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Title: Does ‘hacking’ surface type affect equine forelimb foot placement, movement symmetry or hoof impact deceleration during ridden walk and trot exercise?

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The study was approved by the Royal Veterinary College Ethics and Welfare Committee and informed owner consent was obtained prior to undertaking the study.

Summary

Reasons for performing study: Both pleasure and competition horses regularly exercise on surfaces such as tarmac, gravel, and turf during 'hacking'. Despite this, there is limited evidence relating to the effect of these surfaces upon foot-surface interaction.

Objectives: To investigate forelimb foot placement, hoof vibration and movement symmetry in pleasure horses on three commonly encountered hacking surfaces.

Study design: Quantitative gait study in a convenience sample.

Methods: Six horses regularly partaking in hacking exercise were ridden in walk and trot on all surfaces. Horses were equipped with one hoof-mounted, accelerometer and four body-mounted inertial measurement units (IMUs) to measure foot impact and movement symmetry. High-speed (400 FPS) video footage of foot-placement was acquired (dorsal, palmar, lateral views). Foot-impact and movement symmetry were analysed with a mixed effects model and Bowker symmetry tests for foot-placement analysis.

Results: Vibration power and frequency parameters increase as perceived surface firmness increases from grass, to gravel, to tarmac ($p \leq 0.001$). Vibration power parameters were consistently greater at trot compared with walk ($p \leq 0.001$), but the same was not true for vibration frequency ($p \geq 0.169$). Greatest movement asymmetry was recorded during grass surface trotting. No significant difference in foot-placement was detected between the three surfaces.

Limitations: This was a field study using three commonly encountered hacking surfaces. Surface properties change easily with water content and temperature fluctuations so care must be taken when considering other similar surfaces, especially at different times of the year. Six leisure horses were used so the results may not be representative of horses of all types.

Conclusions and clinical relevance: Vibration parameters generally increase as perceived surface firmness increases. Increasing speed alters vibration power but not frequency. Further investigations are required to determine the role that this may play in the development of musculoskeletal disease in horses.

Introduction

Epidemiological studies have identified ground surface as a risk factor for lameness in race, dressage, and show jumping horses [1–5]. Firm surfaces are a particular concern and are associated with increased injury risk in fast-moving horses [1,2]. Furthermore, submaximal levels of exercise on a concrete surface may initiate joint pathology [6]. Experimental studies have reported that as surface firmness increases, peak horizontal and vertical ground reaction forces, the amplitude of peak vertical deceleration, and resultant vibration frequencies and powers increase [7–11]. These studies have been carried out at high speeds on harnessed Trotter and racehorse training surfaces [9,12] and slow trot has been studied, however, only in small numbers of horses (≤ 3) [11,13,14] or using an experimental surface [7].

In vivo studies have employed multiple methods including limb mounted accelerometers, force measuring horseshoes, high-speed videography and motion capture technologies [10,9,12,7,11,13,14]. While videography and motion capture have been used to calculate foot landing velocities, horse speed, stride length and stride frequency; there has been limited work on the effect of surfaces on foot-placement. Foot-placement classifies how the horse's foot first makes contact with the ground surface, e.g. lateral heel. While it is generally accepted that a well-balanced foot should land flat, to evenly distribute limb force [15], previous work suggests that, at trot, lateral foot placement is most common in the forelimbs [16] and that horses show inconsistencies in foot-placement, which is not influenced by foot confirmation or lameness [17].

Since a high proportion of horses undertake regular 'hacking' exercise, [18] using common surfaces such as; - tarmac, gravel and unmaintained grass it appears pertinent to investigate these generally firm surfaces at walk and non-racing trot speeds. This study uses a combination of previously described techniques including movement asymmetry derived from body-mounted inertial measurement units (IMUs) as an indicator of contralateral differences in peak vertical force [19], high-speed video of foot-placement and hoof mounted accelerometers, to evaluate the horse-surface interaction on three common hacking surfaces: tarmac, gravel, and grass, through the measurement of poll excursion, foot placement, and 3D hoof acceleration to characterise hoof vibration at impact. It is hypothesised that as surface firmness and uniformity increases : 1) horses will become less symmetrical, since firmer surfaces result in higher peak vertical forces [9]and there is an association between contralateral peak force difference and upper body movement symmetry [19], 2) foot placement will become less variable, and 3) vibration power and frequency will increase. Finally, it is hypothesised that 4) hoof vibration power and frequency will be greater in trot compared to walk.

Materials and methods

A convenience sample of six leisure horses (one warmblood cross, three cob types and two native ponies median height: 1.47m, range: 1.35-1.63m; median age 11 years, range:6-16 years) and all considered free from lameness by their owners were used in this study. Informed owner consent was obtained prior to undertaking the study which was approved by the Royal Veterinary College Ethics and Welfare Committee.

Data collection

A testing area 10m x 1.5m was marked out on the following three surfaces:

- flat tarmac (road),
- gravel (public byway)
- grass (edge between road and field)

Horses were ridden, by one of two riders, at walk and sitting trot through the testing area on each surface, until 12 foot-placements (for each forelimb) had been captured by the laterally placed cameras. This required between 8 and 12 passes at walk and trot for each surface. The surfaces were located in close proximity to each other to avoid re-instrumentation of horses and to minimize the effect of fatigue. This study combined three different data collection modalities: a hoof mounted accelerometer to measure foot-surface impact deceleration, body mounted IMUs to measure head displacement to indicate movement symmetry and differences in peak vertical force, and fixed video cameras to record foot-placement. In order maximize the amount of data collected without compromising the quality of the data the three different modalities were not time synchronised.

