BRILL
WAGENINGEN
ACADEMIC

COMPARATIVE EXERCISE PHYSIOLOGY 19 (2023) 473–485

2022

RESEARCH ARTICLE

In vitro effect of horseshoe length on hoof wall deformation, expansion, and strain

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Received 1 December 2022 | Accepted 12 September 2023 | Published online 30 October 2023 | Published in print 20 December 2023

Abstract

Shoeing techniques have the potential to affect hoof growth, causing abnormal hoof conformations, which in turn put affected horses at risk for lameness and injury. Racehorses are often shod with shorter shoe branches which may predispose them to underrun heel hoof conformation. Horseshoe branch length was tested to determine the effect on hoof wall deformations, expansion, strain and fetlock extension during midstance limb loading. Our hypotheses were that shortening of the shoe branch length would increase fetlock extension, increase compressive strains at the heel, and change principal strain directions in a proximodorsal direction. Nine cadaveric forelimbs were loaded *in vitro* to simulate mid-stance from walk to canter loads. Analysis of variance was used to assess the effect of horseshoe (no shoe, short shoe, full shoe, and long shoe) on outcome variables. Hoof wall expansion and lateral hoof wall distortion did not differ among treatments. Principal compressive hoof wall strain magnitudes were greater than principal tensile strain magnitudes. As shoe length increased principal compressive strains decreased, except for the middle quarter location; shear strains increased for distal locations and decreased at the proximal heel location; and principal strain directions viewed on the lateral side of the right hoof rotated in a counterclockwise direction at middle and distal quarter locations. Results do not provide evidence that a shorter shoe increases fetlock extension. Additionally, as the shorter shoe had similar strain results to that of an unshod hoof, it is unclear if a shorter shoe could lead to the development of abnormal hoof conformations. Other factors that may play a role in changes of hoof conformation including surface type, amount of exercise and frequency of trimming as well as other planes within the xyz coordinate system for the fetlock and hoof should be investigated.

Keywords

equine – underrun heel – kinematics – strain – biomechanics

1 Introduction

Underrun heel-hoof conformation is associated with foot pain due to derangement of the normal hoof wall biomechanics, which causes lameness, therefore compromising performance (Mansmann *et al.*, 2010). The underrun heel-hoof conformation potentiates poor support for the heel bulbs, an alteration in the confor-

Published with license by Koninklijke Brill NV | DOI: 10.1163/17552559-20220071
 | ISSN: 1755-2540 (print) 1755-2559 (online)

mation of the horn tubules (more sloping), and an increased length of the hoof lever arm about the distal interphalangeal (coffin) joint (Eliashar, 2012). The longer lever arm associated with under-run heel-hoof conformation increases fetlock torque, promotes fetlock hyperextension, and is a known risk factor for catastrophic fetlock failures in TB racehorses (proximal sesamoid bone fracture, suspensory ligament rupture, severe lateral condylar fracture) (Anderson *et al.*, 2004; Balch *et al.*, 2001; Kane *et al.*, 1998).

Horseshoes are attached to horse's hooves for protection from excessive hoof wear, as a therapeutic mechanism to alter load distribution or to increase hoof-ground traction (Butler, 1995; Floyd and Mansmann, 2007). Horseshoes come in a variety of shapes, sizes, and material composition (Floyd and Mansmann, 2007). Several reports described the effects of shoe configuration on hoof mechanics. Measuring vertical pressure using foil sensors between the shoe and hoof in shoes with varying surface coverage (wide toe, open toe, egg bar, and heart bar shoes) demonstrated that more coverage at the heels with an open toe, egg bar or heart bar shoe resulted in a more even distribution of pressure around the hoof compared to a traditional shoe, as well as increasing the lever arm for the palmar aspect of the hoof. A wide-toe shoe increased stress on the hoof capsule with pressure peaks as the branches narrowed along the hoof wall toward the heels (Hüppler *et al.*, 2016). The effects of 4° heel shoe wedges on hoof wall strains showed that dorsopalmar compressive strain dominated in a flat hoof while the wedge shoe changed strains to dorsopalmar tension at the toe and medial quarter (Bellenzani *et al.*, 2007). Heel expansion with a glue-on shoe (aluminium shoe attached with methylmethacrylate/cyano-methylmethacrylate adhesive) had less heel expansion when compared to a nailed-on metal shoe (Yoshihara *et al.*, 2010). Additionally, heel expansion was shown to be greater with a split toe shoe compared to a conventional shoe, with the heel expansion more like that of a barefoot hoof (Brunsting *et al.*, 2019). While effects of shoe type and the use of pads on hoof mechanics have been studied, the effect of horseshoe length on hoof mechanics has not been investigated according to the authors' knowledge.

Horseshoe length refers to the toe-to-heel dorsopalmar length of the horseshoe relative to the corresponding length of the load bearing portion of the hoof wall. Horseshoe length can be altered through changing the length of the branches, the palmar/plantar ends of the shoe. Common horseshoeing practice is to extend the horseshoe branches to the level of the widest part of the frog along the weight bearing portion of the hoof wall (Floyd and Mansmann, 2007). Often in racehorses branch length is shortened to a position dorsal to the widest part of the frog (short shod) to reduce the risk of the shoes being pulled off during racing (Moyer, 1980). However, short-shoeing may lead to a change in dorsopalmar hoof balance with poor support for the heels, potentially leading to underrun heel-hoof conformation.

We sought to understand how changing the branch length of a horseshoe would affect hoof expansion, hoof distortion and hoof wall surface strain magnitude and directions during simulation of mid-stance limb loading. Our hypotheses were that shortening of the shoe branch length would increase fetlock extension, increase compressive strains at the heel, and change principal strain directions in a proximodorsal direction.

