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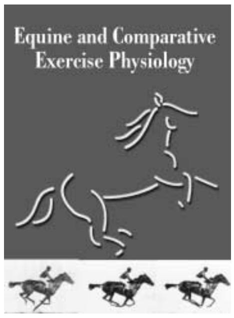

Effects of hoof shape, body mass and velocity on surface strain in the wall of the unshod forehoof of Standardbreds trotting on a treadmill

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Abstract

The purpose of this work is to investigate the effects of body mass (BM), velocity (V), and hoof shape on compressive surface strains in the wall of the front hoof at the trot. Toe angle (TA), heel angle (HA), toe length (TL), medial and lateral wall length (MWL, LWL) and BM were measured for nine adult, unshod Standardbreds. Five rosette gauges were glued around the circumference of the left forehoof of each animal which was then trotted on a treadmill at a set range of velocities from 3.5 to 7.5 m s^{-1}. Analysis of variance (ANOVA) of principal compressive strains ε_2 at midstance identified that all primary variables (BM, V, TA, HA, etc.) had a significant effect as did the interactions of TA × HA and BM × TA. These significant variables explained over 96% of the variation in ε_2. Multiple regression of ε_2 on these variables gave equations which accurately predicted ε_2 within 3%, but the individual coefficients did not accurately describe how each variable affected ε_2. Further tests using bivariate regression gave equations that enabled ε_2 data to be standardized for BM and V at the gauge locations used here. Strain ε_2 increased linearly with mass and curvilinearly with velocity ($\varepsilon_2 \propto V + V^2$), and both caused redistribution of strain to the dorsum and lateral quarter. Variation in each shape variable caused redistribution rather than simple increase or decrease in strains. The primary conclusion with regard to hoof shape is that the effects of change in any one measurement on strain magnitudes are affected by the values of all other measurements. Resolving the interplay among measurements in their effects on ε_2 will need a considerably larger sample size than that used here.

Keywords: hoof; strain; shape; horse; mass; velocity

Introduction

With every footfall, loads acting on the hoof include the impact of its own contact with the substrate, and forces associated with altering the momentum of the limb and body under normal gravity. These loads induce mechanical behaviour in the tissues of the hoof which includes shock waves resulting from the impact, and stresses and strains induced by the forces (Fig. 1). Factors extrinsic to the hoof can modify the applied loading, and intrinsic factors may alter the mechanical behaviour of the hoof under a given load. Extrinsic factors include gait and substrate, as well as human interventions such as shoes and riders[1–3]. Factors intrinsic to the hoof include variation in the physical properties of its constituent tissues and materials[4–6], and its shape[1] (which is most readily apparent as the external shape of the capsule, but which also includes, for example, size and location of the distal phalanx, digital cushion and frog, and dimensions and orientations of tendons and ligaments).

The relationship between external loads and mechanical behaviour of the hoof – modulated by extrinsic and intrinsic factors – is of interest because the tissues and materials of the hoof are able to respond to variation in loading over a time course ranging from weeks to months[7]. They share this property with other tissues having a mechanical function, primarily

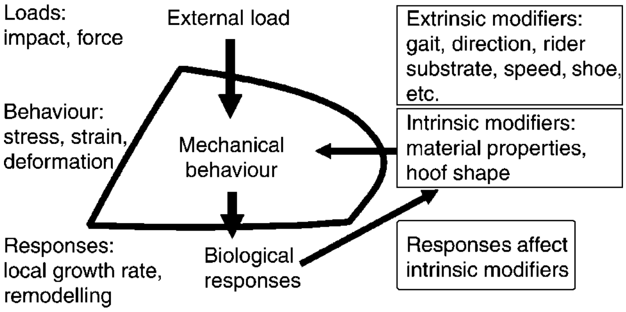

FIG. 1 Conceptual framework of present study. External loads on the hoof induce mechanical behaviour in its materials and tissues. Loads are modified by extrinsic factors, and mechanical behaviour by intrinsic factors, including hoof shape. Over time mechanical behaviour elicits biological responses which can modify hoof shape, and hence behaviour – a classic feedback loop

bones and muscles. For the hoof, responses include differential rates of growth of the wall[8] and cartilages[9], and what might be termed remodelling of both living and keratinized tissues[10]. These responses are well documented empirically[8], but have received minimal experimental attention as to what stimulates them. It is presumed they are normally adaptive, i.e. appropriate for the stimulus, but this has not been verified. One possible specific stimulus for response is change in local strain magnitudes in the tissues of the hoof, averaged over time, though this suggestion has yet to be demonstrated.

Much of our recent work has focused on the loading-behaviour relationship, as a precursor to investigating characteristics of the responses to measured stimuli. By measuring surface strain on the capsule, rather than forces directly, we have quantified the effect of some extrinsic factors on mechanical behaviour of the hoof, for example: gait, with or without rider; straight versus turn; shod versus unshod and open ground versus treadmill[1-3]. These factors either alter strain magnitudes over the whole capsule, or cause a redistribution of strains, usually from one side to the other. In a turn, for example, strain magnitudes on the quarter on the inside of the turn increase by over 40% compared to those on the straight, with a concomitant decrease on the outer quarter[1].

The present work has two further objectives in the context of loading and mechanical behaviour. The first is to investigate the effects of two more extrinsic factors – body mass and velocity of locomotion – on principal strain magnitudes recorded at the surface of the hoof wall. Vertical force on the hoof at midstance changes with both variables. Force appears to have a significant linear correlation with velocity within gaits, at least for the walk and trot[11]. We are interested in establishing whether strain also changes linearly, or if it has different relationships with velocity and body mass. Defining the relationships will allow strain records from future experiments on trotting Standardbreds to be standardized for body mass and velocity.

The second objective is to revisit the question of how hoof shape affects strain magnitudes within the material of the hoof wall. We have approached the question before[1] using strain gauges glued to the surface of the hoof wall *in vivo*, and demonstrated that the principal compressive strain magnitude (ε_2) varied with toe angle (TA) and toe length (TL). The data were not standardized for body mass or velocity. In a second approach, we used finite element analyses of computer models to isolate the effects of various hoof shape measurements – including toe and heel angles (TA, HA), and toe length (TL) – on principal strain magnitudes[12]. The beauty of this method is that we could manipulate one or two shape measurements at a time, holding the others constant, but it was not practicable to study interactions among all of the measurements.

