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A preliminary study on pressure-plate evaluation of forelimb toe–heel and mediolateral hoof balance on a hard vs. a soft surface in sound ponies at the walk and trot

M. OOSTERLINCK*[†], E. ROYAUX[†], W. BACK[†‡] and F. PILLE[†]

[†]Department of Surgery and Anaesthesiology, Faculty of Veterinary Medicine, Ghent University, Merelbeke, Belgium
[‡]Department of Equine Sciences, Faculty of Veterinary Medicine, Utrecht University, The Netherlands.

*Correspondence email: maarten.oosterlinck@ugent.be; Received: 11.02.13; Accepted: 02.11.13

Summary

Reasons for performing study: Thus far, pressure-plate analysis has been limited to measurements on a hard surface, whereas equine athletes routinely perform on a deformable substrate.
Objectives: To explore pressure-plate analysis on arena footing.
Study design: Nonrandomised crossover study using noninvasive techniques.
Methods: Five sound, unshod ponies were walked and trotted over a pressure plate in 2 different conditions. In the first session, the plate was covered with only a 5 mm rubber mat, and in the second session, with an additional 50 mm layer of sand and synthetic fibres. Limb loading and timing variables (peak vertical force, vertical impulse, peak vertical pressure, hoof contact area and stance phase duration) were obtained. Toe–heel and mediolateral hoof balance of the vertical force were calculated throughout stance (126 Hz).
Results: Peak vertical force, vertical impulse, peak vertical pressure and stance phase duration were decreased on the soft substrate, while hoof contact area increased. At impact, there was more even load distribution between the toe and heel region on the soft vs. hard surface. At mid-stance, there was more loading of the toe region on the soft compared with the hard surface. At impact, there was more even load distribution between lateral and medial on the soft vs. hard surface at walk, but not at trot.
Conclusions: Comparison of observed vs. expected impulse indicated that the main factor involved in the lower loading on the soft surface is the dampening effect of the soft substrate, although definitive conclusions require concurrent force-plate analysis. The pressure plate permitted quantitative evaluation of hoof balance of the vertical force on a deformable surface at the walk and trot and proved that there is more even load distribution on arena footing.

Keywords: horse; arena footing; gait analysis; pressure distribution; track surface

Introduction

Technology is gradually becoming available to provide the equine clinician and farrier with objective and quantitative biomechanical tools for the assessment of equine locomotion [1]. A pressure plate has been used alone or in combination with a force plate to study the static [2] and the dynamic pressure distribution underneath the hoof [3] and to study the effect of regular trimming [4–6] and shoeing with a rolled toe [7]. Pressure-plate analysis has been used in the evaluation of equine limb loading and its symmetry [8], hoof contact area [9], the pressure distribution within each hoof [10] and the toe–heel and mediolateral hoof balance of the vertical ground reaction force [11]. The strength of pressure-plate systems is that, noninvasively, they can give information about the symmetry in force distribution between limbs as well as the pressure distribution over the contact area of the hoof. However, a pressure plate cannot be used interchangeably with a force plate to measure absolute values of limb loading, because it has limitations in accuracy [12], especially at impact and breakover [13].

Thus far, pressure-plate analysis in horses has focused mainly on measurements on a hard surface, whereas equestrian sports are routinely performing on a soft, deformable surface. Statically, pressure-measuring equipment has been used for the evaluation of the effect of ground surface deformability, trimming and shoeing on hoof loading [14] and for proving that sole fillers redistribute pressure from the wall to the sole [15]. Based on its successful application for the analysis of footprints of humans walking in sand [16], we speculated that equine pressure-plate analysis might be performed during locomotion on a sand track. The aim of the present study, therefore, was to explore the possibilities and limitations of pressure-plate analysis for the evaluation of hoof loading and balance of the vertical ground reaction force on a hard vs. a deformable substrate, as used in riding arenas. The hypothesis was that pressure-plate analysis of hoof loading and balance of the vertical force at the walk and trot would be significantly different on hard compared with soft surfaces.

Materials and methods

Ponies

Given that available plate dimensions are relatively small (2 m × 0.4 m), ponies were used to increase the likelihood of hooves fully contacting the measurement area. Five healthy, clinically sound, unshod ponies of the faculty's teaching herd were used (4 geldings and one mare; mean ± s.d. age 12 ± 4 years; body mass 281 ± 33 kg; height at the withers 1.19 ± 0.05 m). The body mass of each pony was recorded before the start of each measuring session.

