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THE MODULUS OF ELASTICITY OF EQUINE HOOF WALL: IMPLICATIONS FOR THE MECHANICAL FUNCTION OF THE HOOF

J. E. DOUGLAS[1], C. MITTAL[2], J. J. THOMASON[1] AND J. C. JOFRIET[2]

[1]*Equine Research Centre and Department of Biomedical Sciences, University of Guelph, Guelph, Ontario, Canada N1G 2W1* and [2]*School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1*

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Summary

During normal weight-bearing and locomotion, the equine hoof wall deforms in a consistent pattern: the proximal dorsal wall rotates caudo-ventrally about the distal dorsal border and there is latero-medial flaring posteriorly. The aim of this study is to examine whether there are regional differences in the modulus of elasticity of hoof wall material and whether such differences correlate with the pattern of deformation which occurs *in vivo*.

The modulus of elasticity of equine hoof wall was determined in tension and compression for samples from six forefeet. Samples were tested at the mid-point of the inner and outer halves of the wall thickness at two positions along the proximo-distal axis of the dorsal wall, and from the mid-point of its thickness at the lateral and medial quarters. Test samples were oriented both parallel and perpendicular to the tubules that characterise the microstructure of the wall. The colour of each sample was noted, and the moisture content measured.

The range in the mean modulus of elasticity for all samples and tests was 460–1049 MPa, the dorsal outer wall having the highest values, the dorsal inner wall the lowest, and the quarters having intermediate values. The mean value obtained for the quarters was similar to the average of the values for the dorsal inner and outer walls. At all sites, the modulus of elasticity was marginally higher in compression than in tension, possibly owing to microstructural defects. The difference in stiffness between the outer wall and the inner wall was inversely related to moisture content.

The difference in stiffness between the dorsal outer and inner walls demonstrates that the equine hoof wall has a comparatively rigid external capsule with a lining of lower stiffness. This arrangement presumably provides some stress protection to the internally adjacent living tissues. The similarity in stiffness between the samples from the quarters and the mean of the two dorsal wall sites suggests that the wall at the quarters has a similar change in stiffness across its thickness as the dorsal wall. However, the reduced thickness of the wall at the quarters compared with the dorsal wall means that, functionally, the quarters are more flexible than the dorsal wall. This will facilitate the flaring of the lateral and medial walls which occurs during weight-bearing. Anisotropy was evident only in tensile tests of the dorsal wall samples. Contrary to popular assertions that white hooves are mechanically inferior, horn pigmentation had no detectable effect on stiffness.

Key words: equine hoof horn, modulus of elasticity, hoof function, horse.

Introduction

Interposed as it is between the ground and the skeleton, the equine hoof acts to modulate irregularities in externally applied loads. It attenuates the impact of its own contact with the ground (Dyhre-Poulson *et al.* 1994) and deforms differentially under the transfer of weight-bearing and locomotive forces between the ground and the third phalanx.

During the stance phase of locomotion, the dorsal wall of the equine hoof flattens (Fig. 1) as the proximal dorsal wall rotates caudoventrally about the distal border (Lungwitz, 1891; Thomason *et al.* 1992). This posterior movement of the dorsal wall is accompanied by abaxial movement of the quarters and heels (Lungwitz, 1891; Colles, 1989; Thomason *et al.* 1992). The influence of local differences in hoof wall stiffness on this pattern of deformation is the focus of this study. Specifically, we have measured the modulus of elasticity of hoof wall under physiologically relevant conditions. This work is more comprehensive than previous reports (Landeau *et al.* 1983; Leach and Zoerb, 1983; Bertram and Gosline, 1986, 1987) in that it describes hoof wall stiffness in both tension and compression from a number of sites which vary proximo-distally and circumferentially around the wall, mechanical anisotropy is investigated, and all experiments were carried out under physiological conditions of strain magnitude and moisture content.

Materials and methods

Source of material and preparation of test samples

The forefeet (four left, two right) used in this study were obtained from six different horses (*Equus caballus*) which ranged in age from 1 to 15 years, were of mixed breed and gender, and which were destroyed for reasons other than musculoskeletal disease. No ponies were used. All feet were obtained within 24 h of death and were stored in humidified moisture-proof containers at 4 °C until test samples were prepared and tested. Four feet were black, one was white and one was striped.

