Correlations between sole thickness and hoof wall thickness in Thoroughbreds.

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A special note to my wife, Sarah, for her patience and support during this study.

Abstract

Reasons for performing the study: There is limited research on the relationship between hoof wall thickness and sole thickness. This study aims to examine this and provide knowledge that improves farriery.

Objective: To determine if there is a correlation between hoof wall thickness and sole thickness in unshod Thoroughbreds, thereby providing a basis for a simple method to calculate sole thickness.

Method: Thirty unshod, fore and hind, Thoroughbred cadaver feet were sourced. These were cut transversely distally from and parallel to, the coronary hairline to measure the hoof wall thickness. An anterior cut was performed on the hypothesised apex of the distal border of distal phalanx to measure sole thickness. Three predetermined points on the hoof wall and sole were measured using digital calipers.

Results: Results from the study found a correlation between hoof wall thickness and sole thickness. The mean hoof wall thickness measured 9.81mm with the mean sole thickness being 8.55mm, resulting in a moderate correlation. The variance between fores and hinds showed no significant difference, whilst the variance between left and right feet showed the left significantly thinner than the right.

Conclusion: The results proved a correlation between mean hoof wall thickness and mean sole thickness in the data collected. Additionally it provided more evidence of laterality differences in hooves. This thesis will be of relevance to farriers in the field.

Declaration

I hereby declare that the work within this fellowship dissertation is my own. Any sources have been duly referenced and any illustrations or diagrams that are not mine are used with permission of the owner.

Table of Contents

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Introduction

One of the first lessons we are taught as farriers is the importance of identifying good quality and healthy hooves. The quality of horse's hooves can vary between individuals, the influence of a strong, functional foot on the athletic career of a performance horse and the importance of proper farriery becomes obvious (O'Grady, 2018). Good foot trimming is a combination of assessment of the whole horse, leg and hoof, skill and experience. Often trimming and shoeing methods are based on theoretical assumptions and aesthetic decisions derived from empiric experience rather than constant guidelines that can be applied on an individual basis (O'Grady, 2009).

The term hoof balance refers not only to the geometric shape of the hoof, but also to how the hoof and each limb interact with the contact surface, with the aim of reducing risk of injury and lameness and maximising efficiency of the foot and limb (Johnston and Back, 2006; Curtis, 2018). Hoof balance is an important part of foot trimming, however, the term can be widely interpreted. What is undoubtably true, is that better understanding of the horn structures of the equine foot, leads to better hoof-care.

The equine hoof is a tough epidermal structure that encases and protects the vascular and skeletal structures within. The equine foot is designed to perform numerous functions including, bearing the weight of the horse, protecting the structures contained, absorbing concussion and providing traction (O'Grady, 2006). During locomotion, the weight bearing capability of the hoof allows it to absorb and dissipate the horse's body weight through a single digit. This unique and complex structure means when load is placed on the hoof the descending body weight and resisting ground force deforms the hoof capsule, the dorsal wall flattens as the proximal dorsal wall rotates caudoventrally about the distal border, this posterior movement of the dorsal wall is accompanied by abaxial movement of the quarters and heels (Douglas, 1996).

It is widely accepted that strong thick walls and a thick sole contribute to good foot conformation and soundness. Bowker, 2003 stated "good conformation" includes several variables such as thick-walled hooves that will resist drying and have "normal" growth qualities. The sole should be thick enough to resist most external traumas, as well as be shed normally (Bowker, 2003). Thin, brittle walls can split, crack and excessively flare and thin soles can predispose to haemorrhage or haematoma formation in the dermal tissue resulting in bruising, corns, abscesses and discomfort during locomotion. Excessive trimming of soles can increase the occurrence of these ailments, while exfoliating of the sole plane can be important especially in determining correct hoof balance that may be hidden under a callused sole.

When trimming, farriers usually visually assess the correct amount of hoof wall depth and dorsal thickness to be removed. The author’s preferred method is to trim to the top of the white line. It is not possible to measure sole thickness (ST) without the use of imaging modalities. The common and not very accurate method has been to palpate the sole with the thumb. Hoof wall thickness (HWT) has been successfully investigated (Moore, 2016). The functional importance of sole depth has not yet been established and despite its position, structure and function, minimal research has been conducted to investigate sole depth and consequently it’s correlation to hoof wall thickness (Hampson et al, 2011).

Sole depth is commonly measured as the distance from the distal tip of the distal phalanx to the ground surface on a lateral radiograph. This single reference point apparently has been selected for convenience and there is no evidence to suggest that the measurement actually represents the extent of the solear structure (Hampson et al, 2011). This author believes this measurement represents the tip of distal phalanx elevation as opposed to sole depth.

It is believed that dorsum epidermal wall thickness and epidermal sole thickness are similar (Curtis, 2018). If this correlation can be proved, it will provide a more accurate guide to the thickness and trimming of the sole. It has been suggested that the sole has a uniform thickness. The sole thickness assists and protects the distal phalanx so plays a vital role in hoof health. This author believes solear trimming should be kept to a minimum, as this is a controllable factor in foot preparation unlike hoof conformation and the changing environmental conditions. The plane of the distal phalanx is defined by the angles of the sole (Savoldi and Rosenberg, 2003).

Sole Anatomy

The solear surface of the hoof capsule is an arched structure occupying the space between the front and bearing border of the hoof wall. The solear horn has a tubular and intertubular form and is produced from the stratum germinative covering the dermal tissue, arranged as papillae underlying the base the distal phalanx (Reilly, 2006).

The sole is usually slightly concave and has a hard flakey appearance and structure. The primary role of the sole is protection. Given its position, it is vulnerable to wear and injury and its vaulted structure can help reduce these. This vaulted shape also allows the sole to yield slightly as body weight passes via the distal phalanx during locomotion and is part of the anti-concussion mechanism. It is subject of debate whether the sole should bear some direct weight. For this study it is assumed that it is possibly a weight bearing structure as all specimens were unshod. It is said the sole can contain approximately 31% water (Curtis, 2018).

Hoof Wall Anatomy

The hoof capsule is a highly keratinised epidermal structure which is avascular and devoid of nerve endings (Reilly, 2006). Tubular and intertubular hoof wall are formed at the top of the hoof by constant proliferation of epidermal basal cells of the coronary band (Pollitt, 2008). The bulk of the hoof wall consists of the stratum medium, which is the main load bearing part of the hoof wall and extends from the coronary band to the bearing border (Pollitt, 2001) The dorsal hoof wall is noted to be of uniform thickness when viewed in a transverse section from its origin the coronary band to the ground bearing surface. In healthy horn, approximately 25% of the wall is comprised of water. There are 3 layers to the hoof wall:

1. The stratum externum (periople) is the outermost layer of the hoof, it is produced from basal layer and papillae on the perioplic corium and is a continuation of the epidermis of the skin. It provides a protective layer to the most juvenile portion of the wall.

2. The stratum medium (wall) makes up the main mass of the hoof wall. It is produced from the basal layer and the papillae on the coronary corium and consists of tubular, intratubular and intertubular horn. The axial portion lacks pigment and is known as zona alba.

3. The stratum internum comprises the inner layer of the hoof wall. It is the connective region of the hoof wall which attaches the stratum medium to the distal phalanx. The

distal phalanx and therefore the horse is effectively suspended within the hoof capsule by the connective tissue of stratum internum (Curtis, 2018).

The bulk of the hoof wall consists of the stratum medium, this is considered to have an anatomical design that confers strength in multiple directions (Pollitt, 2008). The stratum medium consists of tubules running proximodistally, parallel to the surface and intertubular material which is arranged tangentially around the circumference of the hoof (Thomason, et al, 1992). The stratum medium has four distinct zonal variations in tubule density. This arrangement of tubules within the hoof capsule is likely to be one factor determining hoof function (Reilly, 2006). A dorsopalmar decrease in tubule density occurs at each of the zones, each zone approximately 25% of the hoof wall.

Horn tissue consists of dozens of different keratin molecules, with differing biomechanical properties and molecular weights, with varying degrees of hardness and sulphur concentration (Pollitt, 2004). At the nanoscale level, intermediate filaments (7-10μm) act as fibres embedded in an amorphus protein matrix (Mahrous, et al, 2023). Aligned intermediate filaments form macro fibrils, roughly 700μm in diameter, that are dispersed inside disc shaped cells around 10-40μm across and 5μm thick (Mahrous, et al, 2023). Concentric lamella, each made from a single layer of cells, create cylindrical structures called tubules, they run from top to bottom of the hoof wall (Wang et al, 2016). The tubules have a 200-300μm diameter with a central medulla or tubule medullary cavity of about 50μm (Figure 1). Intertubular regions consist of lamellae at an oblique angle with the long axis of the tubules (Bertram and Gosline, 1986).

Keratin is a protein composite, consisting of two phases: a fibre phase mainly constructed from long slender x-helical microfibrils, which is cross linked to an amorphus protein matrix phase (Fraser and MacRae, 1980). The cells responsible for keratin synthesis, termed keratinocytes, die in the final stages of differentiation when disulphide cross linking are established in the keratin proteins within their cytoplasm. The extensive molecular cross linking within the keratin provides a stable composite of long, thin fibres embedded in a surrounding matrix (Bertram and Gasline, 1987). These cells are held together by disulphide bonds between the amino acids, methionine and cysteine. Methionine and cysteine contain sulphur, which is required in the final stages of keratinisation, allowing the horn to harden fully as the cells die. Areas of horn such as frog and sole have fewer horn tubules and less disulphide bonds. This means they are not as strong but they have a higher number of lipids and sulphydryl groups (proteins containing sulphur) which provide elasticity to those areas (Pollitt, 1998). The stiffness of hoof horn, similar to other keratinised tissues, is affected by the moisture content of the tissue. The inner structures of the hoof capsule are in contact with vascular tissue and fully hydrated while the outer structures are exposed and influenced by environment conditions.

The stratum internum is found on the inner surface of the stratum medium and consists of the primary and secondary epidermal lamellae (SEL). It is produced from the lower border of the coronary corium. This layer interdigitates with dermal (sensitive) lamellae that cover the parietal surface of the distal phalanx and the abaxial surfaces of the collateral ligaments, where they are positioned within the hoof. These lamellae consists of around 600 non-pigmented keratinised primary epidermal lamellae, each of which bares 100-150 non keratinised secondary dermal lamellae (SDL).

These SEL dovetail with the SDL of the laminal corium. Between the dermal and epidermal lamellae is a thin cellular layer labelled as the basement membrane, which undergoes constant remodeling (Pollitt, 2001). This facilitates the SEL sliding past the SDL by breaking and reforming in a staggered, ratchet-like manner so that the keratinised cells can move distally, yet still support load (Pollitt, 2004). This cell-to-cell coupling is called desmosome, one of the stronger cell to cell adhesion types and are found in tissue that experience intense mechanical stress.