Measurement system and data collection

The ponies were led first at walk and subsequently at trot over the pressure plate (Footscan 3D 2m-system)[a], embedded between high-density polyethylene plates in the middle of a 20-m-long track and covered with a 5-mm-thick rubber mat with a shore hardness of 65 ± 5, as described previously [8,9]. The pressure plate consists of 16,384 sensors in a matrix with a spatial resolution of 2.6 sensors/cm^2 and a pressure range of 0–200 N/cm^2. Following 5 min of warming up, the ponies were led from their left side over the measuring system by an experienced handler, on a long lead rope, without interfering with their speed or head motion. The average speed over the pressure plate was measured using 2 gates of photoelectric sensors with a 2 m interval centred over the measuring area. Although acceleration was not measured, the 20-m-long track ensured that the effect of acceleration and deceleration at the start and end of each trial was minimised over the central measuring area. A trial was considered valid if the pony moved at a constant pace, looked straight ahead, the gait speed was within a narrow preset range and the hoof of at least one forelimb fully contacted the plate surface. Five valid measurements of each forelimb were collected.

The hard-surface trials were performed along the 20 m flat rubber surface. For the sand trials, performed one week later, a trough was constructed on top of the standard hard surface. The wooden trough (2 m wide, 7 m long and 7.5 cm deep) was created over the measuring area, lined with a plastic sheet and filled to a depth of 5 cm with a mixture of sand (particle size 250–500 μm; density 2590 kg/m^3) and textile fibres (2 kg fibres/m^3 sand). The sand track ran from 3 m before to 2 m beyond the pressure plate. Before every measurement, the surface of the soft surface was levelled. The threshold of the pressure plate was adjusted according to the offset value obtained by the weight of the overlying substrate, avoiding premature activation of the sensors [13].

Data processing and statistical analysis

Limb loading and timing variables (peak vertical force [PVF; in newtons per kilogram], vertical impulse [VI; in newtons seconds per kilogram], peak vertical pressure [PVP; in newtons per square centimetre per kilogram], hoof contact area [CA; in square centimetres] and duration of the stance phase [ST; in milliseconds]) were obtained. Hoof prints were divided into a toe and a heel region by a line through the maximal hoof width, and into a medial and a lateral zone by a line through the central part of the toe and midway between the heels, as described previously [10,11]. The corresponding vertical forces (VF) were sampled at 126 Hz, and toe–heel and mediolateral hoof balance were calculated and presented as mean ± s.d. curves throughout the stance phase, as follows [11]:

$$\text{Toe–heel balance} = \frac{VF_{Toe} - VF_{Heel}}{0.5(VF_{Toe} + VF_{Heel})} \times 100\%$$

The limited measurement area did not allow consistent evaluation of stride time; however, recording consecutive left and right hoof strikes in several of the trials allowed us to evaluate step time, which in sound animals may be supposed to be half the stride time. Consequently, based on a limited number of trials, duty factor (stance time/stride time) could be calculated.

Theoretically, total VI during a stride should equal body weight multiplied by stride time [17]. To evaluate the measuring error of the pressure plate on both surfaces, the expected (body weight × stride time) and observed (sum of the VI of the 4 limbs) total VI (in newtons) were calculated.

Data were prepared for analysis using Microsoft Office Excel 2007[b]. Statistical analysis was performed using IBM SPSS Statistics 19[c], with statistical significance set at P<0.05. Data are presented as means ± s.d. Kolmogorov–Smirnoff and Shapiro–Wilk tests were used to identify significant departures from a normal distribution. Student's paired *t* test was used to compare the ponies' body mass and speed between the measurements on the hard and soft surface. Linear mixed-model analysis, with pony as a random factor and track (hard vs. soft surface), limb (left vs. right), gait (walk vs. trot) and their interaction, was used to compare limb loading and timing variables (PVF, VI, PVP, CA, ST) between the hard and soft surface measurements, and with pony as a random factor and track (hard vs. soft surface), gait (walk vs. trot) and their interaction, was used to compare step time and duty factor between the hard and soft surface. Student's *t* test with Bonferroni adjustment was used to compare the expected and observed total impulse. As the hoof balance values at impact, mid-stance and the end of the stance phase had significant departures from a normal distribution that could not be resolved after transformation, a Kruskall–Wallis test was performed, with *post hoc* pairwise comparisons (soft vs. hard surface) using Mann–Whitney *U* tests with Bonferroni adjustment.

