Digital Radiographic and Magnetic Resonance Imaging of the Normal Equine Foot: a Focus on the Soft Tissue Structures of the Hoof Wall and Sole

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Masters of Science in the Graduate School of The Ohio State University

By

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2012

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Abstract

The equine foot is an anatomically complex structure, in which soft tissue attachments between the distal phalanx (DP) and the hoof capsule support the entire musculoskeletal system. Equine laminitis affects these soft tissues of the foot and commonly leads to its structural collapse. Radiography is commonly used to diagnose laminitis and guide treatment and therapy. Several measurements to assess the position of the DP in relation to the hoof capsule have been described. Many of those have not been fully validated and the soft tissues in the sole area have not been the focus of previous diagnostic imaging evaluations. Our objectives were to establish normal hoof wall and sole measurements for Digital Radiography (DR) and Magnetic Resonance Imaging (MRI), to correlate and compare DR measurements with those made on MR images, to compare DR measurements before and after barium application to the surface of the sole, and to evaluate inter- and intra-observer correlation. We also aimed to distinguish if the two soft tissue layers seen on DR correspond to the epidermal and dermal layers as suggested previously and if these structures can also be imaged in the sole region. Fifty cadaver front feet of 25 adult horses of various breeds were imaged with DR and a 3 Tesla MR and various measurements were performed. Normal DR and MRI measurements are presented and statistically different (P < 0.0001). However, the difference is small (< 2mm). Measurements with barium applied to the surface of the sole were consistently smaller, than measurements without barium on the sole (P <
0.0001). There was good overall inter- and intra-observer correlation between DR (0.98/0.98) and MR (0.99/0.99) measurements. MRI measurements of the deep/sublamellar dermis and interdigitating epidermal and dermal layer corresponded to the lucent soft tissue opaque band surrounding the DP on DR images. Our measurements not only support established measurements, but also offer new approaches to quantitatively assess the anatomy of the equine foot.
Dedication

This work is dedicated to my wonderful family.
Acknowledgments

I would like to thank my research committee, Dr. Wm Tod Drost, Dr. Lisa J. Zekas and Dr. James K. Belknap for their patience, guidance and support during my residency and this research project.

I would also like to thank Dr. Rebecca R. Garabed for her patience and support in the statistical analysis.

I would like to thank Dr. Steven E. Weisbrode, Dr. Famke Aeffner and Steven J. Horvath at the Goss Laboratory for their practical support in evaluating histologic specimens, illustration of images and collection of gross specimens.

I would also like to thank Dr. Michael Knopp, Francisco R. Aguila and Daniel J. Clark for the support and assistance in image acquisition at the Wright Center of Innovation in Biomedical Imaging.

I would like to thank Dr. Eric M. Green, my resident mates and technicians of the Veterinary Medical Center Imaging Service.

A very special thank-you is extended to Dr. Niklas J. Drumm for his invaluable support, dedication and patience in all aspects of this project.

This project would not have been possible without the support of my family.
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F. Aeffner, R. Weeren, S. Morrison, I.N.M. Grundmann, S.E. Weisbrode, "Synovial
Osteochondromatosis With Malignant Transformation to Chondrosarcoma in a
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Fields of Study

Major Field: Veterinary Clinical Science

vii
# Table of contents

Abstract ................................................................. ii
Dedication ................................................................. iv
Acknowledgements ...................................................... v
Vita .............................................................................. vi
List of Tables ............................................................ ix
List of Figures ............................................................ x
Chapter 1: Introduction .................................................. 1
Chapter 2: Materials and Methods ................................. 4
Chapter 3: Results ...................................................... 8
Chapter 4: Discussion .................................................. 11
References ..................................................................... 16
Appendix A: Tables ..................................................... 18
Appendix B: Figures ..................................................... 22
List of Tables

Table 1. Magnetic resonance imaging sequence parameters ...........................................18

Table 2. Digital radiography and magnetic resonance imaging measurements ..............19
List of Figures

Figure 1. Digital radiographs with and without barium on the surface of the sole ..........22
Figure 2. Magnetic resonance images with and without fat equivalent material ..........24
Figure 3. Digital radiographic measurements ..........................................................25
Figure 4. Magnetic resonance imaging measurements ..............................................27
Figure 5. Digital radiographic ratios ........................................................................30
Figure 6. Magnetic resonance imaging ratios ...........................................................32
Chapter 1: Introduction

