. For each track test these parameters were averaged over 2 or 3 strides.

Shock parameters. Peak of acceleration (SHOCK) was maximum deceleration recorded at hoof impact. Shock duration (SHODUR) was measurement of time between the beginning of impact and the return to zero acceleration.

Vibration parameters. Mean frequency (FREQ) was the ratio between total number of vibrations and duration of impact vibrations. Vibration duration (VIBDUR) was time between the beginning of impact and the end of oscillatory acceleration. Root mean square (RMS) was the mean value ob-

Table 2. *Details of the horses used for the track test*

G = gelding, S = stallion

Horse	Age (yrs)	Sex	Weight (kg)	Track test number
1	8	G	615	1, 6, 10, 14, 16
2	11	G	695	2, 7, 11, 15, 17, 20, 23, 26
3	16	G	615	3, 8, 12, 18
4	17	G	610	4, 9, 13, 19, 21, 24, 27, 29
5	8	G	550	5, 22, 25, 28
6	5	S	475	A1, T1
7	4	S	485	A2, T2

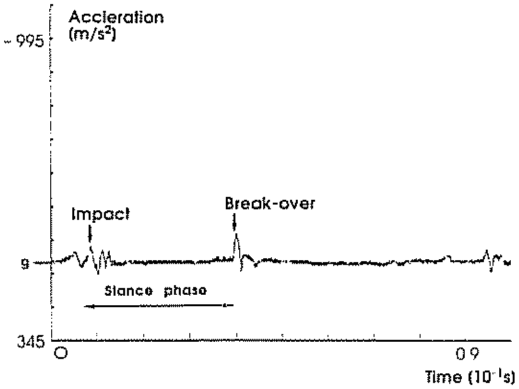

Fig. 3. Hoof acceleration/time curve of a trotting stride on a track composed of wood fibers (G = gravity acceleration).

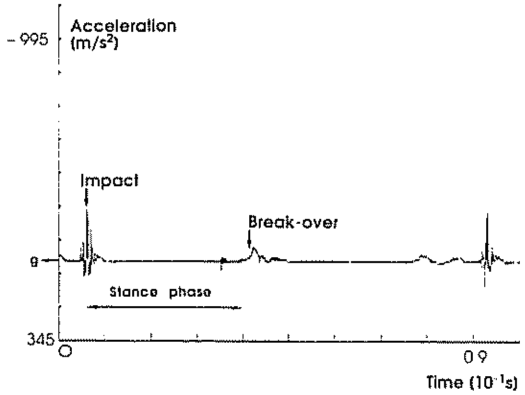

Fig. 4. Hoof acceleration/time curve of a trotting stride on the treadmill (G = gravity acceleration).

tained by the following formula[3]:

$$\mathrm{RMS} = \sqrt{\frac{1}{\mathrm{VIBDUR}} \int \mathrm{Acceleration}^2 \cdot \mathrm{dt}}$$

There is a simple relationship between the RMS-value and the power content of impact vibrations. Maximum modulus of the Fast Fourier Transform (MODFFT) was ampli-

Table 3. *Mean kinematic parameters measured on the different track surfaces* (±*SD*)

Track	Track test no.	SHOCK ($m\ s^{-2}$)	SHODUR (ms)	FREQ (Hz)	VIBDUR (ms)	RMS ($m\ s^{-2}$)
Asphalt	1–5	707.9	1.2	592	32.5	123.5
$n=7$	A1–A2	±66.5	±0.2	±141	±12.2	±22.5
Gravel + sand	6–9	60.3	1.8	361	21.9	25.1
$n=4$		±34.3	±0.8	±36	±11.5	±13.4
Wood fibers	10–13	69.3	12.4	64	57.8	32.7
$n=4$		±46.2	±3.8	±28	±12.2	±8
Sand	14–15	41.8	2.0	510	9.5	21,8
$n=2$		±7.9	±1.0	±354	±2.5	±8.6
Sand	16–19	58.6	3.6	238	28.1	26.1
$n=4$		±15.2	±2.1	±158	±10.8	±9.5
Gravel + sand	20–22	37.6	13.5	49	75.7	13.2
$n=3$		±28.9	±0.0	±11	±20	±4.7
Sawdust + sand	23–25	31.1	29.8	41	54.2	12.6
$n=3$		±8.9	±11.2	±7	±6.9	±2.9
Wood chips	26–28	48.4	19.0	47	99.2	18.7
$n=3$		±16.8	±3.6	±10	±38.1	±5.2
Gravel	29	372.5	2.5	392	45.0	60.0
$n=1$						
Rubber belt	T1–T2	232.9	3	282	24.0	57.1
$n=2$		±25.9	±0.0	±117	±11.3	±14.0
Significance		$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

tude of the first harmonic from the frequency spectrum obtained by the Fast Fourier Transform of the impact acceleration.