2 Materials and methods

Study design

The effects of application of a horseshoe and horseshoe branch length on hoof wall strains and deformations, hoof expansion, and fetlock extension were assessed during loading of cadaveric equine limbs in a mechanical testing system to simulate weight-bearing during the middle of stance up to a canter load. Indices of hoof wall motion were measured during loading when the hoof was unshod (NS, no shoe treatment) and shod with a shoe of three different branch lengths (short, full, long). The order of the three shoe length treatments was different among individual limbs so that variance associated with the effect of order of treatment (e.g. potential stress relaxation of the cadaveric limb during repeated testing) could be partitioned out from the variance associated with the effect of shoe length. Specifically, the three treatments of interest have six possible orderings that can be assigned to each horse. With six orderings and nine horses, a compromise was made of only considering three orderings out of the six, which results in three replicates for each order. The unshod condition was tested before and after the shoe length treatments as another method to assess any effect of repeated limb loading on study outcomes. An analysis of variance that accounted for repeated measures was used to determine differences in hoof wall mechanics during limb loading among shoe length treatments.

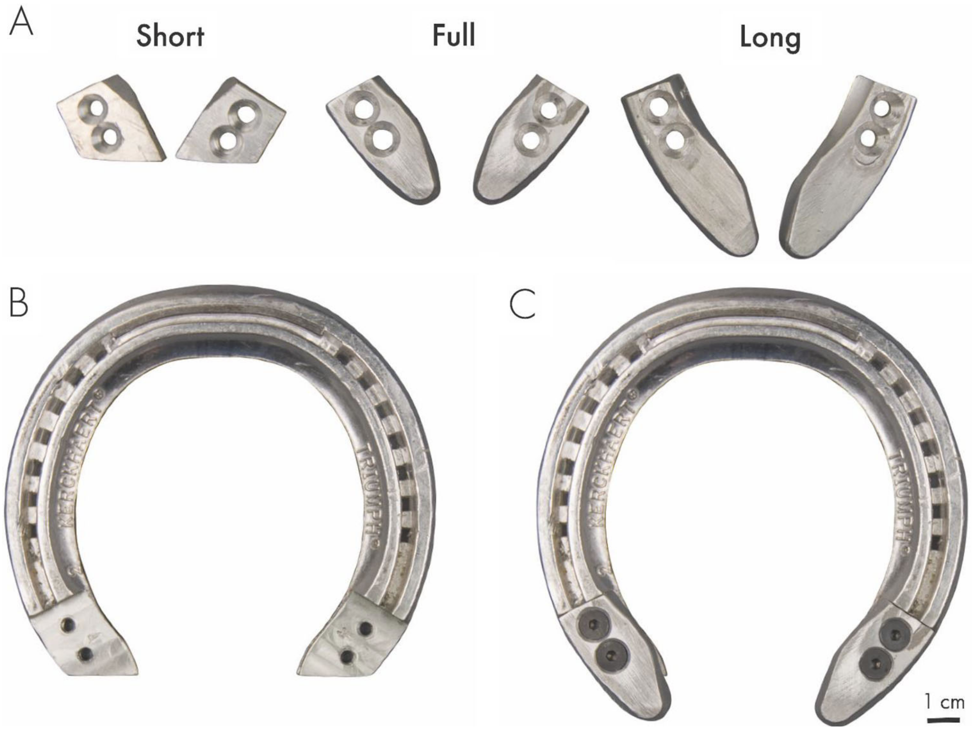

FIGURE 1 Figure 1. (A) Shoe branch lengths. (B) Modified shoe without the branch lengths attached showing predrilled holes to screw the branch lengths to. (C) Modified shoe with full pieces that have been screwed into place to show how the shoe was set up with the heel pieces attached.

Horseshoe lengths

A horseshoe was customised to incorporate the short, full, and long horseshoe lengths (Figure 1A-C). These lengths were defined as the palmar extent of the horseshoe branch aligned with:

- the widest part of the frog at the heels (Full);
- 9% shorter than full shoe length, dorsal to the widest part of the frog (Short);
- 9% longer than full shoe length, palmar to the widest part of the frog (Long).

The 9% difference was determined by measurements of 10 hooves from the forelimbs of 10 deceased racehorses that had been shod by racetrack farriers using the following formula:

$$\% \text{ difference} = (V1 - V2)/V1 \times 100$$

where V1 is the dorsopalmar length from the toe to a chord between the heels at the widest part of the frog, V2 is the dorsopalmar length from the toe to a chord between the palmar end of shoes. The percent difference (9%) was 10.6 ± 0.02 mm.

Limb specimens

Nine unilateral forelimbs from nine riding type horses (median age 16 years, range 6-25 years; 4 females, 4 geldings, 1 unknown; 3 Quarter Horse, 3 Thoroughbred, 1 Appaloosa, 1 Paint, 1 unknown) that were euthanised for reasons unrelated to lameness were removed by transection at the level of the middle of the radius to maintain the passive components of the fetlock stay apparatus. (Kingsbury *et al.*, 1978; Singer *et al.*, 2015) Criteria for limb selection included absence of evidence of orthopaedic disease in either front limb and absence of hoof capsule abnormalities. Limbs were wrapped in water-tight bags and stored frozen at −20 °C to maintain limb and hoof hydration until limbs were thawed to room temperature prior to instrumentation and testing.

Limb preparation

Hooves were trimmed and shoes were applied by a single Certified Journeyman farrier to ensure uniformity in hoof balance. To simulate the hoof's interaction with substrate, a silicone-based hoof packing material (Sil-Pak, Vettec Hoof Care, Pomona, CA, USA; Stiffness: 2e^6 N/m) was applied on the solar surface of the hoof to the level of the weight bearing surface of the hoof wall (NS condition) or shoe. Four nails secured the shoe to the hoof, 2 nails in the toe and 1 nail in each quarter through the manufacturer's (Aluminum Triumph, The Royal Kerckhaert Horseshoe Company, Rapenburg, the Netherlands) pre-drilled nail holes. To avoid disruption of the hoof wall instrumentation, nails were not clenched to allow for application and removal of the horseshoe after testing the initial NS condition and before the final NS condition after the horseshoe treatments had been completed.

Horseshoe design

Each limb was fitted with a full branch length shoe as defined above. A step was machine cut in the shoe to allow for the different length branches to be rigidly interlocked on the shoe with two screws placed through predrilled and tapped holes in the shoe. Different length branches were interchanged during testing while the shoe template remained affixed to the hoof (Figure 1A-C).