Results

There were no significant differences in body mass and in speed between the trials (281 ± 33 vs. 285 ± 39 kg; walk, 1.26 ± 0.15 vs. 1.21 ± 0.08 m/s; and trot, 2.68 ± 0.26 vs. 2.54 ± 0.58 m/s).

A representative example of one left forehoof measurement on the hard and on the soft surface is presented in Figure 1. The pressure distribution on the hard surface presented a peripheral load distribution (Fig 1a), whereas on the soft surface, a larger and more centrally located load distribution was observed (Fig 1b). During the sand trials, the hooves did not 'bottom out' or touch the rubber mat.

The mean ± s.d. left, right and combined (left and right) loading and timing variables (PVF, VI, PVP, CA and ST) are shown in Table 1. The PVF, VI, PVP and ST were significantly decreased on the soft substrate, while CA increased significantly (P<0.001). The left and right CA were not significantly different. Left and right PVF and VI were significantly different on the hard and soft surfaces (P<0.001), whereas left and right ST were significantly different on the soft surface (P<0.001) but not on the hard surface, and left and right PVP were significantly different on the hard surface (P<0.001) but not on the soft surface.

Mean ± s.d. expected and observed total VI are presented in Table 2. The observed VI at the walk on a hard surface was significantly higher than the expected VI (P = 0.028), whereas there were no significant differences between the expected and observed total VI at the walk on a soft surface and at the trot on both surfaces.

At the walk, the ponies presented similar step times on a soft compared with a hard surface (505 ± 39 compared with 504 ± 18 ms). At the trot, there was a slight reduction in step time (hence, a higher stride frequency) on a soft compared with a hard surface (254 ± 21 vs. 288 ± 12 ms); this was not significantly different. There were no significant differences in duty factor between the hard and soft surface at the walk and trot, respectively (0.68 ± 0.02: walk, hard surface; 0.66 ± 0.05: walk, soft surface; 0.49 ± 0.04: trot, hard surface; 0.47 ± 0.08: trot, soft surface).

The data from left and right toe–heel and mediolateral hoof balance overlapped and are therefore presented together (Figs 2, 3). At impact, there was more even load distribution between the toe and heel region on the soft compared with the hard surface at the walk (P<0.001) and at the trot (P = 0.039). At mid-stance, there was significantly more loading of the toe region on the soft compared with the hard surface at the walk (P = 0.044) and at the trot (P = 0.005), whereas no significant differences could be detected at the end of the stance phase.

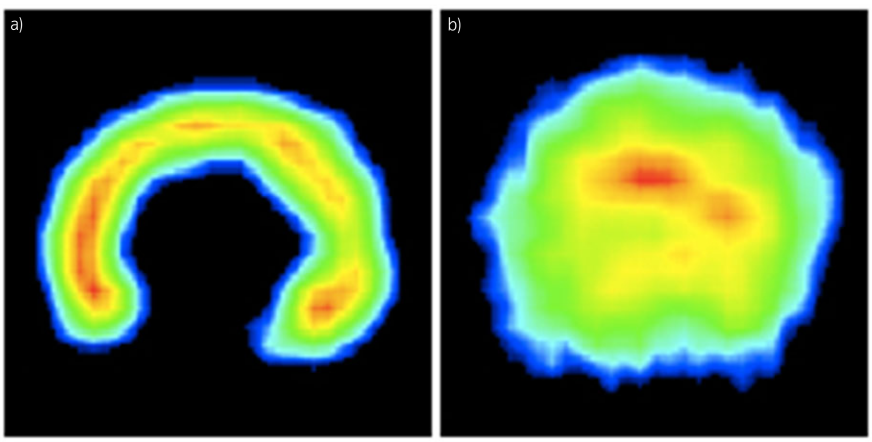

Fig 1: Representative example of the left forehoof of a pony at the walk on the hard (a) and on the soft surface (b). The pressure distribution is colour-coded from blue (low pressure) to red (high pressure). Every individual pixel corresponds to one single pressure sensor (spatial resolution of 2.6 sensors/cm^2).The image represents the total pressure recorded during the complete stance phase.