Hoof impact deceleration: The left forelimb was equipped with one high range (±1000g), tri-axial accelerometer[a] attached firmly to the dorsal hoof wall with a mounting bracket and electrical tape (fig1). Tri-axial acceleration was logged at 5000 Hz per individual channel with a 14 bit analogue to digital converter. The recording was started and stopped manually before and after each of the six exercise conditions. Only one forelimb was instrumented to preserve the equipment as the accelerometer wires fatigue easily.

Data were processed using Biometrics Datalog[b] and custom written MATLAB[c] scripts. Periods of steady state locomotion were extracted from the accelerometer trace by visually observing for equal distances between the repeated abrupt decelerations which signify foot-surface impact. Eight stretches of steady state locomotion were identified for each horse, at each gait on each surface, from which the middle stride was selected for further analysis. The beginning of impact was manually determined as the point of abrupt deceleration in the proximodistal direction. A fast Fourier transform (FFT) was performed with frequency bands of 9.8Hz width, up to a maximum centre frequency of 2495Hz, corresponding to the cut-off frequency of the low-pass filter internal to the accelerometer datalogger. The FFT was applied for 30ms from the beginning of impact; in keeping with previously reported hoof braking times of 20-50ms [13]. Bands with centre frequencies >1503Hz contained less than $1g^2$ of power and were therefore not carried through for analysis. Proximodistal and craniocaudal channels were analysed as they were considered most physiologically useful with the proximodistal plane parallel to the dorsal hoof wall and the craniocaudal plane perpendicular to the dorsal hoof wall (fig1).

From the FFT the following parameters were calculated to characterise the deceleration signal (vibration):

- Total signal power (TotSigPower) = the sum of the signal powers in all frequency bands up to the centre frequency 1503Hz
- Maximum signal power (MaxSigPower) = the peak signal power
- Frequency max (fqMax) = the centre frequency of the band containing the maximum signal power (MaxSigPower).

A Shapiro-Wilk statistic for normality was performed on all hoof deceleration parameters. Data were not normally distributed and were therefore transformed ($\log_{10}$). The transformed data were subsequently analysed using a linear mixed effects model. Horse was included as a random factor with surface, gait, and surface-gait interaction, as fixed factors. If there was no surface-gait interaction, this was removed from the final model. Model residual histograms and Q-Q plots were inspected visually for outliers. Estimated marginal means (EMM) were back-transformed and are reported in the text alongside p-values.

Poll movement symmetry: Four inertial measurement units (IMU[d]) were mounted with double-sided tape (tuber sacrale, each tuber coxae) or attached to the bridle headpiece (poll). The IMU data was transmitted wirelessly at 100Hz to a laptop running MT Manager[d] software. Poll movement symmetry was recorded in both walk and trot and recording was manually started and stopped at the beginning and end of each trial (pass through the data collection area). Multiple trials were analysed to ensure that more than 25 strides in total were analysed for each horse under each exercise condition.

Custom written MATLAB scripts were used to double integrate vertical acceleration of the IMU to vertical displacement and segmented into individual strides according to published protocols [20–22]. Maximal (HDmax) and minimum (HDmin) poll displacement (as indicators of asymmetry of forelimb loading) were extracted from vertical poll displacement and average values were calculated for each horse under each exercise condition. Statistical analysis was performed on absolute values studying changes in the amount of movement asymmetry independent of the direction of asymmetry (which may be different between individual horses). A linear mixed effects model was constructed where horse was included as a random factor, surface as a fixed factor and stride time (the average time in milliseconds per stride) as a covariate. Stride time was removed from the final model if it was found to be insignificant. Model residuals histograms and Q-Q plots were evaluated visually for outliers. Further analysis of 'stride time' was also conducted using a repeated measures ANOVA following confirmation that normality assumptions had been met through the use of a Shapiro-Wilk Statistic.

Foot-placement: Three high-speed video cameras (400 FPS, Nikon1[e]) were used to film foot-placement. Two tripod mounted cameras were placed laterally to capture dorsopalmar foot-placement. Dorsal and palmar views were acquired with a handheld camera to capture lateromedial foot-placement. Video data were evaluated and the first twelve strides to include the whole foot-placement in focus were selected for analysis. Dorsopalmar foot-placement was classified into toe, heel or flat and lateromedial foot-placement classified into lateral, medial or flat. If ≥9/12 (75%) foot-placements were the same classification, this was recorded as the predominant foot-placement for that foot. If <9/12 were the same the foot was given an overall classification of 'mixed'[17]. A Bowker symmetry test found no significant difference ($p = 0.59$) between left and right fore-feet. Pooled left and right foot data was therefore used in further Bowker symmetry tests to identify differences in foot placement across the three surfaces.

Significance was set at $p<0.05$ and Bonferroni corrections applied for multiple comparisons. All statistical analyses were performed in IBM SPSS Statistics 22.0[f] with the exception of the Bowker symmetry tests which were run in command line scripts retrieved from (http://john-uebersax.com/stat/mh.htm). Graphs were produced in Microsoft Excel[g].

Results

Stride time: Average stride time across all three surfaces was 1020.5±90.5ms at walk and 690.8±20.2ms at trot. Repeated measures ANOVA showed no significant difference in stride time at walk (grass 1015 ms; gravel 1011 ms; tarmac 1035 ms; $p=0.223$) or trot (grass 686 ms; gravel 698 ms; tarmac 688 ms; $p=0.438$) across the three surfaces.