Limb instrumentation

The hoof was instrumented with strain gauges and kinematic markers. Local deformation was measured using rosette strain gauges (VPG, Malvern, PA, USA) rectangular, 45° three-element) attached at six locations: three proximal to distal locations on the quarter (widest part of the hoof) and heel (halfway between the quarter and palmar aspect of the heel) of the lateral hoof wall. Gauges were placed at approximately 25, 50 and 75% of the total distance from the hairline (coronet band) to the hoof solar margin. Proximal to distal locations were proximal heel (PH), middle heel (MH), distal heel (DH), proximal quarter (PQ), middle quarter (MQ) and distal quarter (DQ) (Figure 2A). The middle arm of the rosette gauges was oriented parallel to the longitudinal axis of the horn tubules (Figure 2A). The 90-270° axis of the gauge coordinate system was aligned with the tubules. Strain gauges were attached to a signal conditioning system (SCXI-1520, PCI-MIO-16E4 Labview 7.1, National Instruments Corporation, Austin, TX, USA).

Hoof wall deformation was measured with kinematic markers applied to the medial and lateral aspects of the hoof quarter and heel, placed at 33% and 66% of the distance from the coronet band to the hoof solar margin (Figure 2B). Kinematic markers were spherical balls (3/8' diameter polytetrafluoroethylene balls, McMaster-Carr, Atlanta, GA, USA) covered by silver reflective tape (Scotchlite 3M, St. Paul, MN, USA) attached to 4.8 mm diameter Steinmann pins. Pins were placed approximately 5 mm into the hoof wall avoiding damage to underlying soft tissue structures.

To measure fetlock extension, pins were inserted perpendicular to the long axis of the limb in a lateromedial direction in predrilled 4 mm diameter holes in the proximal and distal quarter of the length of the bone aspects of MC3 and P1 (Figure 2C). Dorso-palmar radiographs (Digital processor: Mark III, Sound-Eklin DR, Carlsbad, CA, USA, Generator: HF100/30+, MinXray, Inc., Northbrook, IL, USA) were taken (58 kVp, 10.2 mAs, 1 meter film-focal distance) of the instrumented limb to allow conversion of kinematic marker positions to MC3 and P1 reference frames to be used later for angle measurements within the Motus software (Motus 9.0, VICON, Centennial, CO, USA).

Mechanical testing

Mechanical loading was performed in a servohydraulic material testing system (Model 662.10A-08, MTS Systems Corporation, Eden Prairie, MN, USA, Model 809; MTS Systems Corp., Minneapolis, MN, USA) equipped with an axial-torsional load transducer (axial load range 220 kN, resolution 22 N, torsional range 2.5 kNm resolution 0.25 Nm) and software (Multipurpose Testware, TestStarII, MTS Systems Corporation). The proximal end of the radius was potted in an aluminium cylinder with polymethylmethacrylate (PMMA, Co Tray Plastics, GC America Inc, Alsip, IL, USA) and secured to the mechanical testing system. The foot was secured to the system actuator via a translation table on linear bearings to allow the hoof to translate dorsally during limb loading which maintained the radius and metacarpal bones parallel to the axis of loading. Initial positioning was standardised by obtaining a physiologic (mean 210°) palmar fetlock angle at a load of ~700 N. The limb was preconditioned by 200 sinusoidal cycles (700-1,800 N) at 0.25 Hz under axial displacement control with rotation displacement fixed. Subsequently, the limb was similarly loaded (700-6,700 N) for three sinusoidal cycles at 0.25 Hz (~3,350 N/s) to capture peak vertical forces for stance (1,800 N), walk (3,600 N), trot (4,600 N) (Kingsbury *et al.*, 1978) and canter (6,700 N) while axial load and displacement data were captured at 60 Hz. Strain data were collected at 20 Hz to allow for multiplexing of the 24 channels. Video images (Photron Fastcam PCI cameras and Fastcam Viewer Photron, San Diego, CA, USA) were acquired at 60 Hz from palmaromedial and palmarolateral positions (S-PRI, AOS Techologies, AG, Dättwil, Switzerland) to capture the positions of kinematic markers in a calibrated 3D field. One limb did not achieve 6,700 N during testing, so 6,200 N was selected as the maximum load for data analysis to compare data at loads that were achievable for all specimens.

Data reduction

Strain measurements from the rosette gauges were reduced to principal strain magnitudes and directions