The equine foot is an anatomically complex structure in which laminar attachments between the distal phalanx (DP) and the keratinized part of the hoof wall suspend the DP and therefore support the entire musculoskeletal system. The laminar attachments consist of the interdigitating epidermal and dermal lamellae. In between the dermal lamellae and the DP is the deep (sublamellar) dermis which provides the vascular supply to the lamellae.\textsuperscript{1,2,3} In the sole region the lamellae continue into the terminal dermal papillae and epidermal sockets which are also interdigitating and supported by the deep dermis.\textsuperscript{2}

Equine laminitis, a squeala of multiple disorders in the horse, affects this complex lamellar apparatus leading to separation of the dermal and epidermal lamellae and thus structural failure due to multiple events including inflammatory and vascular derangements.\textsuperscript{4,5} Acute laminitis has been associated with numerous diseases affecting the gastrointestinal, respiratory, reproductive, endocrine or musculoskeletal system.\textsuperscript{6,7,8} Although still not completely understood, the reported pathogenesis of laminitis is multifactorial, leading to alterations in the hemodynamics of the hoof and inflammation-induced damage of the lamellae.\textsuperscript{4,7,9} This may disrupt the intimate connections between the DP and the cutaneous elements of the hoof and often results in the painful structural collapse of the foot and the eventual demise of the animal. This disruption of the intimate
lamellar connections leads to rotation and/or distal displacement, also termed “sinking”, of the DP.\textsuperscript{10,11}

Radiographic measurements assessing the position of the DP in relation to the hoof capsule include 1) distance between the dorsal surface of the DP and the dorsal hoof wall to assess rotation of the DP\textsuperscript{12} and 2) vertical distance from the proximal margin of the hoof capsule to the extensor process of the DP (“founder distance”) to assess distal displacement of the DP.\textsuperscript{13} Although assessing distal displacement of the DP by evaluating the distance between the dorsodistal margin of the DP to the ground surface of the sole (thickness of the sole) has also been described,\textsuperscript{14} reference values were not established for this measurement. Only one study established reference values for the latter measurements on digital radiographs (DR).\textsuperscript{15} As previously mentioned the surface of the sole may be difficult to distinguish on radiographs. To better evaluate sole thickness equine clinicians readily use metallic markers on the surface of the sole. To our knowledge there has not been a study to compare radiographic measurements before and after positive radiographic marker application on the surface of the sole.

While displacement of the DP only reflects the consequence of lamellar injury, the encasing keratinized hoof capsule hinders direct evaluation of the lamellar apparatus. This makes the lamellae one of very few soft tissue structures in the horse inaccessible to physical and ultrasonographic evaluation.

Using analog radiographs, two distinct bands of different soft tissue opacity are observed in the dorsal hoof wall.\textsuperscript{12} Delineation of these two layers has become more well-defined with increased contrast resolution of DR. Although it has been suggested
that the outer more opaque layer is the keratinized hoof wall (epidermis) and the more lucent layer is the underlying lamellae and dermis, this has not been documented.\textsuperscript{12} Distinct soft tissue layers in the sole area have not been described. Because the lamellar and inner dermal layers, in contrast to the outer epidermis, are not affected by trimming, alteration of these layers could be a more reliable diagnostic measurement in laminitis evaluation than dorsal hoof wall thickness.

Recent equine laminitis research using Magnetic Resonance Imaging (MRI) described the detailed soft tissue changes of the dorsal hoof wall in the acute phase of the disease.\textsuperscript{16} In this study correlation of measurements for the different layers on DR in comparison to MRI was hindered since the outer margin of the hoof wall was not well delineated on MRI. Also the sole region was not evaluated in this study.

Because of lower expense and higher availability, DR is likely to remain the more commonly used modality to evaluate laminitis despite the superior soft tissue resolution of MRI.\textsuperscript{17} The knowledge gained from MRI could potentially improve differentiation of soft tissue bands seen on DR.