Temporal stride characteristics. Stance phase duration (STAND) was measurement of the time between the beginning of impact and the lift-off of the toe (Fig. 2). Stride frequency (SFREQ) was the number of strides per unit time obtained from measurement of stride duration. This temporal stride parameter was the time required to complete one stride measured as the interval between the beginning of the impact from 2 successive strides (Fig. 2).

Statistical analysis

The mean parameters obtained for each track with different horses (Table 3) and the mean parameters measured with each horse on different tracks (Table 4) were tested to distinguish the influence of track and horse on the parameter values. To identify significant differences between groups (i.e. tracks or horses) a one-way analysis of variance was used with $p<0.01$.

MODFFT	STAND (ms)	SFREQ (Hz)
1 027	276.4	1.37
±488	±28.5	±0.04
630	290.8	1.29
±16.27	±23.3	±0.05
1 342	278.8	1.25
±10	±17.9	±0.08
456	249.5	1.22
±209	±11.5	±0.05
827	282.5	1.25
±318	±14.5	±0.07
2 728	324.7	1.31
±1 161	±58.2	±0.05
1 228	321.3	1.27
±161	±40.1	±0.05
3 133	350.3	1.3
±1 265	±52.8	±0.02
1 366	269.0	1.40
662	326.5	1.25
±291	±47.4	±0.13
$p<0.01$	NS	NS

To compare all physical and kinematic parameters in the different tracks multivariate statistics were used.[1,22] A principal components analysis was applied to the data obtained for each track test.

RESULTS

Acceleration/time curves

The acceleration/time curves revealed a wide range of impact intensity with regard to the hardness of the track surface (Figs. 2, 3, 4). On each curve, the stance phase and the swing phase were distinguishable. The stance phase began and ended with vibrations periods. Between the impact and the break-over the hoof stayed at rest and the acceleration reached a constant value. During the swing phase, hoof acceleration changed continuously, but the variation of amplitude was too small to be clearly observed at the scale used in Figs. 2–4.

Kinematic parameters

The kinematic parameters of the 33 tests represented 68 strides from 7 horses. Averaging of all the tests obtained on the same track indicated a variety of responses to the hoof impact (Table 3). SHOCK (coefficient of variation = 144%) and FREQ (coefficient of variation = 96%) were quite different in accordance with the hardness of the track surface. The maximum value of the shock impact recorded on asphalt reached -806 m s^{-2}.

The analysis of variance on the mean parameters obtained for each horse on the various tracks were not different ($p>0.11$) for SHOCK, SHOCKDUR, FREQ, VIBDUR, RMS or MODFFT, while the stride parameters STAND and SFREQ were different ($p<0.01$) (Table 4).

Multivariate analysis

The data for the first two component axes have been summarised in (Figs. 5 and 6).

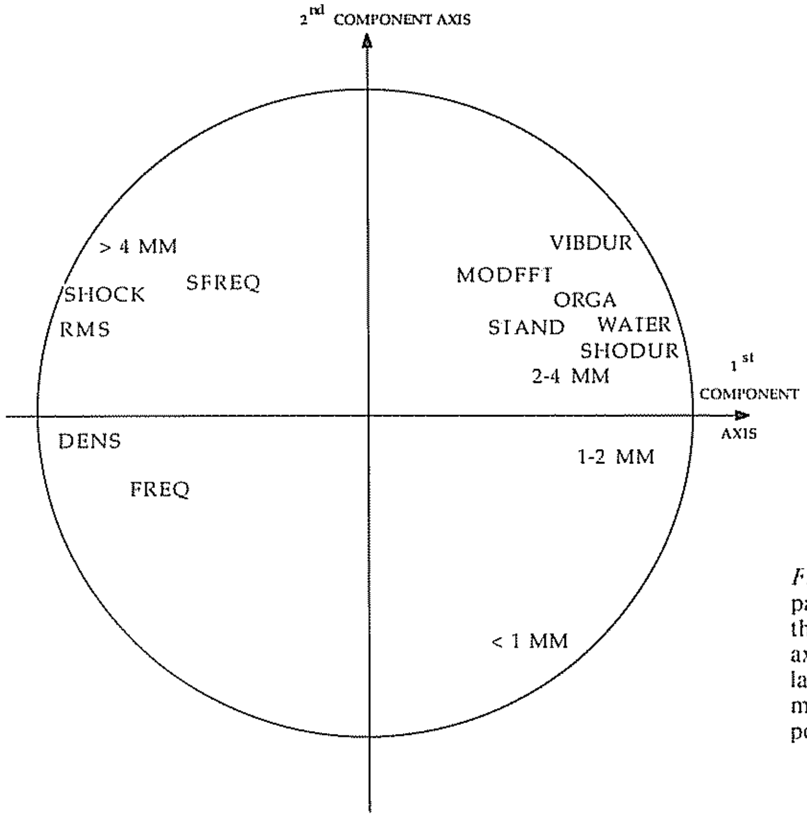

Fig 5 Results of principal component analysis on the first two component axes: diagram of the correlations between the parameters and principal component axes.