TABLE 1: Mean ± s.d. left, right and combined left and right limb loading and timing variables and duration of the stance phase of 5 sound unshod ponies (281 ± 33 kg) at the walk and trot on a hard vs. a soft surface

	Hard surface			Soft surface		
Variable	Left	Right	Combined	Left	Right	Combined
Walk						
Peak vertical force (N/kg)	6.11 ± 1.05	7.18 ± 1.27	6.64 ± 1.27	4.06 ± 0.82	5.21 ± 1.10	4.64 ± 1.12
Vertical impulse (N s/kg)	2.89 ± 0.41	3.45 ± 0.54	3.17 ± 0.50	2.05 ± 0.50	2.70 ± 0.58	2.37 ± 0.63
Peak vertical pressure (N/cm^2 kg)	0.06 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
Hoof contact area (cm^2)	107.4 ± 9.3	111.2 ± 7.3	109.3 ± 8.5	188.5 ± 29.3	196.4 ± 22.0	192.4 ± 26.0
Duration of stance phase (ms)	706 ± 5	706 ± 46	707 ± 47	662 ± 54	690 ± 62	676 ± 59
Trot						
Peak vertical force (N/kg)	7.52 ± 1.53	9.35 ± 1.61	8.44 ± 1.81	6.18 ± 1.43	6.97 ± 1.25	6.57 ± 1.38
Vertical impulse (N s/kg)	1.29 ± 0.30	1.57 ± 0.31	1.43 ± 0.34	1.02 ± 0.24	1.14 ± 0.22	1.08 ± 0.24
Peak vertical pressure (N/cm^2 kg)	0.07 ± 0.01	0.08 ± 0.01	0.07 ± 0.02	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
Hoof contact area (cm^2)	109.3 ± 9.1	110.4 ± 10.4	109.9 ± 9.7	189.8 ± 34.4	193.0 ± 22.0	191.6 ± 28.5
Duration of stance phase (ms)	284 ± 13	273 ± 18	279 ± 17	224 ± 40	256 ± 26	240 ± 37

All variables were significantly different between the hard and soft substrate (P<0.001).

At hoof impact, there was a more even load distribution between lateral and medial on the soft compared with the hard surface at the walk (P = 0.006); however, this was not significantly different at the trot, and no other significant differences in mediolateral balance were observed.

Discussion

This study is the first to explore equine pressure-plate analysis during locomotion on a mixture of sand and textile fibres. The pressure plate allowed quantification of limb loading, timing and toe–heel and mediolateral hoof balance of the VF at the walk and trot on different surfaces. Ponies rather than horses were used to increase the likelihood of recording complete hoof strikes in each pass over the measuring area. Recording consecutive contralateral hoof strikes in each trial was not considered essential in the present study, because it was focused on the effect of a soft surface on pressure redistribution and hoof balance of the vertical ground reaction force. In contrast with previous studies using consecutive contralateral hoof strikes in each trial and reporting a high degree of contralateral symmetry in sound ponies [8,9], left and right limb data in the present study had significant differences. This is most probably associated with the fact that they were not consistently recorded in one single trial. Although other studies have shown that this pressure-plate system is equally useful in larger horses, the measurement of contralateral and/or consecutive hoof strikes then becomes more difficult [2–7,10–13], and consequently, left and right limb data often have to be recorded in separate trials. Undoubtedly, this contributes to intertrial variability, which could obscure the difference in symmetry between sound and lame horses in a clinical situation. Therefore, a larger measurement area is needed for routine application of this technique when the evaluation of symmetry is of primary interest.

Limb loading and timing

In agreement with other studies [18–20], our results show a decrease in limb loading (PVF and VI) on the soft surface, while there were no significant differences in body mass and speed of the ponies between the 2 conditions, and this may be relevant to injury prevention, as suggested by Robin *et al*. [18].

The hoof prints on the soft surface had a significantly larger hoof CA compared with the hard surface, which was highly repeatable at both walk and trot. These results during locomotion are in agreement with earlier studies on the static load distribution on a layer of sand [14,15] and confirm the pressure redistribution from the periphery to the solar area on a soft surface, which may decrease stress acting on the hoof wall. Given that pressure is defined as force divided by CA, the lower PVP is a combined effect of the lower VF and the larger hoof CA.

There was a significantly shorter stance phase duration on the soft track with no significant differences in speed between both conditions. This may be associated with track-specific gait adaptations, such as a higher stride frequency and a shorter stride length on a soft surface, as reported in other studies [18,19,21]. However, we did not demonstrate significant differences in step time and duty factor.

The comparison between the expected total VI and the observed total VI recorded by the pressure plate was used to evaluate the measuring error on both surfaces. The absence of an increased discrepancy between the expected and observed total VI confirmed that the lower force registered on the soft surface is not attributable to an increased measuring error of the pressure plate. This supports the hypothesis of dampening effects on the soft surface as the main reason for the lower limb loading, although definite conclusions on this issue require further study with concurrent force-plate analysis.

