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Variation in surface strain on the equine hoof wall at the midstep with shoeing, gait, substrate, direction of travel, and hoof shape

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Summary

Objectives were to examine the deformation of the healthy equine front hoof during locomotion, by recording strains on its outer surface, and to test whether its mechanical behaviour is significantly altered under different locomotory conditions and variation in hoof shape. Strains were recorded *in vivo* from 5 rosette gauges around the circumference of the right forehooves of 12 horses. The magnitudes and orientations of principal strains at the midstep were compared statistically for different conditions of shoeing (shod vs. unshod), gait (walk vs. trot), substrate (treadmill vs. ground), and direction of travel (straight, right turn, left turn). Principal strains were regressed on 4 variables describing hoof shape - toe length, toe angle, and medial and lateral wall angle - to describe their contribution to variations in strain and hoof deformation.

Shoeing did not essentially change the magnitudes of the larger, compressive principal strain, but caused some strain reorientation. Shoes decreased the variation in strains indicating that they tend to stabilise the deformation of the hoof. Strain magnitudes were significantly greater at trot than walk, but there was little change in orientation indicating that the general pattern of deformation of the hoof is constant between these 2 gaits. Strain patterns showed small but significant differences between locomotion on the treadmill and on ground, with the differences being more apparent at the toe than at the sides of the hoof. When turning, the quarter on the inside of the turn experienced 40% more strain than during straightline motion, while strain was similarly reduced on the opposite quarter. Strain magnitudes increase with toe length and toe angle, but were inversely proportional to medial and lateral angles. The change with toe length correlated with the range of body size of the animals in the sample. The change with toe angle was contrary to that found in *in vitro* tests. The change with medial and lateral angles indicated that hooves with more upright quarters are stiffer and possibly provide less impact absorption.

Introduction

Previous studies of surface strain on the hoof wall of the equine forefoot (Knesevik 1962; Colles 1989; Preuschoft 1989; Thomason *et al.* 1992) have demonstrated repeatable patterns of strain during the stride cycle. A single pattern predominates for most of the stance, with some variation in strain magnitudes but little in their orientation, and this pattern can be reconciled with known deformations and loads on the hoof (Thomason *et al.* 1992). Despite the presence of a recognisable strain pattern, there is considerable variation in strains at comparable sites on the hooves of different individuals, and among strides made by the same individual even when running on a treadmill (Thomason *et al.* 1992). The purpose of this study was to initiate a systematic investigation of the magnitudes and causes of variation in surface strain patterns.

Hoof strain is recorded from 5 sites on the right forehooves of 12 individuals, and 2 separate statistical tests are conducted. The first test compares strains under different locomotory conditions: shoeing (shod vs. unshod), gait (walk vs. trot), substrate (treadmill vs. ground) and direction of travel (straight vs. left and right turn). The aims were to test whether each of these conditions significantly alters the mechanical function of the hoof, and to determine the relative effect of each on strain magnitudes and orientations. The second test assessed the relationships between strains and individual variation in 4 variables describing hoof shape: toe length, toe angle, and medial and lateral angle of the wall. These tests link the mechanical function of the hoof to the importance of hoof balance (Moyer and Anderson 1975; Balch *et al.* 1991a).

The broader aim of the work was to help establish a baseline picture of the normal mechanical behaviour of a healthy front hoof. The underlying premise is that a detailed understanding of normal hoof function is prerequisite to a full interpretation of the aetiology and pathology of common lamenesses of mechanical origin.

Materials and methods

Experimental animals

Twelve horses of mixed breed, gender, age and size were used. There were 6 Standardbred mares, one Thoroughbred gelding, one pony stallion, and the remainder were mares or geldings of mixed breed. The reason for such a heterogenous group was to focus the study on strain patterns and variations that are common to all equine hooves, rather than those of a particular breed.

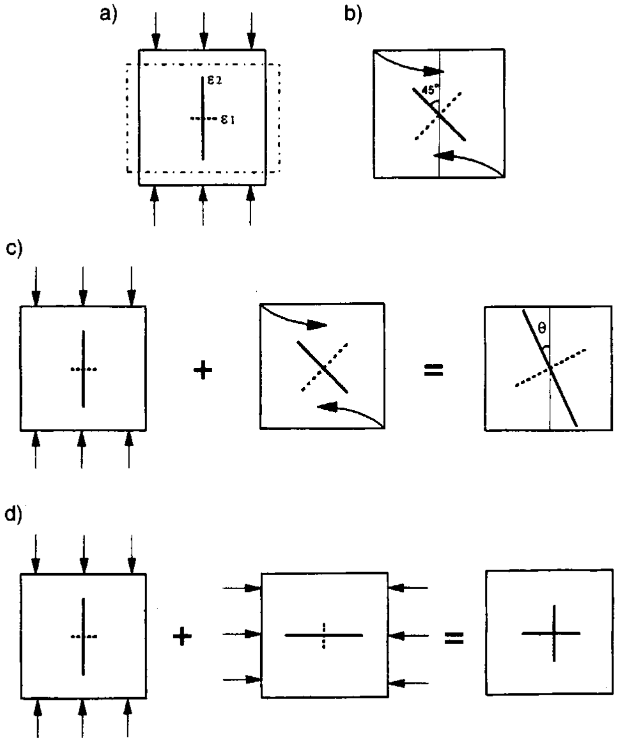

Fig 1: (a) Principal strains $\varepsilon 1$ and $\varepsilon 2$ in a small block of material subjected to a distributed vertical compressive load. Dashed lines represent the deformed block. (b) Principal strains under torsional loading. (c) Principal strains under a combination of compression and torsion. Angle θ depends on the relative magnitudes of the 2 loads. If compression predominates the angle is small; if torsion predominates it approached 45°. (d) Principal strains under biaxial compression. Solid strain lines represent compression, dotted lines represent tension.

Theoretical background

A brief introduction to principal strains is given here to assist in interpreting the output from the rosette gauges used in the experiment. Further details may be found in many introductory engineering texts (Beer and Johnston 1981).

If a small block of material is loaded with an evenly distributed compressive force along its axis (Fig 1a) the primary strain at its centre is compressive and parallel to the force and to the axis. The block shortens along that axis but attempts to retain its original volume by expanding along its secondary, perpendicular axis, as shown by the dashed outline. The perpendicular expansion induces a secondary strain (also known as Poisson strain) which is roughly one third of the primary strain for most materials (a ratio known as Poisson's ratio). The 2 perpendicular strains are the principal strains and their orientations are, in this case, parallel and perpendicular to the axis of the block. By convention, tension is considered positive and compression negative. The tensile principal strain is designated as $\varepsilon 1$, the compressive strain as $\varepsilon 2$.