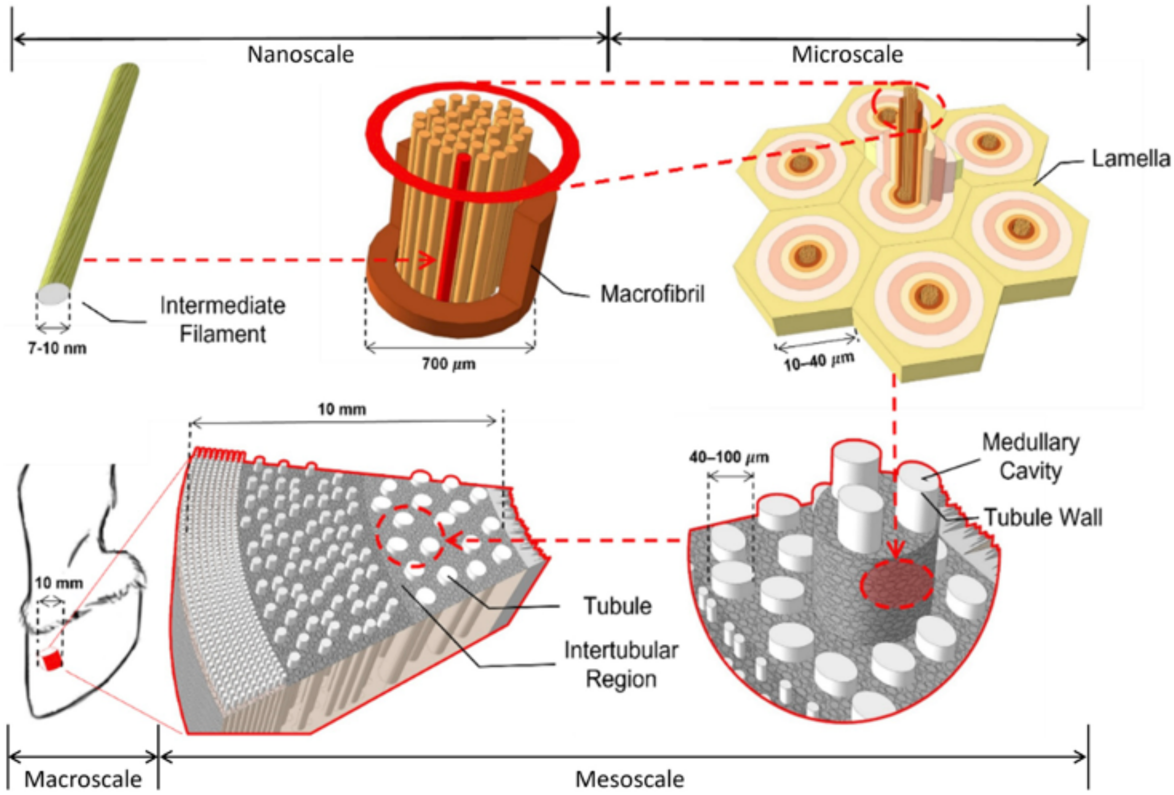

Figure 1: *The Hierarchial structure of an equine hoof wall (Mahrous et al, 2023) with permission (Appendix 1)*

Reasons for performing this study

If this study shows a correlation between true hoof wall thickness and sole thickness, it will give farriers a better understanding of how much sole depth is present, therefore improving foot trimming, hoof health and soundness.

Hoof wall thickness can be measured externally by using the following equation, as depicted in figure 2.

$$\text{Hypotenuse} \times \sin(B) = \text{opposite}$$

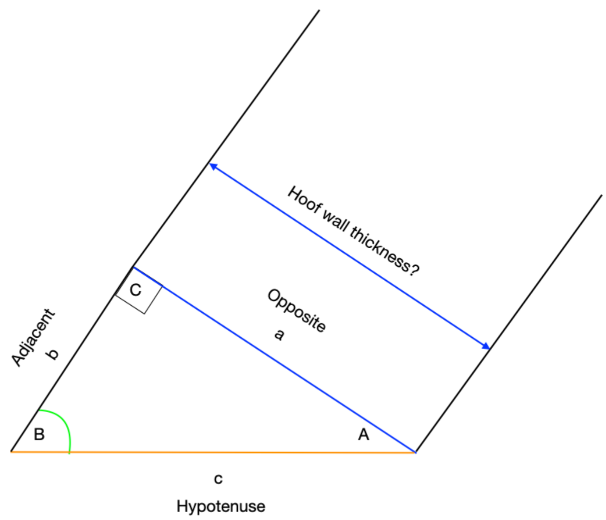

Figure 2: *Hoof wall thickness calculation*

If there is a correlation between hoof wall thickness, which can be measured externally and sole thickness, which cannot, it would be possible to accurately predict sole thickness.

Aim

To investigate the hypothesis that there is a correlation between epidermal hoof wall thickness (HWT) and epidermal sole thickness (ST) in Thoroughbred hooves.

Objectives

The objectives of this study:

1. To measure and collect data from three points in the dorsal region of the hoof wall and epidermal sole.

2. To compare the three regions lateral, central and medial and statistically determine if there is a correlation.

Methods and materials

All cadaver samples used for this study were a selection of Thoroughbred front and hind feet unshod for a least five months. All specimens were collected from two separate locations, approximately 20 miles apart, where they had been living predominantly outdoors. The feet were free of gross pathologies such as laminitis, gross hoof capsule distortions, cracks or serious hoof defects. All limbs were frozen at -18 to -20°C within 12 hours of euthanasia. The cuts were made with a band saw[1] whilst frozen and then left to thaw for 10 hours before measurements were taken. Each measurement was performed three times using digital calipers[2] and the data was recorded in a spread sheet[3].

To control data integrity and focus on maintaining reliability across different dimensional feet the hoof capsules were measured from the hair line to the distal border of the hoof wall at the mid-centre of the dorsum. A transverse cut was made at one quarter of the hoof length, distal and parallel to the coronary band (figure 3). This method follows Moore (2016).

Figure 3: *Position of transverse cut*

The anterior cut to measure sole depth was made at the hypothesised apex of the distal border of distal phalanx (ADP) this line is identified by hoof mapping the solear surface of hoof capsule. The hoof mapping process followed that of Moon (2019), using the positions of solear landmarks (Figure 4).

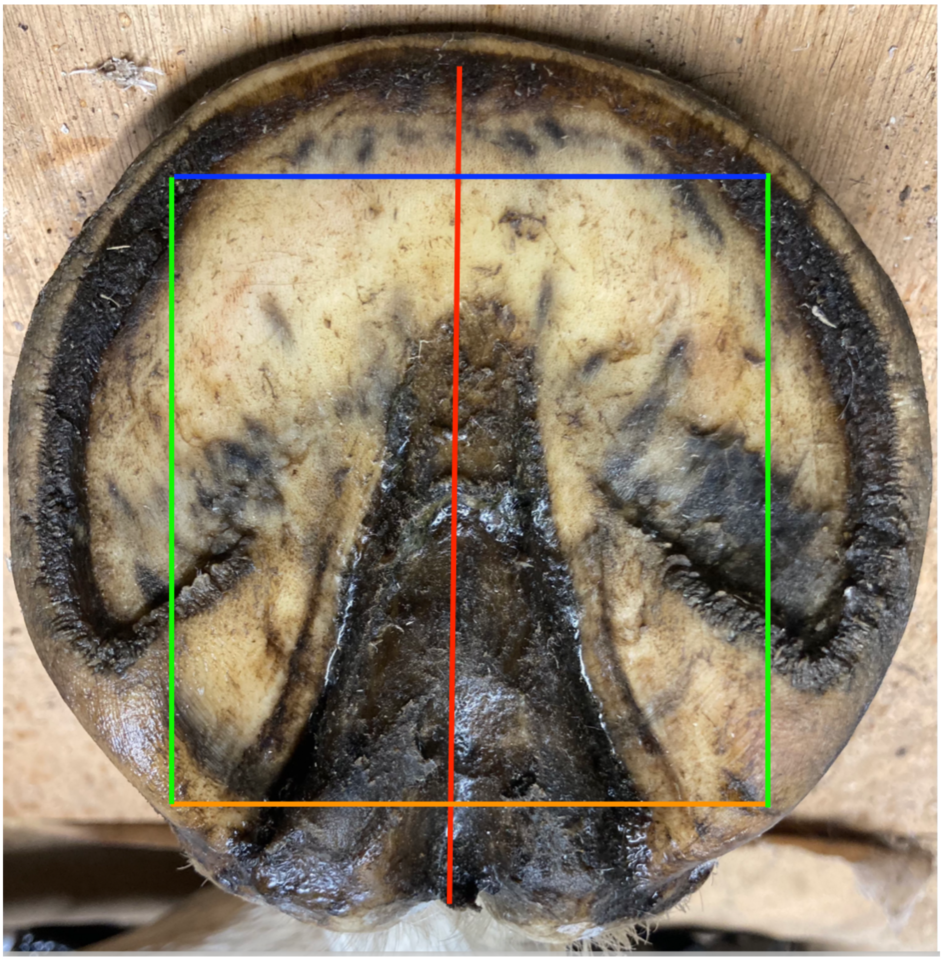

Figure 4: *Hoof mapping using solear landmarks: A line drawn down the middle of the frog and across the sole to the centre of the toe (red line). Two parallel lines each side of centre line were drawn from the buttress of the heel at the last point forward to the white line (green line).*
A line drawn perpendicular to the centre line from the two green lines where the green lines meet the white line (blue line).
The buttresses of the heel were marked at the most caudal part of the bearing surface of the hoof wall (orange line).

All horses used in this study were euthanised for reasons not linked to this study. All cadaver samples arrived with full verbal agreement to be used in the aid of science.

Following the sectioning of the hoof capsule corresponding lines were applied to the transverse portion of the hoof. The point at which these lines met the hoof wall determined the repeatable hoof wall thickness measuring points (figure 5).

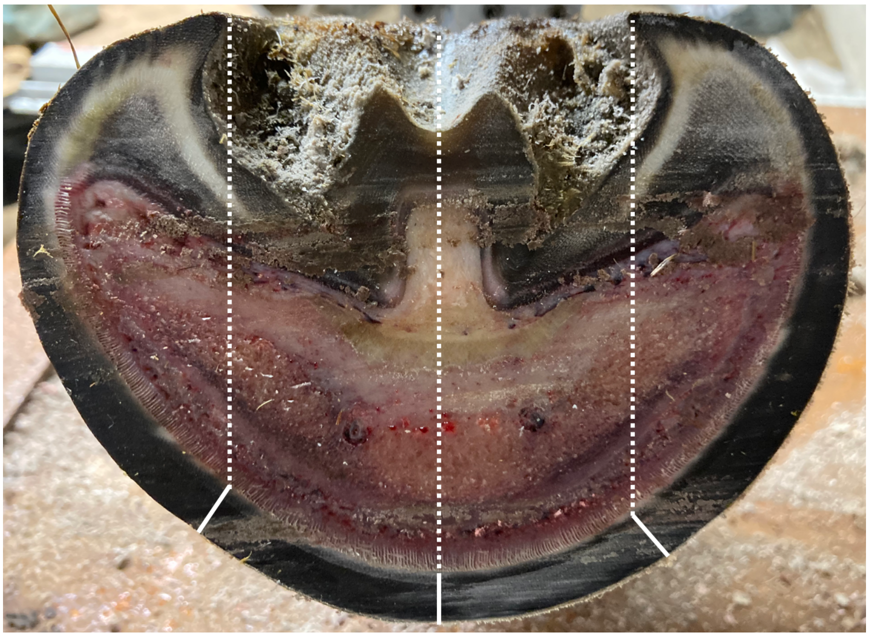

Figure 5: *Hoof wall measuring points indicated by solid white lines, repeatable mapping locations indicated by dotted white.*

The sole thickness measuring points were positioned lateral and medial at the hoof wall and sole junction, with a central measuring point located equidistant between them (figure 6).

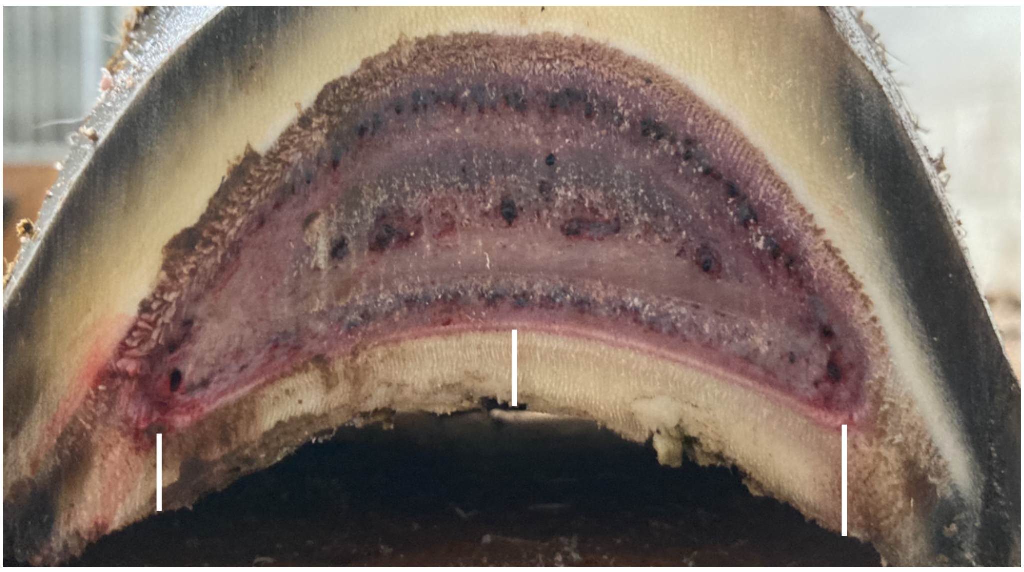

Figure 6: *Sole thickness measuring points indicated in white*

The data was then analysed to compare the medial, central and lateral hoof wall measurements versus medial, central and lateral sole measurements. This was followed by calculating the average hoof wall and average sole measurements and correlating the two, as well as analysis of fore and hind and right and left feet.