Poll movement symmetry: A total of 1584 strides from the six horses were analysed across the 6 exercise conditions in walk and trot. Mean HDmin and HDmax were calculated from an average of 44 (range 21-70) strides for each horse for each condition. Mean values were used for further analysis. Stride time was not a significant covariate ($p\geq0.17$) and was therefore excluded from the final model. At walk, across all three surfaces, there was no significant difference in HDmin (grass 22.4 mm; gravel, 20.4 mm; tarmac 12.9 mm;

$p \geq 0.242$) or HDmax (grass 22.5 mm; gravel, 20.4 mm; tarmac 12.9 mm; $p \geq 0.643$). At trot, there was no significant difference in HDmin across the three surfaces (grass 8.0 mm; gravel, 11.0 mm; tarmac 11.5 mm; $p \geq 0.490$). There was, however, a significant difference in HDmax at trot between grass and gravel (grass 13.2 mm; gravel 6.8 mm; $p=0.011$) and grass and tarmac (tarmac 7.0 mm $p=0.013$).

Hoof-impact deceleration: For each surface and gait combination the results were calculated from 8 foot-surface impacts per horse. Back-transformed estimated marginal means are presented in the text. Further information regarding the intra-horse variation in hoof-impact deceleration parameters are available in supplementary items 1 and 2.

TotSigPower; There was not a significant interaction between surface and gait with regard to proximodistal TotSigPower ($p=0.107$). However, proximodistal TotSigPower was significantly different between walk and trot ($p<0.001$) with an estimated marginal mean (EMM) of 8910 g^2 at walk and 17619 g^2 at trot, independent of surface type. Furthermore, there was a significant difference in proximodistal TotSigPower across all three surfaces ($p<0.001$), independent of gait with EMMs increasing from grass (4345 g^2), to gravel (14521 g^2) to tarmac (31167 g^2) (fig 2).

Craniocaudal TotSigPower showed a significant interaction between surface and gait ($p=0.041$). Walk on grass resulted in significantly lower craniocaudal TotSigPower than all other exercise and gait combinations (walk-grass 1524 g^2; walk-gravel, 4623 g^2; walk-tarmac, 7194 g^2; trot-grass, 4305 g^2; trot-gravel, 9057 g^2; trot-tarmac, 26062 g^2 $p<0.001$). Trotting on tarmac was significantly higher than all other exercise and gait combinations ($p<0.001$). Trot on gravel was significantly higher than trot on grass ($p<0.001$). On each of the three surfaces trot always resulted in higher craniocaudal TotSigPower than walking ($p<0.001$) (fig 2).

MaxSigPower: There was no interaction between surface and gait for proximodistal MaxSigPower ($p=0.298$). However, proximodistal MaxSigPower was greater at trot (987 g^2) compared to walk (593 g^2 $p<0.001$) independent of surface and increased from grass (514 g^2), to gravel (14521 g^2) to tarmac (31167 g^2 $p \leq 0.02$) independent of gait (fig 3).

There was a significant interaction between surface and gait with regard to craniocaudal MaxSigPower ($p=0.015$). With the exception of the gravel surface, this was reflected as significant differences between walk and trot exercise conditions with walk on grass and walk on tarmac significantly lower than trot on all three surfaces (walk-grass, 217 g^2; walk-gravel, 368 g^2; walk-tarmac, 256 g^2; trot-grass, 529 g^2; trot-gravel, 552 g^2 ; trot-tarmac, 835 g^2; $p<0.001$). Walk on gravel was significantly lower than trot on tarmac ($p=0.01$) but there was no significant difference between walk and trot on gravel ($p=0.494$) or between walk on gravel and trot on grass ($p=0.842$) (fig 3).

fqMax: In both the proximodistal and the craniocaudal plane there was no significant interaction between surface and gait in terms of fqMax ($p\geq0.406$). In both planes, surface was independently significant ($p<0.001$) but gait was not ($p\geq0.169$). Proximodistal fqMax showed significant differences across all three surfaces ($p<0.001$) with proximodistal fqMax increasing from grass (41Hz) to gravel (87Hz) to tarmac (247Hz). Craniocaudal fqMax was significantly different between grass (44Hz) and tarmac (187Hz $p<0.001$) and gravel (49Hz) and tarmac (187Hz $p<0.001$) but not between grass and gravel ($p=1.0$) (fig 4).

Foot placement: There was no significant difference in lateromedial or dorsopalmar foot-placement classification across the three surfaces, at walk or trot ($p\geq0.5$). At walk, a 'flat' dorsopalmar foot-placement was most common. Overall, lateromedial foot-placement at walk was more variable between horses, with similar proportions of mixed and flat classifications across all three surfaces. At trot 'mixed' foot-placement classification was most common for both lateromedial and dorsopalmar foot placements (fig 5).

Discussion

The present study aimed to investigate the effect of 'hacking' surface on poll movement symmetry, foot-placement, and hoof vibration parameters. In this group of horses, foot placement was not significantly affected by surface but poll movement asymmetry, at trot, was increased on the grass surface. Vibration power parameters (TotSigPower and MaxSigPower) were consistently greater at trot compared to walk. However, this was not the case for vibration frequency (fqMax). Overall, vibration parameters increased as surface firmness increased from grass to gravel to tarmac.

Stride time: Stride time was not significantly affected by surface type. Studies in harnessed trotters have reported differences in stride length and frequency between surfaces with stride length decreasing and stride frequency increasing on more deformable surfaces, however, unlike the current study, the trotting speed was controlled in these studies [9]. The surfaces in our study were all 'firm' with limited scope for the feet to penetrate them; this could contribute to the consistent stride time seen across the surfaces. The horses in our study were not constrained to a specific speed, asked to perform at maximal exertion, or ridden in a particular outline. These factors could potentially make speed adaptations to different surface types unnecessary or too small to measure.

Poll movement symmetry: HDmax, indicated a greater degree of asymmetry at trot on grass compared with tarmac and gravel. This opposed hypothesis 1. Grass was considered the least firm of the surfaces so we expected horses to be most symmetrical on this surface as peak vertical force is lower on soft surfaces [9] and head movement symmetry is correlated with contralateral differences in peak vertical force [19]. This unexpected finding could result from surface topography as a slightly undulating, unmaintained grass surface was used in this study. This could have resulted in a consistent unsteady head carriage leading to greater HDmax. Often flat, well-maintained surfaces are investigated so the effect of surface topography may have been overlooked previously. Despite grass consistently being the last surface to be exercised upon, we feel confident that fatigue was unlikely to confound symmetry results since only short periods (<10 minutes per surface) of low-intensity exercise were conducted.