If the block is now twisted (Fig 1b), one upper corner tends to move closer to the opposite lower corner, hence shortening the block along a diagonal. The other diagonal is lengthened, so the 2 principal strains are now approximately equal in magnitude, still perpendicular to each other, but now oriented along 45° to the block's axes. When principal strain records show the absolute magnitude of $\varepsilon 1$ approximately equal to that of $\varepsilon 2$, torsional loading may usually be inferred as the cause.

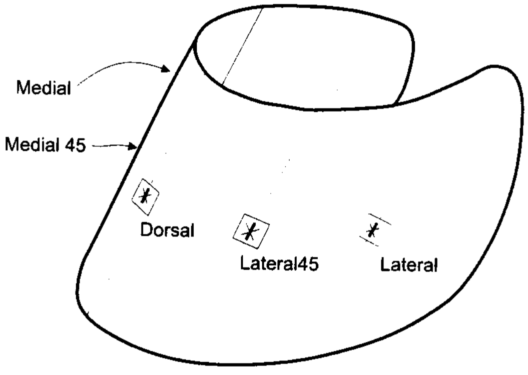

Fig 2: Stylised representation of the hoof wall showing the position of the dorsal, lateral45 and lateral gauges. The medial45 and medial gauges are opposite their lateral counterparts. The gauges are located halfway between the coronary band and bearing surface, and have their central element aligned with the tubules visible in the wall (thin solid lines).

If loads act on the block in combination, the principal strains from each component of loading are added (Figs 1c,d). The 2 summations shown in Figure 1 occur in the hoof wall (Thomason *et al.* 1992). One way in which a condition of combined loads may be recognised is when the absolute value of $\varepsilon 1$ differs markedly from one third of $\varepsilon 2$, but is not equal to $\varepsilon 2$ as in the case of torsional loading. The condition in Figure 1d is known as biaxial compression in which both principal strains are compressive. This occurs when the primary compressive strains, from equal compressive forces along both axes, more than cancel out the tensile Poisson strains. If one compressive strain is smaller, it might negate the Poisson strain of the other without exceeding it. In this case, one of the combined principal strains would be reduced to zero, a condition which also occurs in the hoof wall.

Strain gauges record the strains acting on a small region of material immediately deep to the gauge. In most biological situations, the exact combination of loads acting on the region being sampled is not known ahead of time and rosette gauges must be used. These gauges have 3 elements at 45° intervals and the magnitudes and orientations of the 2 principal strains can be calculated from their output. Single element gauges record only in one direction and can give misleading results if they are not aligned with the larger principal strain. The drawback of using rosettes, rather than single-element gauges, is that each needs 3 sets of wires and strain amplifiers.

Strain measurements

Five rosette strain gauges were attached to the right forehoof of each animal, having previously been soldered to lead wires and connectors. The hoof surface was prepared and the gauges were attached with cyanoacrylate adhesive, following the procedures of Colles (1989). The primary axis (central element) of each gauge was aligned with the tubules visible on the surface of the hoof at each site so strain orientation could be determined with respect to the tubules (Fig 2). Two turns of elastic electrical tape were wrapped around the hoof over the gauges to protect them. Only 4 gauges were damaged or pulled loose, and needed replacing, from the 60 used in this experiment.

The gauges were placed around the circumference of the

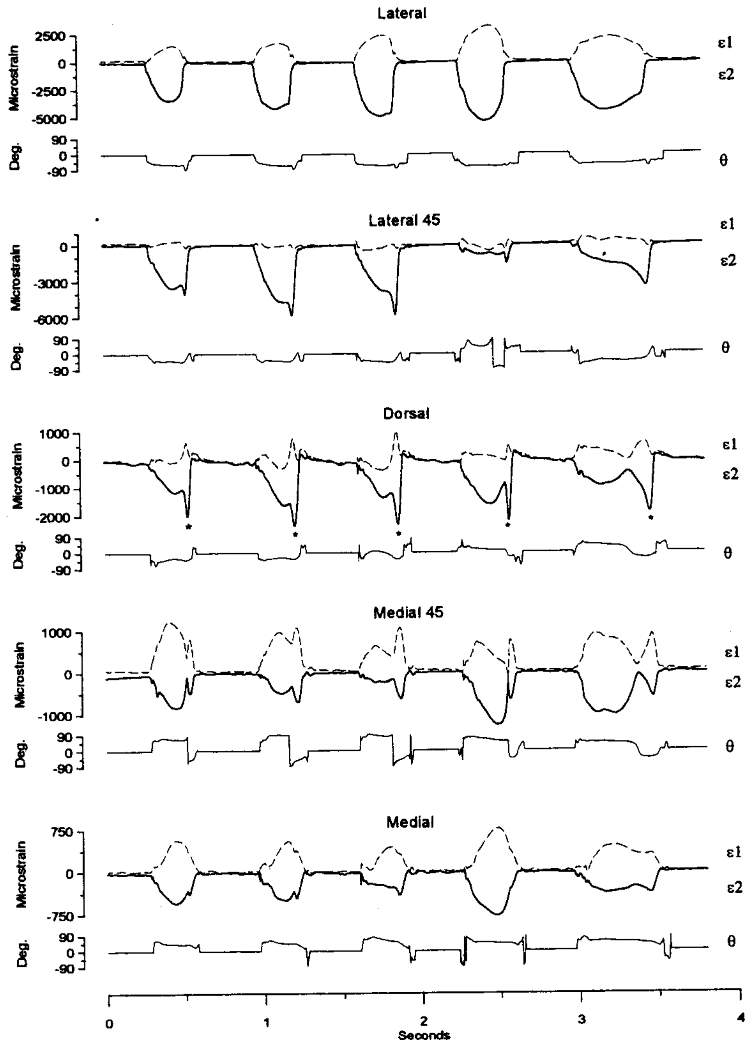

Fig 3: Records from all 5 gauges of a horse trotting unshod on ground in a straight line. They illustrate the differences in curve profile among gauges, and the interstride variability. The asterisks mark the breakover spikes for the dorsal gauges; such spikes are also evident for both 45 gauges. Solid lines on the strain graphs indicate the magnitude of ε2 which is usually compressive (negative); dashed lines represent ε1 which is usually tensile (positive).

hoof, halfway between the coronary band and the wear surface (Fig 2), and were evenly spaced between the widest point at the medial quarter and the equivalent lateral point. The gauge positions were designated: lateral, lateral45, dorsal, medial45, and medial. The dorsal gauge was placed on the midline of the toe. These positions were chosen to verify the strain pattern converging on the coronary band at the toe that was suggested by Thomason *et al.* (1992). They sampled the greater part of the circumference of the hoof wall.