Statistical analysis

The hoof wall and sole data were saved and analysed using Microsoft Excel[3].

Regression was performed to analyse the relationship between hoof wall thickness and sole thickness, to test the hypothesis. A correlation coefficient of zero indicates that no linear relationship exists between two continuous variables, and a correlation coefficient of −1 or +1 indicates a perfect linear relationship. The strength of relationship can be anywhere between −1 and +1.
The coefficient of determination (R^2) is a number between 0 and 1 that measures how well a statistical model predicts an outcome. You can interpret the R^2 as the proportion of variation in the dependent variable that is predicted by the statistical model. The lowest R-squared is 0 and means that the points are not explained by the regression whereas the highest R-squared is 1 and means that all the points are explained by the regression line.

Skewness and kurtosis are the test for normality, to check if the data has a normal distribution ("bell-shaped curve") or not and determine the best statistical test to carry out.

To determine whether the dataset should be analysed as one or split for regression analysis, two-sample t-tests (unequal variances) were performed to determine whether or not there was a significant difference between fore/ hind and left / right hooves. Where p value <0.05, reject null hypothesis and accept the hypothesis that there is a statistical difference between the datasets.

A summary of the statistical analysis completed on the dataset can be seen in Appendix 2.

Results

It was hypothesised that there would be a correlation between hoof wall thickness and sole thickness. The raw data, detailed in Appendix 3, was the basis for the statistical analysis to prove the correlation.

The results indicated a mean hoof wall thickness of 9.81mm (SD=0.88) and a mean sole thickness of 8.55mm (SD = 1.37), as shown in Table 1.
The results showed that the range of average sole thickness was between 5.72mm to 11.88mm, with 66% of feet within a 2mm range (7.51mm to 9.5mm) (figure 7). The range of average hoof wall thickness was between 7.44mm and 11.11mm, with 76% within a 2mm range (9mm – 11mm) (figure 8).

Table 1: *Mean sole and hoof wall thickness with standard deviation*

	Medial Hoof Wall Thickness (mm)	Centre Hoof Wall Thickness (mm)	Lateral Hoof Wall Thickness (mm)	Average Hoof Wall Thickness (mm)	Medial Sole Thickness (mm)	Central Sole Thickness (mm)	Lateral Sole Thickness (mm)	Average Sole Thickness (mm)
Mean	10.10	9.59	9.73	9.81	8.39	8.91	8.36	8.55
Standard Deviation	1.02	0.94	1.03	0.88	1.32	1.70	1.40	1.37

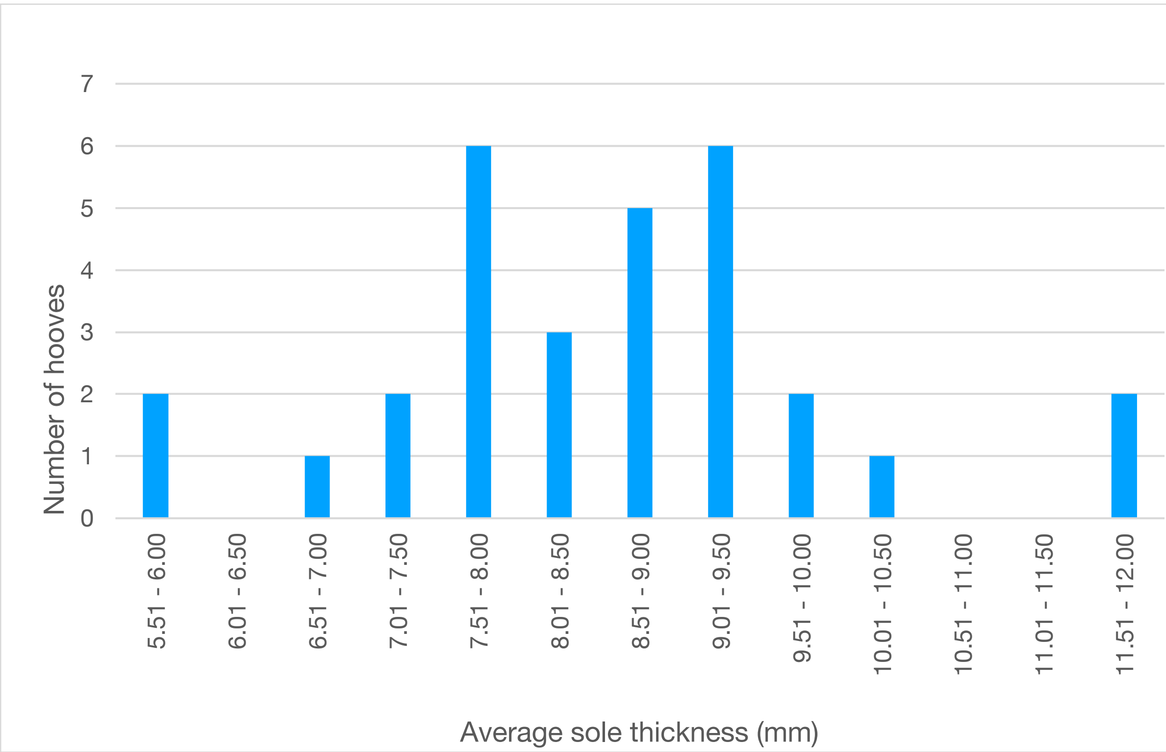

Figure 7: *Graph showing the range of average sole thickness measurements across n=30 feet.*

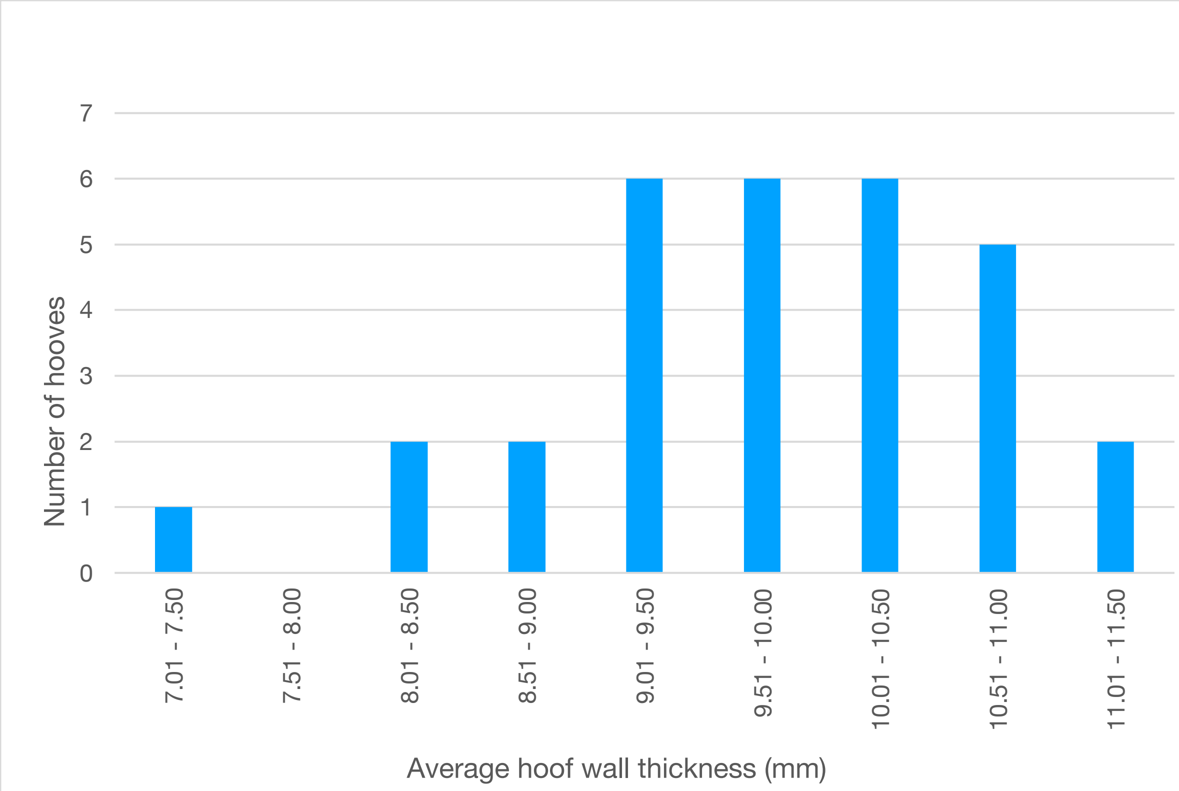

Figure 8: *Graph showing the range of average hoof wall thickness measurements across n=30 feet.*

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The mean thickness differed across the medial, central and lateral hoof wall and sole (figure 9).

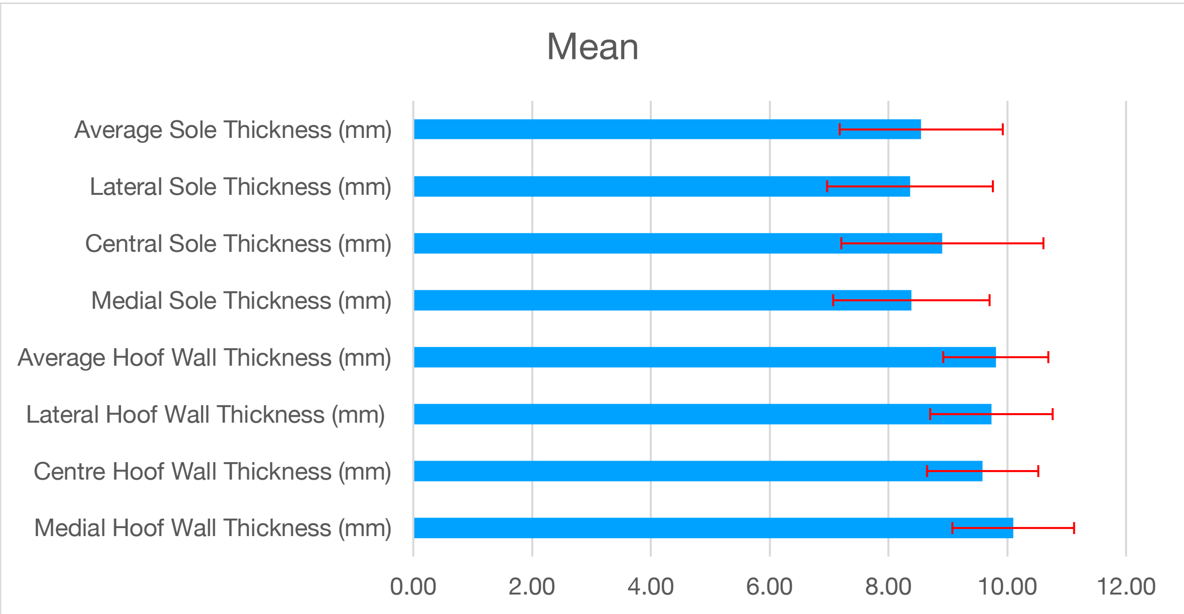

Figure 9: *The mean of the medial, central, lateral and average HWT and ST. Blue representing the mean value and red representing standard deviation.*

The data for fore versus hind feet showed hind medial, lateral and central hoof wall and sole was not significantly thinner than the fore medial, lateral and central hoof wall and sole (table 2).