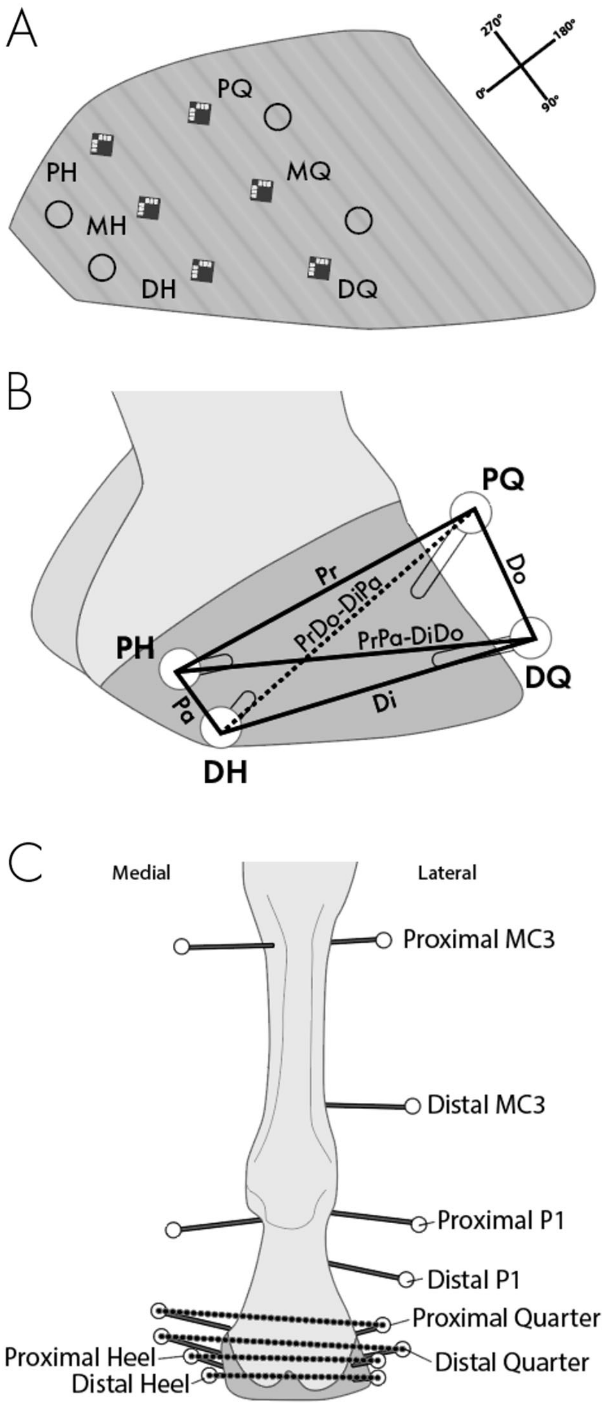

FIGURE 2 Schematic diagrams for video marker and strain gauge locations. (A) Strain gauge (gauge icon) and kinematic marker (open circles) locations on the lateral aspect of the right forelimb hoof. The coordinate system for strain directions is aligned relative to horn tubules. (B) Kinematic hoof markers were placed at 33 and 66% from the hairline to the solar surface of the hoof for both heel and quarter locations. Regional hoof deformation measurements used chords defined between kinematic hoof markers. (C) Palmar view of the limb in the mechanical testing system instrumented with kinematic bone and hoof markers used for measuring fetlock angle and proximal and distal quarter and heel expansions. PH, MH, and DH refer to proximal, middle, and distal heel locations, respectively. PQ, MQ, and DQ refer to proximal, middle, and distal quarter locations, respectively.

with a custom program in Matlab (R2010a, The Mathworks, Natick, MA, USA) based on equations by Schajer (1990). Orientation of the left limb principal strains were mirrored so that the direction of gauges relative to anatomy matched the right limbs.

Fetlock angle, hoof wall deformations and heel expansion were determined from the positions of kinematic markers using kinematic analysis software (Motus 9.0, VICON). Fetlock extension was measured as the palmar angle between MC3 and P1. Lateral wall deformations were determined for six chord lengths between kinematic markers on the lateral side of the hoof (Figure 2B). These chord distances are defined as: Proximal (Pr), Distal (Di), Dorsal (Do), Palmar (Pa), Proximodorsaldistopalmar (PrDo-DiPa) and Proximopalmardistodorsal (PrPa-DiDo). Quarter and heel expansions were calculated by the change in chord distances between medial and lateral markers for proximal and distal quarter and heel segments (Figure 2C).

All kinematic measurements were calculated as the difference from stance load (1,800 N) to 3,600 N, 4,600 N and 6,200 N loads for the respective variables. Load and kinematic data were down sampled to 20 Hz to match the strain data recording rate. To ensure that data at specific loads were compared, a forecast technique (MS Excel, Microsoft, Redmond, WA, USA) interpolated strain and kinematic data for the desired loads. Linear and angular resolutions of kinematic markers were 0.01 mm and 0.11°.

Statistical analysis

An analysis of variance (Proc Mixed, SAS Institute, Cary, NC, USA) that accounted for repeated measures was used to assess the effects of being barefoot (NS) and shod with shoes of different length (short, full, long) on hoof wall strains, deformations, heel expansion and fetlock angle using a commercial statistical program (SAS). Differences likely related to stress relaxation of tissues with repeated loading, were found for most outcome measurements between initial and final NS treatments, so linear adjustments (Excel) were made to normalise all data for the difference between initial and final no shoe values among the sequential order of treatments. Treatment, load, order, and the treatment × load interaction were treated as fixed effects. Horse was treated as a random effect. The treatment × load interaction was not statistically significant ($P > 0.7$) for any variable and therefore removed from the ANOVA model. To determine whether order of shoe treatments (Short, Full, Long) influenced the outcomes, ANOVA was performed on the data without NS treatment. If order was found significant, and the residuals were normally distributed (Shapiro-Wilks test), the model assumptions were assumed to be valid. If order was not found significant, the order effect was removed from the model and the initial NS treatment was added back in and the model re-run.

The residuals from the analysis of variance (ANOVA) were examined for normality using a Shapiro-Wilks test (Proc Univariate, SAS). The residuals were considered normally distributed if $W \geq 0.9$ and the residuals were aligned on the QQ plot. For variables that had ANOVA residuals that were not normally distributed, a box plot (Proc Boxplot, SAS) was used to determine outliers (observations that fell below Q1 – 1.5 IQR or above Q3 + 1.5 IQR). The ANOVA was performed after outlier removal and the residuals assessed for normality. For variables with non-normally distributed ANOVA residuals, the box cox procedure was used to determine a transformation appropriate for each variable (Proc Glmselect and Proc Transreg, SAS). For variables that had any negative values, a constant (equal to the absolute value of the smallest value plus the absolute value of the difference between the smallest and second smallest values) was added to all values for application of the box cox procedure. The transformed data were again run through the ANOVA model and the residuals were assessed for normality. For variables that were still non-normally distributed, the original data were ranked and ranked data were analysed using the analysis of variance. A P-value < 0.05 was considered statistically significant. Least squared means and standard error averaged over all loads for treatment and over all treatments for load are reported for transformed and non-transformed continuous variables.

3 Results

Hoof strains

Principal tensile strains for PH and MH segments decreased while MQ strains increased as loads increased. Principal compressive strains and shear strains increased for all gauges as load increased (Table 1).