Our objectives were to establish normal hoof wall and sole measurements for DR and MRI, to correlate and compare DR measurements with those made on MR images, compare DR measurements before and after barium application to the surface of the sole, and to evaluate inter- and intra-observer correlation. We also aimed to distinguish, if the two soft tissue bands seen on DR correspond to the epidermal and dermal layers and if these structures can also be imaged in the sole region.
Chapter 2: Materials and Methods

Fifty cadaver front feet were obtained from 25 horses euthanized for reasons other than lameness or laminitis. Multiple breeds were represented, including Quarter Horses (7), Thoroughbreds (4), Standardbreds (3), American Paint Horses (2), American Paso Finos (2), Mixed breed Horse (2), American Saddlebreds (1), Arabian (1), Pinto (1), Rocky Mountain horse (1) and Tennessee Walker (1). Horses ranged in age from 3 to 37 years (mean = 15 years). The distal extremities were disarticulated proximal to the metacarpophalangeal joint, thoroughly cleaned, and shoes and nails were removed. To prevent desiccation, the feet were sealed into plastic bags, immediately cooled and frozen the same day at -20°C.\textsuperscript{18}

Lateromedial, horizontal dorsopalmar and dorsal 65° proximal-palmarodistal radiographs of each frozen distal extremity were made using an indirect flat panel digital radiography system (Eklin Medical Systems, Santa Clara, CA). A thin layer of one to four mm of a positive contrast medium (Barium sulfate E-Z-Paste (60% w/w), E-Z-EM Canada Inc, Lake Success, NY) was applied to the distal surface of the sole, extending from the palmar aspect of the sole to the mid-sagittal aspect of the sole, paralleling the solar margin of the DP (Figure 1). Lateromedial and horizontal dorsopalmar radiographs were repeated. A radiographic marker was placed in the mid-sagittal plane for lateromedial radiographs and mid-dorsal plane for dorsopalmar images to assist with
magnification correction. Any metal detected radiographically was removed to prevent susceptibility artifacts during MRI. The distal extremities were thawed for 18 to 24 hours prior to MR imaging. The hoof and sole surfaces were covered with fat equivalent material (Lundy’s Refined Lard, Premium Standard Farm/Lundy Packing, Clinton, NC)(Figure 2), placed horizontally in a knee coil (Philips SENSE Knee-8 Coil, Achieva, 8 channel receive only) and imaged using a 3 Tesla (T) magnet (Philips, Achieva 3T, Cleveland, OH). After a localizer spin echo sequence, proton density (PD) and 3D gradient echo (GRE) T2* images were acquired in transverse, sagittal and dorsal planes. The sequence parameters are summarized in Table 1. The transverse plane was oriented perpendicular to the dorsal hoof wall of the DP. The dorsal plane was oriented perpendicular to the weight-bearing surface of the foot.

All DR and MR images were stored in DICOM format and evaluated using a DICOM viewer (eFilm, Merge Healthcare, Milwaukee, WI).

Following MR imaging, the distal extremities were sectioned in a sagittal plane using a band saw. Tissue specimens were collected from the distal half of the dorsal hoof wall and medial, lateral and mid sagittal aspect of the sole. The samples were fixed in formalin for at least 48 hours and trimmed for paraffin embedding and tissue sectioning. Slides were stained with hematoxylin and eosin and contained the corium, lamellae and a small part of the keratinized hoof wall. Histopathologic evaluation was performed by a board-certified veterinary pathologist (SEW) to confirm absence of lamellar disease.

The DR and MR images were randomized and then measured and reviewed by two board-certified veterinary radiologists (WTD, LJZ), one board-certified equine
surgeon (JKB) and one radiology resident (INMG). The measurements performed are included in Table 2 and illustrated in Figures 3-6. Measurements of the sole were made using DR images with and without barium on the surface of the sole. DR measurements with barium on the surface of the sole were compared to DR measurements without barium and to MR measurements. Dorsal hoof wall measurements were made on lateromedial radiographs, measuring distal to the extensor process and proximal to the tip of the DP (Figure 3). The overall hoof wall thickness was measured as well as the inner dermal and lamellar layers and the outer epidermal layer. On the dorsopalmar radiographs, the distolateral and distomedial hoof wall thickness were measured from the most distal and lateral/medial aspect of the DP perpendicular to the outer margin of the lateral/medial hoof wall (Figure 3).

The mid-sagittal sole thickness was measured on the lateromedial radiograph from the dorsodistal tip of the distal phalanx, perpendicular to the distal margin of the barium painted sole. For DR images without barium on the sole, each investigator estimated the surface of the sole. Along with overall sole thickness, the inner dermal and lamellar and outer epidermal layers were measured separately. On the horizontal dorsopalmar image, the lateral and medial sole thickness were measured from the most distal and lateral/medial aspect of the distal phalanx to the distal surface of the sole.