Table 2: *T-Test: Two sample assuming unequal variances (Fore and Hind Feet)*

	Hind Lateral Sole	Fore Lateral Sole	Hind Central Sole	Fore Central Sole	Hind Medial Sole	Fore Medial Sole	Hind Lateral Wall	Fore Lateral Wall	Hind Central Wall	Fore Central Wall	Hind Medial Wall	Fore Medial Wall
Mean	8.08	8.55	8.30	9.31	8.36	8.41	9.42	9.95	9.60	9.58	9.91	10.23
Variance	0.97	2.60	0.98	3.87	0.85	2.40	0.52	1.36	0.63	1.08	0.41	1.49
Observations	12.00	18.00	12.00	18.00	12.00	18.00	12.00	18.00	12.00	18.00	12.00	18.00
df	28.00		26.00		28.00		28.00		27.00		27.00	
t Stat	-0.99		-1.86		-0.11		-1.54		0.06		-0.93	
P(T<=t) two-tail	0.33		0.07		0.91		0.14		0.95		0.36	
t Critical two-tail	2.05		2.06		2.05		2.05		2.05		2.05	
Variance Interpretation	Variance difference between hind lateral sole and fore lateral sole (fore: 2.602; hind: 0.969)		Variance difference between hind central sole and fore central sole (fore: 3.867; hind: 0.978)		Variance difference between hind lmedial sole and fore medial sole (fore: 2.41; hind: 0.853)		Variance difference between hind lateral wall and fore lateral wall (fore: 1.36; hind: 0.517)		Variance difference between hind central wall and fore central wall (fore: 1.085; hind: 0.633)		Variance difference between hind medial wall and fore medial wall (left: 1.49; right: 0.41)	
t Stat and P(T<=t) two-tail Interpretation	Hind lateral sole is not signifanctly thinner than the fore lateral sole (T = -0.985451441, p = 0.333)		Hind central wall is not signifanctly thinner than the fore centrak wall (T = -1.862676463, p = 0.074)		Hind medial wall is not signifanctly thinner than the fore medial wall (T = -0.112974845, p = 0.911)		Hind lateral wall is not signifanctly thinner than the fore lateral wall (T = -1.536225315, p = 0.136)		Hind central wall is not signifanctly thinner than the fore central wall (T = 0.057012667, p = 0.955)		Hind medial wall is not signifanctly thinner than the fore medial wall (T = -0.925673883, p = 0.363)	

As significant differences in hoof wall and sole thickness between hind and fore hooves were not detected (Figure 10), but left and right were (figure 11), the relationship between hoof wall and sole thickness was analysed separately for left and right hooves (Table 4).

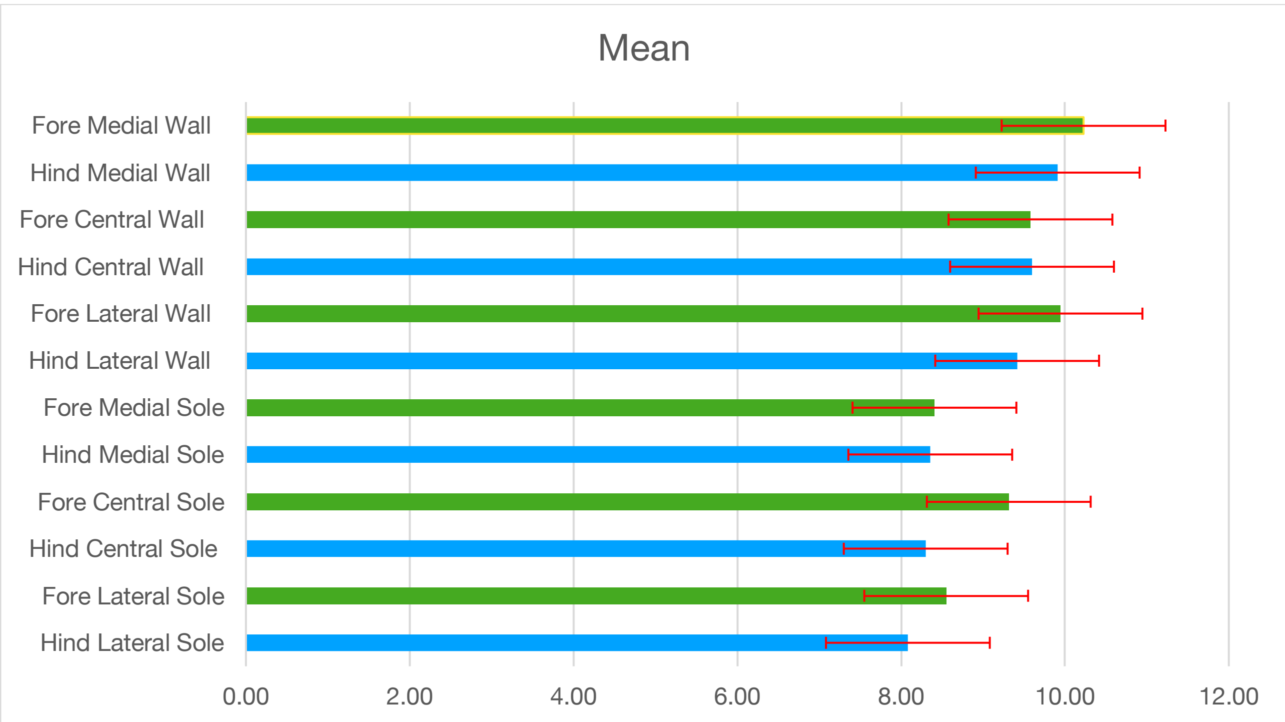

Figure10: *The mean of the medial, central and lateral HWT and ST, split between fore and hind. Green representing the mean fore values, blue representing the mean hind values and red representing standard deviation.*

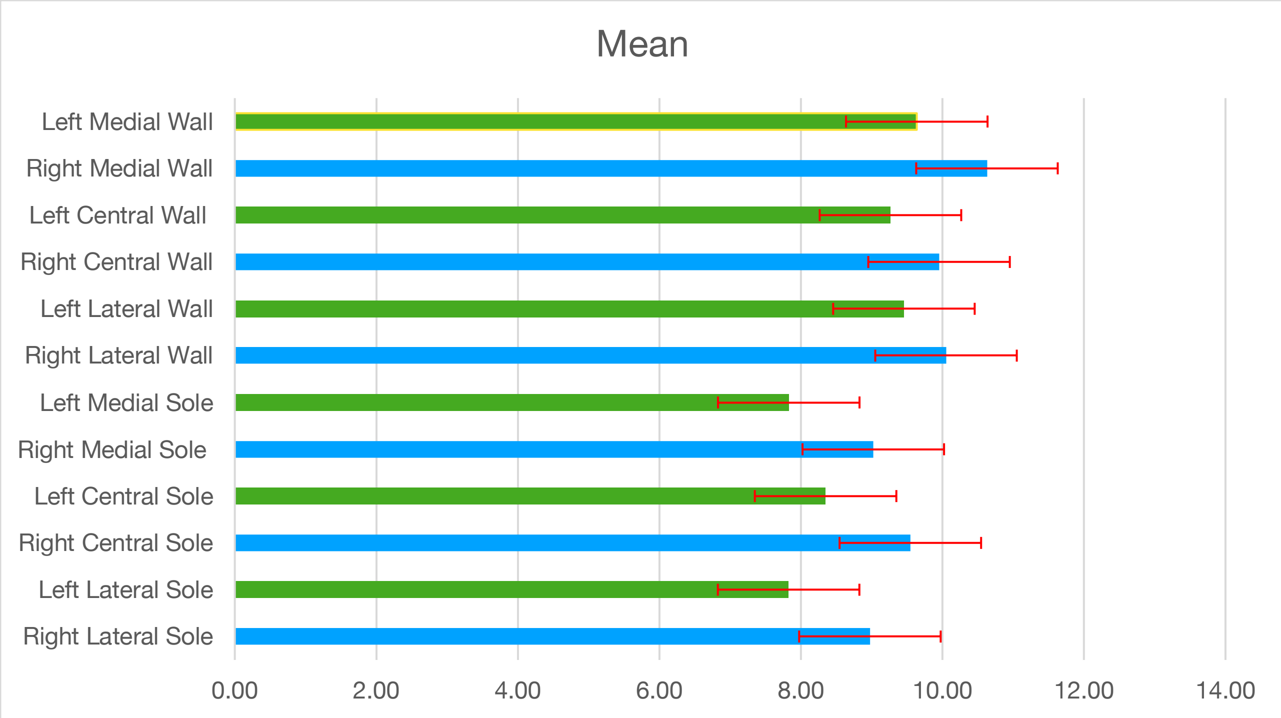

Figure 11: *The mean of the medial, central and lateral HWT and ST, split between right and left. Blue representing the mean right values, green representing the mean left values and red representing standard deviation.*

Data taken from the right and left feet showed the left feet were significantly thinner than the right across four of the six measured positions (lateral sole, medial sole, central wall and medial wall). The two remaining points, central sole and lateral wall were not significantly thinner (table 4).

Table 4: *T-Test: Two sample assuming unequal variances (Right and Left Feet)*

	Right Lateral Sole	Left Lateral Sole	Right Central Sole	Left Central Sole	Right Medial Sole	Left Medial Sole	Right Lateral Wall	Left Lateral Wall	Right Central Wall	Left Central Wall	Right Medial Wall	Left Medial Wall
Mean	8.98	7.83	9.55	8.35	9.02	7.83	10.05	9.46	9.95	9.27	10.63	9.64
Variance	2.39	1.04	3.72	1.66	1.70	1.17	1.08	0.94	0.53	1.00	0.98	0.69
Observations	14.00	16.00	14.00	16.00	14.00	16.00	14.00	16.00	14.00	16.00	14.00	16.00
df	22.00		22.00		25.00		27.00		27.00		26.00	
t Stat	2.37		1.97		2.71		1.61		2.17		2.95	
P(T<=t) two-tail	0.03		0.06		0.01		0.12		0.04		0.01	
t Critical two-tail	2.07		2.07		2.06		2.05		2.05		2.06	
Variance Interpretation	Variance difference between left lateral sole and right lateral sole (left: 1.03; right: 2.38)		Variance difference between left central sole and right central sole (left: 1.66; right: 3.72)		Variance difference between left medial sole and right medial sole (left: 1.17; right: 1.69)		Variance difference between left lateral wall and right lateral wall (left: 0.94; right: 1.08)		Variance difference between left central wall and right central wall (left: 0.999; right: 0.532)		Variance difference between left medial wall and right medial wall (left: 0.69; right: 0.978)	
t Stat and P(T<=t) two-tail Interpretation	Left lateral sole is signifanctly thinner than the right laternal sole (T = 2.367370315, p = 0.027129577)		Left central sole is not signifanctly thinner than the right central sole (T = 1.970914107, p = 0.06)		Left medial sole is signifanctly thinner than the right medial sole (T = 2.709761501, p = 0.01)		Left lateral wall is not signifanctly thinner than the right laternal wall (T = 1.61309215, p = 0.118)		Left central wall is signifanctly thinner than the right central wall (T = 2.166954959, p = 0.039)		Left medial wall is signifanctly thinner than the right medial wall (T = 2.948741864, p = 0.007)	

Average hoof wall thickness versus average sole thickness revealed a moderate correlation R^2 =0.459. 46% of the variability in the outcome data can be explained by the regression model (figure 12). The strongest correlation was seen in the medial hoof wall thickness versus medial sole thickness analysis revealing a positive linear relationship (R^2 =0.530). 53% of the variability in the outcome data can be explained by the regression model (figure 13).