Twelve test samples were sawn from each hoof (Fig. 2). ‘Dorsal proximal’ samples were centred on the division between the proximal and middle thirds of the wall, and ‘dorsal distal’ samples were centred on the division between the middle and distal thirds. Two rectangular samples were sawn from the full thickness of the wall at each level (dorsal proximal and dorsal distal), the long axis of one oriented parallel to the tubules (‘proximo-distal’ samples) and of the other perpendicular to the tubules (‘medio-lateral’ samples). Each full-thickness sample was then split in half parallel to the outer wall, yielding outer and inner wall samples.

In addition to the dorsal wall samples, two samples were prepared from each of the medial and lateral quarters. From each quarter, one sample was cut with its long axis parallel to the tubules, the other with its long axis perpendicular to the tubules. In all cases the ‘proximo-distal’ sample was taken from a more proximal and palmar site on the quarter of the foot than was the ‘medio-lateral’ sample (Fig. 2). These samples encompassed the full thickness of the wall and were not divided into inner and outer samples (the wall at the quarters is approximately half as thick as the dorsal wall). The nominal size of each sample was 30 mm long and 5 mm square in cross section. Before testing, the exact dimensions were measured with Vernier calipers and the samples were weighed (Mettler AJ 100: Mettler Instrument Corp., Hightstown, New Jersey, USA). After the test, each sample was dried to constant mass at 103.5 °C and its initial moisture content was calculated as a percentage of its original mass.

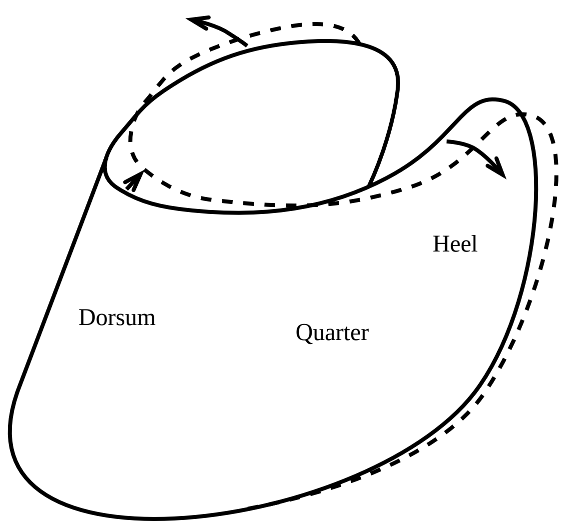

Fig. 1. Diagrammatic representation of the dorso-lateral view of an equine hoof. The solid line represents the shape of the unloaded hoof and the dashed line shows the change in shape which occurs during weight-bearing. The dorsal wall flattens and moves palmarly, particularly proximally, accompanied by abaxial movement of the quarters and heels.

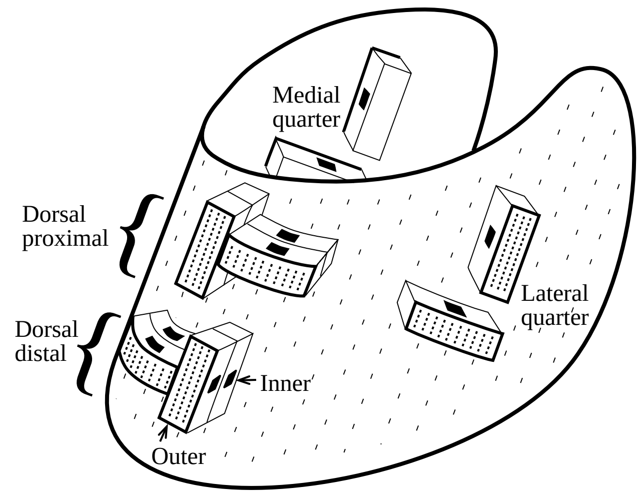

Fig. 2. Hoof wall sampling sites. The dashed lines represent the orientation of hoof wall tubules. Samples were prepared from the full thickness of the wall at the medial and lateral quarters, one sample having its long axis parallel to the tubules and one perpendicular at each site. Similar samples were prepared from the proximal and distal dorsal wall, the thickness of the dorsal wall allowing division into inner and outer wall samples at this site. The black rectangles represent strain gauge attachment sites.

