# Hoof Wall Thickness in Equine Feet: The Relevance to Foot Function

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## *List of Abbreviations*

| | |
|---|---|
| HWZ | Hoof Wall Zonation |
| SD | Standard Deviation |
| SMZA | *Stratum Medium Zona Alba* |
| TD | Tubule Density |
| T:HQ | Toe to Heel Quarter |
| THWT | Total Hoof Wall Thickness |

# Contents

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## Summary

***Reasons for performing the study*:** To have a clearer understanding of circumferential hoof wall thickness and its possible relevance to foot function.

***Objectives*:** To determine whether a common toe to heel quarter ratio exists in hoof wall thickness and to compare it to the hypothesis that the hoof wall is twice as thick at the toe than at the heel quarters (2:1). To compare left and right hoof wall thickness and investigate whether breed, foot shape and sole plane have an influence on toe to heel quarter ratio.

***Sample population*:** 20 pairs of cadaver front feet (n=40) from different breeds of domestically kept horses and ponies.

***Methods*:** A transverse cut, parallel to the coronary band was made on all the feet in the study at a distance of 25% of the total dorsal wall length distal to the coronary band. The hoof wall thickness was measured on all the feet using digital callipers, at seven predetermined points.

***Results*:** The mean ± SD (1.77 ± 0.664 mm) hoof wall thickness ratio between the toe and heel quarter was significantly less than 2:1 ($p<0.05$). The right toe thickness mean ± SD (10.26 ± 2.72 mm) was significantly greater ($p<0.05$) than the left fore (10.13 ± 2.58 mm). The total hoof wall thickness showed a significant difference ($p<0.001$) between the right fore (mean ± SD 57.35 ±11.40 mm) and the left fore (56.36 ± 11.03 mm). The hoof wall ratio in relation to breed could not be determined due to the small sample size. Triangular and oval shaped feet, as well as concave soles were not significant ($p>0.05$), whereas round and square shaped feet and flat soles were ($p<0.001$).

***Conclusion and clinical relevance*:** Anatomically, the wall is designed with a horn tubule and moisture gradient, to help dissipate force with areas of high stress having increased numbers of horn tubules and a thicker hoof wall. In the present preliminary study the hoof capsule was found to decrease in thickness from the toe to the heel, but the toe to heel quarter ratio was significantly less than previously suggested. The mean toe and total hoof wall thickness was thicker in the right fore, than in the left fore. Breed, foot and sole planes had mixed results, with further studies needed to ascertain a clearer understanding of the relevance of these to foot function. Further studies on excessive dorsal wall rasping and the consequential effects on foot function, by reducing the natural toe to heel quarter ratio, is recommended.


Key words: hoof wall; hoof wall thickness; hoof wall ratio; horse; foot function.

# Introduction

The equine foot is a single digit, locomotor organ (Reilly 2006). Due to its anatomical construction it is capable of withstanding a large amount of force. A galloping horse will apply approximately 1000 kg of weight/force through the foot (Pollitt 1995). It is because of its unique and complex 3-dimensional structure that these forces are tolerated. When a load is placed on the horse's foot, the descending body weight and ground resistance distorts the hoof capsule by concaving the dorsal wall and expanding the quarters (widest part of the foot) with the toe experiencing the greatest amount of biomechanical and physiological stress (Hampson and Pollitt 2011) (Figure 1a&b).

The hoof wall decreases in thickness from the midline (toe) to the heels (Baxter 2011; Hampson and Pollitt 2011; Pollitt 2004). A study of the Australian feral horse (Brumbie) in 2011, found the toe to be twice as thick as the heel quarters (Hampson and Pollitt 2011). This represents a 2:1 ratio between the toe and heel quarters (T:HQ). This circumferential variation in thickness is thought to affect the flexibility of the hoof wall at different locations. This allows greater rigidity in high force areas (the toe) and more flexibility where expansion and retraction are needed (the heels) (Hampson and Pollitt 2011). Anatomically, the hoof wall is constructed to aid this variation. The outer horn tubules are designed to bear weight and the hoof wall must be robust in these areas to support the hoof capsule as it deforms with load bearing (Hampson and Pollitt 2011). The arrangement of the tubular horn within the hoof wall as well as the natural moisture content, helps to facilitate this expansion and provides rigidity, protection and shock absorption to the foot. The hoof capsule plays a significant part in dampening concussive locomotory forces (Dyhre-Poulson *et al.* 1994) and it could be considered the thicker the hoof wall the stronger the foot, whereas the thinner the wall the weaker the foot.

The hoof capsule is the part farriers influence when shoeing horses. What is achieved when trimming and shoeing the foot has an effect on the horse, both short and long term. The soundness and athletic ability of the horse can often depend on the ability of the farrier to balance and maintain the feet, according to the conformation of the horse and the work it is required to do. With this in mind a great deal of thought and anatomical understanding is needed before hoof is removed from the foot, in particular the dorsal wall.