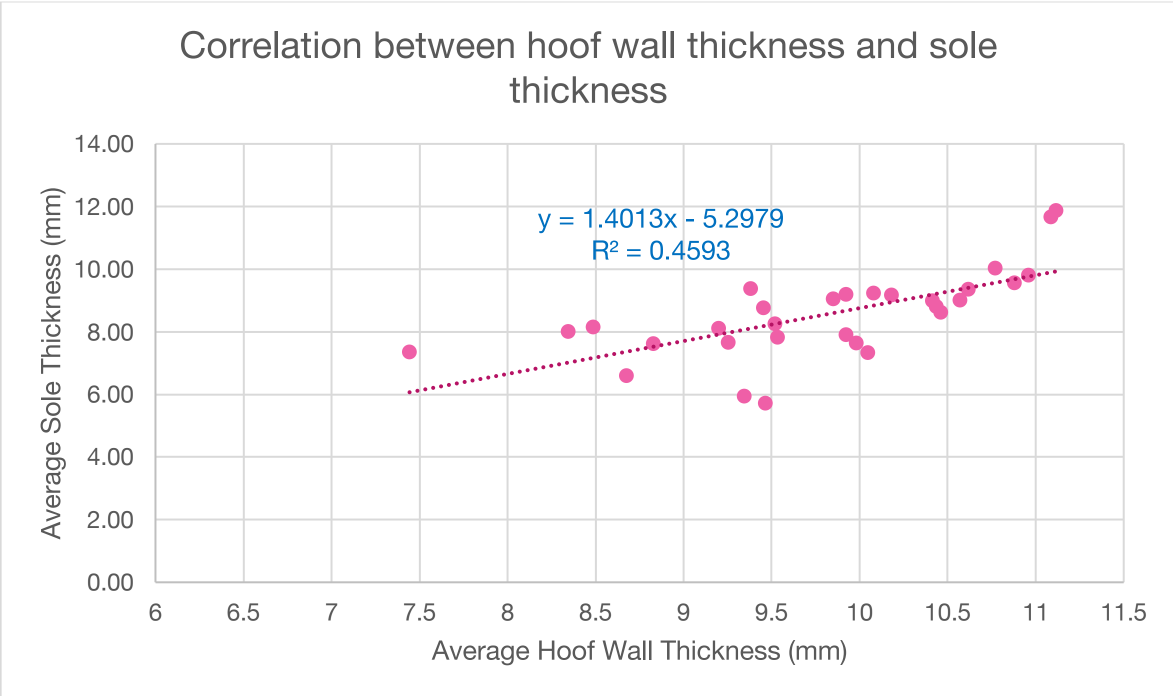

Figure 12: *Scatter graph showing average hoof wall thickness versus average sole thickness.*

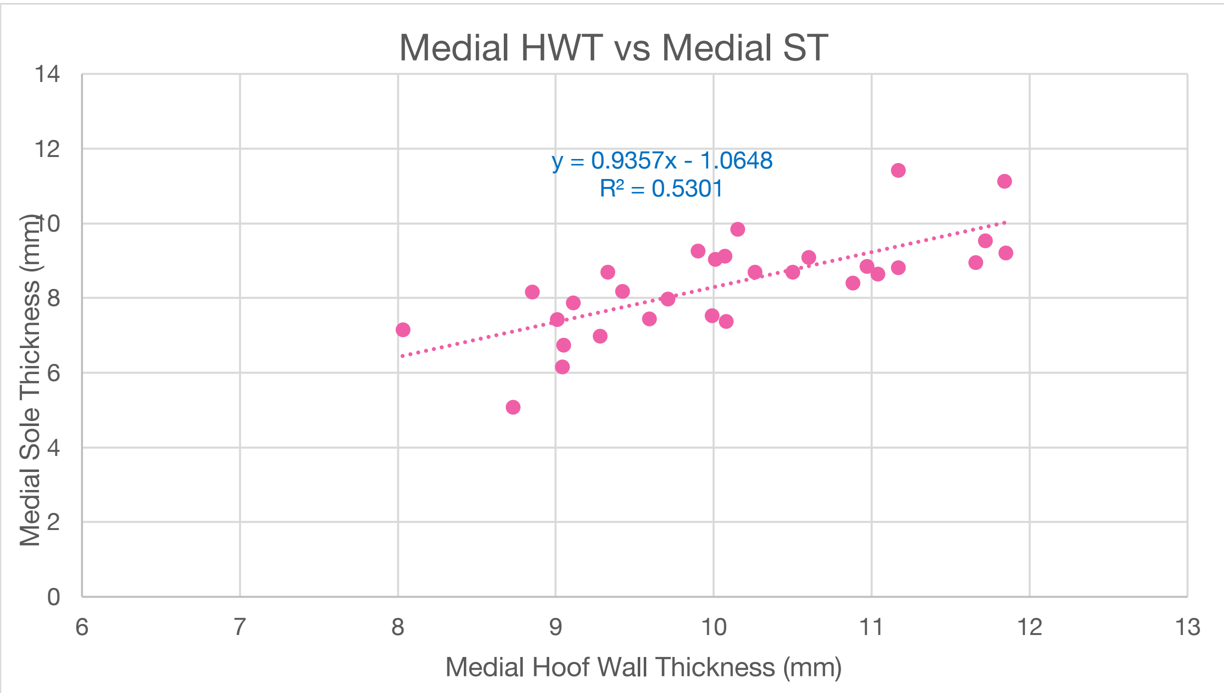

Figure 13: *Scatter graph showing medial hoof wall thickness versus medial sole thickness.*

Central hoof wall thickness versus central sole thickness revealed the weakest relationship (R^2 = 0.154). 15% of the variability in the outcome data can be explained by the regression model (figure 14). Lateral hoof wall thickness versus lateral sole thickness revealed a moderate positive linear relationship (R^2 = 0.337). 34% of the variability in the outcome data can be explained by the regression model (figure 15).

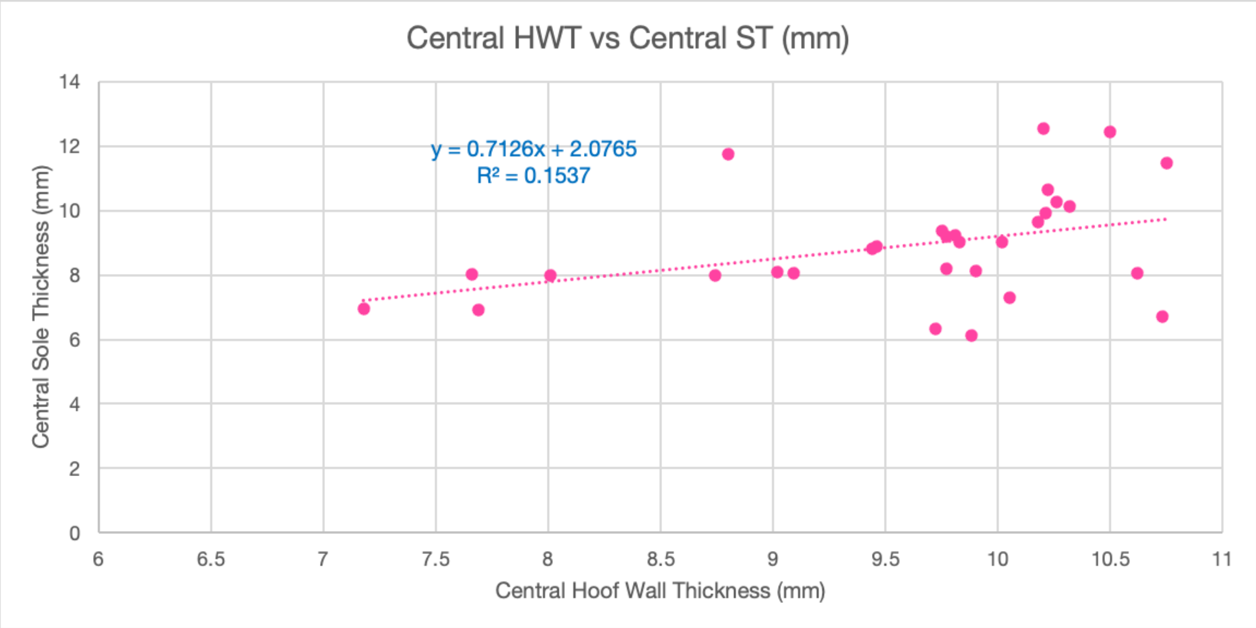

Figure 14: *Scatter graph showing central hoof wall thickness versus central sole thickness.*

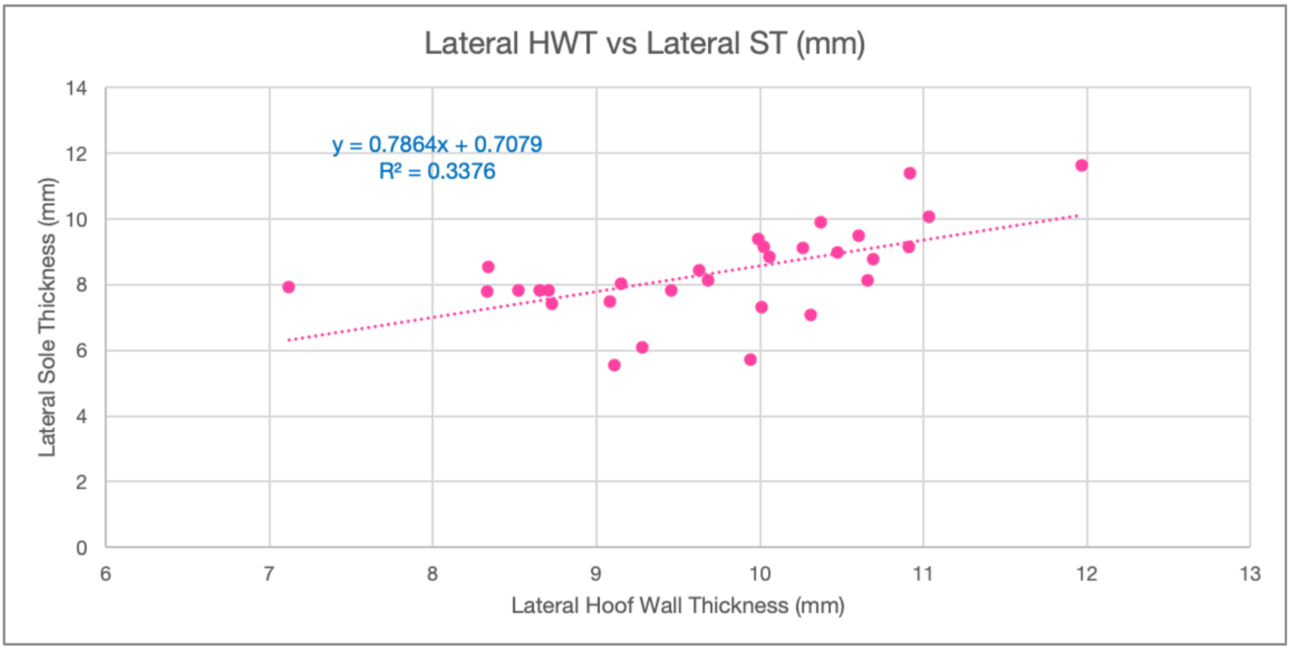

Figure 15: *Scatter graph showing lateral hoof wall thickness versus lateral sole thickness.*

There was a significant difference between left and right hoof wall thickness and sole thickness correlations. The correlation of the average hoof wall and sole thickness across the left feet was weak ($R^2 = 0.186$), resulting in only 19% of the variability being explained by the regression model (figure 16). On the right feet, the same analysis resulted in 59% of the variability being explained by the regression model, showing a good positive correlation of $R^2 = 0.59$ (figure 17).