The leads from all 5 gauges were held to the limb at the pastern, cannon and forearm with Vetrap bandage[1], leaving slack wire across each joint for mobility. The gauge leads were connected at the withers to main leads which were tethered to a girth strap by a quick release mechanism. For treadmill tests the main leads were 3 m long, otherwise they were 15 m long, and led to a bank of 15 strain conditioning amplifiers, 3 per rosette (DiCaprio and Thomason 1989). Before beginning the experimental runs, the amplifiers were each set close to zero output with the foot held off the ground. Final zeroing was performed on the recorded data (see *Data reduction* below). During each experimental run, output voltages from the amplifiers, proportional to the strains, were sampled at 333 Hz per channel using an analogue-to-digital converter (Dash 16)[2], mounted in a generic 386 PC. Once the animal had reached a steady speed, strain was recorded for all 15 channels simultaneously for 5 s. Runs were repeated to aim for a minimum of 10 strides recorded for each of the conditions outlined in the protocol below (The number of strides per condition varied from 7 to 19 over all the records).

Experimental protocol

Four variables were manipulated: shoeing, gait, substrate, and direction of travel. It was not logistically feasible to manipulate all variables for all horses. Gait and shoeing were always changed. It was not always possible to test the animals both on the treadmill and on open ground, or to test them shod and unshod on the treadmill and on ground. The problem of missing

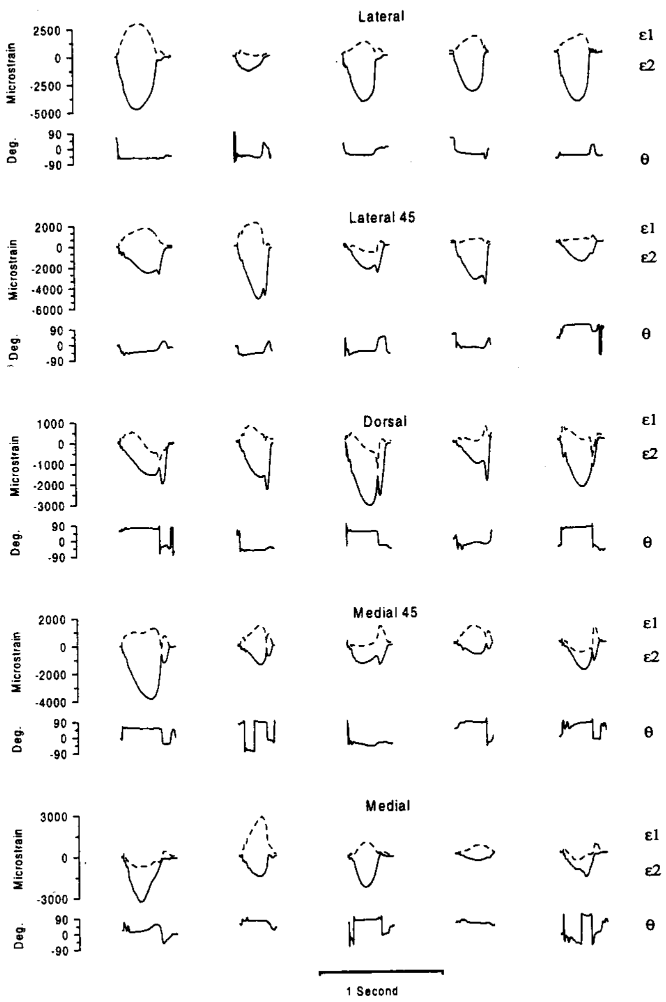

Fig 4: Records of a single stride from all 5 gauges on 5 different horses trotting unshod on ground in a straight line. They illustrate some commonalities in profile, indicative of the underlying patterns, and also show individual variation.

one or 2 combinations of variables for any one individual was overcome by pooling the data for the statistical analyses.

Shoeing: Gauges were applied to a hoof which was already fitted with a shoe. The animal was run at both gaits, with the substrates and directions being altered where possible. The shoes were then removed from both front feet, taking care not to dislodge the gauges on the right foot. Runs were repeated for the same conditions of gait, substrate, and direction as when shod. Shoe type was not taken into account, as the aim was simply to test the effects of having or not having a shoe.

Gait: Every condition of shoeing, substrate and direction that was possible for a given animal was repeated at a walk and a trot.

Substrate: The animals were first run on a treadmill in the nearby Equine Research Centre, at both gaits. They were then taken to a paddock and led by hand in a straight line past the recording equipment. The paddocks used either had short turf or hard soil, which presumably adds some variability to the results that was not accounted for here.

Direction: Once straight-line records had been made in the paddock, the animals were led around the equipment in a 20 m diameter circle, first one way and then the other to give 3 possible directions: straight, turn left, and turn right.

Measuring hoof shape

Four variables describing hoof shape were measured for the right forehoof of 10 of the 12 horses: (1) *toe angle*, between the plane of the bearing surface and the dorsal wall at the toe; (2) *toe length*, from the coronary band to the point of intersection of the bearing surface and dorsal wall (or the projected point of intersection if the wall was rounded off at the toe); (3) *medial angle*, between the wall at the widest point of the medial quarter and the plane of the bearing surface, and (4) *lateral angle*, measured similarly to the medial angle but on the lateral quarter. Medial and lateral angles were used as convenient descriptors of the asymmetry of the hoof in dorsal view. They quantify the orientation of the bearing surface to the wall at the quarters and encompass components of both common measures of medial and lateral balance, i.e. the orientation of the bearing surface with respect to the axis of the third metacarpal, and the medial and lateral widths with respect to the central sulcus (Balch *et al.* 1991a).

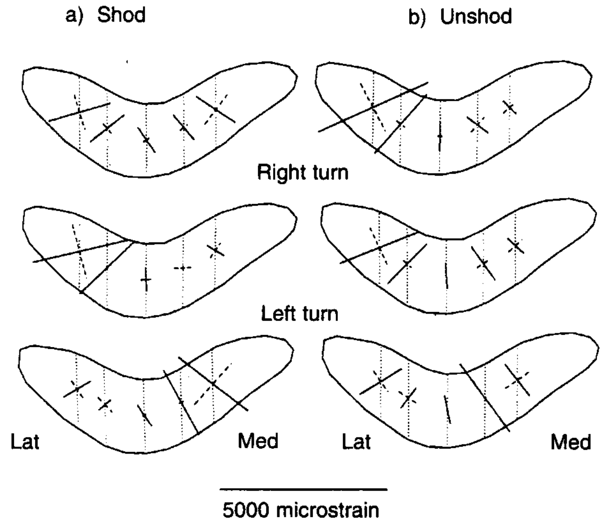

Fig 5: Midstep principal strains for all 5 gauges for a horse trotting on ground. (a) shod. (b) unshod. The upper row is for motion in a straight line, the middle row is a right turn, the lower row is a left turn. The hoof wall has been figuratively flattened out, to show all 5 gauges sites, by moving the heels and quarters abaxially and dorsally. This follows the method of 'Ungulographie' of Knezevik (1962). Solid lines indicate compressive strain, dashed lines indicate tension. The fine dotted lines indicate the approximate orientation of the tubules through each gauge site.