In the present work we return to the use of strain gauges *in vivo*, but on a sample of horses of known breed and body weight, moving on a treadmill at controlled speeds and a single gait (the trot). The specific intentions are to quantify the effects – and any interactions among them – of body mass, velocity, and five hoof-shape measurements on magnitudes of principal strain ε_2.

Materials and methods

Nine Standardbred horses – adult (>4 years old) and of mixed gender – from the teaching herd at the Ontario Veterinary College were used in this study. All were unshod and their hooves had been trimmed on a regular 6-weekly schedule. The exact time since the last trimming was not recorded, but growth effects on ε_2 magnitudes within this time period are mechanically insignificant[13]. Some horses had previously been trained to run on a treadmill, and all were exercised on it twice before the experiment. The experimental protocol was pre-approved by the University's Animal Care Committee and met Canadian federal guidelines on animal use in research.

Data collection

Each horse was weighed on its day of testing and videos were taken of its left forefoot in dorsal, solar and lateral views. Frames from the videos were later analysed with digitizing software (Optimas; BioScan, Inc., Edmonds, WA, USA), and five measurements were taken from the images of each hoof: toe angle (TA), heel angle (HA), toe length (TL) and medial and lateral wall lengths (MWL and LWL). We have previously illustrated and described these measurements and the methods for making them[14].

After the videos were taken, rosette strain gauges (gauge type N32-FA-2-120-11; Showa Measuring Instruments Co. Ltd, Tokyo, Japan) were glued with cyanocrylate adhesive at five positions around the circumference of the hoof wall, as in previous work[1]. Each gauge was 1/3 of the way down the wall (between coronary band and distal margins). One was at the toe (dorsal gauge), one at the widest point of each quarter (medial and lateral gauges), and the final two gauges were put between the dorsal and quarter gauges (medial 45 and lateral 45 gauges).

The horse was warmed up for 2–3 min on the treadmill, and was then trotted over a range of velocities: 3.5, 4.0, 5.0, 6.0, 7.0 and 7.5 $m s^{-1}$. All horses managed three or more velocities, usually in two recording runs with a short rest break in between. The trot was the only gait considered.

Strains in the hoof wall during motion were recorded digitally at 66.7 Hz/channel with custom-built dataloggers (DataGator; Scientific Solutions, formerly of Eden Mills, Ontario, Canada). From the strain records, principal compressive strain ε_2 ($\mu\varepsilon$, microstrain) was calculated at midstance for an average of 79 strides per velocity per horse (max. 135, min. 8), for a total of 3859 strides.

Statistical analysis

Correlations among measurements

Correlations among the body mass and shape measurements were tested for each pairwise combination. This was to test whether the measurements were independent or linked.

Analysis of variance

Magnitudes of the principal compressive strains ε_2 at midstance were subjected to an analysis of variance (ANOVA) using Procedure GLM in SAS (SAS Institute Inc., Cary, NC, USA). Firstly the strains were tested for normality and the following transformation was found to be necessary to normalize them: $\varepsilon_2^{\mathrm{T}} = \sqrt{(-\varepsilon_2)}$. Secondly, a full ANOVA model was tested, which included as fixed terms: gauge position, mass, all of the hoof-shape measurements, velocity, velocity squared, and all two- and three-way interactions among these primary terms. Non-significant terms were then removed iteratively and interactively (at an α-level of 0.05) from the full model until only significant terms and interactions remained.

Multiple and bivariate regression

Once only significant terms and interactions remained in the ANOVA model, a multiple regression was performed of the untransformed strain data on the terms in the model. The aim was to derive equations based on the significant terms to allow prediction of ε_2 at each gauge site from measurements of body mass, hoof shape and velocity. In addition, the values of ε_2 predicted from the multivariate model were regressed separately on each primary term (e.g. mass, and the shape measurements) in a bivariate regression. (Predicted rather than raw values of ε_2 were used in the bivariate regression, because Procedure GLM calculates predicted values for missing raw data, and these were, therefore, available for inclusion.) The coefficients from multivariate and bivariate regressions quantifed the relationships of ε_2 to body mass and velocity. They also allowed discussion of the effects of hoof shape on its mechanical behaviour as measured by surface strains.

Results

Summary statistics and correlations

Individual body masses ranged from 417.5 to 528.0 kg, a span of 110.5 kg. Toe angles ranged from 47.5° to 58.3°. These and the other measurements are shown in Table 1 with summary statistics.

There were generally no significant correlations among body mass and the shape measurements (Table 2). The exceptions were: toe angle with medial wall length ($r = 0.7112$; $P = 0.032$) and heel angle with lateral wall length ($r = -0.6922$; $P = 0.039$).

Description of strains

Individual averages of ε_2 for each horse at each velocity and gauge site fell in the range of -1000 to -6020 $\mu\varepsilon$ (microstrain; the minus sign indicates compression). There was a general trend for compressive strains to increase (become more negative) with velocity at the trot at all gauge sites (Fig. 2), but the change was frequently curvilinear (e.g. at the lateral gauge of horses 8 and 2). There was also evidence in

Table 1 Mass, hoof shape measurements and summary statistics for the nine Standardbred horses used in this study

Horse	BM (kg)	TA (°)	HA (°)	TL (cm)	MWL (cm)	LWL (cm)
1	421.5	52.1	40.4	9.0	5.9	6.1
2	425.0	51.5	33.6	9.4	6.5	7.0
3	424.0	47.5	37.3	9.9	5.9	6.4
4	460.0	48.6	40.6	9.1	5.8	5.6
5	471.0	52.8	46.9	9.1	6.0	6.0
6	425.5	48.2	33.2	9.9	5.9	6.3
7	528.0	49.2	28.8	8.5	5.7	6.4
8	417.5	48.0	48.2	8.9	5.4	5.7
9	509.0	58.3	39.0	9.0	6.5	6.1
Mean	453.5	50.7	38.7	9.2	6.0	6.2
SEM	13.83	1.15	2.11	0.16	0.12	0.13
Max	528.0	58.3	48.2	9.9	6.5	7.0
Min	417.5	47.5	28.8	8.5	5.4	5.6

BM – body mass; TA – toe angle; HA – heel angle; TL – toe length; MWL – medial wall length; LWL – lateral wall length; SEM – standard error of the mean.