Hoof balance of the vertical ground reaction force

In the present study, the toe–heel balance curves showed a more equal force distribution between the toe and heel region at impact on the soft, more deformable substrate. This is associated with the spreading of the soft substrate underneath the hoof, which cannot occur on a hard surface. The decrease in heel loading relative to the toe zone at impact may have a protective effect on anatomical structures in the heel region. This change

TABLE 2: Mean ± s.d.expected and observed total vertical impulse of 5 sound unshod ponies (281 ± 33 kg) at the walk and trot on hard and soft surfaces

	Walk		Trot	
	Hard surface	Soft surface	Hard surface	Soft surface
Expected vertical impulse (N)[a]	2573.54 ± 162.95*	2576.51 ± 63.55	1472.58 ± 70.78	1300.70 ± 103.93
Observed vertical impulse (N)[b]	3236.50 ± 264.83*	2468.77 ± 223.84	1480.64 ± 239.61	1134.32 ± 110.80

[a]Expected vertical impulse = body weight × stride time. [b]Observed vertical impulse = sum of pressure-plate values for all 4 limbs (including limited number of hind hooves, not included in the rest of the study). *Significant difference between rows (P<0.05).

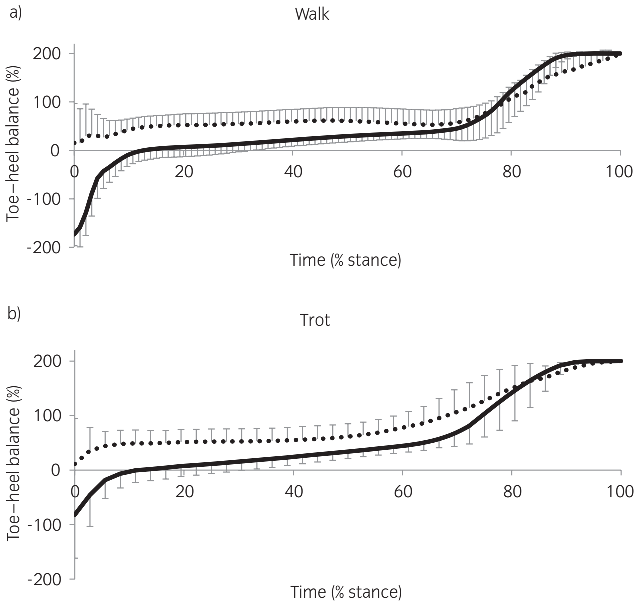

Fig 2: Mean ± s.d. curves of the toe–heel hoof balance of the forelimbs of the 5 ponies on a hard surface (continous line) and on a soft surface (dotted line) at the walk (a) and trot (b).

in toe–heel hoof balance at impact, as well as the increased loading of the toe region at mid-stance on the soft compared with the hard surface, may be related to the increased forward rotation of the hoof in the soft substrate, as described in a kinematic study by Scheffer and Back [22].

We observed higher lateral loading at impact, which is in agreement with literature [4,23]; the sinking in the soft substrate resulted in a more equal force distribution between the medial and the lateral part of the hoof compared with the hard surface.

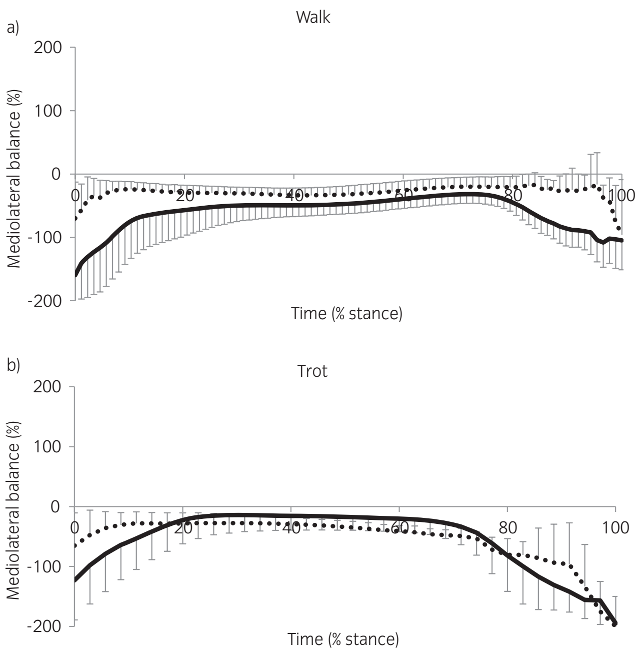

Fig 3: Mean ± s.d. curves of the mediolateral hoof balance of the forelimbs of the 5 ponies on a hard surface (continuous line) and on a soft surface (dotted line) at the walk (a) and trot (b).