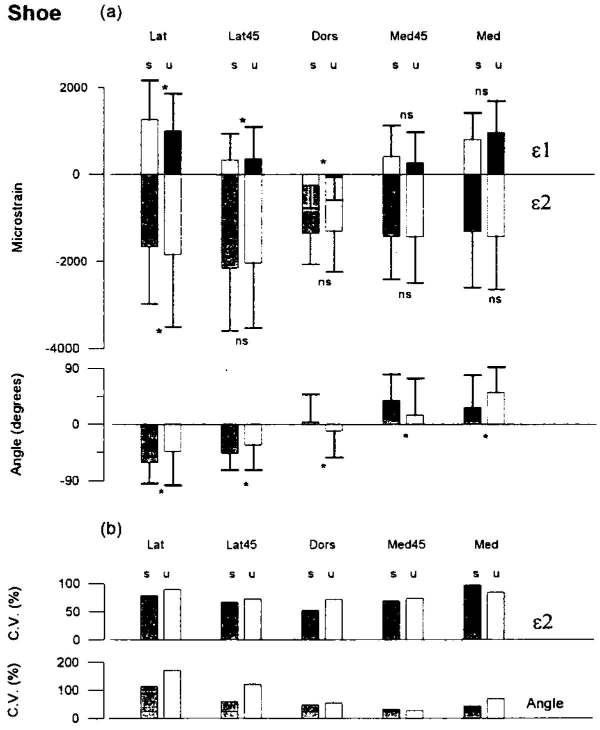

*Fig 6: (a) Graphs of the means of $\varepsilon1$, $\varepsilon2$, and the angle of the $\varepsilon2$ with respect to the hoof tubules for all 5 gauges. The data are pooled for all individuals and are sorted by shoeing condition: s, shod; u, unshod. The 'error bars' indicate the s.d. for each mean. Differences between shod and unshod means are indicated for each gauge by: *, significant; ns, not significant ($P<0.05$). (b) Graphs of the coefficients of variation (C.V.) for $\varepsilon2$ and the angle.*

All measurements were made from photographs of the foot taken in lateral and dorsal views. This protocol was developed, and its reliability tested, for a separate study of hoof shape (J. Staples, A. Negri and J. Thomason, unpublished data). The lateral view was taken parallel to the sole and centred on the midpoint of the bearing surface. It proved impossible to take the dorsal view from the most desirable position, parallel to the solar surface and centred on the midline at the toe, and a standard procedure was therefore adopted. The dorsal view was taken with the horse standing on a flat, level surface, and with the camera 2 m in front of the hoof and 0.6 m from the ground.

All photographs included a scale bar and individual code number. The measurements were made directly from the 35 mm negatives using a video-digitising system comprising a CCD black and white camera with macro lens (CCD-72)[3], a video-digitising card (OFG-640)[4], mounted in a generic 486 PC, and Optimas image-analysis software[5]. Hoof angle and toe length were measured from the lateral views. Medial and lateral angles were measured from the dorsal views. The slight parallax error in the 2 abaxial angles, owing to the camera position, was assumed to be consistent among individuals because of the standard procedure adopted.

Data reduction

Raw strains were converted to principal strain magnitudes and orientations using a computer programme based on the formulae in Dally and Riley (1965). The programme prompted for manual correction of any zero offset of the raw strains and set the strain between steps to zero. All principal strain files were plotted on axes of strain (or strain orientation) vs. time and examined to check for correct zeroing before proceeding to the following step. Principal strain values at the midstep (i.e. the midpoint between impact and toe-off, which are both clearly defined on strain records) were extracted from the continuous data.

Statistical tests

The statistical tests on the locomotory variables looked for significant differences in strain between conditions (e.g. shod vs. unshod, walk vs. trot). For the shape variables the tests assessed the amount of strain change with change in, for example, toe angle.

The tests used the pooled midstep data from all individuals to examine variation within the whole sample group rather than variation within individuals. The tests were nested analyses of variance (ANOVA) of unbalanced design using the procedure GLM (general linear model)[6]. Significance was evaluated with an F test on the ANOVA output.

The first test was for interactions among the 4 locomotory variables (e.g. are the results for shoeing different at a walk than at a trot?). Where interactions were found, the data were first tested unsorted, then sorted on the second variable before testing the first.

The effects of shoeing and gait were tested separately using a confidence limit of $P<0.05$ for the degree of significant difference, applying a Bonferroni correction if sorted on a second variable. Where P values are not specified in the results for significant differences, they at least meet this criterion. The effects of substrate and direction were combined in a single Duncan's least significant difference test that compared means and s.d. for data for all 4 conditions.

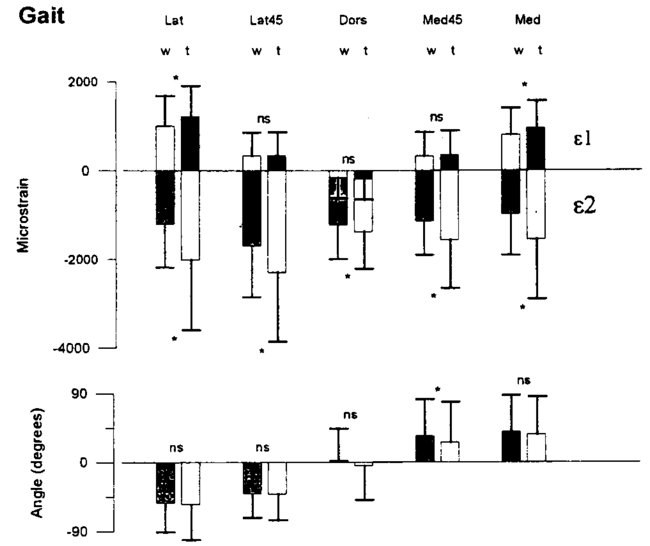

Fig 7: Graphs of the means of ε1, ε2, and the strain angle, sorted by gait: w, walk; t, trot. Other details are in the caption for Figure 6a.

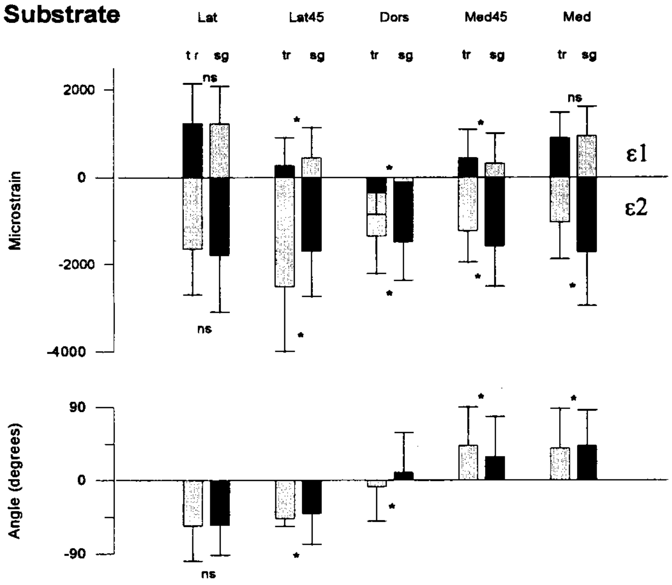

Fig 8: Graphs of the means of ε1, ε2, and the strain angle, sorted by substrate: tr, treadmill; sg, moving straight on ground. Other details are in the caption for Figure 6a.