Table 2 Pairwise correlations (and *P-values*) among the shape variables measured for each hoof capsule. Only the two values in bold are significant ($P < 0.05$)

	Body mass	Toe angle	Toe length	Heel angle	Medial wall length	Lateral wall length
Body mass	1					
Toe angle	0.4584 *0.215*	1				
Toe length	0.6125 *0.080*	−0.2850 *0.457*	1			
Heel angle	−0.2989 *0.435*	0.1195 *0.759*	0.1300 *0.739*	1		
Medial wall length	0.1434 *0.713*	**0.7112** ***0.032***	−0.2388 *0.468*	−0.3000 *0.433*	1	
Lateral wall length	−0.0600 *0.878*	0.0891 *0.822*	0.3243 *0.395*	−**0.6922** ***0.039***	0.5896 *0.095*	1

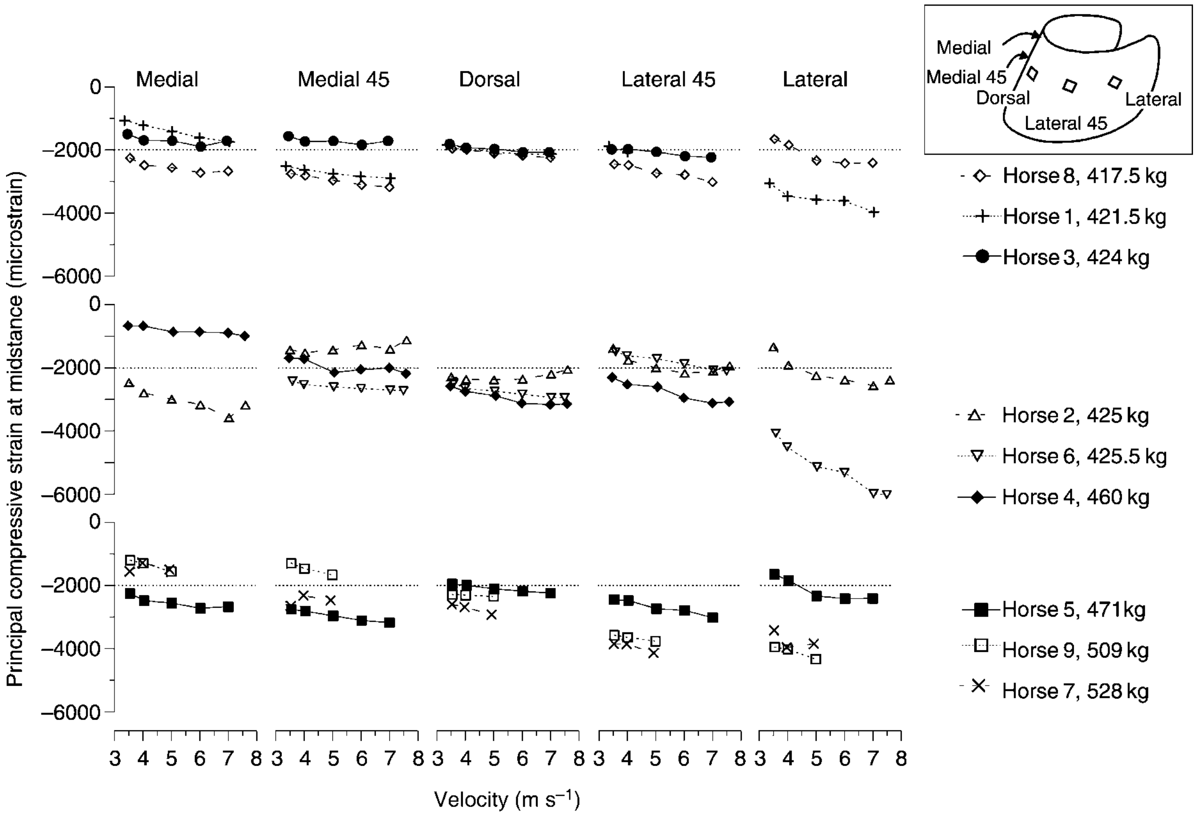

FIG. 2 Graphs of mean principal compressive strain ε_2 (microstrain, $\mu\varepsilon$) at each gauge site and for each horse versus treadmill velocity ($m\,s^{-1}$). Horses are ranked by body mass, and separated into three groups to minimize cluttering of symbols; all *Y* axes are the same. Dotted lines at $-2000\,\mu\varepsilon$ are included for reference

a few cases of redistribution of strains around the hoof with increasing velocity. For example, the dorsal and medial 45 gauges of horse 2 showed strain decreasing with speed (becoming less negative), while the other 3 gauges showed strain increases.

On first inspection, body mass had little discernible effect on ε_2 (Fig. 2); strains on the hooves of light and heavy individuals were in the same range. Maximal strains were observed on the lateral gauge of a 425-kg animal (horse 6) which was at the light end of the mass range.

Statistical results

Analysis of variance

Variables and interactions having a statistically significant effect on principal strain ε_2 were toe length (TL), toe angle and heel angle and their interaction (TA, HA, TA × HA), body mass and its interaction with toe angle (BM, BM × TA), medial and lateral wall lengths (MWL, LWL), and velocity and velocity squared (V, V^2). The ANOVA model incorporating just these terms explained more than 96% of the variation in ε_2 (Table 3).