While there is limited evidence to suggest that movement symmetry is altered by surface type in the sound horse, it is common practice to utilise a firm surface during lameness investigations to highlight the lame(r) limb [15]. Furthermore, forelimb lame horses have been shown to be most asymmetrical when trotting in a circle on a firm surface compared to soft, whereas, asymmetry did not significantly differ between surfaces in sound horses [23]. In line with this previous work [23] our data suggests that firm surfaces do not adversely alter movement symmetry in sound horses during straight-line trot.

Foot-placement: Dorsopalmar and lateromedial foot placement did not vary significantly across the three surfaces at walk or trot so Hypothesis 2 is not supported. ‘Mixed’ dorsopalmar and lateromedial foot-placement classifications were most common at trot which is in agreement with previous work [17]. However, at walk our results differ from previous work as we reported ‘flat’ as the most common classification whereas others reported ‘mixed’ [16]. The previous study utilised time-synchronised lateromedial and dorsopalmar camera views, resulting in a greater number of classifications (e.g. lateral heel) which could contribute to a greater proportion of ‘mixed’ foot-placements.

As horses show a high level of stride-to-stride variability in foot-placement, which is not associated with conformation, movement symmetry or surface, foot-placement may be a less interesting parameter when investigating the effect of different surfaces or farriery interventions on distal limb kinematics. Furthermore, a high proportion of ‘mixed’ classifications seems reasonable given that ‘natural’ surfaces are rarely completely flat and hence the use of a consistent foot landing pattern would appear suboptimal.

Foot-impact deceleration – Surface: Independent of gait, surface had a significant effect on all three foot-impact deceleration parameters (TotSigPower, MaxSigPower, and fqMax) in the proximodistal plane. In the craniocaudal plane, there was a significant interaction between gait and surface for both TotSigPower and MaxSigPower. Craniocaudal fqmax was independently affected by surface. Hypothesis 3 is therefore partially supported.

Increasing power and frequency parameters with increasing surface firmness holds true across different gaits having previously been reported in slow trotting horses [7,11], fast trotting harnessed Trotters, [9] and Thoroughbreds at trot, canter and gallop [12][10]. Our results corroborate this association in slow trotting horses and demonstrate the same is true at walk. Firm surfaces may induce vibrations of greater power and frequency as they deform less during foot-surface impact compared to 'soft' surfaces. Deformation or structural damping is one of two key damping mechanisms. The second, frictional damping, occurs through the displacement of particles moving horizontally through or across the surface [11]. Tarmac does not undergo any relevant structural damping during a horse's foot-surface contact and the subsequent loading of the horse limb, however, frictional damping does occur as the foot slides across the surface. Gravel could be considered to have greater frictional damping properties than tarmac due to its loose top. Grass has structural damping properties as it can deform. It is interesting to note that there was a significant interaction between surface and gait in the craniocaudal power parameters but not in those of the proximodistal plane. This could indicate that the craniocaudal plane is more sensitive to changes in surface and gait, potentially because the time taken for the hoof to come to a stop is influenced by both speed and surface properties [24,25].

It is relatively intuitive to consider differences in foot-surface impacts between firm and soft surfaces but we have demonstrated a significant difference between three surfaces perceived to be firm, (especially during a dry summer). Others have demonstrated differences between surfaces considered soft [26]. This is a useful reminder of the complexity of the foot-surface interface and that surface firmness is only one of many surface properties which influence the foot-surface interaction [27]. Furthermore, it should be borne in mind that both surface properties, horse management and exercise programme, including the variety of exercise activities and surfaces used influence orthopaedic health [3–5,28,29]. However, further research is needed to fully understand the potential protective effects of exercising on a variety of surfaces.

Foot-impact deceleration – Gait: In general vibration power parameters (TotSigPower and MaxSigPower) were significantly higher at trot than at walk, which was not the case for frequency (fqMax), therefore hypothesis 4 is only partially supported. Trotting could result in higher power parameters than walking as foot landing velocity and force increase with speed [30,31]. Peak deceleration has been shown to increase with increasing trot speed [25] and though not reported explicitly here, we noted higher peak decelerations at trot compared to walk. The absence of a significant difference in fqMax between walk and trot may be because the material properties of the foot and surface were constant between gaits, and frequency is highly influenced by material properties. Similar frequencies across a range of trotting speeds has been reported previously [25] and an ex vivo study found a decrease of ~50 Hz between hoof-impacts occurring at 0.75m/s and 1.25m/s [32], similar to the non-significant differences reported in our study.

Like others who have utilised hoof-mounted accelerometers, we have reported high levels of within horse variation regarding vibration parameters [9,7,11,14,25,33,34]. In order to minimise the within horse variation, the accelerometer was not removed between trials in this study. As foot-placement appears highly variable from stride-to-stride [17] this could be a potential source of stride-to-stride variability. Ex-vivo work found no significant difference in hoof-impact frequencies between different dorsopalmar hoof-strike angles [35].

Conclusions and future work

Surface properties are readily altered by changes in water content and temperature affecting the foot-surface impact [10,34,35]. This should be taken into account if applying these results to similar surfaces, especially at different times of year (the current study was conducted in July 2015, an unusually warm, dry English summer). Furthermore, this study was restricted to leisure horses and so the application of the study findings to competitive horses should be done with care.