Table 4. *Mean kinematic parameters measured on the different testing horses* (±*SD*)

Horse	SHOCK ($m\ s^{-2}$)	SHODUR (ms)	FREQ (Hz)	VIBDUR (ms)	RMS ($m\ s^{-2}$)	MODFFT	STAND (ms)	SFREQ (Hz)
Horse 1	176.2	4.9	181	32.3	50.2	1 049	253.6	1.23
n=5	±256.7	±5.2	±122	±26.9	±44.3	±609	±15.9	±0.08
Horse 2	156.3	7.0	318	34.8	41.3	944	270.6	1.33
n=8	±219.7	±5.6	±289	±17.3	±46.4	±413	±11.2	±0.03
Horse 3	220.8	5.5	404	36.4	48.7	946	302.5	1.23
n=4	±284.8	±6.7	±249	±14.2	±37.2	±262	±15.6	±0.06
Horse 4	172.3	11.8	213	61.2	33.9	1 680	318.1	1.34
n=8	±264.8	±11.9	±220	±34.1	±32.1	±1 074	±44.7	±0.05
Horse 5	176.5	18.5	167	67.5	35.8	2 466	339.8	1.27
n=4	±245.1	±13.1	±217	±35.2	±37.8	±1 623	±47.6	±0.06
Horse 6	503.7	2.5	521	34.5	77.2	1 086	337	1.28
n=2	±408.9	±0.7	±222	±3.5	±42.3	±309	±32.5	±0.18
Horse 7	463.2	1.5	407	21.5	79.5	541	291.5	1.41
n=2	±299.7	±1.41	±293	±7.8	±17.7	±120	±2.1	±0.01
Significance	NS	NS	NS	NS	NS	NS	$p<0.01$	$p<0.01$

NS = no significant differences between horses

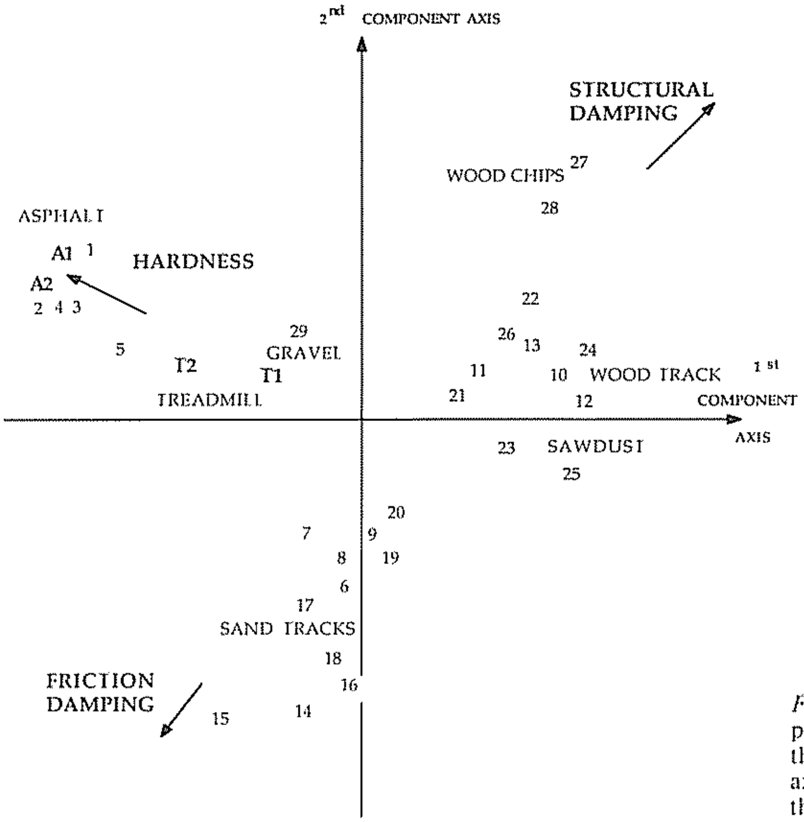

Fig 6 Results of principal component analysis on the first two component axes: comparison between the track surfaces.

These illustrations give a synthetic view of the relationships between parameters (Fig. 5) and compared the track surfaces with regard to their properties (Fig. 6). The first and second axes explained 46.9% and 21.5% of the total variation; the diagram represented 68.4% of the total variation.

In Fig. 5, the first component axis distinguished the more significant parameters: DENS, WATER, ORGA, SHOCK, FREQ, VIBDUR, SHODUR and RMS. It also partially separated the track surfaces by particle size. The second component axis distinguished the tracks in respect of their fine particle size (< 1 mm). The parameters ORGA, WATER and VIBDUR only partially differentiated the tracks.