Principal tensile strains showed no differences among treatments (Table 2, Figure 3A). Principal compressive strains were larger than principal tensile strains in magnitude. Principal compressive strains decreased from the unshod condition with the application of a long shoe, except in the MQ location. Shear strains had the largest increases with application of a shoe in the DQ

TABLE 1 Least squared means and standard error for principal tensile, compressive and shear strain magnitudes by load when averaged over all treatments[1,2]

Gauge	Load			*P*-value
	3,600 N	4,600 N	6,200 N	
Principal tensile strain (με)				
PH	88[a] ± 36	83[a] ± 36	52[b] ± 36	0.01
MH	128[a] ± 249	40[b] ± 249	−123[c] ± 249	<0.0001
DH	525[a] ± 134	550[a] ± 134	550[a] ± 134	0.77
PQ	179[a] ± 80	200[a,b] ± 80	222[b] ± 80	0.053
MQ	414[a] ± 255	466[a] ± 255	539[b] ± 255	0.0002
DQ	261[a] ± 113	255[a] ± 113	245[a] ± 113	0.87
Principal compressive strain (με)				
PH	−327[a] ± 160	−387[b] ± 160	−483[c] ± 160	<0.0001
MH	−876[a] ± 233	−1,075[b] ± 233	−1,554[c] ± 233	<0.0001
DH	−582[a] ± 409	−712[a] ± 409	−991[b] ± 409	<0.0001
PQ	−516[a] ± 174	−637[b] ± 174	−829[c] ± 174	<0.0001
MQ	−680[a] ± 161	−804[a,b] ± 161	−1,073[b] ± 161	<0.0001
DQ	−479[a] ± 89	−521[a] ± 89	−645[b] ± 89	<0.0001
Maximum shear strain (με)				
PH	328[a] ± 109	368[a,b] ± 109	456[b] ± 109	0.01
MH	996[a] ± 223	1,086[a] ± 223	1,389[b] ± 223	0.0001
DH	1,339[a] ± 433	1,521[b] ± 433	1,839[c] ± 433	<0.0001
PQ	781[a] ± 262	903[a] ± 262	1,074[b] ± 262	<0.0001
MQ	1,183[a] ± 139	1,347[b] ± 139	1,650[b] ± 139	<0.0001
DQ	1,112[a] ± 210	1,226[a,b] ± 210	1,458[b] ± 210	0.01

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 PH = proximal heel; MH = middle heel; DH = distal heel; PQ = proximal quarter; MQ = middle quarter; DQ = distal quarter.

location and increasing shoe length in the MH and DH locations (Figure 3B). Shear strains did not vary among treatments in the PH and PQ locations (Table 2, Figure 3C).

Strain direction
Principal directions for tensile strains rotated in a clockwise manner in relation to the orientation of the tubules on the lateral wall of the right hoof with increasing load for PH, DH and PQ gauges by 15, 34, and 3°, respectively (Table 3, Figure 2A). For principal compressive and shear strain directions the PH, MH, and PQ rotated clockwise with increasing load by 5, 12, and 3°, respectively, while the DH and DQ rotated counterclockwise by 6 and 14°, respectively (Figure 3B,C).

Principal tensile strains directions rotated counterclockwise by 9° for the MQ gauge with increasing branch length (Table 4, Figure 2A). Principal compressive and shear strain directions rotated in a counterclockwise manner by 9° and 11°, respectively, for the MQ and DQ locations.

Fetlock extension
Fetlock extension increased as load increased (Table 5). Fetlock extension increased with increasing shoe length ($P < 0.0001$, Table 6); however, differences among treatments were small (≤1°).

Hoof expansion
Hoof expansion increased with increasing load for proximal and distal heel and quarter variables (Table 5). Hoof expansion differences were not detected among shoe lengths (Table 6).

Hoof deformation
Distance between lateral hoof wall segments decreased with increasing loads for Pr, Di, PrDo-DiPa, and PrPa-DiDo variables; and increased with increasing loads for Pa and Do variables (Table 5). Hoof deformations were not detected among any of the shoe length treatments (Table 6).

TABLE 2 Least squared means and standard error for principal tensile, compressive and shear strain magnitudes by treatment when averaged over all loads[1,2]

Gauge	Treatment				*P*-value
	NS	Short	Full	Long	
Principal tensile strain (µε)					
PH	58^{a} ± 37	69^{a} ± 37	80^{a} ± 37	90^{a} ± 37	0.13
MH	−26^{a} ± 250	1^{b} ± 250	29^{a,b} ± 250	56^{a,b} ± 250	0.06
DH	507^{a} ± 135	530^{a} ± 135	553^{a} ± 135	576^{a} ± 135	0.45
PQ	209^{a} ± 80	203^{a} ± 80	197^{a} ± 80	192^{a} ± 80	0.86
MQ	458^{a} ± 255	468^{a} ± 255	478^{a} ± 255	489^{a} ± 255	0.80
DQ	239^{a} ± 113	249^{a} ± 113	258^{a} ± 113	268^{a} ± 113	0.85
Principal compressive strain (µε)					
PH	−431^{a} ± 160	−410^{a,b} ± 160	−388^{a,b} ± 160	−367^{b} ± 160	0.001
MH	−1,268^{a} ± 234	−1,202^{a,b} ± 234	−1,135^{a,b} ± 234	−1,069^{b} ± 234	<0.0001
DH	−861^{a} ± 410	−795^{a,b} ± 410	−728^{b,c} ± 410	−662^{c} ± 410	<0.0001
PQ	−743^{a} ± 174	−688^{b} ± 174	−634^{b,c} ± 174	−579^{c} ± 174	0.0003
MQ	NA[3]	−828^{a} ± 161	−858^{a,b} ± 161	−871^{b} ± 161	0.69
DQ	−604^{a} ± 90	−567^{a,b} ± 90	−529^{a,b} ± 90	−492^{b} ± 90	0.005
Maximum shear strain (µε)					
PH	489^{a} ± 111	319^{b} ± 111	333^{b} ± 111	395^{a,b} ± 111	0.30
MH	1,241^{a,b} ± 226	983^{a} ± 226	1,124^{a,b} ± 226	1,279^{b} ± 226	0.03
DH	1,368^{a} ± 435	1,575^{a,b} ± 435	1,625^{a,b} ± 435	1,698^{b} ± 435	0.003
PQ	951^{a} ± 263	897^{a} ± 263	910^{a} ± 263	918^{a} ± 263	0.87
MQ	NA[3]	1,555^{a} ± 140	1,139^{b} ± 140	1,487^{a} ± 140	0.0002
DQ	843^{a} ± 216	1,347^{b} ± 216	1,421^{b} ± 216	1,450^{b} ± 216	<0.0001

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 PH = proximal heel; MH = middle heel; DH = distal heel; PQ = proximal quarter; MQ = middle quarter; DQ = distal quarter.
3 NA = These variables did not have NS included in the model as order was found to be significant upon initial testing of the model.