Overall this study supports existing data describing increasing vibration power and frequency with increasing surface firmness in trotting horses, and confirms a similar pattern in walk. Furthermore, compared to walk, trot results in higher hoof-vibration powers but not frequencies. Finally, we suggest that the high stride-to-stride variation in hoof-mounted accelerometer derived data could be linked with high stride-to-stride variation in foot-placement, though more work is needed to corroborate this.

Figure legends:

Figure 1: Accelerometer attached to the dorsal hoof wall (a). Wire secured with a distal limb boot and upper limb strap with Velcro (b). Datalogger mounted to a neck strap (b). The proximodistal axis of the accelerometer is parallel to the dorsal hoof wall (c-purple arrow) and the craniocaudal axis perpendicular to the dorsal hoof wall (c-blue arrow).

Figure 2: Proximodistal (a) and craniocaudal (b) TotSigPower (Log10g^2) at walk (light purple) and trot (dark purple) on grass, gravel and tarmac surfaces. The results represent measurements from 8 foot-surface impacts per horse per condition for a total of 6 horses, showing range (whiskers), Interquartile range (box), median (line in box) mean (x) and outliers (o). (significant difference from: a=grass-walk, b=gravel-walk, c=tarmac-walk, d=grass-trot, e=gravel-trot, f=tarmac-trot)

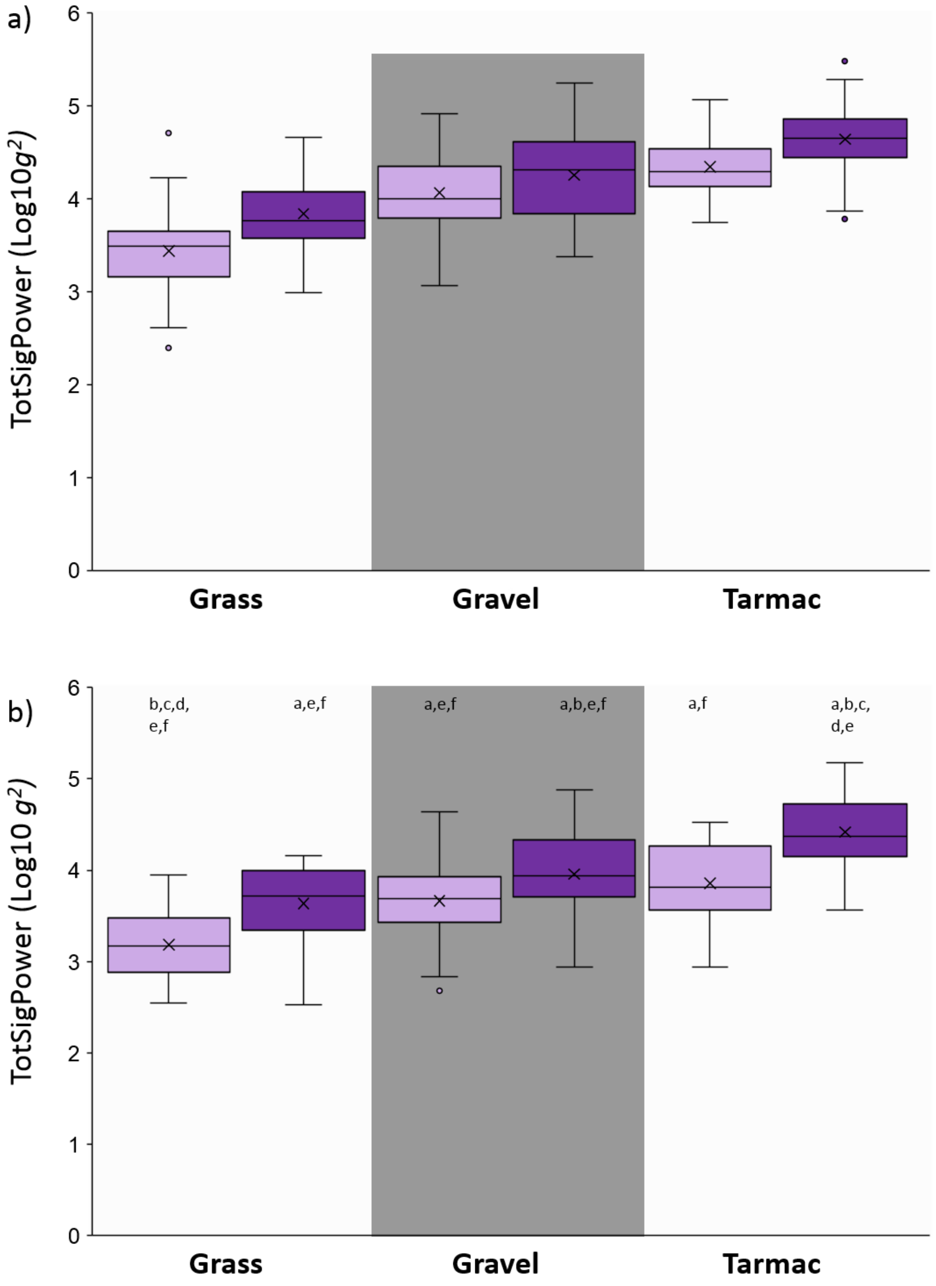


Figure 3: Proximodistal (a) and craniocaudal (b) MaxSigPower (Log10g^2) at walk (light purple) and trot (dark purple) on grass, gravel and tarmac surfaces. The results represent measurements from 8 foot-surface impacts per horse per condition for a total of 6 horses, showing range (whiskers), Interquartile range (box), median (line in box) mean (x) and outliers (o). (significant difference from: a=grass-walk, b=gravel-walk, c=tarmac-walk, d=grass-trot, e=gravel-trot, f=tarmac-trot)