The effects of the shape variables were assessed separately using *Type III* regressions in GLM. This procedure also took the locomotory variables into account by incorporating them in the intercept of the regression line as follows:

$$Y = a + s + g + sd + (b \times X) \qquad \textit{Equation 1}$$

where *Y* is strain magnitude or orientation; *X* is one of the 4 hoof measures; *a* is the base intercept; *s*, *g*, and *sd* are the respective effects on the base intercept of shoeing, gait, and substrate combined with direction, and *b* is the slope of the line which describes the relationship of primary interest here. The significance of all coefficients (lower case letters) in *Equation 1* was tested at a probability level of $P<0.05$. Predicted values of Y were calculated for X values at each end of the measured range of each variable, using only significant coefficients in the calculation.

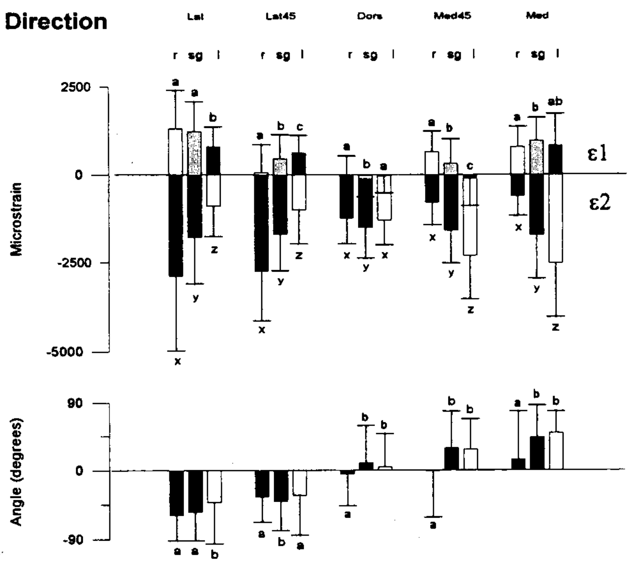

Fig 9: Graphs of the means of ε1, ε2, and the strain angle, sorted by direction: l, left turn; r, right turn; sg, moving straight on ground (same data as in Fig 8). For each gauge (i.e. each trio of bars), bars sharing the same letter are not significantly different, and bars with different letters are significantly different (P<0.05).

Correlations were calculated for each pairwise combination of the 4 shape measurements.

Body weights were available for 6 of the animals, including the largest and smallest, and these were used to address the question of how body size might influence the results for toe length. Average midstep strains for each of these individuals, trotting unshod on the treadmill, were regressed on their weights. This regression was compared with that of strain on toe length.

Results

Qualitative description of strains

The patterns: Several features of hoof strain records common to strides for one individual (Fig 3) and for strides from different individuals (Fig 4). The hoof wall was predominantly in compression during the stance phase (Figs 3 and 4) because ε2 was usually larger in absolute magnitude than ε1. In all 5 gauges there was a small oscillation in the strain record on impact, then a smooth rise as weight came to bear on the foot. At breakover, there was a large spike for the 3 gauges nearest the midline (Fig 3; * on dorsal gauge), as the hoof rolls over onto the toe. The lateral and medial gauges showed strain magnitudes varying between uniaxial loading (ε1 is approximately one third ε2) and torsion (ε1 is approximately equal to ε2). The dorsal gauge frequently showed biaxial loading (ε1 is close to zero or negative). Records for the medial45 and lateral45 gauges had characteristics intermediate between those of abaxial and axial gauges.

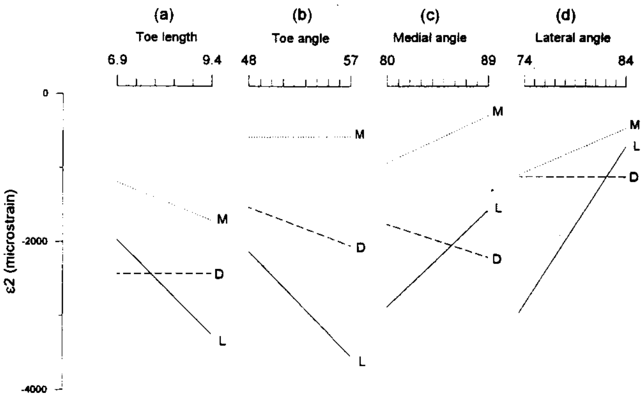

Fig 10: The predicted effect of (a) toe length, (b) toe angle, (c) medial angle, and (d) lateral angle on principal strain ε2. The slope of each line shows the predicted change in strain with change in the X variable. The X axes show the range of length (cm) or angle (degrees) measured for each variable. The negative values of ε2 indicate compressive strain (C). Only predictions for the medial, dorsal and lateral gauges are shown for clarity; results for the other 2 gauges always fell within the extremes of slope shown here.

Strain orientations (θ) change on impact, are usually stable through most of the stride and may change rapidly again towards breakover, particularly for the 3 gauges nearest the midline (Fig 3). At midstep, predominant compressive strains are oriented and therefore they generally converge on the coronary band at the midline (Fig 5).

The variation: Strain magnitudes at each gauge may vary markedly among strides whereas their orientations are considerably less variable (Fig 3). Among individuals (Fig 4), strain magnitudes are widely variable at each site, and variability in orientation increases. The relative proportions of ε1 and ε2 at each site, which indicate loading combinations, are reasonably consistent among strides but show more individual variation.

Shoeing may have observable effects on the midstep strain pattern (Fig 5); for this individual strain magnitudes at the 5 sites are more even when shod than when unshod. But such differences are not as clear in all individuals. In turns, the wall on the inside of the turn is consistently loaded more highly than the outside wall on which strain is reduced (Fig 5). Strains are usually higher at a trot than at a walk.

Results of statistical tests for the locomotory variables

Shoeing: Magnitudes of the predominant compressive strain ε2 (Fig 6a, below the axis) were not altered by shoeing to any statistical significance (ns), except at the lateral gauge. Even at this gauge the change was less than 10% of the mean ε2 unshod. Midstep strain ε1 (Fig 6a, above the axis) was significantly different (*) for 3 gauges, but the direction of change was not consistent. The orientation of strain (Fig 6a, lower graph) changed significantly with shoeing, by between 15° and 24°; strain directions moved closer to that of the tubules.

The coefficients of variation (c.v.) for ε2 and for the angle of orientation were lower when shod for all but one gauge in each case (Fig 6b).