The palmar cortex length was measured from the tip of the distal phalanx to the palmar articular margin of the distal phalanx on the lateromedial radiograph (Figure 5). The dorsodistal hoof wall thickness to palmar cortex length ratio was calculated. The
founder distance was measured from the proximal aspect of the coronary band to the proximal aspect of the extensor process on the lateromedial radiograph.

The same measurements made on DR were subsequently made on MR images (Figures 4 and 6).

To correlate the two distinct soft tissue bands of the dorsal hoof wall noted on DR images to the anatomy seen on MR images, we compared the thickness of the various layers on each modality. For instance, the outer layer noted on DR images was compared to the epidermis (outer epidermal layer without epidermal lamellae), which is seen on MR images and the thickness of the dermis (deep (sublamellar) dermis and lamellar layers of dermis and epidermis), which is seen on MR images.

Descriptive statistics were performed for each measurement. Statistical analysis and inter- and intra-observer methods included analysis of variance (ANOVA). In order to compare all DR and MR measurements, the Student’s T-test (to test that the difference between the DR and MR was significantly different than zero) and linear mixed-effects regression (to estimate the overall difference between DR and MR while controlling for repeated measures of the same horse and leg) were used. To evaluate the significance of barium application to the surface of the sole, a linear mixed effects regression model was used. $P < 0.05$ was considered significant except for the t-tests comparing the DR and MR measures where a stricter cut-off ($P < 0.007$) was used to account for multiple comparisons.
Chapter 3: Results

The DR and MR measurements are listed in Table 2.

The proximal and distal dorsal hoof wall thicknesses measured on DR and MR images were different (P<0.0001). The mean proximal dorsal hoof wall thickness was 18.4mm (SE=0.1mm) on DR and 16.9mm (SE=0.1mm) on MR. The associated dermal measurements were 6.7mm (SE=0.2mm) on DR and 6.6mm (SE=0.1mm) on MR. The distal dorsal hoof wall thickness was 17.9mm (SE=0.1mm) on DR and 16.8mm (SE=0.1mm) on MR. The dermal measurements for DR and MR were 7.2mm (SE=0.1mm) and 6.7mm (SE=0.1mm), respectively. The proximal and distal dorsal hoof wall thicknesses measured on DR and MR images were different (P<0.0001).

The dorsal hoof wall thickness to palmar cortex length ratio was 26.8% (SE=0.2%) on DR and 28.8% (SE ± 0.2%) on MR. The associated dermal dorsal hoof wall thickness to palmar cortex length ratio was 10.7% (SE=0.1mm) on DR and 11.6% (SE ± 0.2%) on MR.

Mean lateral/medial hoof wall measurements were 19.3mm (SE=0.2mm)/19.3mm (SE=0.2mm) on DR and 13.5mm (SE=0.1mm)/13.5mm (SE=0.1mm) on MR. The lateral/medial dermal measurements were 9.1mm (SE=0.1mm)/9.3mm (SE=0.1mm) on DR and 5.5mm (SE=0.1mm)/5.8mm (SE=0.1mm) on MR.
The majority of the sole thicknesses measured on DR and MR were different (P<0.0001) with exception of the medial epidermal sole measurement, which did not differ (P=0.37). The mean mid-sagittal sole thickness was 13.7mm (SE=0.2mm) on DR and 12.3mm (SE=0.2mm) on MR. The associated dermal measurement was 5.6mm (SE=0.1mm) on DR and 4.6mm (SE=0.1mm) on MR. The lateral/medial sole thickness measurements were 20.7mm (SE=0.3mm)/18.9mm (SE=0.3mm) on DR and 18.7mm (SE=0.3mm)/17.4mm (SE=0.3mm) on MR. The associated mid-sagittal dermal sole thickness was 5.6mm (SE=0.1mm) on DR and 4.6 mm (SE=0.1mm) on MR. The lateral/medial dermal sole measurements were 7.5mm (SE=0.2mm)/7.4mm (SE=0.1mm) on DR and 6.2mm (SE=0.1mm)/6.1mm (SE=0.1mm) on MR.

The sole thickness to palmar cortex length ratio was 20.1% (SE ± 0.4%) on DR and 11.6% (SE ± 0.3%) on MR. The associated dermal thickness sole to palmar cortex length ratio was 8.0% (SE± 0.1%).