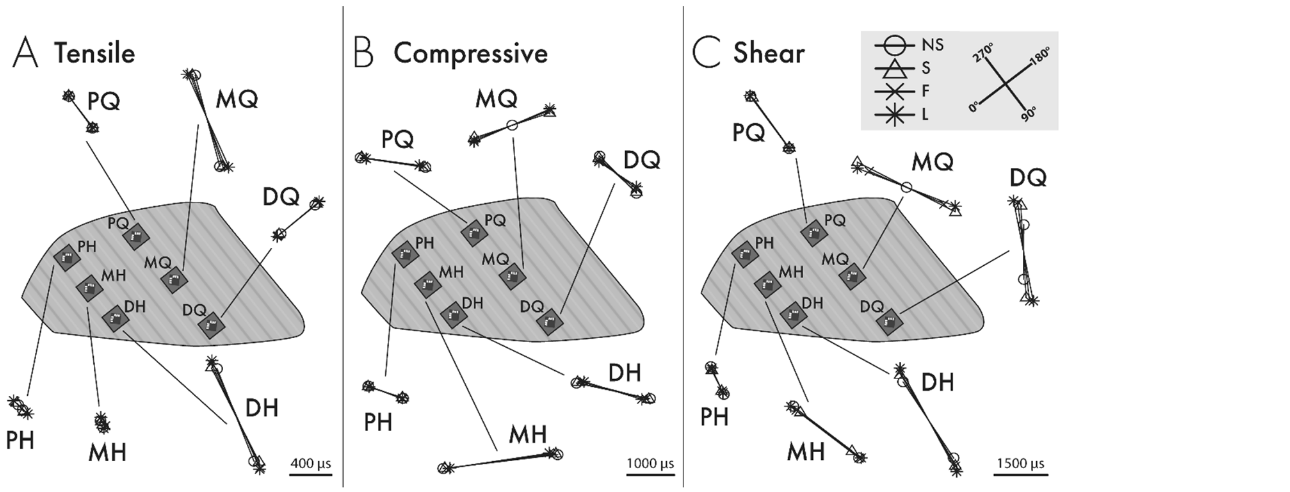

FIGURE 3 The magnitudes and directions of tensile (A), compressive (B) and maximum shear (C) principal strains are illustrated for each location and treatment on the lateral wall of a right hoof. PH = proximal heel, MH = middle heel, DH = distal heel, PQ = proximal quarter, MQ = middle quarter, DQ = distal quarter. Scales are not the same for each panel to allow for visualization of smaller microstrain magnitudes.

TABLE 3 Principal strain directions least squared means and standard errors for compressive, tensile and shear principal strains by load when averaged over all treatments[1,2]

Gauge	Load			P-value
	3,600 N	4,600 N	6,200 N	
Principal tensile direction (°)				
PH	106[a] ± 19	96[a,b] ± 19	91[b] ± 19	0.03
MH	68[a] ± 14	76[a] ± 14	76[a] ± 14	0.27
DH	97[a] ± 16	74[b] ± 16	63[b] ± 16	0.0003
PQ	92[a] ± 16	91[a] ± 16	89[b] ± 16	<0.0001
MQ	74[a] ± 4	74[a] ± 4	73[a] ± 4	0.45
DQ	5[a] ± 0.5	4[a] ± 0.5	4[a] ± 0.5	0.179
Principal compressive direction (°)				
PH	126[a] ± 16	126[a] ± 16	121[b] ± 16	0.01
MH	158[a] ± 14	151[a,b] ± 14	146[b] ± 14	0.002
DH	127[a] ± 16	129[a,b] ± 16	133[b] ± 16	0.06
PQ	137[a] ± 14	136[a] ± 14	134[b] ± 14	0.0002
MQ	164[a] ± 4	164[a] ± 4	162[a] ± 4	0.45
DQ	99[a] ± 8	102[a] ± 8	113[b] ± 8	<0.0001
Maximum shear direction (°)				
PH	81[a] ± 16	81[a] ± 16	76[b] ± 16	0.01
MH	113[a] ± 14	106[a,b] ± 14	101[b] ± 14	0.002
DH	82[a] ± 16	84[a,b] ± 16	88[b] ± 16	0.06
PQ	92[a] ± 0.1	91[a] ± 0.1	89[b] ± 0.1	<0.0001
MQ	119[a] ± 4	119[a] ± 4	117[a] ± 4	0.45
DQ	54[a] ± 8	57[a] ± 8	68[b] ± 8	< 0.0001

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 PH = proximal heel; MH = middle heel; DH = distal heel; PQ = proximal quarter; MQ = middle quarter; DQ = distal quarter.

4 Discussion

The hoof behaved in a manner expected under increasing loading conditions. Fetlock extension increased with increasing *in vitro* limb load simulating the middle of stance, consistent with *in vivo* loading in live horses (Harrison *et al.*, 2010). We found that principle compressive hoof wall strains were larger than principal tensile strains during loading, consistent with Thomason's strain experiments in the hoof wall when measured on the lateral aspect of the hoof (Thomason *et al.*, 1992). Observed heel and quarter expansion with increased loading is consistent with the findings of Douglas *et al.* (1996). We found that expansion of the heels was greater than expansion of the quarters. Three factors could have contributed to this finding. Greater expansion at the heels results from the normal hoof anatomy in which the hoof wall is thickest dorsally, gradually thinning and becoming more flexible toward the palmar aspect of the hoof (Bowker, 2003; Lancaster *et al.*, 2013). The hoof capsule is an open truncated cone with the opening at the heels, allowing the heels to move further than the quarters. In addition, the quarter region of the hoof wall could be constrained by horseshoe nails extending to the widest region of the hoof while the heels would be unconstrained. Increased loading caused the lateral aspect of the hoof wall to lengthen in the proximodistal direction and shorten in the dorsopalmar direction. Thomason *et al.* (1992) modelled hoof behaviour *in vivo* using rosette strain gauges placed at the toe, medial and lateral quarters and showed that the palmar part of the hoof not only flexes outward at the distal margin of the hoof, but that some concavity occurs along the hoof wall as the distal portion slides outward. In the current study shortening in the dorsopalmar direction could be due to concavity of the lateral wall during hoof loading.