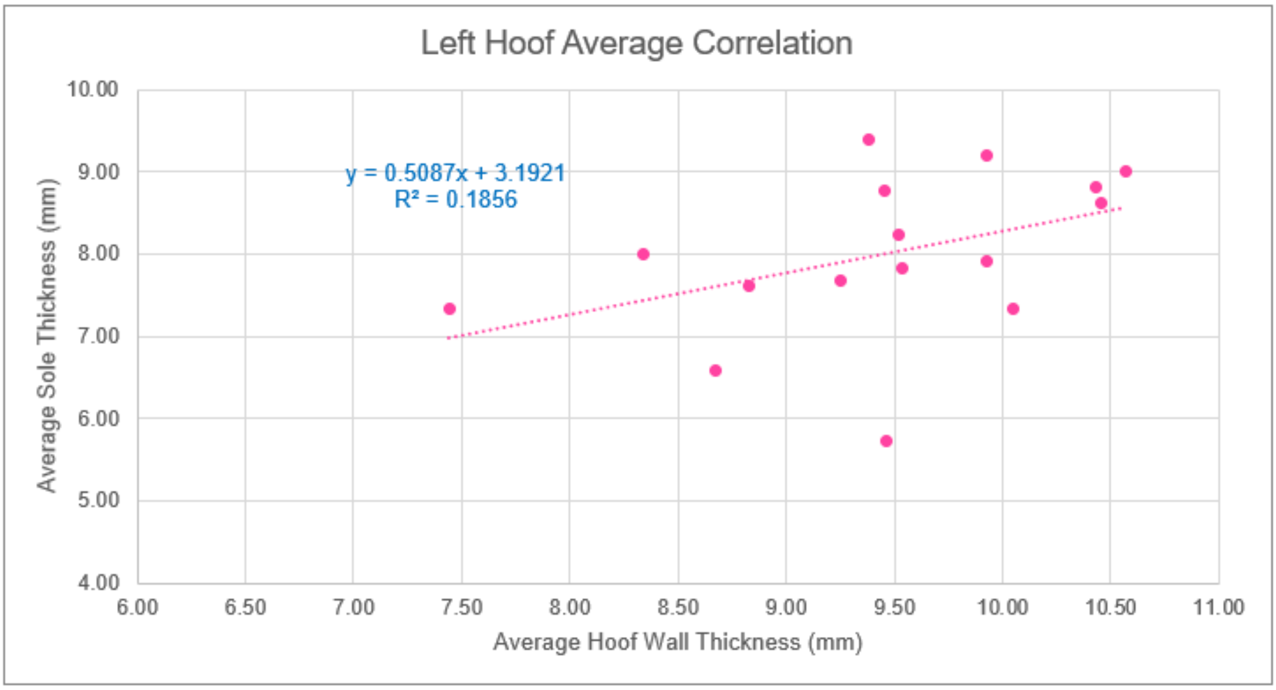

Figure 16: *Scatter graph showing the correlation between average hoof wall thickness and average sole thickness across the left feet.*

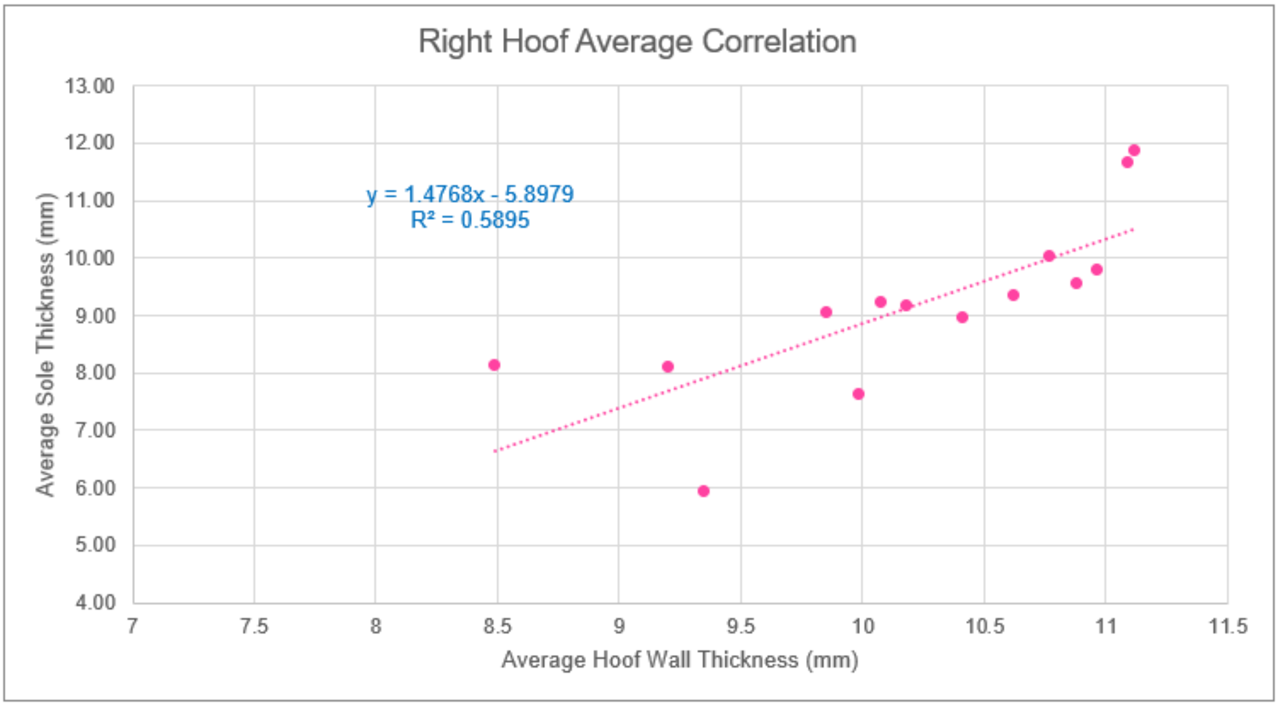

Figure 17: *Scatter graph showing the correlation between average hoof wall thickness and average sole thickness across the right feet.*

The measurements were further analysed for the left and right feet separately and correlations performed for the individual measuring points. The results of which showed the right feet had a stronger correlation across all three positions with the right lateral displaying the strongest correlation (R^2 = 0.549) (figure 18) followed by the right medial (R^2 = 0.452) (figure 19). The weakest correlation of the right feet was the central position (R^2 = 0.164) (figure 20).

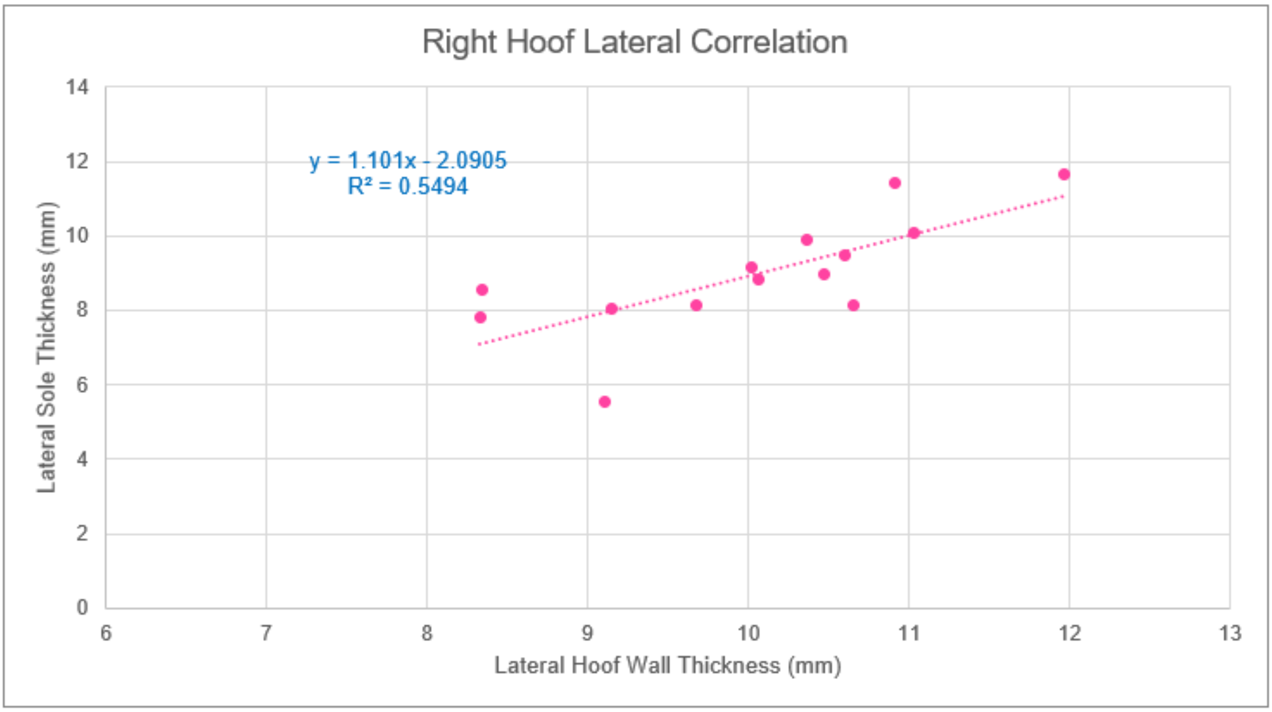

Figure 18: *Right lateral hoof wall thickness versus right lateral sole thickness revealed a good positive linear relationship (R^2 = 0.549). 55% of the variability in the outcome data can be explained by the regression model.*

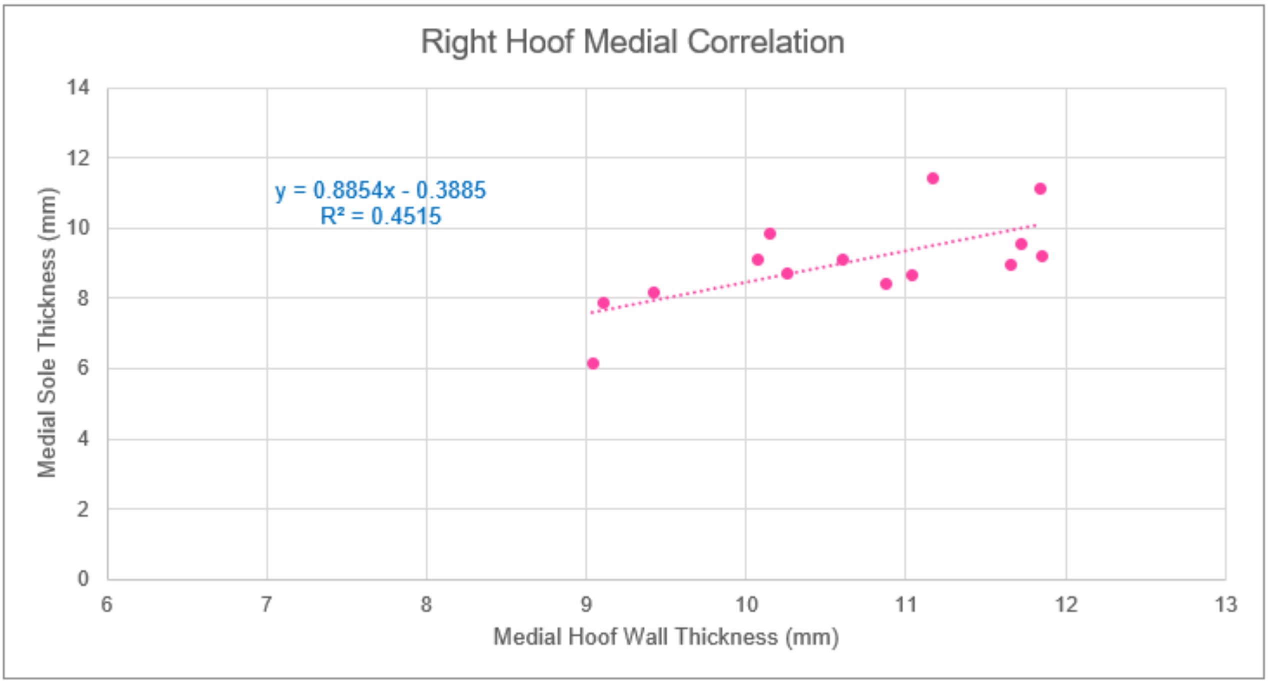

Figure 19: *Right medial hoof wall thickness versus right medial sole thickness revealed a moderate positive linear relationship (R^2 = 0.452). 45% of the variability in the outcome data can be explained by the regression model.*