Table 3 Results of the analysis of variance (ANOVA) for transformed data. The terms in the model are interactions of the primary factors (TL, TA, etc.) with gauge position g, which means that each gauge is different from the others. Two 3-way interactions were significant: TA × BM × g and TA × HA × g. The only term common to all gauges is the velocity-squared term, V × V

Source	DF	Sum of squares	Mean square	*F*-value	*P* > *F*
Model	45	14815.40689	329.2313	103.43	< 0.0001
Error	154	490.19784	3.1831		
Corrected total	199	15305.60474			
R^2		0.967973			
Terms in model	DF	Type III sum of squares	Mean square	*F*-value	*P* > *F*
TL × g	4	407.893172	101.9733	32.04	< 0.0001
TA × g	4	1095.799198	273.9498	86.06	< 0.0001
TA × WT × g	4	846.525764	211.6314	66.49	< 0.0001
TA × HA × g	4	615.036036	153.759	48.3	< 0.0001
HA × g	4	706.375642	176.5939	55.48	< 0.0001
MWL × g	4	718.555283	179.6388	56.44	< 0.0001
LWL × g	4	1371.091344	342.7728	107.69	< 0.0001
WT × g	4	841.278805	210.3197	66.07	< 0.0001
V × g	5	287.056328	57.41127	18.04	< 0.0001
V × V	1	44.621493	44.62149	14.02	0.0003

Multivariate regression

Multivariate equations describing the effects of these terms on ε_2 at each gauge site were of the form:

$$\varepsilon_{2g} = i_g + c_{1g}\mathrm{TL} + c_{2g}\mathrm{TA} + c_{3g}\mathrm{TA} \times \mathrm{HA} + c_{4g}\mathrm{BM} \times \mathrm{TA} + c_{5g}\mathrm{HA} + c_{6g}\mathrm{MWL} + c_{7g}\mathrm{LWL} + c_{8g}\mathrm{BM} + c_{9g}V + c_{10g}V^2 \quad (1)$$

where the values for the intercept i and coefficients c_1–c_{10} are given in Table 4. Subscripts g indicate that each gauge had its own set of intercept and coefficients, except for c_{10} which was common to all gauges.

The accuracy of the equations in predicting ε_2 for each gauge and horse is shown in Figs 3a, 4 and 5 by the proximity of the predicted results (open diamonds) to the means of recorded midstance strains for each animal (closed circles). The average separation of predicted from actual values was 55 $\mu\varepsilon$, or approximately 3% of mean strain values. (Unassociated open squares in the figures are where Procedure GLM predicted values for missing data.)

In contrast to this accuracy of prediction, coefficients c_1 to c_8 usually gave lines whose slope (Table 4) did not fit the recorded data (Figs 3a, 4, 5: dashed lines). For example, coefficients c_{8g} for body mass gave lines with excessively steep slopes for the medial 45, dorsal, and lateral 45 gauges (Fig. 3a: dashed lines). Only for velocity (Fig. 3b), heel angle (Fig. 4b), and lateral wall length (Fig. 5c) did the multivariate slopes appear closer to the data. For velocity and velocity squared, coefficients c_{9g} and c_{10} predicted curvilinear rates of change that fitted the data well (Fig. 3b). Strain magnitudes increased with velocity, with maximum linear rates of $-650\ \mu\varepsilon/(\mathrm{m\,s^{-1}})$ at the lateral gauge.

Bivariate regression

In most cases, slopes of the bivariate regressions of strains on individual mass, velocity or shape variables fit the data more obviously than the multivariate slopes. On increase in body mass, the bivariate slopes (Table 4, Fig. 3a: solid lines) indicated a redistribution of strain, rather than a general increase. This was shown by the reduction in strain magnitude medially on the hoof wall with an increase dorsally and laterally. The greatest slope, at the lateral 45 gauge, shows a $-1700\ \mu\varepsilon$ increase in strain with 100 kg increase in body mass.

Increase in toe angle by 10° caused a decrease in ε_2 at the medial 45 site of approximately 830 $\mu\varepsilon$, with a similar increase at the lateral 45 site of approximately $-870\ \mu\varepsilon$, and considerably lower changes at all other sites (Table 4, Fig. 4a). Increase in heel angle caused a moderate strain increase at both medial sites, with larger decreases seen from the dorsum laterally (Fig. 4b). The greatest decrease is 930 $\mu\varepsilon$ for a 10° change in heel angle, at the lateral gauge.

Greater toe length increased strain by $-750\ \mu\varepsilon\,\mathrm{cm^{-1}}$ at the lateral site and decreased it at all others. The largest decrease, at the lateral 45 gauge, was 1320 $\mu\varepsilon\,\mathrm{cm^{-1}}$ (Table 4, Fig. 5a). Strains decreased with medial wall length by up to 1390 $\mu\varepsilon\,\mathrm{cm^{-1}}$ at the three most dorsal sites, but increased by up to $-380\ \mu\varepsilon\,\mathrm{cm^{-1}}$ at both quarters (Fig. 4b). A similar pattern was seen for lateral wall length, with reductions of up to 630 $\mu\varepsilon\,\mathrm{cm^{-1}}$ at the three most dorsal sites, and increases of up to $-790\ \mu\varepsilon\,\mathrm{cm^{-1}}$ at the quarters (Fig. 5c).

Table 4 Estimated values for multivariate coefficients c_1 to c_{10} and the intercepts *i* for all variables in equation (1), for each gauge separately. Bivariate estimates are also given for primary variables. The large number of significant figures does not indicate accuracy but is to prevent rounding errors when the coefficients are used in equations (1)–(3)