Measurements before and after barium application onto the surface of the sole varied (P < 0.0001), with a mean value of 2 mm.

The mid-sagittal sole thickness had the least significant difference with a mean of 1.7 mm (SE=0.1mm). The lateral and medial sole thickness values were more different, with a mean of 2.3 mm/2.3 mm respectively.

There was good overall inter- and intra-observer correlation between DR (>0.98/0.98) and MR (>0.99/0.99) measurements.

MRI measurements of the deep/sublamellar dermis and interdigitating epidermal and dermal layer had fair to moderate correlation to the lucent soft tissue opaque band.
surrounding the distal phalanx on DR images. This was lowest (0.32) for the medial lamellar/deep dermal sole thickness.
Chapter 4: Discussion

The current study assessed the different layers of the hoof capsule using DR and MRI. The use of barium for DR and lard for MRI as contrast markers improved the delineation of the hoof wall and sole surfaces allowing for more precise placement of measurement calipers. The measurements made on DR were consistently on average approximately 2 mm greater than those made on MRI. This suggests that hoof wall and sole measurements used to discriminate laminitic from normal horses may apply to MR measurements if one accounts for the 2 mm difference. The thickness difference between DR and MRI is similar to a study evaluating chronic laminitis on radiographs and MRI, where a difference of less than 2 mm between measurements was also reported.

The primary difference between DR and MR measurements was better tissue contrast resolution noted on MR images, which may allow for more precise positioning of calipers at the tissue interfaces when making measurements. This was important, because it allowed us to distinguish the tissue components of the two soft tissue layers (outer opaque and inner more lucent) of the hoof wall, that can be delineated on DR.

The outer layer has been suggested to be the keratinized part of the epidermis and the inner layer was thought to correlate to the the interdigitating epidermal and dermal lamellae and deep dermis in a study utilizing analog radiographs. However, no
comparison to MRI or gross specimens were made.\textsuperscript{12} Even though DR and MRI
correlation was only fair to mild, the actual difference was less than 2mm and therefore
likely not clinically relevant.\textsuperscript{16,17} We established reference values for the thickness of the
dermis including the lamellae and also for the keratinized epidermis and correlated those
to the inner and outer layers seen on radiographs. This provides the clinician with
information on normal thickness of the lamellae and deep dermis on DR. Since the more
lucent layer, containing the lamellae and deep dermis are not affected by hoof trimming,
but are the primary tissues affected in laminitis, assessment of this layer may be a more
reliable and sensitive measure in laminitis evaluation.\textsuperscript{20} Because of our overall strong
inter-observer measurement correlation, we believe these measurements made by
different clinicians should lead to similar results.

The dorsal hoof wall thickness measured on radiographs is critical in assessment of
DP displacement. These measurements were performed in this study immediately distal
to the extensor process and the dorsodistal aspect of the DP in order to determine
rotational displacement. Our measurements for the dorsal hoof wall exceeded those of
other studies by slightly more than 2mm,\textsuperscript{12,13,17} but they are similar to those reported in
recent studies.\textsuperscript{15,16} These differences are likely due to variation in study population and
different imaging techniques for both radiography and MRI in these studies. Slight loss of
the superficial aspect of the dorsal hoof wall due to overexposure\textsuperscript{21} on analog radiographs
may also account for measurement differences.

In order to account for magnification and breed variation, the dorsal hoof wall
thickness to palmar cortex length ratio is used.\textsuperscript{12} Our average value (26.8 ± SD 2.6\%) for
this ratio is slightly greater than described for analog radiographs (24.1 ± 2.0%)\textsuperscript{12} but similar to a more recent study utilizing DR (26.9 ± SD 2.1%).\textsuperscript{16}

Sole thickness was assessed at the dorsodistal aspect of the DP to the sole surface, and is an important measurement for dislocation of the DP. Our mid-sagittal sole thickness measurements with barium on the surface of the sole are greater, when compared to a study where no radiographic marker was used\textsuperscript{12} but only slightly smaller than a study where the bottom of the sole was marked with barium paste.\textsuperscript{15} Besides differences in study population, more precise measurements made with barium on the sole on DR images may have accounted for these results.