Two different aspects of the effect of the track substrate on hoof balance must be discussed. First, after initial contact the sand under the hoof gradually deforms during the stance phase, resulting in additional energy dissipation and rapid support of the complete solar area. The sinking of the initial contact zone of the hoof into the soft surface enables reallocation of forces in alignment with the limb axis, which has been documented with a dynamometric horseshoe [24]. These authors concluded that this mechanism limits extrasagittal forces and therefore results in lower stress on collateral ligaments and associated structures [24]. Second, horses' limbs are moved and positioned differently during locomotion on a soft compared with a hard surface. Several studies have reported a shorter stride length and a higher stride frequency of horses moving on a soft surface compared with a hard surface [18,19,21]. The ponies in the present study had a slightly higher stride frequency on a soft surface at the trot; at the walk, this difference was less pronounced, which may be associated with the depth of the soft substrate (5 cm). However, for step time and duty factor the differences between both surfaces did not reach statistical significance.

In the present study in ponies, we did not observe the distinct contralateral differences in mediolateral hoof balance of the VF that have been described in sound horses by Oosterlinck *et al*. [11]. This may be due to several factors including, but not limited to, breed differences in ponies compared with horses, motor laterality and handler effects.

Limitations of the study

The present study does not allow validation of pressure-plate analysis on arena footing, because absolute force values obtained from a solitary pressure plate cannot be used interchangeably with force-plate data, and dynamic calibration with a concurrently installed force plate is needed to overcome this issue [12,13]. Therefore, the observed differences in limb loading on the hard compared with the soft surface have to be interpreted cautiously. However, this pressure plate with 2.6 sensors/cm^2 did provide valuable information on the relative distribution of forces acting on the toe compared with the heel and the medial compared with the lateral part of the hoof, whereas force-plate analysis needs to be combined with kinematic techniques to determine the exact position of the hoof on the plate, before the point of force application and the point of zero moment can be located relative to the hoof [25].

Measurements on a hard and a soft surface were performed on 2 separate days. Between-day variability may have contributed to the distinct differences between both surfaces. On a hard surface, pressure-plate measurements have a high level of between-day repeatability [8]. Therefore, a major confounding effect of between-day variability is considered unlikely.

A further limitation of this study is the manual subdivision of the hoof pressure images into a medial and a lateral zone and a toe and a heel region, as mentioned in previous studies on hoof balance [10,11]. To maximise the information obtained from the high sensor density of the pressure-measuring system, with one pixel representing an area of only 0.39 cm^2, a pixel-level approach as described in humans by Pataky and Goulermas [26] should be explored further.

Conclusions

This study is the first to explore equine pressure-plate analysis during locomotion on surfaces mimicking arena footing. We documented a decrease in stance phase duration and limb loading on a soft vs. a hard surface, and a more equal force distribution between the toe and heel region and between the medial and the lateral hoof zone on a deformable surface, especially at hoof impact. Although concurrent force-plate analysis would be required to draw definitive conclusions, our results suggest that the main factor involved is the dampening effect of the soft substrate. This study may lead to future evidence-based evaluation of horses with conformation deficits and the effect of therapeutic farriery in clinically relevant conditions, such as arena footing. Pressure-plate analysis shows promise for quantifying the effect of track composition on hoof balance, which may ultimately result in preventive measures for equine athletes.

Authors' declaration of interests

No competing interests have been declared.

Ethical animal research

Ethical review not currently required by this journal. All ponies in the present study are part of the faculty's teaching herd, and the techniques are noninvasive.

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Department of Surgery and Anaesthesiology, Faculty of Veterinary Medicine, Ghent University.

Authorship

Study conception and design was performed by M. Oosterlinck and F. Pille; acquisition of data and data analysis was done by M. Oosterlinck and E. Royaux; all authors contributed to data interpretation, drafting and revising the article and final approval of the submitted version.

Manufacturers' addresses

[a]RSscan International, Olen, Belgium.
[b]Microsoft Corporation, Redmond, Washington, USA.
[c]IBM Corporation, Armonk, New York, USA.

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