Increasing shoe length resulted in a small increase in fetlock extension (≤1°). Our hypothesis was that a shorter shoe branch would increase fetlock extension with less support at the heels. Our findings of the longer branch increasing fetlock extension were unexpected but potentially explained from work by Hüppler *et al.*

TABLE 4 Principal strain directions least squared means and standard errors for principal compressive, tensile and shear strains by treatment when averaged over all loads[1,2]

Gauge	Treatment				*P*-value
	NS	Short	Full	Long	
Principal tensile direction (°)					
PH	$94^a \pm 20$	$94^a \pm 20$	$101^a \pm 20$	$101^a \pm 20$	0.53
MH	$74^a \pm 14$	$75^a \pm 14$	$75^a \pm 14$	$69^a \pm 14$	0.78
DH	$76^a \pm 17$	$81^a \pm 17$	$79^a \pm 17$	$78^a \pm 17$	0.96
PQ	$90^a \pm 16$	$90^a \pm 16$	$91^a \pm 16$	$91^a \pm 16$	0.22
MQ	$69^a \pm 4$	$72^{a,b} \pm 4$	$75^{b,c} \pm 4$	$78^c \pm 4$	0.0003
DQ	$5^a \pm 0.5$	$4^a \pm 0.5$	$4^a \pm 0.5$	$4^a \pm 0.5$	0.18
Principal compressive direction (°)					
PH	$124^a \pm 16$	$124^a \pm 16$	$124^a \pm 16$	$124^a \pm 16$	1
MH	$150^a \pm 14$	$151^a \pm 14$	$152^a \pm 14$	$153^a \pm 14$	0.96
DH	$132^a \pm 16$	$131^a \pm 16$	129a ± 16	$128^a \pm 16$	0.43
PQ	$135^a \pm 14$	$135^a \pm 14$	$136^a \pm 14$	$136^a \pm 14$	0.06
MQ	$159^a \pm 4$	$162^{a,b} \pm 4$	$165^{b,c} \pm 4$	$168^c \pm 4$	0.0003
DQ	$99^a \pm 8$	$102^{a,b} \pm 8$	$106^{a,b} \pm 8$	$110^b \pm 8$	0.004
Maximum shear direction (°)					
PH	$79^a \pm 16$	$79^a \pm 16$	$79^a \pm 16$	$79^a \pm 16$	1
MH	$105^a \pm 14$	$106^a \pm 14$	$107^a \pm 14$	$108^a \pm 14$	0.96
DH	$87^a \pm 16$	$86^a \pm 16$	$84^a \pm 16$	$83^a \pm 16$	0.43
PQ	$90^a \pm 14$	$90^a \pm 14$	$91^a \pm 14$	$91^a \pm 14$	0.06
MQ	$114^a \pm 4$	$117^{a,b} \pm 4$	$120^{b,c} \pm 4$	$123^c \pm 4$	0.0003
DQ	$54^a \pm 8$	$57^b \pm 8$	$61^b \pm 8$	$65^b \pm 8$	0.004

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 PH = proximal heel; MH = middle heel; DH = distal heel; PQ = proximal quarter; MQ = middle quarter; DQ = distal quarter.

(2016). Adding hoof heel support with a longer horseshoe branch hoof tends to decrease downward heel rotation in soft surfaces (Hüppler *et al.*, 2016). Although the experimental set-up did not allow alteration of the hoof rotation in a substrate, the lengthening of the horseshoe branch appears to have altered the degree of fetlock extension, potentially altering the biomechanics of the hoof. The longer branch of the shoe was prevented from rotating within a softer surface in the current study as an unyielding surface was used for testing. It is possible that constraint of distal interphalangeal (coffin) joint rotation could account for the slight increase in fetlock extension because fetlock and coffin joint motions are both affected by tension in the deep digital flexor tendon.

Horseshoe length had no statistically significant effect on hoof wall deformations. Horseshoes are fixed to the hoof with nails at locations dorsal to the widest part of the hoof, thus dorsal to all measurement sites in this study. Consequently, changing the length of the shoe palmar to all attachment sites may not affect lateral movement of the heel and quarter portions of the hoof. It is possible that since all shoes were attached in the same manner with toe and quarter nails, there were no changes in how the hoof was allowed to move, indicating that the amount of hoof wall coverage is less important than how the hoof is constrained by nail placement. Nail placement has been found to alter hoof mechanics in that placing nails closer to the heel of the hoof restricts expansion of the heels (Dahl *et al.*, 2023).

Horseshoe length affected the magnitude of principal compressive and shear strains, with no significant alteration in principal tensile strains. Principal compressive strains decreased from NS to a long shoe. This could be due to a more even distribution of forces applied to the hoof wall with increasing ground coverage that occurs with the longer branch length. A more even distribution of pressure between the shoe and hoof around the weight bearing surface of the hoof was found when coverage at the heels was increased with bar shoes (Hüppler *et al.*, 2016). Perhaps the same effect is occurring with the longer branches as with the bar shoe. However, prin-

TABLE 5 Fetlock angle, hoof expansion, and wall deformation variables (least square means and standard error) by load when averaged over all treatments[1,2]

Variable	Load			*P*-value
	3,600 N	4,600 N	6,200 N	
Fetlock extension				
Fetlock angle (°)	213^{a} ± 3	218^{b} ± 0.03	225^{c} ± 0.03	<0.0001
Hoof expansion				
Proximal heel (mm)	0.35^{a} ± 0.11	0.68^{b} ± 0.11	1.46^{c} ± 0.11	<0.0001
Distal heel (mm)	0.42^{a} ± 0.08	0.70^{b} ± 0.08	1.31^{c} ± 0.08	<0.0001
Proximal quarter (mm)	−0.03^{a} ± 0.10	0.001^{a} ± 0.10	0.14^{b} ± 0.10	0.0004
Distal quarter (mm)	0.13^{a} ± 0.10	0.25^{b} ± 0.10	0.49^{c} ± 0.10	<0.0001
Wall deformation				
Pr (mm)	−0.24^{a} ± 0.07	−0.38^{b} ± 0.07	−0.45^{b} ± 0.07	<0.0001
Di (mm)	−0.08^{a} ± 0.05	−0.13^{a} ± 0.05	−0.26^{b} ± 0.05	<0.0001
Pa (mm)	−0.08^{a} ± 0.05	−0.11^{a} ± 0.05	0.07^{b} ± 0.05	0.0037
Do (mm)	0.03^{a} ± 0.04	0.06^{a,b} ± 0.04	0.08^{b} ± 0.04	0.02
PrDo-DiPa (mm)	−0.09^{a} ± 0.06	−0.17^{b} ± 0.06	−0.29^{c} ± 0.06	<0.0001
PrPa-DiDo (mm)	−0.18^{a} ± 0.10	−0.28^{b} ± 0.10	−0.35^{b} ± 0.10	0.001

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 Pr = proximal; Di = distal; Do = dorsal; Pa = palmar; PrDo-DiPa = proximo-dorsaldistopalmar; PrPa-DiDo = proximopalmar-distodorsal.