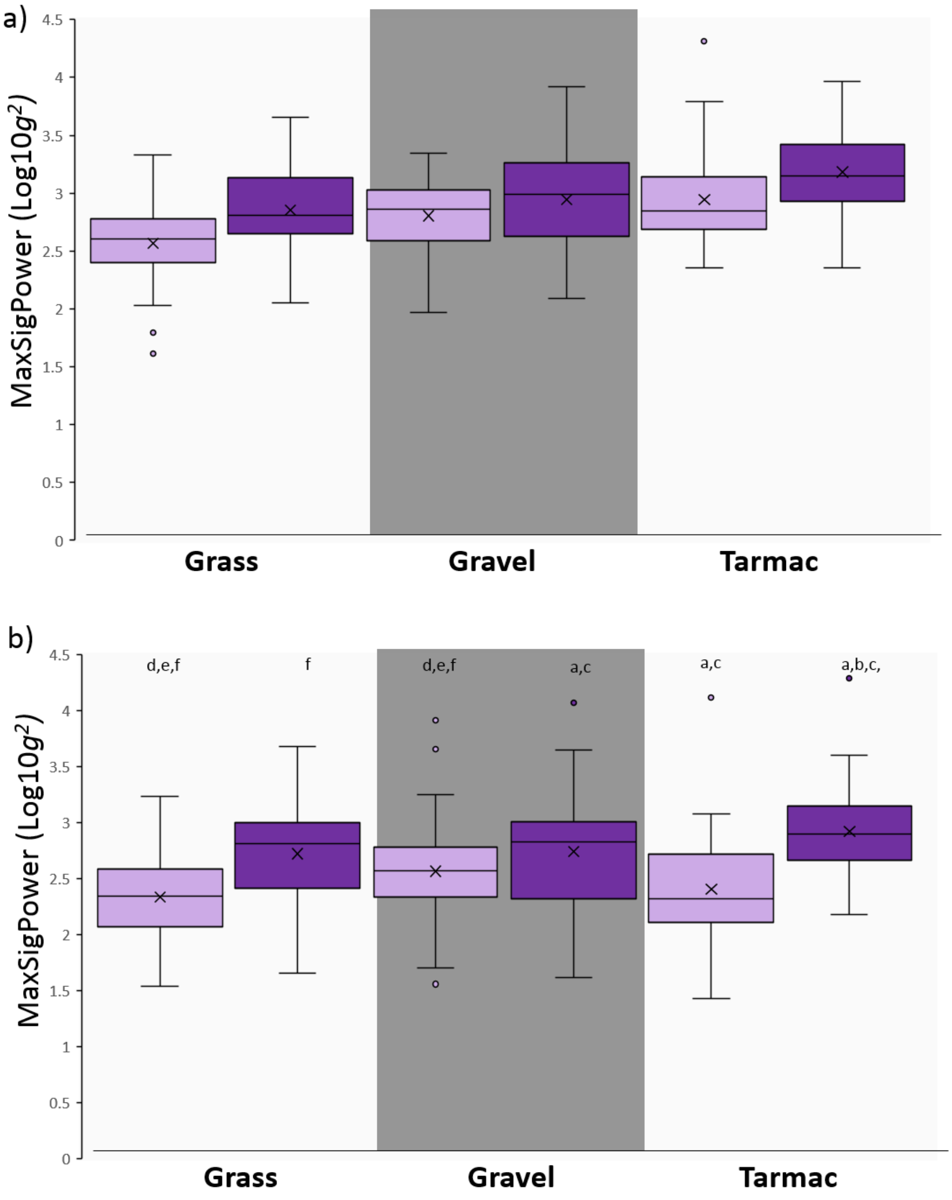


Figure 4: Proximodistal (a) and craniocaudal (b) fqMax (Log10Hz) at walk (light purple) and trot (dark purple) on grass, gravel and tarmac surfaces. The results represent measurements from 8 foot-surface impacts per horse per condition for a total of 6 horses, showing range (whiskers), Interquartile range (box), median (line in box) mean (x) and outliers (o).