Shoeing condition interacted significantly (P<0.005) with substrate/direction for ε2 and the angle, but not in all cases for ε1. When shod and unshod data for ε2 or the angle were presorted by substrate/direction, a few significant differences were seen, but there was no apparent pattern to their occurrence among gauges and directions.

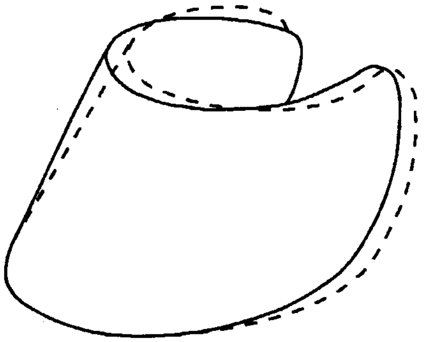

Fig 11: Stylised representation of the hoof wall to show the 2 main components of deformation on loading: caudal rotation of the toe, and flaring of the heels and quarters. The unloaded hoof is solid, the loaded hoof is dashed.

Gait: The magnitude of compressive strain ε2 increased significantly (P<0.005) from a walk to a trot for all gauges (Fig 7: *). The magnitude of the change varied from 10 to 30%, being largest laterally and smallest at the toe. The change in ε1 was only significant for the 2 abaxial gauges. Strain orientation did not change significantly except for a small but significant change at the medial45 gauge. Gait interacted with substrate and direction (details under those headings).

Substrate: The 3 gauges closest to the midline showed significant changes in all 3 strain values, ε1, ε2, and the angle (P<0.01), and ε2 for the medial gauge also changed significantly (Fig 8). The trend was from laterally dominated values of ε2 on the treadmill towards more evenly distributed magnitudes of ε2 for locomotion on ground.

Substrate interacts with shoeing and gait. When the treadmill vs. ground data were presorted by shoeing condition or by gait, a few tests that were significant for the unsorted data became nonsignificant for sorted subsets, and *vice versa.* The number of such reversals was too small to show much pattern but they seemed to occur mainly for the walk and when the animal was unshod.

Direction: The direction of travel made large and significant differences in the magnitudes of ε2 (P<0.01), but little change in strain orientation (Fig 9). In a right turn, the lateral side of the right foot was on the inside of the turn. In this case, ε2 was 40% higher laterally (Fig 9; black bar below the axis) than when moving straight (grey bar), but declined progressively towards the medial side of the foot where it was only 40% of the straight value. The reverse was true for a left turn (white bars): ε2 was higher medially and declined laterally. On the side away from the turn, the tensile values of ε1 may equal or exceed the compression of ε2.

The biaxial compression normally seen at the toe also affected the medial45 and lateral45 gauges when each was on the outside of the turn (ε1 was close to 0, or negative). When on the inside, these gauges were loaded in almost pure torsion (ε1 was approximately equal to ε2).

Direction interacted significantly with gait. Strain on the wall to the outside of a turn was higher for a walk than for a trot, contrary to the general increase in strain magnitudes at a trot. Direction also interacted with shoeing, showing a few, randomly distributed reversals, as for the interaction between substrate and shoeing.

Results of statistical tests for the hoof shape variables

Most of the gauge sites showed significant changes in strain with each of the 4 shape variables, but the correlations were all low. Values of r^2 ranged from 0.05–0.45 for ε2, being lower at the toe and higher at the quarters. For the strain angle, r^2 ranged from 0.05–0.17, with the lower values again occurring at the dorsal site.

Changes in shoeing condition, gait and direction all affected the relationships between strain and the 4 shape variables, but only change in direction was capable of completely masking the effects of shape.

Toe length: Toe length ranged 6.9–9.4 cm for the sample group, mean 8.30 cm. The regression showed that principal strain ε2 became more compressive (negative) with increasing toe length for all but the dorsal gauge during straight-line motion (Fig 10a). The rate of increasing compression was maximal for the lateral gauge, at 513 με (microstrain)/cm. This was equivalent to 20% of the mean ε2 for that gauge per centimetre.

A regression of the magnitudes of ε2 on toe length gave a predicted increase of approximately -2000 με in compression over the range 6.9–9.4. This is less than the predicted change in strain magnitude of -3200 με over the corresponding 182–525 kg range in bodyweight.

Toe angle: Toe, or hoof, angle varied 48–57° for the sample group, mean 51.8°. Principal strain ε2 became more compressive with increasing hoof angle for all but the medial gauge (Fig 10b). The highest rate of increase, 157 με/degree for the lateral gauge, corresponded to 6% of the mean ε2 for that gauge/degree.

Medial and lateral angles: For the sample group, medial angle varied 80–89° and lateral 72.5–84°. The 2 angles were correlated ($r^2 = 0.5351$). Principal strain ε2 became less compressive with an increase in either angle for all but the dorsal gauge (Figs 10c, d). The greatest rate of decreasing compression was for the lateral gauge with change in the lateral angle; the rate of 213 με/degree represented 11% of the mean ε2/degree.

Discussion

Strain patterns and hoof deformation

The results confirmed previous observations based on fewer animals and gauges (Thomason *et al.* 1992): strains on the dorsal two thirds of the hoof wall tend to converge towards the coronary band at the toe, with torsion at the quarters and biaxial compression dorsally (Fig 5). This is a pattern common to the front hooves of all horses studied so far and may be interpreted in terms of the known loads applied to the hoof and to the overall deformation of its wall.

The 2 main loads are the force transmitted from the third phalanx through the laminar junction, which has components of weightbearing and the torque from the deep digital flexor tendon (Coffman *et al.* 1970), and the ground reaction force, which is distributed around the margin of the wall and is oriented vertically at the midstep (Biewener *et al.* 1983). The deformation induced by these loads also has 2 main components (Fig 11): caudal rotation of the toe (Fischerleitner 1974) under the force transmitted from the third phalanx, and spreading of the heels (Colles 1989) which appears to be a consequence of the motion at the toe.

Under the load from the third phalanx, the wall at the toe is pulled caudally and ventrally, rotating about the contact zone with the ground, which contracts the coronary band and stretches the free distal border of the wall. It is this action which inclines all the strains towards the midline at the coronary band. The biaxially compressive strains at the toe result from vertical compression due to the animal's weight combined with horizontal compression as the wall at the toe becomes flatter (Fig 11; dashed outline).

A natural corollary of the motion at the toe is for the quarters to spread laterally. This movement can be demonstrated by cutting out a paper model of the shape shown in Figure 5, connecting the 'heels' with a length of tape to restore the 3-D shape, and pushing down on the wall at the 'toe' with the model on a flat surface. The 'toe' sinks, and the 'quarters' flare abaxially. Under this scenario, heel spreading results from the movement at the quarters, rather than *vice versa*. This suggestion is supported by the recent finding that pressure in the digital pad is reduced during weightbearing (Dyhre-Poulsen *et al.* 1994). The authors suggested that reduced pressure indicated increased hoof volume, which contradicts the older idea that pressure due to vertical movement of the frog was responsible for heel spreading.