TABLE 6 Fetlock angle, hoof expansion and wall deformation variables (least square means and standard errors) by treatment when averaged over all loads[1,2]

Variable	Treatment				*P*-value
	NS	Short	Full	Long	
Fetlock extension					
Fetlock angle (°)	217.9^{a} ± 3	218.3^{b} ± 3	218.6^{b,c} ± 3	218.9^{c} ± 3	<0.0001
Hoof expansion					
Proximal heel (mm)	0.85^{a} ± 0.12	0.84^{a} ± 0.12	0.82^{a} ± 0.12	0.81^{a} ± 0.12	0.4
Distal heel (mm)	0.81^{a} ± 0.08	0.81^{a} ± 0.08	0.81^{a} ± 0.08	0.82^{a} ± 0.08	1.0
Proximal quarter (mm)	0.05^{a} ± 0.10	0.04^{a} ± 0.10	0.03^{a} ± 0.10	0.03^{a} ± 0.10	1.0
Distal quarter (mm)	0.27^{a} ± 0.10	0.28^{a} ± 0.10	0.30^{a} ± 0.10	0.31^{a} ± 0.10	0.3
Wall deformation					
Pr (mm)	−0.35^{a} ± 0.07	−0.36^{a} ± 0.07	−0.36^{a} ± 0.07	−0.36^{a} ± 0.07	1.0
Di (mm)	−0.13^{a} ± 0.05	−0.15^{a} ± 0.05	−0.16^{a} ± 0.05	−0.15^{a} ± 0.05	0.4
Pa (mm)	−0.01^{a} ± 0.06	−0.09^{a} ± 0.05	−0.06^{a} ± 0.06	−0.08^{a} ± 0.06	0.7
Do (mm)	NA[3]	0.04^{a} ± 0.06	0.06^{a} ± 0.04	0.06^{a} ± 0.04	0.9
PrDo-DiPa (mm)	NA[3]	−0.18^{a} ± 0.06	−0.18^{a} ± 0.06	−0.18^{a} ± 0.06	1.0
PrPa-DiDo (mm)	−0.24^{a} ± 0.10	−0.26^{a} ± 0.10	−0.28^{a} ± 0.10	−0.30^{a} ± 0.10	0.6

1 Within a row, values that do not share a superscript are statistically different at $P < 0.05$.
2 Pr = proximal; Di = distal; Do = dorsal; Pa = palmar; PrDo-DiPa = proximo-dorsaldistopalmar; PrPa-DiDo = proximopalmar-distodorsal.
3 NA = These variables did not have NS included in the model as order was found to be significant upon initial testing of the model.

cipal shear strains increased in the middle and distal heel locations with increasing horseshoe length.

Changes in principal shear and compressive strain directions with increasing shoe length were observed in the middle and distal quarter regions as well as principal tensile strain direction for the middle quarter. It is possible that the quarters are restricted by horseshoe nails placed in the widest part of the hoof, affecting the change of principal compression and shear strain directions. As movement of quarter of the hoof may have been restricted by the nail, the middle and distal quarter locations closest to the nail region would be constrained as the hoof was loaded and forces distributed more toward the heels as the branches lengthened. Additionally, as load increased, the distal quarter rotated counterclockwise while the rest of the gauges rotated in a clockwise manner which could potentially be explained by proximity to the most palmar nail placed within the quarter of the hoof.

Limitations of the study included the *in vitro* and short-term nature of the mechanical tests. While findings observed with increasing horseshoe length were relatively small, the effect of the changes in the live horse over months could be larger and result in a clinically relevant change in hoof conformation. While passive structures of the fetlock stay apparatus were maintained in the cadaveric limb preparation, potential muscle contributions to loading of distal tendons were not incorporated in the study. However, passive structures are the largest contribution to maintaining fetlock support during locomotion (Wilson *et al.*, 2001). Motion of hoof wall kinematic markers out of the plane of mediolateral heel and quarter expansion and rotation of pins for lateral wall markers were unaccounted for in the study. Consequently, changes in chord distances could have incorporated linear and rotational transformations. Ultimately increased confidence in our findings would have to be obtained by 3-dimensional measurement systems. Hoof rotation that might occur in natural surfaces was prevented by rigid attachment to a flat metal plate. Repeating the study on more natural surfaces would be important to consider.

In conclusion, under the conditions studied, there is no evidence that horseshoe length affects hoof wall expansion and deformation; however, principal compressive and shear strain magnitude and direction altered with shoe branch length. Shorter shoe lengths did not increase fetlock extension, however, longer branch lengths did increase fetlock extension. Increasing shoe branch length decreases compression along the lateral hoof wall which could indicate a more even distribution of forces along the hoof wall with increased support at the heels. However, the shortening of shoe branch length did not influence hoof mechanics on a flat rigid surface as expected and does not appear to contribute to the development of underrun heels over time. Further studies should be done to see whether the effects of surface type, exercise, and trimming and shoeing frequency with varying shoe lengths change overall hoof conformation over time.

Acknowledgements

Supported in part by the Center for Equine Health with funds provided by the State of California satellite wagering fund and contributions by private donors as well as funds provided by the Veterinary Orthopedic Society. The authors thank Matthew Seitzler, Shane Westman, Chrisoula Skouritakis, and Dr. Andrew Blandino for technical and statistical assistance.

Authors' contribution

All authors contributed equally to the writing of this paper. All authors read and approved the final manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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