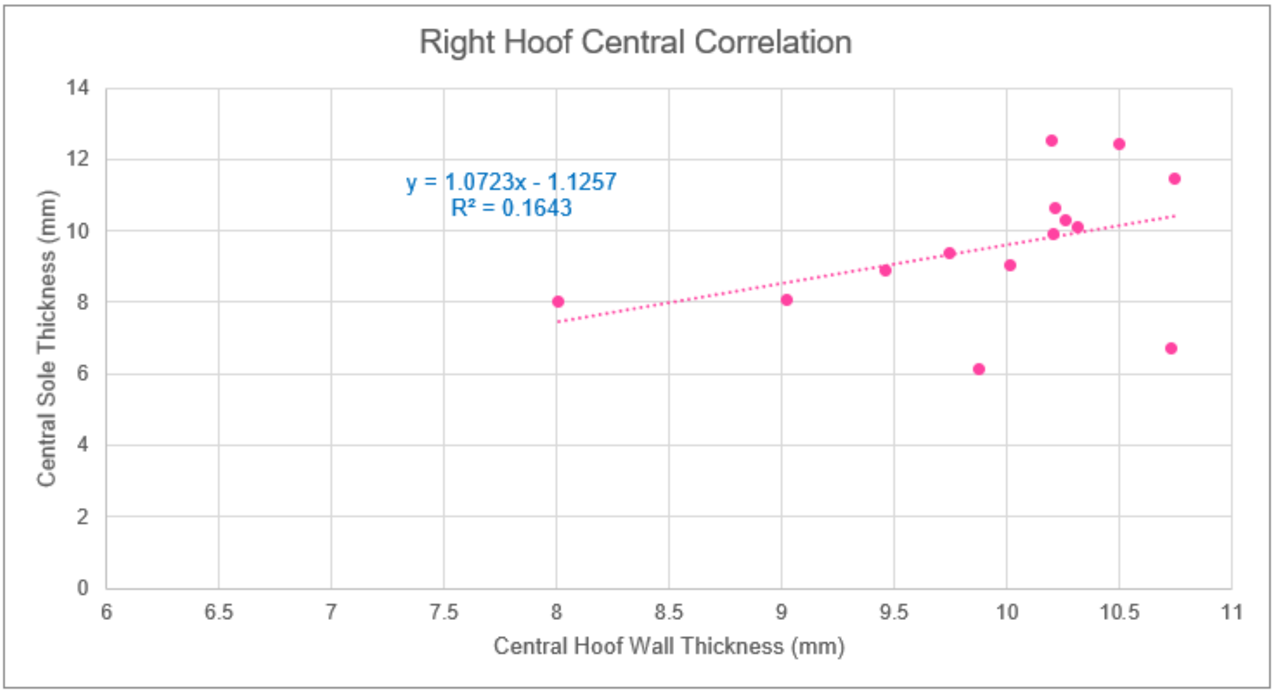

Figure 20: *Right central hoof wall thickness versus right central sole thickness revealed a weak positive linear relationship (R^2 = 0.164). 16% of the variability in the outcome data can be explained by the regression model.*

The results showed the closest correlation between right and left feet was at the medial measuring point with the left revealing a moderate positive relationship (R^2=0.385) (figure 21). The remaining two positions, central (R^2=0.056) and lateral (R^2=0.060), revealed very weak relationships (figure 22; figure 23).

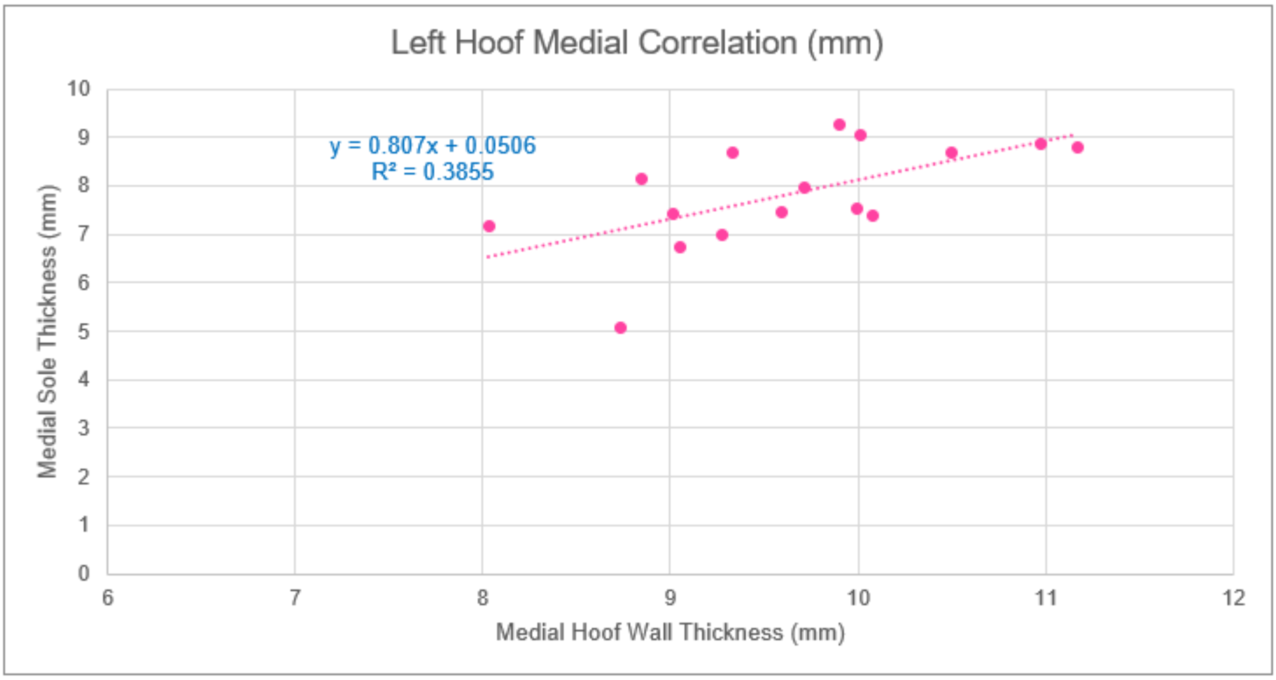

Figure 21: *Left medial hoof wall thickness versus left medial sole thickness revealed a moderate positive linear relationship (R^2 = 0.385). 39% of the variability in the outcome data can be explained by the regression model.*

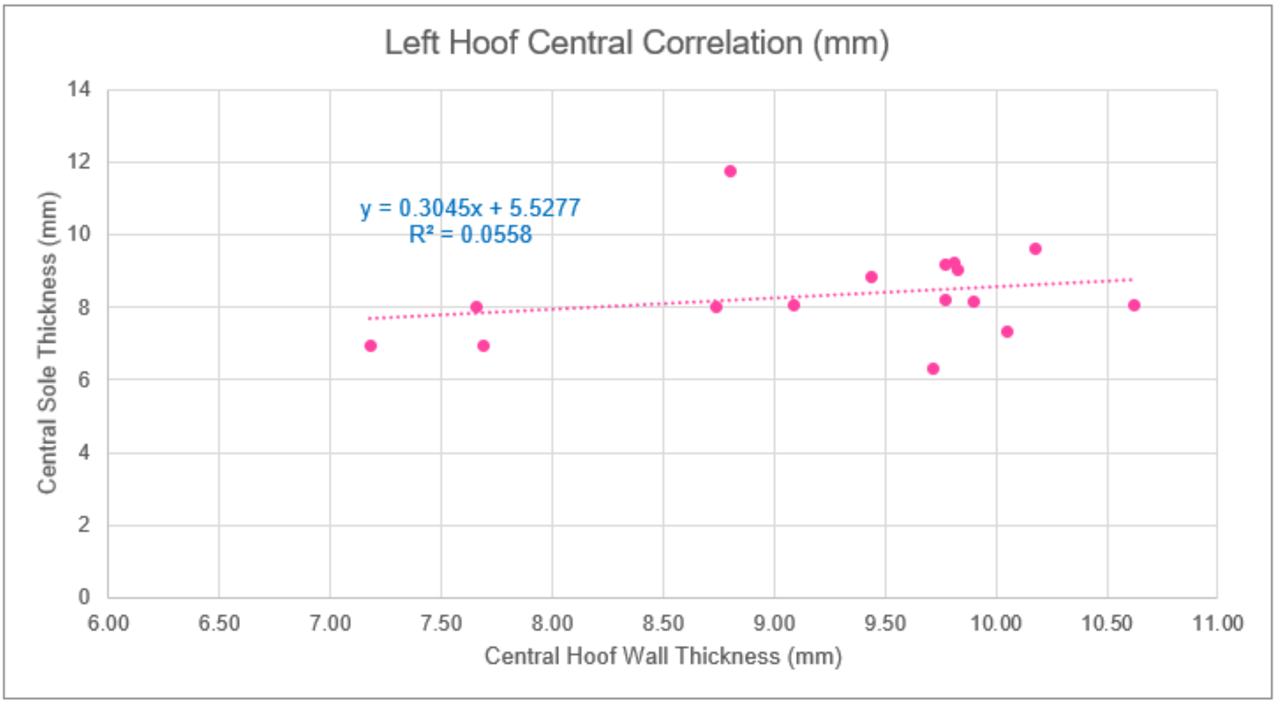

Figure 22: *Left central hoof wall thickness versus left central sole thickness revealed a very weak positive/ no linear relationship (R^2 = 0.056). 6% of the variability in the outcome data can be explained by the regression model.*

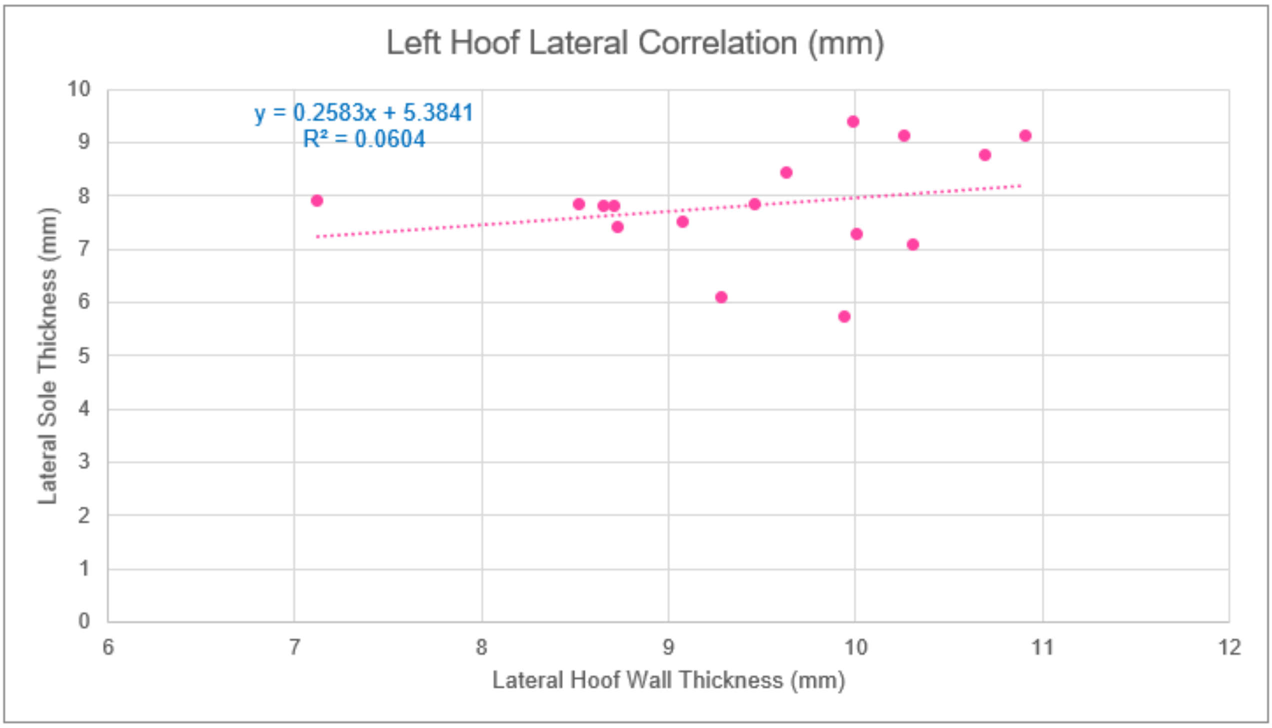

Figure 23: *Left lateral hoof wall thickness versus left lateral sole thickness revealed a very weak positive/ no linear relationship (R^2 = 0.060). 6% of the variability in the outcome data can be explained by the regression model.*

Discussion

This study investigated a correlation between hoof wall thickness and sole thickness in n= 30 unshod Thoroughbred feet. The objective of the study was to strengthen knowledge and understanding of the relationship between the hoof wall and the sole, thus gaining more information about the solear structure and function.