Variable (unit)	Coefficient	Multivariate estimate	Error of estimate	*t*-value	$P > t$	Bivariate estimate
Medial gauge						
Intercept (με)	*i*	93054.1418	6644.6786	14.00	<0.0001	
TL (με cm^{-1})	c_1	348.5766	110.6389	3.15	0.0020	216.8
TA (με deg^{-1})	c_2	−1445.7702	117.6127	−12.29	<0.0001	−6.6
TA × HA (με/°/°)	c_3	39.2493	2.8372	13.83	<0.0001	
TA × WT (με/°/kg)	c_4	NC				
HA (με deg^{-1})	c_5	−2093.2423	143.9941	−14.54	<0.0001	−12.6
MWL (με cm^{-1})	c_6	−17.2336 (NS)	207.5937	−0.08	0.9339	−381.5
LWL (με cm^{-1})	c_7	−2556.4234	118.7996	−21.52	<0.0001	−792.5
WT (με kg^{-1})	c_8	−7.4012	1.3374	−5.53	<0.0001	4.8
V (με/(m s^{-1}))	c_9	−440.7308	77.8692	−5.66	<0.0001	
Medial 45 gauge						
Intercept	*i*	−844431.2852	112298.0677	−7.52	<0.0001	
TL	c_1	8071.2776	1069.8425	7.54	<0.0001	378.2
TA	c_2	15066.2095	2081.8180	7.24	<0.0001	82.7
TA × HA	c_3	−162.0488	22.1924	−7.30	<0.0001	
TA × WT	c_4	−17.2553	2.3519	−7.34	<0.0001	
HA	c_5	8254.4921	1117.7099	7.39	<0.0001	−11.1
MWL	c_6	−5121.0552	1081.8605	−4.73	<0.0001	1388.1
LWL	c_7	966.5783	141.3092	6.84	<0.0001	627.6
WT	c_8	940.1540	126.2947	7.44	<0.0001	2.6
V	c_9	−372.0925	77.9910	−4.77	<0.0001	
Dorsal gauge						
Intercept	*i*	−824944.6739	112298.0677	−7.35	<0.0001	
TL	c_1	7809.2074	1069.8425	7.30	<0.0001	197.3
TA	c_2	15321.5857	2081.8180	7.36	<0.0001	13.0
TA × HA	c_3	−169.2745	22.1924	−7.63	<0.0001	
TA × WT	c_4	−16.5695	2.3519	−7.05	<0.0001	
HA	c_5	8542.7297	1117.7099	7.64	<0.0001	16.8
MWL	c_6	−8845.6210	1081.8605	−8.18	<0.0001	151.8
LWL	c_7	1525.9493	141.3092	10.80	<0.0001	218.8
WT	c_8	886.7647	126.2947	7.02	<0.0001	−5.1
V	c_9	−393.3792	77.9910	−5.04	<0.0001	
Lateral 45 gauge						
Intercept	*i*	470746.5839	122501.0751	3.84	0.0002	
TL	c_1	−4020.9392	1158.5732	−3.47	0.0007	1324.2
TA	c_2	−8877.6816	2282.7395	−3.89	0.0002	−86.8
TA × HA	c_3	113.8101	23.9913	4.74	<0.0001	
TA × WT	c_4	8.2823	2.5961	3.19	0.0017	
HA	c_5	−5681.1829	1206.5314	−4.71	<0.0001	28.3
MWL	c_6	5433.6682	1212.7239	4.48	<0.0001	105.5
LWL	c_7	−318.8221	141.5969	−2.25	0.0258	399.5
WT	c_8	−462.3713	138.8933	−3.33	0.0011	−17.2
V	c_9	−469.1196	78.4694	−5.98	<0.0001	
Lateral gauge						
Intercept	*i*	9253.9181	4189.6786	2.21	0.0287	
TL	c_1	−2650.7353	206.9363	−12.81	<0.0001	−748.2
TA	c_2	−618.5887	66.9079	−9.25	<0.0001	−36.5
TA × HA	c_3	NC				
TA × WT	c_4	NC				
HA	c_5	219.1527	10.3367	21.20	<0.0001	93.2
MWL	c_6	5884.1522	844.0011	6.97	<0.0001	−298.5
LWL	c_7	264.7941 (NS)	592.7759	0.45	0.6557	−646.6
WT	c_8	0.9612 (NS)	1.1467	0.84	0.4032	−7.2
V	c_9	−646.0934	78.5425	−8.23	<0.0001	
Common coefficient						
V × *V*	c_{10}	29.8482	7.1079	4.20	<0.0001	

NS – not significant; NC – not able to be computed.

Discussion

Validation of results

The range of strains recorded is within that of similar previous works in which different samples of horses were run on treadmills or overground[1–3].

Correlations among variables

The small number of correlations among shape variables (Table 2) is perhaps unexpected. A change in each shape variable does affect the mechanical behaviour of the hoof (as shown by the changes in ε_2), and the regions