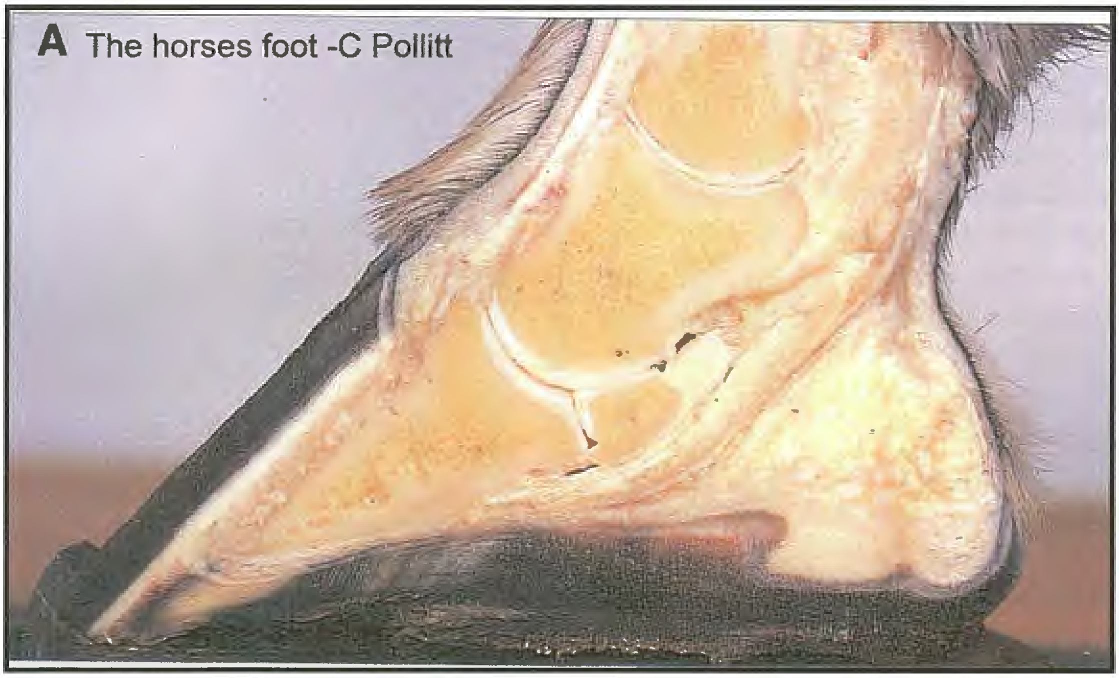


**Figure 1a.** *Sagittal view of a foot at the landing phase of the stride. Note the dorsal wall is slightly convex, but remains the same thickness from the coronary band to the distal border (photo from Pollitt 1995 with permission).*

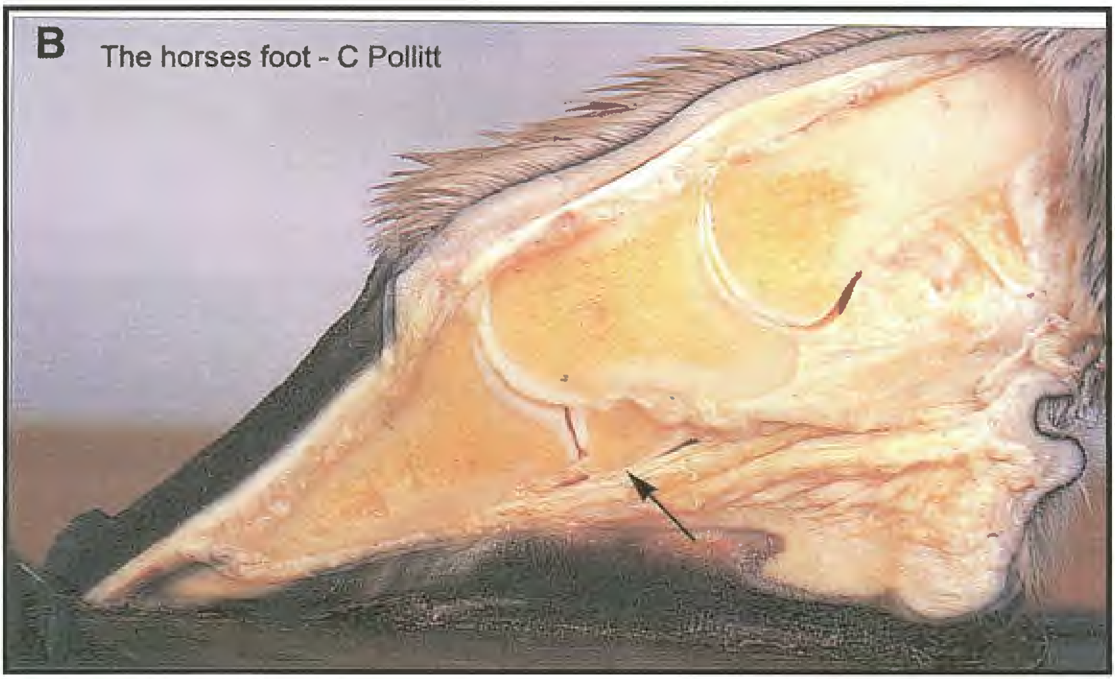


***Figure 1b.*** *Sagittal view of the same foot as figure 1a showing the foot under load (1000 kg). Note the dorsal wall concaving as the distal phalanx descends distally and rotates caudally pulling the dorsal wall caudally, due to the laminal connection (photo from Pollitt 1995 with permission).*