There were many significant correlations ($p < 0.05$) between the physical and kinematic parameters. DENS was highly correlated with SHOCK, FREQ, RMS. Particle size distribution (2–4 mm, 1–2 mm and < 1 mm), WATER and ORGA were negatively correlated with SHOCK, FREQ and RMS. SHOCK and RMS were positively correlated with SFREQ. FREQ increased simultaneously with SHOCK. FREQ was positively correlated with RMS. SFREQ was positively correlated with DENS and negatively correlated with the small particle size distribution (< 1 mm).

The results of the principal component analysis were plotted relative to the first two component axes (Fig. 6). Away from the origin, the nearer the tracks to one another, the more similar their properties. The harder tracks were located on the left and the softer tracks on the right. The treadmill belt was tested by two horses (T1, T2) that also trotted on the asphalt (A1, A2). Asphalt was on the left and the tracks composed of wood and sand on the right along an oblique line.

The gravel pathway and the treadmill belt were located at mid-distance between the harder and softer tracks. The oblique line contained wooden materials in the upper part and mineral materials in the lower part.

The terms 'structural damping' and 'friction damping' describe the damping system of the track surface (SHOCK reduction) in relationship with its composition and particle size (< 1 mm). Structural damping means that impact loading is damped by deformation of viscoelastic particles. Friction damping means that impact loading is damped by displacement of small particles over the others. The track surfaces having structural damping were separated by a higher ORGA, WATER and 2–4 mm values and lower SHOCK values. The track surfaces having friction damping were separated by a lower ORGA and WATER values and higher SHOCK and < 1 mm values.

DISCUSSION

Few studies in horses have used acceleration measurements to describe the kinematics of motion.[6,17] However, the range of shock acceleration measured on the different track surfaces was consistent with the results obtained in other hoof acceleration studies of horses[1,2,17] and human athletes.[8,9,11] The acceleration/time curves recorded at the moment of impact in this study were similar in amplitude[2,17] and shape[2] to observations reported previously. The measurement of the acceleration during the complete limb cycle appears to be the first quantitative study of the hoof shock and vibration in horses. For example, the maximum passive force at impact on asphalt could be estimated to be 1 842 N for a trotting horse of 578 kg body weight (i.e. the digit mass is about 0.45% of body weight[23] and mean maximum deceleration on asphalt was -708 m s^{-2}). During impact, the hoof would be exposed to a vibrating force at 590 Hz which progressively decreases because of the viscoelastic damping. The shock at impact seems to increase with the stride frequency.

Most track testing has used the drop hammer technique which provides acceleration, force and displacement measurements of an impactor falling from a few cm.[4,12,17,26] The apparatus could not reproduce the same mechanical strains as the hoof of a moving horse, and so a horse equipped with a hoof accelerometer could be a valuable track testing method.

The mechanical track properties had a great influence on the shock and vibration parameters. DENS seems to be the primary factor which influences SHOCK, FREQ and RMS of impact. The shock and vibration were reduced on the track surfaces composed of a high percentage of ORGA (e.g. wood), WATER and small particle size distribution.

The destructive power of the undamped impact could be minimized by riding on track surfaces which absorb the initial shock of the hoof. From this point of view, the more efficient track tested here seemed to be the one with structural damping. The tracks composed of a large proportion of organic particles had the greatest damping ability, e.g. tracks containing wood fibers, wood chips and sawdust. In another study,[2] leather chips and pieces of polymer mixed with sand appeared to have structural damping properties similar to wood fibers.

The loose sand, which is a two phase system (i.e. particles and water), has a friction damping capacity that could be controlled by the water content. It was demonstrated that the optimum water content depended on the particle size distribution and was about 8 to 17%.[4,17] This range of moisture content provided the maximum compaction of the sand layer.

Measurement of hoof acceleration has been shown to be a useful method for comparing the effects of different track surfaces on the dynamic parameters of hoof impact. The variety of dynamic responses of the track surface suggested that the choice of the track materials could influence the gait biomechanics. The results of the multivariate analysis indicated the track surfaces could be classified into three types of mechanical behaviour; dense hard surfaces (e.g. asphalt), surfaces with friction damping (e.g. sand) and surfaces with structural damping (e.g. wood fibers). However, more investigations are necessary to match the track to the biomechanics of the moving horse in order to prevent the destructive effects of undamped impact and to improve athletic performance.

ACKNOWLEDGEMENTS

Funding for this project was provided in part by the organisations Haras Nationaux and INRA. We are indebted to the Director, Mr Lhemanne for permitting measurements on the horses and allowing access to all the tracks of the French National Equestrian School. We gratefully thank Mr Galloux for his technical support.

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