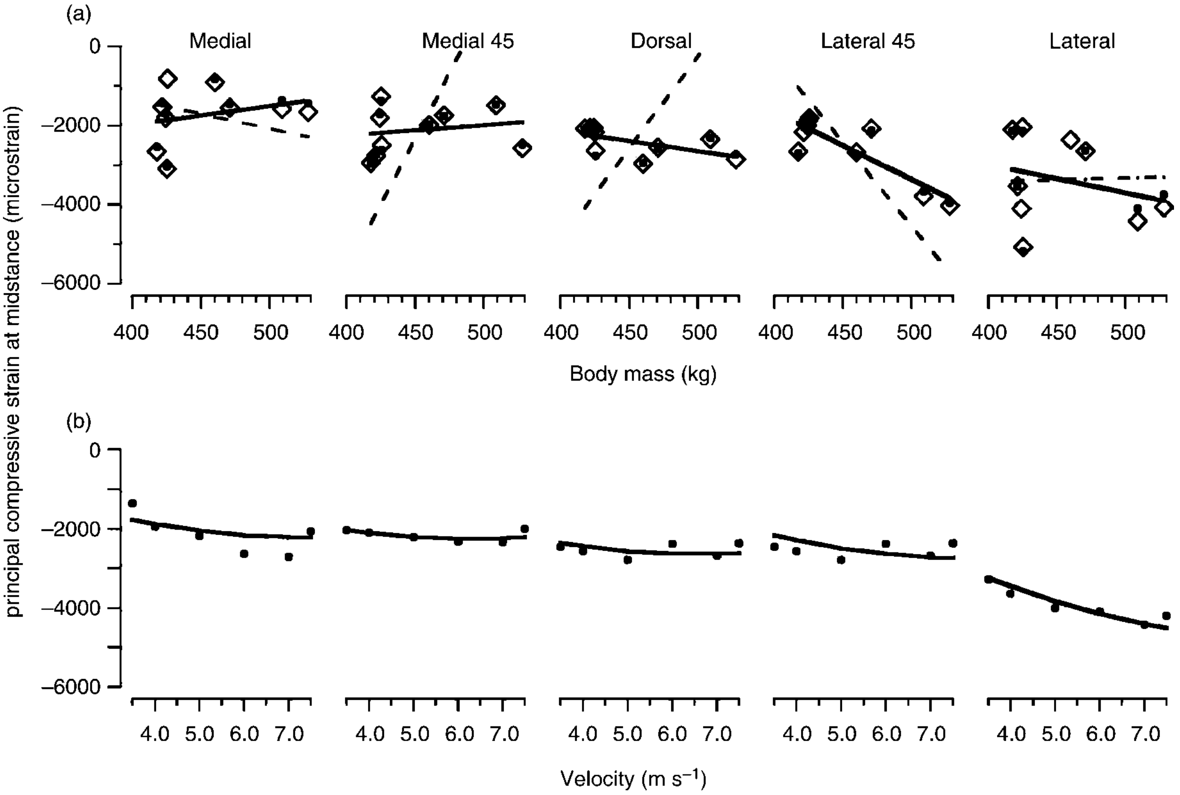

Fig. 3 (a) Graphs of mean ε_2 for each horse at each gauge site (at all velocities) versus body mass (small closed circles). Open diamonds are the predicted values from equation (1). Slopes from the multivariate regressions (dashed lines) and bivariate regressions (solid lines) are shown. (b) Graphs of ε_2 versus velocity for all horses pooled, with multivariate regressions from equation (1) (solid lines)

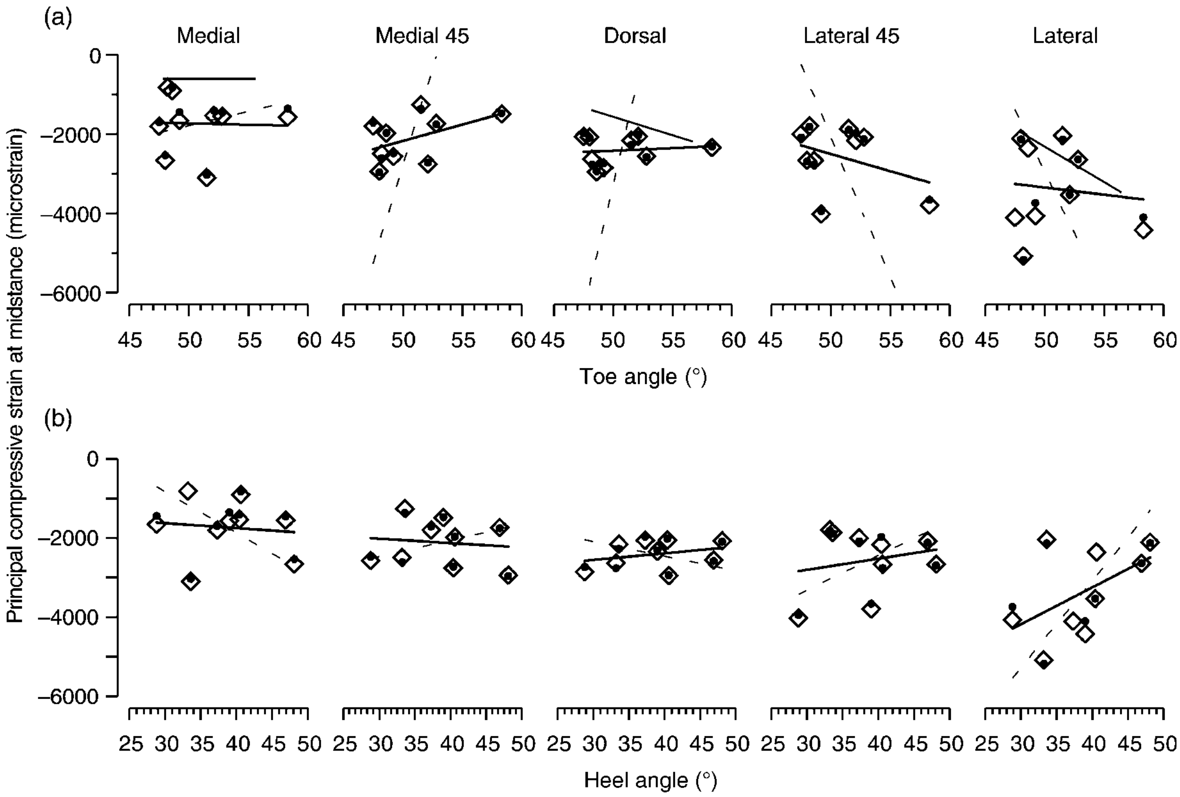

Fig. 4 Graphs of mean ε_2 for each horse at each gauge site versus (a) toe angle and (b) heel angle. Symbols and lines as in Fig. 3a. Thin solid lines in (a) are from data of Thomason[1]