Tensile and compressive testing

All samples were tested longitudinally in a materials testing machine (Instron 4204: Instron Canada Ltd, Burlington, Ontario, Canada) at a crosshead speed of 5 mm min^{-1}, which was calculated to give an approximate strain rate of $0.005\times10^{6}\,\mu\varepsilon\,s^{-1}$ ($0.005\,\varepsilon\,s^{-1}$). The strain rate obtained experimentally, however, was approximately $0.001\times10^{6}\,\mu\varepsilon\,s^{-1}$. The discrepancy between the intended and actual strain rates was due to slippage of the sample within the crosshead jaws. The inter-grip distance was maintained at approximately 16 mm.

The force applied to the sample was recorded from the materials testing machine and was subsequently converted to stress using the cross-sectional area of the sample. Strain was recorded from two single-foil strain gauges (N11-FA-2-120-11: Showa Measuring Instruments Co., Ltd, Tokyo, Japan) attached to the faces of the sample cut radially through the wall (Fig. 2). This method of strain measurement was chosen because preliminary tests indicated that the samples tended to slip in the loading clamps, making crosshead displacement an unacceptable method of strain measurement. Two gauges were placed symmetrically on the length and width of each inner–outer (radial) face of the sample, with their long axes aligned as closely as possible with that of the sample (Fig. 2). The symmetrical placement eliminated bending effects about the axis connecting the two gauges. The gauges were placed over the neutral axis of any bending which occurred in the inner–outer plane of the sample.

The attachment sites were trimmed flat with a razor blade and cleaned with 70 % ethanol before attachment of the gauges with cyanoacrylate adhesive (The Borden Co. Ltd, Willowdale, Ontario, Canada). Gauge excitation and signal conditioning were provided by amplifiers (DiCaprio and Thomason, 1989) whose output was sampled simultaneously with the force record into a personal computer at 10 Hz.

The testing protocol was consistent: each sample was subjected to approximately 5000 $\mu\varepsilon$ in compression and then to approximately 10 000 $\mu\varepsilon$ in tension. These magnitudes of strain approximate the usual peak operating strains *in vivo* (Thomason *et al.* 1992) and are below the yield strain of the material (Leach and Zoerb, 1983; Bertram and Gosline, 1986, 1987).

Calculation of modulus of elasticity and statistical analyses

Data were manipulated using the software packages Excel (v. 4.0: Microsoft Corporation, Redmond, Washington, USA) and Statview (v. 4.01: Abacus Concepts Inc., Berkeley, California, USA) and the statistical analysis was performed using Data Desk (v. 4.2: Data Description Inc., Ithaca, New York, USA). The modulus of elasticity was calculated separately in compression and tension for each sample by fitting linear regression lines to the stress/strain curves. The mean output of the two strain gauges was used in the calculation in order to compensate for any bending of the sample which occurred during testing.

The strain rate obtained during each test was determined. Differences in strain rate were investigated between the two directions of loading (paired *t*-test) and between the two sample orientations (unpaired *t*-test).

After checking for normality of the data using normal probability plots, the following statistical tests were carried out. A paired *t*-test was used to determine the degree of similarity between the compressive (E_C) and tensile (E_T) moduli of elasticity of the material. The nature of the relationship between compression and tension was then investigated further using Pearson's product-moment correlation and linear regression. All further tests were carried out on the compressive and tensile data separately.

The modulus values from the dorsum of the hoof only were examined by analysis of variance (ANOVA) with the following factors included in the model: individual horse; colour of horn; direction of stress in relation to the orientation of the tubules; proximal wall *versus* distal wall; and inner wall *versus* outer wall. Differences in moisture content between the inner and outer dorsal wall samples were also examined using ANOVA.

ANOVA was used to investigate any difference between the stiffness of samples taken from the medial and lateral quarters. The moduli of the dorsal outer wall samples were then compared with those of the samples taken from both quarters combined (ANOVA). Horn colour and direction of stress application with respect to the tubular axis were included as factors in this analysis. Using Pearson's product-moment correlation, the relationship between modulus and moisture content was determined. The dorsal inner wall samples were investigated separately from the remainder of the samples in this analysis. In all cases where ANOVA showed a significant main effect, Scheffé's method was used as a *post-hoc* test.

Results

Mean values for the width and height of the test samples were 5.1±1.7 and 5.9±2.1 mm respectively. Mean sample length was 30.1±4.9 mm (mean ± S.D., N=72). A representative data set is shown in Fig. 3. Results are summarised in Fig. 4 and Table 1 and are quoted as the mean ± one standard deviation unless otherwise stated.