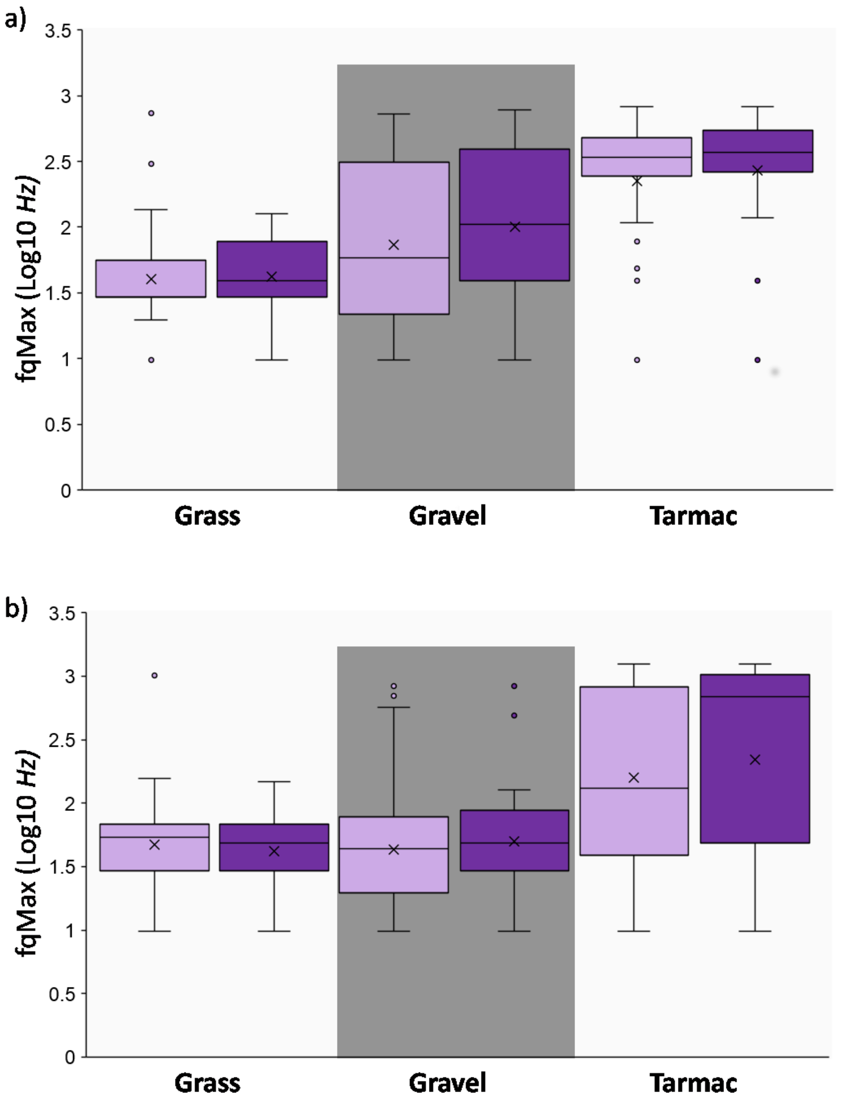
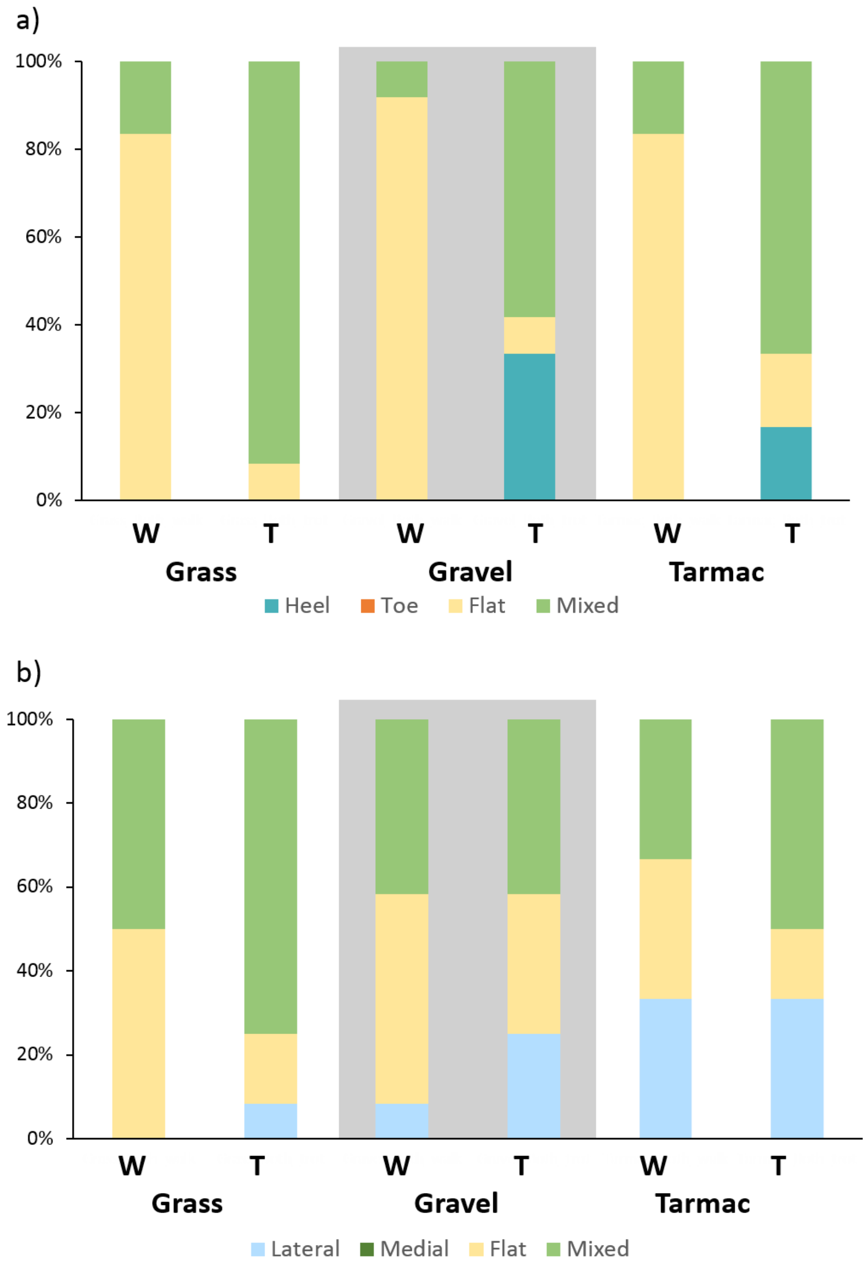


Figure 5: Dorsopalmar (a) and lateromedial (b) foot-placement displayed as percentage of horses (n=6) falling into each category at both walk (W) and trot (T)



Manufacturers' addresses

[a-b]Biometrics Ltd, Newport,UK

[c]The Mathworks, Natick, MA, US

[d]Xsens Technologies BV, Enschede, The Netherlands

[e]Nikon Cooperation, Tokyo, Japan

[f]SPSS Inc., Chicago, Illinois, USA

[g] Microsoft Office 2016, Microsoft Corporation, Redmond, WA

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Supplementary item 1: Proximodistal median and interquartile range (IQR) TotSigPower, MaxSigPower and FqMax from a total of 8 steps per horse per exercise condition.