The relative effects of the locomotory variables on strain variation

The observed patterns in hoof strain were modified but not overridden by the effect of any of the variables manipulated or measured here.

Direction: Change in direction has the greatest effect on strain patterns by shifting the load distribution preferentially to the quarter that is on the inside of the turn. Increases in the magnitude of ε2 of up to 40% are experienced on the inside quarter, with a concomitant reduction on the outside quarter. Interestingly, strain magnitudes are higher on the outside quarter at a walk than at a trot, indicating that the outside of the foot is unloaded more at the trot. This reversal of the general increase in strains from walk to trot may be responsible for the interaction between gait and direction.

Gait: The next most significant variable is gait. The increase in compressive strain from walk to trot is to be expected and is presumably also a function of increasing speed. Speed was not recorded, and fluctuations in it are probably responsible for some interindividual variation, as well as interstride variation in stance duration and strain magnitudes (Fig 3). But changes in gait and speed appear not to alter the fundamental deformation pattern of the hoof, as is shown by the minimal change in strain orientation.

Shoeing: Shoeing had little effect on the magnitudes of the larger principal strain ε2, which is unexpected and perhaps a little surprising. Strain orientations, however, do change significantly which indicates that shoeing does subtly modify the 3-D deformation of the hoof. The decrease in strain variation with shoeing indicates that the shoe tends to even out any irregularities of loading. The general interpretation of the changes is that the shoe does not impede the sinking at the toe under the pull from the third phalanx, but does impede motion at the quarters to a limited extent, and redistributes the forces transmitted between the ground and the hoof wall generally to reduce strain variation. These results appear to indicate that shoeing is not particularly detrimental to the mechanical function of the hoof, because shoes alter that function to such a small extent.

Substrate: Running on a treadmill, as expected, tended to distribute strain more evenly around the hoof, and also reduced interstride variation for each individual, without causing a substantial modification in the mechanical behaviour of the hoof. The fact that $\varepsilon 2$ was significantly different at 4 out of 5 gauge sites, and that stride kinematics were also altered (Barrey *et al.* 1993), introduces a note of caution against conducting locomotory studies entirely on a treadmill. While underlying mechanical characteristics are retained, locomotion is undeniably different on a treadmill than on open ground.

Interactions among variables: The interaction of gait and direction was largely on the outside wall of a turn, where strains are low, and has been discussed above. The interaction of shoeing with direction is difficult to assess because there is no clear pattern to the occurrence of reversals in significance when the data are sorted both on shoeing condition and direction. Certainly, no great change in mechanical behaviour was indicated by these few, randomly occurring reversals, which leads to the conclusion that the interaction of shoeing and direction is not of great functional importance.

The effects of the shape variables on strain variation

Deformation of the hoof wall during weightbearing was definitely dependent upon its shape, as would be expected, but the relationships are complex. Compressive strain increases with toe length and hoof angle, but is inversely proportional to the medial and lateral angles. All of these changes may be completely overridden if the animal turns to either side, but are influenced to a relatively minor extent by changes in gait or shoeing condition.

Several papers have presented the results of locomotory changes using wedges on the shoes to alter hoof balance (Balch *et al.* 1991b) which is a technique used in corrective shoeing (Turner 1986). The present work presents the effects of natural variation in strain magnitudes with hoof shape. It, therefore, addresses the normal variability of strains in healthy feet rather than that under experimental or pathological conditions. Some of the results are unexpected, particularly for toe angle, which underscores the importance of examining the range of mechanical function in 'normal' feet in addition to analysing the effect of common manipulations of foot shape and orientation.

The relationships between strain magnitude and the shape variables were all significant and explain up to 45% of the variation in strain magnitudes at the quarters.

Toe length: The largest proportional change in strains occurred with toe length, up to 20% of the mean strain/centimetre. This result is to be expected because longer toes increase the leverage of the ground reaction force about the laminar junction and coffin joint. But all of the predicted change in strain with toe length can be accounted for by the predicted change with bodyweight. The importance of the result is that it provides the first demonstration, to my knowledge, of an intuitively obvious situation: hoof strain is greater in larger horses. Given the predeliction of some of the larger breeds of horses to mechanical problems in the hoof wall, an obvious sequel to this work is a study of hoof strains in breeds of extreme size.

Toe angle: The increase in strain at most sites with toe angle - up to 6%/degree - is perhaps unexpected. It says that more upright hooves experience more strain, whereas we might expect higher strain on inclined hooves because the third phalanx is suspended more directly under the wall at the toe. In a more inclined hoof, the downward force from the third phalanx has a greater turning moment on the wall than if the wall is closer to upright. The expected result was in fact obtained by Thompson *et al.* (1993) in *in vitro* tests: strain magnitudes increased on the quarters with hoof angle, but declined at the dorsal site. Thompson and colleagues altered hoof angle with wedges over a range of 55–78°, compared with 48–58° in this study. In the present case, the regressions showed strain magnitudes increasing at all sites but the medial gauge (Fig 10b), with a gradient such that the change was greatest laterally and least medially. The most plausible explanation of the disparity between the 2 studies is simply in the differences between the *in vivo* and *in vitro* tests: artificially altering hoof angle may have produced different results from natural variation in hoof angle among several individuals.

Medial and lateral angles: All of the hooves studied were asymmetrical; they were more upright medially by between 1° and 7°. Such asymmetry is to be expected (Hood *et al.* 1992), as is the relationship between the 2 angles. Increase in either angle (which is much the same as increase in both angles together in this case) decreased the magnitude of strain in the hoof wall at all but the dorsal gauge. That the dorsal gauge behaves differently may be interpreted in terms of its biaxial loading.

The general decrease in strain may lead to the interpretation that higher medial and lateral angles are better, but this is equivocal. Deformation of the hoof wall is subject to conflicting requirements. On the one hand it should be sufficient for the hoof to provide a cushion against the impact and loads it experiences, both for its own internal tissues and for the tissues more proximal in the digit. On the other hand, it should not deform to such an extent that its material fails, either in a single event or as a result of fatigue by repetition. Higher angles at the quarters may reduce strain in most of the hoof wall but, because this indicates the hoof is stiffer as a structure, it may also reduce the cushioning ability of the hoof. Further work is necessary to define optimal medial and lateral angles using strain gauges and accelerometers in combination on hooves of different angles.