Both the compressive and tensile data satisfied criteria for normality. The modulus in compression was significantly higher than that in tension ($P\leqslant 0.0001$), with a strong linear correlation (r=0.970; 95 % confidence interval 0.951–0.981) and a linear relationship of the form $E_C=1.02E_T+27.6$, where E_C and E_T are measured in MPa.

Analysis of all the samples as a group, and of the dorsal wall samples only, revealed no difference in strain rate between the 'proximo-distal' samples and the 'medio-lateral' samples. The strain rate in compression (1060±750 $\mu\varepsilon\,s^{-1}$) was significantly higher than that in tension (640±300 $\mu\varepsilon\,s^{-1}$) owing to different amounts of slip in these two modes of loading.

Analysis of the samples taken from the dorsal wall showed no effect of individual horse, colour of horn or proximo-distal site of sampling on either compressive or tensile stiffness. The

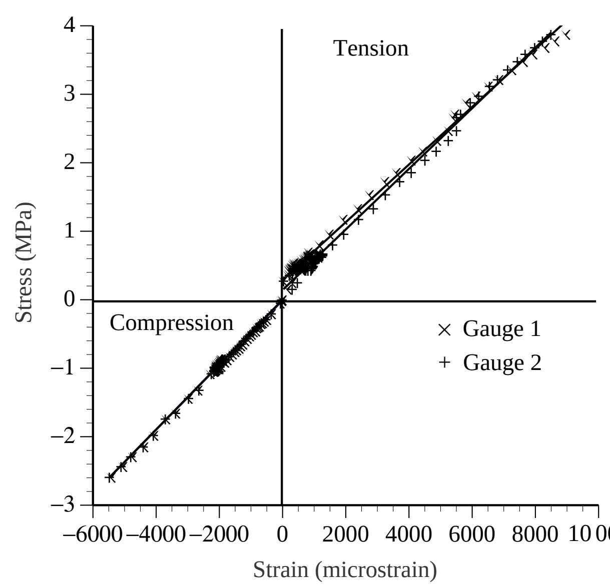

Fig. 3. Representative stress/strain curves for a sample of hoof wall from the medial quarter. The outputs of both strain gauges are shown, with lines of least-squares linear regression.

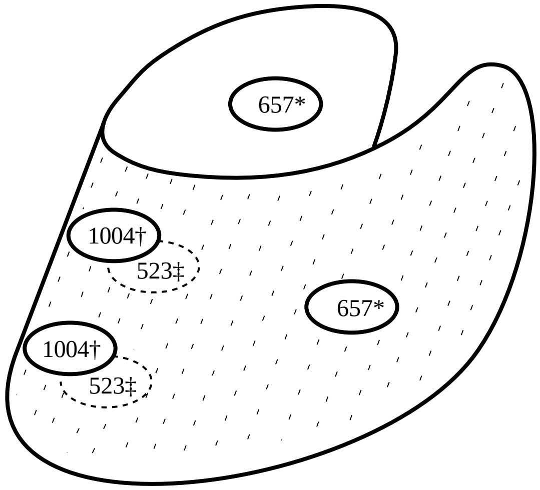

Fig. 4. Summary of the results obtained in compression. All values are means and are measured in MPa. *Medial and lateral quarters. †Dorsal outer wall. ‡Dorsal inner wall.

mean modulus of elasticity of the dorsal outer wall samples was 1004±198 MPa in compression and 955±199 MPa in tension. This was significantly ($P \leqslant 0.0001$) stiffer than the dorsal inner wall samples, which had moduli of 523±91 MPa (compression) and 502±98 MPa (tension). In tension only, dorsal outer wall samples stressed parallel to the orientation of the tubules were significantly stiffer (998±242 MPa) than those stressed perpendicular to them (912±143 MPa; P=0.041). The dorsal inner wall samples showed a similar but not significant trend, with mean tensile moduli of 544±54 MPa (parallel to the tubules) and 460±114 MPa (perpendicular).

The dorsal inner wall samples had a significantly higher moisture content than the dorsal outer wall samples ($P \leqslant 0.0001$), with average moisture levels of 35.5±2.5 % (inner wall) and 27.9±1.7 % (outer wall). Among the outer wall samples (dorsal outer and quarters only), there was evidence of an inverse linear relationship between modulus of elasticity and moisture content in both compression (correlation coefficient r=–0.771; 95 % confidence interval –0.868 to –0.618) and tension (r=–0.781; 95 % confidence interval –0.874 to –0.633). The equations describing the linear relationship between modulus of elasticity (MPa) and moisture content (x, %) are: $E_C=-69x+2930$ and $E_T=-68x+2840$. When the dorsal inner wall samples only were analysed, the relationship was not significant (compression: 95 % confidence interval –0.592 to 0.173, r=–0.248; tension: 95 % confidence interval –0.504 to 0.292, r=–0.127).