Farriery influence and human accuracy were controlled to the best of the authors ability, with all of the specimens under his control prior to euthanasia. The horses were trimmed for field rest with no sole removed and the hoof wall bevelled with only the distal third of the hoof wall flare dressed. This ensured all feet started the study with a controllable, hoof preparation by the same farrier.

The data (n=30) showed the mean hoof wall thickness measured 9.80mm (SD = 0.88 mm). The medial measurement was the greatest (M = 10.10 SD = 1.02 mm), suggesting the hoof wall increases or can adapt to load. Pollitt (1992) stated the morphology of epidermal cells changed due to the imposed stresses. A similar mechanism, which is responsible for hoof growth, is applied to the ability of the hoof to remodel. The data positions for the medial and lateral hoof wall measurements were as predicted and followed the data of a study by Hobbs (2022), in which epidermal hoof was thicker medially than laterally.

Sole depth data was collected over three points, corresponding to the medial, central and lateral hoof wall data points, shown in the methods and materials. The morphology of the soles was examined, all soles had no callus sole to remove. The sole depth (M = 8.55 SD = 1.37 mm) indicated the central sole thickness was thicker than the medial and lateral. Environmental and climate effects were a consideration as the horses were euthanised at different seasonal times. This may have resulted in differing substrate and ground conditions of the horse's habitat, prior to euthanasia. Hampson (2011) stated he found different sole depths from three groups, feral horses from soft substrate, feral horses from hard substrate and domestic Thoroughbreds. Feral horses from hard substrate habitats had a greater mean sole depth than feral horses from soft substrate habitats. Furthermore, both populations had a greater mean sole depth than managed Thoroughbreds.

The mean central sole depth of 8.90 mm (SD = 1.70) may imply that the hoof adapts its solear depth to match its environment, this is suggested by Hampson (2011).

Grundmann (2012) found lateral and medial epidermal sole depth to be greater near the hoof wall sole junction, which may imply that there could be differing growth rates of sole horn across the solear plane. However, this action may be due to rate of wear influence by mechanical load and hoof morphology. The concept of differential growth rate for epidermal sole has not been proposed. A controlled study of regional growth rate of sole horn would confirm or refute this assumption (Hampson, 2011).

Hoof growth rate is principally related to the number of keratinocytes duplicating from the basal layer and papillae and how well these can swell whilst differentiating in interpapillary space. The process of soft tissue cells making hard ones is essential as the sole can be a weight bearing structure. This process is, in theory, possible by the ability of dead, soft structures to reorganise single keratin filaments into large connective bundles under pressure (Al-Agele, 2019). This process could explain the variation in sole measurements across the hooves, with the sole responding and adapting to pressure from the horse's body weight and external forces. The role of the hoof adapting to contact between horse and ground is essential, for strong hooves and sound horses.

Bowker (2003) stated that as the foot interacts with its environment, it responds and becomes remodeled to form a strong foot. He argued that the influence of environment on the hoof is even stronger than genetics.

The statistical analysis reported that there was no variance difference between fore and hind feet, this was not anticipated as the different tasks of the fore and hind hooves and limbs are reflected in their anatomy. For example, in cannon bone length and shape, the metacarpus is shorter than the metatarsus and the cross section of these bones differ. The front hoof capsules have shorter heel length and different hoof angles than hinds (Stachurska, 2008). Viewed from the solear surface, the front hooves are wider and rounder than the hinds, which are narrower and more triangular or pear shaped (Back et al, 2001). The fronts have a less concave sole and a shorter and broader frog (Stachurska, 2008).

The different hoof conformation between fore and hind feet is influenced by distal phalanx shape. The shape differs by virtue of the influence of weight bearing, which is greater over the front hooves than the hind. This is reflected in the solear surface being more vaulted and the parietal surface being more upright and angled in the fore distal phalanx bone.

There was a significant difference in the hoof wall and sole thickness between left and right. The results showed that the left lateral and the left medial sole was significantly thinner than the right. The left central and the left medial hoof wall were significantly thinner than the right.

These findings pose questions relating to the reasons for the significant difference. Laterality has been investigated in feral and domesticated equids. Different horse breeds are reported to have variable, individual and population laterality. Thoroughbreds have been shown to have a longer third metacarpal bone on the right than the left (Cully et al, 2018).

The effect of asymmetry on the limb is a considerable factor, conformation and posture variants have an influence on leg length. Leg length asymmetry causes a difference in loading and differing compensatory mechanisms (Wilson et al, 2009). The author has mentioned that the hoof is a dynamic structure capable of modifying its conformation to the forces placed on it. This statement supports findings by Van Heel et al (2006) who found that foals which developed a preference to protract the same limb whilst grazing developed more asymmetrical feet than foals who did not develop this preference.

This study confirms a correlation between hoof wall thickness and sole thickness ($R^2 = 0.46$) in n=30 unshod Thoroughbreds, proving that once HWT is identified, an assessment of ST can be made. In individual feet, variation in the thickness of the sole was observed across the three measuring points, however the findings give a better understanding and accurate evaluation of sole thickness, when compared to manual palpitation.

The author also believes the sole thickness data will benefit the farrier, when aligned with radiographs to create a greater insight into hoof morphology.

This study has described the position, structure and function of the hoof wall and sole of the horse, in detail. The HWT (9.81mm) and sole thickness (8.55mm) indicate the small parameters a farrier is working with every day

Assumptions of sole depth can be misleading, whether assessing manually or reviewing radiographs. Sole dermis thickness, similar to epidermal sole thickness, can vary across a single hoof and different environmental substrate (Hampson, 2011). The thickness of the sole dermis can be difficult to validate on a radiograph, therefore a simple method to calculate sole thickness is important.

Limitations of the study

The study was performed on one breed (Thoroughbreds) and thirty feet. The measuring points were all in the dorsal aspect of the hoof capsule as this is where the author hypothesised the necessity to establish an accurate sole depth. The environmental and seasonal factors were a variable, but it was not considered necessary to control this as it would not be possible during everyday farriery work and therefore reflected the relevance of this study on the work of the practicing farrier.

Repeating the study on a population of non-Thoroughbred horses, all of the same breed, with additional measuring points across the hoof capsule would add greater knowledge of the hoof morphometrics and the relationship between the hoof wall and the sole.

Conclusion

A method for identifying a correlation between HWT and ST in Thoroughbred horses has been established. The study has highlighted some variation in sole thickness across the hypothesised apex of the distal phalanx. This method offers a proven approach. It is, however, recommended to be used as an additional aid to hoof evaluation.

Radiographic imaging is, the “gold standard” in internal structure evaluation and plays a very important role in farriery but for most horses the availability of radiographs and MRIs is not an option.

This study has provided a foundation for the understanding of hoof wall thickness and sole thickness correlation.

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Appendices

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Multimodule imaging of the hierarchical equine hoof wall porosity and structure

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BACK

CLOSE WINDOW

Appendix 1: *Authorisation to use image in figure 1, stating it is not required for non-commercial use.*

	Medial Hoof Wall Thickness (mm)	Centre Hoof Wall Thickness (mm)	Lateral Hoof Wall Thickness (mm)	Average Hoof Wall Thickness (mm)	Medial Sole Thickness (mm)	Central Sole Thickness (mm)	Lateral Sole Thickness (mm)	Average Sole Thickness (mm)
Mean	10.10	9.59	9.73	9.81	8.39	8.91	8.36	8.55
Standard Error	0.19	0.17	0.19	0.16	0.24	0.31	0.25	0.25
Median	10.04	9.82	9.97	9.92	8.67	8.86	8.12	8.70
Standard Deviation	1.02	0.94	1.03	0.88	1.32	1.70	1.40	1.37
Sample Variance	1.05	0.88	1.06	0.78	1.73	2.89	1.95	1.88
Kurtosis	-0.79	0.75	0.23	0.30	1.04	-0.18	0.72	0.93
Skewness	0.13	-1.19	-0.31	-0.64	-0.04	0.52	0.25	0.29
Range	3.82	3.57	4.85	3.67	6.34	6.42	6.10	6.16
Minimum	8.03	7.18	7.12	7.44	5.09	6.13	5.55	5.72
Maximum	11.85	10.75	11.97	11.11	11.43	12.55	11.65	11.88
Count	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Confidence Level (95.0%)	0.38	0.35	0.38	0.33	0.49	0.64	0.52	0.51

Appendix 2: *Statistical summary*

Foot	Hoof Width (mm)	Hoof Length (mm)	Medial HWT (mm)	Central HWT (mm)	Lateral HWT (mm)	Average HWT (mm)	Medial ST (mm)	Central ST (mm)	Lateral ST (mm)	Average ST (mm)
Right Fore	135	141	11.66	10.75	10.47	10.96	8.96	11.46	8.97	9.80
Right Fore	121	128	10.26	10.32	10.66	10.41	8.70	10.12	8.12	8.98
Left Fore	125	136	9.71	8.80	9.63	9.38	7.97	11.74	8.44	9.38
Right Fore	133	135	11.84	10.50	10.92	11.09	11.14	12.44	11.40	11.66
Right Fore	132	134	11.17	10.20	11.97	11.11	11.43	12.55	11.65	11.88
Left Fore	117	125	9.28	10.18	10.31	9.92	6.99	9.63	7.09	7.90
Left Fore	130	134	8.73	9.72	9.94	9.46	5.09	6.33	5.73	5.72
Right Fore	134	138	9.04	9.88	9.11	9.34	6.17	6.13	5.55	5.95
Left Hind	123	121	9.33	9.77	9.46	9.52	8.69	8.19	7.84	8.24
Left Hind	125	123	9.01	8.74	8.73	8.83	7.43	7.99	7.42	7.61
Left Fore	130	125	8.85	7.66	8.52	8.34	8.16	8.01	7.84	8.00
Right Hind	111	115	10.88	10.73	8.33	9.98	8.40	6.70	7.80	7.63
Left Hind	120	124	10.08	10.05	10.01	10.05	7.38	7.31	7.30	7.33
Right Hind	119	122	9.42	9.02	9.15	9.20	8.18	8.09	8.04	8.10
Left Hind	115	119	9.90	9.81	8.65	9.45	9.26	9.23	7.81	8.77
Left Fore	125	126	9.59	9.09	9.08	9.25	7.45	8.05	7.50	7.67
Right Fore	140	135	10.60	10.26	9.68	10.18	9.10	10.28	8.12	9.17
Left Fore	142	136	10.50	10.62	10.26	10.46	8.69	8.07	9.12	8.63
Left Hind	116	120	9.99	9.90	8.71	9.53	7.54	8.13	7.81	7.83
Right Hind	118	118	10.15	10.02	10.06	10.08	9.84	9.02	8.83	9.23
Right Hind	116	134	10.07	9.46	10.02	9.85	9.12	8.89	9.15	9.05
Left Hind	121	135	10.01	9.77	9.99	9.92	9.04	9.18	9.38	9.20
Left Fore	122	128	10.97	9.83	10.91	10.57	8.85	9.02	9.14	9.00
Right Fore	120	130	11.72	10.22	10.37	10.77	9.54	10.66	9.91	10.04
Right Fore	119	129	11.85	9.75	11.03	10.88	9.22	9.38	10.06	9.55
Right Hind	124	133	11.04	10.21	10.6	10.62	8.64	9.93	9.5	9.36
Left Fore	118	127	11.17	9.44	10.69	10.43	8.81	8.82	8.78	8.80
Left Hind	115	126	9.05	7.69	9.28	8.67	6.74	6.93	6.1	6.59
Right Fore	124	132	9.11	8.01	8.34	8.49	7.88	8	8.55	8.14
Left Fore	126	135	8.03	7.18	7.12	7.44	7.16	6.95	7.92	7.34

Appendix 3: *Data collected from n=30 feet*