Similar to the radiographic assessment of the dorsal hoof wall, the sole can also be separated into two soft tissue bands. The correlation of the lucent inner band to deep dermis and lamellae and the outer band to the keratinized part of the epidermis was also found for the sole area. In the future, measuring the lucent band may be a better measurement, as it is not influenced by trimming.

A less common, but clinically important manifestation of laminitis is lateral or medial uni-axial sinking of the DP, which is assessed on dorsopalmar radiographs.\textsuperscript{22} We established reference values for the lateral/medial hoof wall thickness, which was not measured in any of the previously mentioned studies and can be used to assess uni-axial sinking. We also established reference values for lateral/medial sole thickness, which could also be utilized for assessment of uni-axial sinking of the DP.\textsuperscript{23} Similar to another study\textsuperscript{15} lateral sole thickness was consistently greater than the medial sole thickness. Even though the average difference was only 2mm between the lateral and medial sole
thickness, in multiple individual measurements a disparity was present up to 10mm in
some animals. This did not apply for the lateral and medial hoof wall thickness. Due to
these differences in the normal foot, a diagnosis of medial uni-axial sinking using only
the lateral/medial sole thickness must be made with caution and incorporation of
lateral/medial hoof wall measurements may be crucial.

There are limitations to our study. The influence of weight bearing on the
thickness of the hoof wall or sole is not known. Although it should not be a factor in
high-field MRI studies (which would be performed in recumbent clinical patients), it
needs consideration in DR. However, the fact that our dorsal hoof wall thickness
measurements were the same or greater than studies performed in the standing horse
indicates, that there is not likely to be a large effect of weight bearing as one would
expect a displacement of the DP away from the hoof wall if weight bearing impacted the
relationship of the DP to the hoof wall.

In conclusion, our documentation that 1) the inner lucent layer of the dorsal hoof capsule
observed on DR corresponds to the lamellae and deep dermis, and 2) good correlation
between observers in determining the thickness of this layer indicates that quantification
of the thickness of this band may be more reliable in assessing early lamellar
injury/damage than assessment of the entire hoof wall. This same concept appears to be
true for assessment of the thickness of the sole, where there was less variability in the
assessment of the lucent layer than in measurements that incorporated the more opaque
layer which includes the keratinized epidermal layer. For assessment of uni-axial sinking,
comparison of the lateral/medial hoof wall measurements are likely be more useful than
the lateral/medial sole measurements. Although DR and MR measurements of the same feet were statistically different, the difference was small and consistent indicating that DR is an accurate imaging technique for quantification of measurements and changes of thickness of the hoof wall and sole. Future studies are needed to perform the same quantifications presented in the current study on feet from clinical laminitis cases in order to further quantitate differences in the measurements of the different layers in affected animals.
References


Appendix A: Tables

<table>
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<th>TR (ms)</th>
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Table 1. Magnetic resonance imaging sequence parameters:\(^1\):

\(^1\)FOV: field of view; TR: time to repetition; TE: time to echo; 3DGRE: three-dimensional gradient recall echo; PD: Proton density.
Table 2 DR and MR measurements in mm:\(^1\):

\(^1\)DR: digital radiography; MR: magnetic resonance imaging; dphw: dorsal proximal hoof wall thickness; dphw-e: dorsal proximal epidermal thickness; dphw-d: dorsal proximal dermal thickness; dphw-l: dorsal proximal lamellar thickness; dphw-dd: dorsal proximal deep dermal thickness; ddhw: dorsal distal hoof wall thickness; ddhw-e: dorsal distal epidermal hoof wall thickness; ddhw-d: dorsal distal dermal thickness; ddhw-l: dorsal distal lamellar thickness; ddhw-dd: dorsal distal deep dermal thickness; lhw: lateral hoof wall thickness; lhw-e: lateral epidermal thickness; lhw-d: lateral dermal thickness; lhw-l: lateral lamellar thickness; lhw-dd: lateral deep dermal thickness; mhw: medial hoof wall thickness; mhw-e: medial epidermal thickness; mhw-d: medial dermal thickness; mhw-l: medial lamellar thickness; mhw-dd: medial deep dermal thickness; sms: mid-sagittal sole thickness; sms-e: mid-sagittal epidermal sole thickness; sms-d: mid-sagittal dermal sole thickness; sms-p: mid-sagittal papillar sole thickness; sms-dd: mid-sagittal deep dermal sole thickness; sl: lateral sole thickness; sl-e: lateral epidermal sole thickness; sl-d: lateral dermal sole thickness; sl-p: lateral papillar sole thickness; sl-dd: lateral deep dermal sole thickness; sm: medial sole thickness; sm-e: medial epidermal sole thickness; sm-d: medial dermal sole thickness; sm-p: medial papillar sole thickness; sm-dd: medial deep dermal sole thickness; fd: founder distance; dhwpcr: dorsal hoof wall to palmar cortex ratio; ddpcr: dorsal dermis to palmar cortex ratio; spcr: mid-sagittal sole to palmar cortex ratio; sdpcr: mid-sagittal sole dermis to palmar cortex ratio.