The samples from the medial and lateral quarters did not differ in their moduli of elasticity. The horn at these sites showed no evidence of mechanical anisotropy. The dorsal outer wall samples were significantly stiffer than the samples from the quarters ($P \leqslant 0.0001$) in both tension (dorsal outer wall, 955±199 MPa; quarters, 607±100 MPa) and compression (dorsal outer wall, 1004±198 MPa; quarters, 657±132 MPa). Horn colour did not affect stiffness in this analysis.

Discussion

Relationship between moduli in tension and compression

The equine hoof horn samples tested in this study were slightly stiffer in compression than in tension. This may be the result of the faster strain rate in the compression tests. If so, this would indicate that hoof horn is a viscoelastic material. Previous studies have given conflicting answers regarding the effect of strain rate on the properties of hoof horn. Landeau *et al.* (1983) tested samples at strain rates varying from 10 to 100 mm min^{-1} and reported no effect on compressive modulus. Butler and Hintz (1977), however, stated that strain rate did affect the yield point. From the current data, it is not possible to establish whether the difference in strain rate was indeed responsible for the difference in modulus of elasticity. Plots of modulus of elasticity against strain rate for both compression and tension data showed no evidence of a consistent relationship between the two parameters.

An alternative explanation for the difference is that hoof horn contains a number of structural flaws or microcracks. These would have little effect on its compressive stiffness, but would tend to gape and weaken the sample under tension. The existence of such defects has been reported in the hoof walls of horses with poor-quality horn, both at the weight-bearing surface (Kempson, 1987; Zenker *et al.* 1995) and more proximally in the wall (Zenker *et al.* 1995). Although it has

Table 1. *Moduli of elasticity (*E*) in tension and compression and of moisture content, of hoof wall separated by sampling site*

Sample site	N	E (tension) (MPa)	E (compression) (MPa)	Moisture content (%)
Dorsal outer wall (all)	22	955±199	1004±198	27.9±1.7
Dorsal outer wall (parallel*)	11	998±242	1049±231	
Dorsal outer wall (perpendicular*)	11	912±143	963±162	
Dorsal inner wall (all)	24	502±98	523±91	35.5±2.5
Dorsal inner wall (parallel*)	12	544±54	560±60	
Dorsal inner wall (perpendicular*)	12	460±114	487±103	
Medial and lateral quarters (all)	24	607±100	657±132	32.5±1.2

Values and means ± S.D.

*Denotes the relationship between the tubular axis and the direction of load application.

Table 2. *Comparison of current results with previous values obtained for the modulus of elasticity of equine hoof horn*

Modulus of elasticity: compression (MPa)	Modulus of elasticity: tension (MPa)	Materials and methods
310		Mixed sample position, horn fully hydrated[a]
308–500		Outer dorsal wall, normal moisture content
172–283		Inner dorsal wall, normal moisture content[b]
	410–485	Dorsal wall samples, horn fully hydrated[c]
	2630	Dorsal wall samples, samples equilibrated at 75% relative humidity (RH) pre-test[d]
1004	955	Outer dorsal wall, normal moisture content
523	502	Inner dorsal wall, normal moisture content
657	657	Quarters, normal moisture content[e]

All values are means. Where two values are given they represent different directions of testing.
[a]Landeau *et al*. (1983); [b]Leach and Zoerb (1983); [c]Bertram and Gosline (1986); [d]Bertram and Gosline (1987); [e]this paper.

been shown that the surface of the hoof wall is loaded predominantly in compression during the stance phase (Thomason *et al.* 1992; J. J. Thomason, in preparation), nothing is known about the strains experienced by the bulk of the stratum medium or by its inner face. Given the compression at the outer surface, the expansion of the heels (Lungwitz, 1891; Colles, 1989; Thomason *et al.* 1992) and the torsion experienced by the quarters (Thomason *et al.* 1992), it is likely that the inner parts of the wall are largely under tension. If small structural defects are present within the material, this may affect the mechanical performance of the wall *in vivo*.