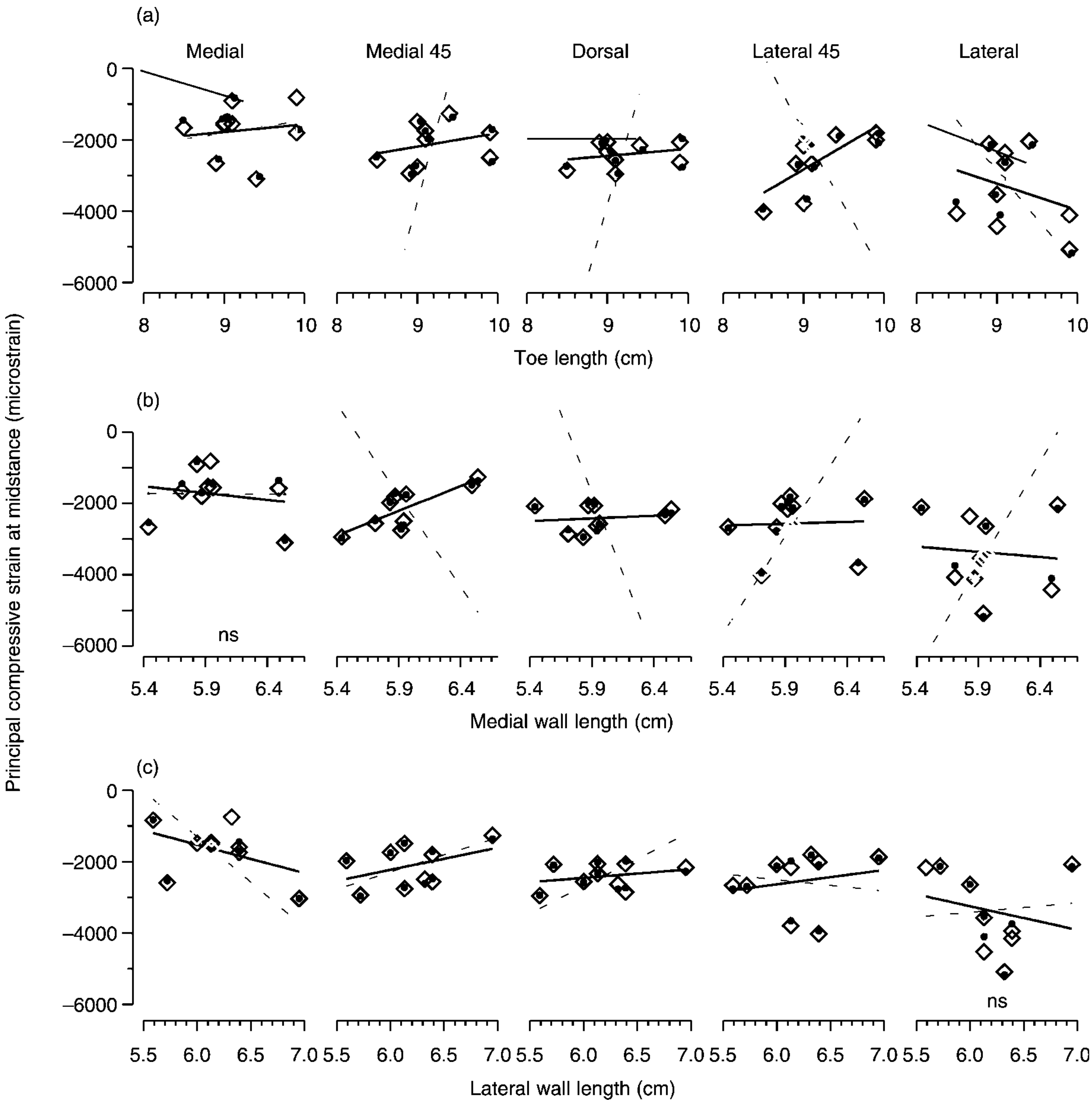

Fig. 5 Graphs of mean ε_2 for each horse at each gauge site versus (a) toe length, (b) medial wall length, and (c) lateral wall length. Symbols and lines as in Fig. 3a. Thin solid lines in (a) are from data of Thomason[1]

of the hoof measured by each variable are all part of the same capsule. On this basis we might expect that a change in one shape measurement might cause changes in the others, and, therefore, some correlation between them. The present results show only weak correlation: two out of a possible ten pairs. In a study with a similar sample size to this, but using more measurements[14], we found patterns of correlation among hoof shape variables. The density of significant correlations was similarly low (33 out of 190) but did show patterns that differed depending on toe angle. The tentative conclusion from present and previous results is that hoof shape measurements are not strongly correlated, contrary to our expectation.

Strain ε_2 versus body mass and velocity

The study achieved its first objective of quantifying relationships between ε_2 and body mass and velocity at a trot, but using the calculated coefficient to standardize strain records for mass and velocity is not entirely straightforward.

Increase in body mass redistributed strain, and presumably loading, away from the medial quarter of the forehoof towards the toe and lateral quarter (Fig. 3a). Consequently, hoof strain records for unshod Standardbreds cannot be normalized to mass simply by dividing them by the individual's mass. Normalization to mass is a common practice for records of ground reaction force, and is appropriate for those data[15,16]. For strains, the bivariate coefficients in Table 4 should be used to derive a standardized strain ε_{2S} at a consistent standard body mass BM_S, say 500 kg, based on the recorded strains at each site ε_{2Rg} and the test animal's actual body mass BM_R. The calculations need to be done separately for each gauge site (and are only appropriate for the sites used here):

$$\varepsilon_{2Sg} = \varepsilon_{2Rg} + c_{8g}(BM_R - BM_S) \qquad (2)$$

Strain ε_2 also showed a different response to changes in velocity than ground reaction forces which have been reported to change linearly with body mass, though no coefficients were given[11]. The strains at each gauge site clearly showed curvilinear responses of quadratic form, and normalization should be to a standard velocity V_S, say $5\,\mathrm{m\,s^{-1}}$. We agree with McLaughlin and colleagues[11] that the effects of velocity cannot be disregarded, and that recording at a constant, standard velocity is one way of avoiding the issue. If velocity cannot be controlled, but can be measured, its effects can be taken into account. As with the correction for mass, the calculations need to be done for each gauge site, based on the recorded strains ε_{2Rg} and velocity V_R, but in this case, the multivariate coefficients from Table 4 can be used:

$$\varepsilon_{2Sg} = \varepsilon_{2Rg} + c_{9g}(V_R - V_S) + c_{10}(V_R - V_S)^2 \qquad (3)$$

The two equations can be combined to standardize for mass and velocity simultaneously, simply by adding the term from equation (2) [$+c_{8g}$ ($BM_R - BM_S$)] to equation (3).