			TotSigPower (g^2)		**MaxSigPower (g^2)**		**FqMax (Hz)**	
Gait	**Surface**	**Horse**	**median**	**IQR**	**median**	**IQR**	**median**	**IQR**
Walk	Grass	1	2475	2209	374	122	39	12
Walk	Grass	2	3518	2205	268	143	54	54
Walk	Grass	3	5718	2675	587	457	34	63
Walk	Walk	4	956	1347	218	314	29	15
Walk	Grass	5	3720	1896	510	577	29	10
Walk	Grass	6	1939	2087	266	324	29	24
		median	**2997**	**2146**	**321**	**319**	**32**	**20**
Walk	Gravel	1	7933	15081	450	555	49	100
Walk	Gravel	2	54708	36513	1709	979	308	159
Walk	Gravel	3	8113	5917	539	361	20	78
Walk	Gravel	4	9600	10555	582	305	20	530
Walk	Gravel	5	12205	7861	1031	170	39	12
Walk	Gravel	6	5578	5910	305	244	78	166
		median	**8856**	**9208**	**560**	**333**	**44**	**129**
Walk	Tarmac	1	17574	5843	659	644	303	83
Walk	Tarmac	2	24287	15404	702	404	435	220
Walk	Tarmac	3	62017	13049	1805	594	635	105
Walk	Tarmac	4	20311	13754	619	760	298	178
Walk	Tarmac	5	13497	6291	661	630	322	188
Walk	Tarmac	6	15559	6534	439	286	425	78
		median	**18942**	**9791**	**660**	**612**	**374**	**142**
Trot	Grass	1	7950	22456	643	1097	39	10
Trot	Grass	2	19239	14456	1624	612	68	44
Trot	Grass	3	4463	2356	496	152	44	88
Trot	Grass	4	3308	2457	327	259	63	42
Trot	Grass	5	9174	3481	1018	1292	39	10
Trot	Grass	6	4357	1835	592	265	29	51
		median	**6207**	**2969**	**618**	**439**	**42**	**43**
Trot	Gravel	1	27148	27858	1667	1897	132	154
Trot	Gravel	2	41870	16283	1139	377	264	383
Trot	Gravel	3	23575	38252	1073	1439	205	393
Trot	Gravel	4	5036	6594	270	410	103	154
Trot	Gravel	5	20808	8232	1726	1269	39	42
Trot	Gravel	6	15125	12705	571	405	151	486
		median	**22192**	**14494**	**1106**	**840**	**142**	**269**
Trot	Tarmac	1	53870	42557	2305	3417	190	139
Trot	Tarmac	2	44265	28712	1236	785	381	261
Trot	Tarmac	3	78005	124036	2494	3435	537	110
Trot	Tarmac	4	24566	15862	708	813	352	166
Trot	Tarmac	5	25900	28655	1134	834	317	95
Trot	Tarmac	6	44997	39462	1256	922	537	273
		median	**44631**	**34087**	**1246**	**878**	**366**	**153**

Supplementary item 2: Craniocaudal median and interquartile range (IQR) TotSigPower, MaxSigPower and FqMax from a total of 8 steps per horse per exercise condition.

			TotSigPower (g^2)		**MaxSigPower (g^2)**		**FqMax (Hz)**	
Gait	**Surface**	**Horse**	**median**	**IQR**	**median**	**IQR**	**median**	**IQR**
Walk	Grass	1	1506	2617	175	223	63	17
Walk	Grass	2	1240	1334	165	103	68	20
Walk	Grass	3	1352	1464	238	227	29	49
Walk	Walk	4	1113	2517	230	489	34	32
Walk	Grass	5	1869	1445	364	251	44	24
Walk	Grass	6	1427	2659	203	136	59	24
		median	**1389**	**1990**	**217**	**225**	**51**	**24**
Walk	Gravel	1	8216	6421	641	1328	15	22
Walk	Gravel	2	5604	8299	506	202	44	232
Walk	Gravel	3	2662	1414	312	181	29	68
Walk	Gravel	4	2859	1494	239	95	34	12
Walk	Gravel	5	6950	4042	573	587	63	39
Walk	Gravel	6	3235	2397	272	357	68	56
		median	**4420**	**3220**	**409**	**279**	**39**	**48**
Walk	Tarmac	1	18443	6765	476	344	103	198
Walk	Tarmac	2	5472	6440	159	235	913	1074
Walk	Tarmac	3	3778	2007	147	106	107	76
Walk	Tarmac	4	22195	11716	565	221	112	310
Walk	Tarmac	5	9461	14555	322	300	78	840
Walk	Tarmac	6	3990	3832	92	101	674	415
		median	**7466**	**6603**	**240**	**228**	**110**	**363**
Trot	Grass	1	3824	3160	394	425	29	10
Trot	Grass	2	9324	3697	843	312	59	32
Trot	Grass	3	1929	3525	308	362	34	42
Trot	Grass	4	4758	3232	597	676	59	54
Trot	Grass	5	12136	6570	1294	525	59	17
Trot	Grass	6	2131	3414	263	392	49	39
		median	**4291**	**3470**	**496**	**408**	**54**	**35**
Trot	Gravel	1	22382	8512	1117	1475	29	12
Trot	Gravel	2	17418	18145	681	106	78	51
Trot	Gravel	3	7385	4816	317	966	20	56
Trot	Gravel	4	8290	6112	724	483	63	56
Trot	Gravel	5	8661	6480	968	294	49	22
Trot	Gravel	6	3047	2616	182	58	88	34
		median	**8476**	**6296**	**703**	**389**	**56**	**43**
Trot	Tarmac	1	44173	45951	1908	2079	171	225
Trot	Tarmac	2	65547	56669	1319	826	972	176
Trot	Tarmac	3	10227	8063	359	257	1045	310
Trot	Tarmac	4	36906	25955	1256	777	10	46
Trot	Tarmac	5	28366	32007	877	662	425	884
Trot	Tarmac	6	17996	17707	459	343	1065	227
		median	**32636**	**28981**	**1066**	**720**	**698**	**226**