Relationship between stiffness and moisture content

The moisture content of hoof horn has been shown to affect its mechanical properties (Butler and Hintz, 1977; Bertram and Gosline, 1987; Küng *et al.* 1993). It is therefore important that horn be tested at physiological moisture levels if the data are to be relevant to the *in vivo* situation. Leach (1980) measured the moisture contents of inner and outer dorsal wall samples and obtained values of 27.6 % and 20.0 % respectively. Butler and Hintz (1977) reported a value of 27.7 % for samples which were presumably a mixture of inner and outer wall. In the present study, the average moisture content of dorsal inner wall samples was 35.5±2.5 % and that of dorsal outer wall samples was 27.9±1.7 %. These are slightly higher than those obtained by Leach (1980) but are reasonably close to the *in vivo* situation.

The greater moisture content of inner wall samples when compared with outer wall samples and the inverse relationship between horn stiffness and moisture content parallel the findings of Leach (1980) and Leach and Zoerb (1983). Differences in moisture content are to be expected both in terms of the anatomical position and in terms of the mechanical function of the inner and outer parts of the wall. The inner wall is adjacent to fully hydrated soft tissues, whereas the outer wall is exposed to the atmosphere. A gradient of stiffness between the relatively rigid outer horn and the soft tissues of the dermis will help to reduce stress values at the interface between epidermis and dermis and will reduce the magnitude of the peak stress experienced by the soft tissues during locomotion.

The moisture content of the dorsal inner wall samples (35.5±2.5 %) is close to the level that Bertram and Gosline (1987) recorded for fully hydrated horn (40.2±2.7 %). These authors obtained a value of 410±32 MPa for the tensile modulus of this horn (Table 2), which is close to our value of 502±98 MPa. Bertram and Gosline (1987) also demonstrated that fully hydrated horn has a lower work of fracture (i.e. is more prone to crack propagation) than normally hydrated horn. This is consistent with the finding that microcracks are more common in the middle and inner zones of the stratum medium of the distal border than in the outer zone (Zenker *et al.* 1995).

Differences in moisture content may explain the greater stiffness of the dorsal outer wall samples (moisture content 27.9±1.7 %) than of the samples from the quarters (32.5±1.2 %). The hoof wall is thinner at the quarters than at the toe, and these samples therefore included horn from closer to the dermis than did the dorsal outer wall samples. This could explain simultaneously the lower stiffness and higher moisture content of the samples from the quarters. Both Leach (1980) and Bertram and Gosline (1987) artificially manipulated the moisture content of equine horn and found that stiffness was reduced at higher moisture levels. This supports a causative relationship between moisture content and stiffness, rather than one which is merely coincidental. The greater pliability of the horn at the quarters is consistent with the documented expansion of the caudal part of the foot during the stance phase of the stride.

Mechanical anisotropy

Samples were prepared with their long axes parallel and perpendicular to the orientation of the tubules to allow investigation of anisotropic behaviour. At the dorsal wall, the tubular and intertubular components of hoof wall material are close to orthogonal, allowing interpretation of anisotropy in terms of the tubular and intertubular axes of the material. At this site, evidence of anisotropic behaviour was found in tension only, the dorsal wall samples showing greater stiffness when loaded in tension parallel to the tubules than when loaded perpendicular to them. This is in contrast to the findings of Bertram and Gosline (1986). Analysis of their data shows that their dorsal wall samples were stiffer (by approximately 18 %) and stronger (by approximately 9 %) when loaded perpendicular to the orientation of the tubules. Leach (1980) obtained similar results in compression, reporting approximately 40 % greater stiffness and a higher yield point of dorsal outer wall samples when loaded perpendicular to the tubules than when loaded parallel to them. In the same study, no such anisotropic behaviour was found in dorsal inner wall samples. The result obtained in the present study for dorsal outer wall samples, although not highly significant (P=0.04), thus differs from previous findings.

At the quarters, the two components of the material are not orthogonal (Bertram and Gosline, 1986). At this site, a load applied perpendicular to the tubules is not necessarily parallel to the intertubular material. The results of testing the samples parallel and perpendicular to the orientation of the tubules at this site can therefore be interpreted only in terms of the tubular axis. No evidence of anisotropy was found along these axes.