Implications of the shape results for hoof growth: Hoof horn cannot have a direct feedback mechanism, as exists in bone, because it is dead material. Any such mechanism must act on the germinative zones at the coronary band and along the secondary laminae. Because hoof shape does alter strains in the hoof wall, regardless of the effect of other variables, strains on the germinative layers are different in hooves of different shape. As with the 'Wolff's Law' mechanism in bone, the integration of sensory input with the response of the growing tissue must be complex. The mechanism has to integrate changes in strain over time. It has to integrate the conflicting effects of the shape variables examined here, some of which increase strains, some of which decrease them. It also has to integrate the effects of all the other variables which affect hoof strain. The present results give a tantalising indication of how such a system might work, but do not provide a quantitative answer. It remains for future work to relate directly strain levels at the coronary band with rates of growth of the hoof wall, or strain levels across the laminar junction with apposition rates of keratin that increase the thickness of the wall (Budras *et al.* 1989). Such experiments are necessary to quantify the nature of the mechanism whereby hoof growth responds to hoof loading.

Future directions

The importance of these results is that they represent the first attempt to quantify the variation in hoof strain, and to identify some of the causal factors of that variation. While the results support considerable advances in both areas, they leave many questions unanswered which may be profitably approached by future research. For example, this work does not fully determine the maximum possible range of variation in hoof strain and deformation because only 2 slow gaits were tested. In addition, only a few of the possible influencing variables are considered. In fact, the number of variables affecting the mechanical performance of the whole hoof is one of the major impediments to understanding its normal mechanical behaviour. Age, breed, gender, size, dynamic conformation of the limb, molecular and microscopic composition of the horn, and relative humidity of the horn are all variables that may be important in addition to the ones considered here. The effects of these presumed variables also need exploring. Until we have a detailed knowledge of the normal range of hoof loading and deformation, and of how each of these variables affects the range, we will not have a complete understanding of the normal function of a healthy hoof.

Conclusions

The basic response of the hoof to load - caudal rotation at the toe, with flaring of the quarters and heels - was consistent under all conditions studied here. It was modified, but not substantially transformed, by each variable studied. Turning elicited the greatest redistribution of strain magnitudes, increasing strains on the inside quarter and decreasing them on the outside quarter of the turn. Increase in speed with gait increased strain magnitudes, as predicted. Shoeing had little significant effect at the gauge sites (half way up the hoof wall), acting more to reduce strain variation than to modify strain magnitudes. Shoeing appeared not to affect deleteriously hoof function. Treadmill and over-ground locomotion have the same basic hoof function, but showed significant differences in compressive strain magnitude. Locomotory mechanics should not be studied entirely on a treadmill.

Variation in strain magnitudes correlated with individual variation in hoof shape, emphasising that changing hoof balance changes hoof function. In particular, the reduction in strain magnitudes with increasing medial and lateral angle is important, because of the implied increase in hoof structural stiffness. But the present results do not permit specific conclusions on functionally desirable hoof shapes, and primarily emphasise the need for further definitive research on the causal relationship between hoof shape and its mechanical function.

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Manufacturers' addresses

[1]3M Animal Care Products, St. Paul, Minnesota, USA.
[2]Keithley Metrabyte Corp., Taunton, Massachusetts, USA.
[3]Dage-MTI Inc., Michigan City, Indiana, USA.
[4]Imaging Technology Inc., Woburn Massachusetts, USA.
[5]BioScan, Inc., Edmonds, Washington, USA.
[6]SAS Institute Inc., Cary, North Carolina, USA.

References

Balch, O., White, K. and Butler, D. (1991a) Factors involved in the balancing of equine hooves. *J. Am. vet. med. Ass.* **198**, 1980-1989.

Balch, O., Ratzlaff, M.H., Hyde, M.L. and White, K.L. (1991b) Locomotor effects of hoof angle and mediolateral balance of horses exercising on a high-speed treadmill: preliminary results. *Proc. Am. Ass. equine Practnrs.* **37**, 687-705.

Barrey, E., Galloux, P., Valette, J.P., Auvinette, B. and Wolter, R. (1993) Stride characteristics of overground versus treadmill locomotion in the saddle horse. *Acta anat.* **146**, 90-94.

Beer, F.P. and Johnston, E.R., Jr. (1981) *Mechanics of Materials.* McGraw-Hill, New York.

Biewener, A.A., Thomason, J.J., Goodship, A. and Lanyon, L.E. (1983) Bone stress in the horse forelimb during locomotion at different gaits: a comparison of two experimental methods. *J. Biomech.* **16**, 565-576.

Budras, K.-D., Hullinger, R.L. and Sack, W.O. (1989) Light and electron microscopy of keratinization in the laminar epidermis of the equine hoof with reference to laminitis. *Am. J. vet. Res.* **50**, 1150-1160.

Coffman, J.R., Johnson, J.H, Finocchio, E.J. and Guffy, M.M. (1970) Biomechanics of pedal rotation in equine laminitis. *J. Am. vet. med. Ass.* **156**, 219-221.

Colles, G.M. (1989) A technique for assessing hoof function in the horse. *Equine. vet. J.* **21**, 17-22.

Dally, J.W. and Riley, W.F. (1965) *Experimental Stress Analysis.* McGraw-Hill, New York.

DiCaprio, R.A. and Thomason, J.J. (1989) An inexpensive strain gauge amplifier and signal conditioner for biological applications. *J. Biomech.* **22**, 167-169.

Dyhre-Poulsen, P., Smedegaard, H.H., Roed, J. and Korsgaard, E. (1994) Equine hoof function investigated by pressure transducers inside the hoof and accelerometers mounted on the first phalanx. *Equine. vet. J.* **26**, 362-366.

Fischerleitner, F. (1974) *Röntgenographische Untersuchungen über den Einfluss der Lageveranderungen des Huf-Strahl und Kronbeines auf die mechanik der Hornkapsel des Pferdes im Belastungsgerat.* Inaugural dissertation, Vienna.

Hood, D.M., Herndon, K., Wilkerson, K., Tatum, M.A. and Hogan, H.A. (1992) Conformational symmetry of the equine digit. In: *Proceedings of Association of Equine sports Medicine.* pp 65-67.

Knesevik, P.F. (1962) Klinik des trachtenzwanghufes und Grundlagen der Ungulographie mit Dehnungsnesstreifen beim Pferde. *Wien Tierartzl. Monatschr.* **49**, 777-824, 869-904, 944-959.

Moyer, W. and Anderson, J. (1975) Lameness caused by improper shoeing. *J. Am. vet. med. Ass.* **166**, 47-53..

Preuschoft, H. (1989) The external forces and internal stresses in the feet of dressage and jumping horses. *Zeit. Saugertier.* **54**, 172-190.

Thomason, J.J., Biewener, A.A. and Bertram, J.E.A. (1992) Surface strain on the equine hoof wall in vivo: implications for the material design and functional morphology of the wall. *J. exp. Biol.* **166**, 145-168.

Thompson, K.N., Cheung, T.K. and Silverman, M. (1993) The effect of toe angle on tendon, ligament and hoof wall strains in vitro. *J. equine vet. Sci.* **13**, 651-654.

Turner, T.A. (1986) Shoeing principles for the management of navicular disease in horses. *J. Am. vet. med. Ass.* **189**, 298-301.