Multivariate regression

The multivariate relationships of ε_2 to the hoof shape measurements are paradoxical at first sight. They explain a very large percentage (>96%) of the variation in strain magnitudes, and allow for extremely accurate prediction of mean strains in individual horses. This indicates that, taken together, the mass, velocity and shape measurements are excellent predictors of hoof strain for this sample of horses. On the other hand, the multivariate coefficients give highly implausible slopes on most of the bivariate graphs (Figs 3a, 4, 5). It is likely that there is a complex interplay among the shape variables in their effect on ε_2 which cannot be resolved by the present statistical analysis, i.e. not on a sample of this size. By 'interplay' we mean that the shape measurements do not vary independently in their mechanical effect on ε_2, even though they show no statistical correlation among each other. The effect of toe angle on ε_2, for example, is altered by weight, heel angle, toe length, and the other shape variables. This interplay probably causes the unusual multivariate coefficients; the subtlety of the mechanical interactions confuses the ability of the statistics to distinguish them. Low ranges of some variables (e.g. 8.5–9.4 cm for TL, and 5.4–6.5 cm for ML) may be partially at fault.

Another piece of information adds a further level of complexity to this interpretation of the paradox. As a test, the relevant hoof measurements, masses, and velocity from two additional Standardbreds from a separate experiment were entered into the multivariate equations. Predicted values of ε_2 were calculated and compared with actual values recorded *in vivo* for these horses while trotting in an outside arena. The comparisons were not even close, with implausible discrepancies of up to 20 000 $\mu\varepsilon$, and a great range of discrepancy among gauge sites. This confirms that the multivariate equations are specific only to the horses in this sample, an observation which does not invalidate the equations. Rather, it emphasizes that these variables cannot be considered to be mechanically independent in their effect on the distribution of loading throughout the capsule. Despite the low level of statistical correlation among the variables (Table 2), they do act in some degree of concert in distributing loads. Because the variables do not correlate well, each animal is likely to have an almost unique combination of them, and a large sample will be necessary to refine the present results.

The functional context of the hoof may hint at a general interpretation of these findings. Hooves are constructed to act at the physical interface with somewhat unpredictable substrates. Their mechanical properties have to be able to withstand considerable potential variability in loading regime. To this end the hoof's materials are constructed with large safety factors, i.e. the stresses and strains experienced under normal operation are small fractions of those necessary to break the materials. The large size of the safety factors allows for considerable latitude in the specific construction of individual hooves. In this context, the lack of correlation among shape variables despite the clear mechanical interplay among them seems to indicate that a wide range of combinations of shape variables is tolerable. This suggestion is supported by the great variety of hoof shape seen in wild and domestic animals.

Bivariate regressions

Bivariate relationships of ε_2 with the hoof shape measurements give results that are generally more readily interpretable than the multivariate ones. They demonstrate that change in strain with any of the variables is not a uniform increase or decrease around the hoof wall, but involves redistribution.

Strain versus mass and velocity

Strain redistribution with varying body mass has already been discussed. Even the changes in strain magnitude with velocity show some redistribution. Strains increase at all sites but by differential rates which are higher laterally. This indicates that the lateral side of the hoof is preferentially loaded at speed.

Strain versus toe angle

In this sample, increasing toe angle shows a general trend towards unloading the medial side at the expense of the lateral side (Fig. 4a). The thin solid lines on the medial, dorsal, and lateral graphs of Fig. 4a show the comparable slopes from previous work[1], which demonstrate a similar trend but more dramatically.

The present results show that the trend to redistribute strains with toe angle has its greatest effect at the medial 45 and lateral 45 sites, i.e. at the junctions of toe and quarters. At the medial 45 site strain decreases with toe angle, with a similar rate of increase at the lateral 45 site, but with less change at all three other sites.

Simple mechanical modelling of the hoof would suggest that the toe was more heavily loaded at lower angles, because the distal phalanx is more directly suspended under the wall. Present results contradict that suggestion.

Strain versus heel angle

Increase in heel angle shows the reverse trend of dramatically unloading the lateral side, while moderately adding load to the medial side of the hoof. This suggests that more upright heels might improve mechanical performance of the hoof laterally, without compromising it medially to any great extent.

Strain versus wall length

Change in wall length, whether at the toe, or on medial or lateral quarters, appears to have similar effects, but of slightly different magnitude. Increased length unloads the dorsal half of the hoof (including the '45' sites) and loads the heels. The effect of toe length on the medial gauge is the only exception to this general trend (Fig. 5a), but the results of previous work[1] fit in with it (see the thin solid lines on medial, dorsal and lateral graphs in Fig. 5a). These results suggest that longer hooves (not taking toe angle into account) tend to distribute load towards the heels.

Finite element (FE) versus in vivo *results*

The present results were used to test the validity of FE modelling of the hoof by generating models of the same shapes as the hooves utilised in this study[17]. The models were remarkably accurate, with the caveat that they tended to emphasize strains at the toe to a greater extent than is seen *in vivo*. See that paper[17] for further details.

When FE methods were used to isolate the effects of changes in one or two shape variables at a time[12], results were generally in accord with the present ones, with relatively minor discrepancies. For example, increase in toe angle alone shifted strain from the toe towards the heels, but more strongly than seen here and the subtleties of the mediolateral shift were not picked up by the model. Results for change in heel angle accorded very well with present ones, showing both dorsopalmar and mediolateral shifts in strains. For toe length, the model predicted reductions in strains at the toe well, but not so well at the heels. Further comparisons are given in the FE paper[12].

When used in conjunction with validating data such as those in the present work, FE methods could become a valuable tool for investigating mechanical behaviour of the hoof, particularly for deeper structures that are not readily amenable to experimental instrumentation *in vivo*.

Conclusions

1. Strains at different sites around the hoof vary in predictable manners with body mass and velocity, allowing strain records to be standardized for both variables.
2. Variation in hoof shape largely causes redistribution of strains rather than uniform changes. Increase in toe angle shifts strains (and presumably loading) from medial to lateral, while increase in heel angle does the reverse. Increase in wall length shifts strains from toe to heel in this sample of horses.
3. Data from experiments such as this are invaluable as corroboration for strains predictable from mechanical models such as those generated in finite element analysis.
4. The mechanical interplay among hoof shape variables is subtle. Further experiments with large sample sizes in conjunction with FE analyses will be necessary to resolve the interplay.
5. Until the mechanical interplay is resolved, the results from single experiments cannot be used to predict strains in single hooves from the general equine population. At such a detailed level of biomechanical behaviour, a hoof is not a hoof is not a hoof (*pace* Gertrude Stein).

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