Given the highly oriented microstructural architecture of hoof horn (Stump, 1967; Leach, 1980), anisotropic mechanical behaviour might be expected. In this study, however, anisotropy was evident in the dorsal wall samples when loaded in tension only. Functionally, horn must be able to cope with a multitude of stresses without undue risk of permanent deformation or failure. Extrapolation from *in vivo* strain records (Thomason *et al.* 1992; J. J. Thomason, in preparation) shows that the hoof wall is subjected to loads which change rapidly in both magnitude and direction, even when the animal is moving in a straight line at a constant speed on a level surface. Stress and strain patterns within the hooves of animals moving over rough terrain, although currently undocumented, must undoubtedly be even more variable. A high degree of mechanical anisotropy is therefore unlikely to be a functionally significant feature of hoof horn.

Comparison of proximal and distal dorsal wall horn

In this study, no difference was found between proximal and distal dorsal wall samples. This is in contrast to the findings of Landeau *et al.* (1983), who reported a higher compressive modulus in distal wall samples. This disparity may be because our ‘distal’ samples were not taken from the horn adjacent to the weight-bearing surface, but were centred around the junction of the middle and distal thirds of the foot.

Effect of horn pigmentation on stiffness

Of the six feet used in this study, four were black, one was white and one was striped. Investigation of the relationship between horn colour and stiffness was not a primary objective of this study but, given the controversy which surrounds this issue in the equine industry, sample colour was recorded. The colour of the horn was not shown to have a statistically significant effect on sample stiffness in either tension or compression in any of the analyses carried out. Other studies which have failed to document an effect of pigmentation on material properties include investigations of compressive stiffness and ultimate compressive strength (Landeau *et al.* 1983), ultimate tensile strength (Küng *et al.* 1993) and fracture toughness (Bertram and Gosline, 1986).

Comparison with previous reports

The values of E obtained in this study (Table 1) are slightly higher than those reported previously (Table 2) and this is probably due to various aspects of the experimental design. First, the moduli of elasticity reported in this paper were determined from strain within the physiological range. Measuring strain on the surface of the hoof wall, Thomason *et al.* (1992) reported a maximum peak principal strain of −4863 $\mu\varepsilon$ (−0.0049 ε) in cantering ponies. Similar maxima have been obtained from the hooves of trotting horses (J. J. Thomason, in preparation). Landeau *et al.* (1983) reported that the compressive modulus of equine hoof horn was smaller at higher strains. A comparison of their Fig. 1 and the data they reported shows an apparent yield point at approximately 50 000 $\mu\varepsilon$, with a modulus pre-yield of 240–480 MPa and post-yield of 34–76 MPa. The force/deformation curve shown by Leach and Zoerb (1983) is a different shape from that published by Landeau *et al.* (1983), but it appears from their Fig. 5 that the modulus of elasticity was measured at compressive strains greater than approximately 22 000 $\mu\varepsilon$. In preliminary tests for the present study, a force/deformation pattern similar to that of Landeau *et al.* (1983) was found, the stiffness of the samples starting to reduce at higher strains. Under normal circumstances, hoof wall material must be operating in its elastic range and the physiologically relevant modulus is thus that obtained in the linear stress–strain range. This means also that the moduli reported herein may only be used for stress analyses within that range.

Sample moisture content will affect the modulus of elasticity. Bertram and Gosline (1986) reported mean values of 410±32 and 485±35 MPa for the tensile modulus of fully hydrated dorsal wall horn. When testing similar samples equilibrated in an atmosphere at 75 % relative humidity, a value of 2630±362 MPa was obtained (Bertram and Gosline, 1987). These samples were subsequently shown to have a moisture content of 18.2 %. In the present study, dorsal outer wall samples had an average tensile modulus of 955±199 MPa and a moisture content of 27.9±1.7 %. The differences in the values obtained in these three studies may be due largely to differences in horn moisture content. Two previous studies of the compressive modulus of horn (Leach and Zoerb, 1983; Landeau *et al.* 1983) also reported lower values of E than were obtained in the present study. Using samples at a physiological moisture content and determining the modulus from relatively high strains (approximately 22 000–43 000 $\mu\varepsilon$), Leach and Zoerb (1983) obtained values of 350–500 MPa in dorsal outer wall samples. Testing in compression at lower and more physiological strains (20 000–30 000 $\mu\varepsilon$) but using fully hydrated samples from both the dorsum and the quarters, Landeau *et al.* (1983) obtained values of 240–480 MPa. In the present study, the dorsal outer wall samples had a mean compressive modulus of 1004±198 MPa. This may be explained by the use of a lower strain range than Leach and Zoerb (1983) and a lower moisture content than Landeau *et al.* (1983).