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Appendix B: Figures

Figure 1. Digital radiographs with (A) and without (B) barium on the surface of the sole¹:

¹Lateromedial and horizontal dorsopalmar images.

Continued
Figure 1 continued

A

B
Figure 2. Magnetic Resonance Images with (A) and without (B) fat equivalent marker\textsuperscript{1}:

\textsuperscript{1}Lard applied to the surface of the hoof and sole
Figure 3. Digital radiographic measurements\(^1\):

\(^1\)Lateromedial and dorsopalmar digital radiographic images; dphw-e: dorsal proximal epidermal thickness; dphw-d: dorsal proximal dermal thickness; ddhw-e: dorsal distal epidermal hoof wall thickness; ddhw-d: dorsal distal dermal thickness; lhw-e: lateral epidermal thickness; lhw-d: lateral dermal thickness; mhw-e: medial epidermal thickness; mhw-d: medial dermal thickness; sms-e: mid-sagittal epidermal sole thickness; sms-d: mid-sagittal dermal sole thickness; sl-e: lateral epidermal sole thickness; sl-d: lateral dermal sole thickness; sm-e: medial epidermal sole thickness; sm-d: medial dermal sole thickness.
Figure 3 continued
Figure 4. Magnetic resonance imaging measurements\textsuperscript{1}:

\textsuperscript{1}Mid-sagittal and dorsal magnetic resonance images; dphw-e: dorsal proximal epidermal thickness; dphw-d: dorsal proximal dermal thickness; dphw-l: dorsal proximal lamellar thickness; dphw-dd: dorsal proximal deep dermal thickness; ddhw-e: dorsal distal epidermal hoof wall thickness; ddhw-d: dorsal distal dermal thickness; ddhw-l: dorsal distal lamellar thickness; ddhw-dd: dorsal distal deep dermal thickness; lhw-e: lateral epidermal thickness; lhw-d: lateral dermal thickness; lhw-l: lateral lamellar thickness; lhw-dd: lateral deep dermal thickness; mhw-e: medial epidermal thickness; mhw-d: medial dermal thickness; mhw-l: medial lamellar thickness; mhw-dd: medial deep dermal thickness; sms-e: mid-sagittal epidermal sole thickness; sms-d: mid-sagittal dermal sole thickness; sms-l: mid-sagittal lamellar sole thickness; sms-dd: mid-sagittal deep dermal sole thickness; sl-e: lateral epidermal sole thickness; sl-d: lateral dermal sole thickness; sl-l: lateral lamellar sole thickness; sl-dd: lateral deep dermal sole thickness; sm-e: medial epidermal sole thickness; sm-d: medial dermal sole thickness; sm-l: medial lamellar sole thickness; sm-dd: medial deep dermal sole thickness.

Continued
Figure 4 continued

Continued
Figure 4 continued
Figure 5. Digital radiographic ratios\(^1\):

\(^1\)distal dorsal hoof wall (ddhw) measurement divided by the palmar cortex length (PCL); distal dorsal hoof wall dermis (ddhw-d) divided by the palmar cortex length (PCL); distal sole mid-sagittal (sms) divided by the palmar cortex length (PCL); distal sole mid-sagittal dermis (sms-d) divided by the palmar cortex length (PCL).
Figure 5 continued
Figure 6. Magnetic resonance imaging ratios:

1Distal dorsal hoof wall (ddhw) measurement divided by the palmar cortex length (PCL); distal dorsal hoof wall dermis (ddhw-d) divided by the palmar cortex length (PCL); distal sole mid-sagittal (sms) divided by the palmar cortex length (PCL); distal sole mid-sagittal dermis (sms-d) divided by the palmar cortex length (PCL).
Figure 6 continued