We assumed that the horn studied was mechanically 'normal'. Feet were chosen on the basis of a 'sound' macroscopic external appearance but no histological work was carried out. Statistically significant differences between individual feet were not detected, although it is possible that the variability inherent in the data could have masked a potential difference. Both Goodspeed *et al.* (1970) and Landeau *et al.* (1983) noted a large degree of variability in the values of E which they obtained. The sizes of the standard deviations shown in Table 1 demonstrate that we also experienced considerable variability in our results. Contributory factors are likely to include the difficulty of sample preparation and testing, variation in sample dimensions, bending of the samples during testing, and the variability that is inherent in all biological materials.

Implications for the deformation pattern in vivo

The sites of strain gauge placement in this study and the greater thickness of the equine hoof wall dorsally than at the quarters necessitate caution in the functional interpretation of these data. Owing to the previously documented difference in the modulus of elasticity of the inner and outer wall (Leach and Zoerb, 1983), the gauges were placed at the mid-point of the inner–outer dimension of each sample in order to measure an 'average' stiffness for each sample. The samples from the quarters spanned almost the entire thickness of the wall at this site, and the gauges were therefore situated approximately at the mid-point of the wall thickness. Gauges placed in the middle of the dorsal outer wall samples were therefore situated one-third of the way in from the outer margin of the wall, and those on the dorsal inner wall samples were situated two-thirds of the way in. In terms of absolute distance from the outer margin of the wall, the samples from the quarters are therefore comparable to those from the dorsal outer wall. In terms of relative distance across the thickness of the wall, however, the values from the quarters are comparable to the average of the values obtained for the dorsal outer and inner walls. These average values (728 MPa and 764 MPa in tension and compression respectively) are similar to the values obtained for the quarters (607 MPa in tension and 657 MPa in compression).

It is likely that the difference in the value of E between the dorsal inner and outer walls reflects the presence of a gradient of stiffness across the thickness of the wall. Although undocumented, a similar change in stiffness is almost certainly present at the quarters. Inspection of samples of wall from this region reinforces this concept. Given the apparent similarity in stiffness of the mid-point of the wall at the two sites tested, and the requirement of the subjacent dermo-epidermal junction for stress protection, the maximum and minimum values for E at these two sites are likely to be similar. The very different wall thicknesses, however, give greater functional stiffness to the dorsal wall than to the quarters, and it is primarily in its role as an organ, rather than a material, that our interest in the hoof wall lies.

The variation in the modulus of elasticity of equine hoof wall material both across its inner–outer dimension and, functionally, around the circumference of the wall is in accordance with the pattern of deformation which occurs *in vivo*. The wall is thicker dorsally than in other parts of the foot (Kainer, 1989) and this, combined with the relative stiffness of the dorsal outer wall, provides the rigidity required for weight-bearing and for suspension of the third phalanx from its inner face. The comparatively low stiffness of the dorsal inner wall samples provides stress protection for the adjacent soft tissues. Expansion of the posterior part of the foot is facilitated by the reduced thickness of the wall at the quarters.

During the stance phase of the stride *in vivo*, the magnitude of the surface strain at the dorsal wall is not substantially different from the surface strain at the quarters (Thomason *et al.* 1992; J. J. Thomason, in preparation). Given the greater functional stiffness of the wall at this site, this implies that the loading on the dorsal wall is greater than at the quarters. Such conclusions must be drawn with caution, however, because the biaxial compression which occurs dorsally (Thomason *et al.* 1992; J. J. Thomason, in preparation) complicates interpretation of the *in vivo* data.

This evidence of a relationship between material stiffness, wall thickness and hoof wall deformation pattern builds upon previous studies elucidating the relationship between hoof capsule adaptation and function. From *in vivo* strain work, Thomason *et al.* (1992) concluded that hoof wall acts as a multidirectional composite material, the mixture of tubular and intertubular material enabling the wall to cope with complex and rapidly changing strain patterns. As demonstrated by the results of the present study and those of Bertram and Gosline (1987), hoof function is further facilitated by the natural regulation of horn moisture content and its relationship to horn stiffness. Finally, evidence of ways in which we may be able to influence function has come from recent work showing a relationship between hoof shape and the strain pattern experienced by its wall (J. J. Thomason, in preparation). Further investigation of these and other factors will allow us positively to influence the function and dysfunction of this important organ.

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