## Literature Review

To the author's knowledge no study on domestic horses or ponies has been conducted to determine the ratio of hoof wall thickness. Numerous authors Douglas *et al.* (1996), Hampson and Pollitt (2011), Pollitt (1996) and O'Grady (2009), have identified the importance of the circumferential gradient in hoof wall thickness, from toe to heel in relation to foot function. A study by Hampson and Pollitt (2011) concluded that the hoof wall in Australian feral horses (Brumbie) was twice as thick at the toe than the heel quarters. This study suggested the importance of the hoof capsule in relation to the biomechanical function of the foot and the outer horn tubules are primarily weight supporting structures. The study indicated removal of these tubules would reduce hoof capsule function as it deforms with load bearing.

Various studies have suggested the importance of hoof wall anatomy in relation to foot function. Reilly *et al.* (1996;1998), identified a decrease in the number of horn tubules from the outer wall (highest), to the inner wall (lowest) and separated the hoof wall into 4 distinct zones. What was evident were the changes in tubular horn size from the outer wall (smaller) to the inner wall (bigger). This hoof wall zonation was also recognised by Pollitt (1996) and Lancaster, Bowker and Mauer, (2013). Lancaster, Bowker and Mauer (2013) also suggested tubular density differentiation around the circumference of the hoof wall, with more tubules per square mm in the outer hoof wall on the medial quarter than the lateral quarter. Bertram and Gosline (1986), Reilly *et al.* (1996) and Kasapi and Gosline (1997) identified the possible link between hoof wall zones and natural fracture mechanisms, used in the delamination of the hoof wall during natural hoof growth and wear.

A study by Bidwell and Bowker (2006) looked at the external environmental influences that may affect hoof wall and laminal morphology as the hoof wall passes from non-weight bearing to weight bearing after birth. They found that the *stratum internum* undergoes morphologic changes shortly after birth. This would concur with Faramarzi, Thomason and Sears (2008) who also suggested the hoof capsule has a potential to remodel and thicken in response to load.

Douglas *et al.* (1996) and Thomason, Biewener and Bertram (1992) indicated that the hoof wall is a viscoelastic structure and the hoof horn was stiffer under compression than tension. A difference in horn stiffness was found to be higher in the outer wall than the inner wall, with horn tubule arrangement and size influencing hoof wall stiffness, but with a suggestion that moisture was a contributing factor. The hoof wall has a natural moisture gradient from outside (lower) to inside (higher) resembling Reilly's *et al.* (1996:1998) hoof wall zonation. This moisture gradient was also suggested by Lancaster, Bowker and Mauer (2013), Hampson *et al.* (2012) and Bertram and Gosline (1987). Bertram and Gosline (1987) manipulated the moisture content of horn explants and found stiffness was reduced at high moisture levels. Both Douglas *et al.* (1996) and Bertram and Gosline (1987) suggested the difference in stiffness between the toe and quarters may be due to moisture, with Douglas *et al* .(1996) concluding the outer hoof wall at the toe was significantly stiffer than the quarters in both compression and tension, facilitating expansion and contraction of the wall.

This preliminary study investigated the ratio of hoof wall thickness from the toe to the heel quarters in all the feet examined. It also compared left and right toe thickness and total hoof wall thickness. Toe to heel quarter hoof wall ratio concerning breed, foot shapes and sole planes were compared to establish if a consistent T:HQ ratio exists.

## Anatomy of the Hoof Wall

The hoof capsule is a highly keratinised epidermal structure, which is avascular and devoid of nerve endings (Reilly 2006). The wall is composed of tubular horn which runs proximodistally and parallel to the surface and intertubular horn, which is arranged tangentially around the circumference of the hoof (Thomason *et al.* 1992). Each horn tubule originates from a single dermal papilla in the coronary corium which is located in the coronary band. The dermal papillae range between 4-6mm in length, but become progressively more slender and shorter (1-2mm) at the border with the laminar corium (Reilly 2006) (Figure 2a). Each papilla fits into a papillary socket located at the proximal extremity of the hoof wall (figure 2b). The inter papillary region located between each papillae is responsible for producing intertubular horn, which binds/cements the tubular horn together. At the front of the hoof, the tubules and intertubular horn intersect orthogonally, while the angle reduces to 45-65 degrees at the sides of the hoof (Thomason *et al.* 1992).

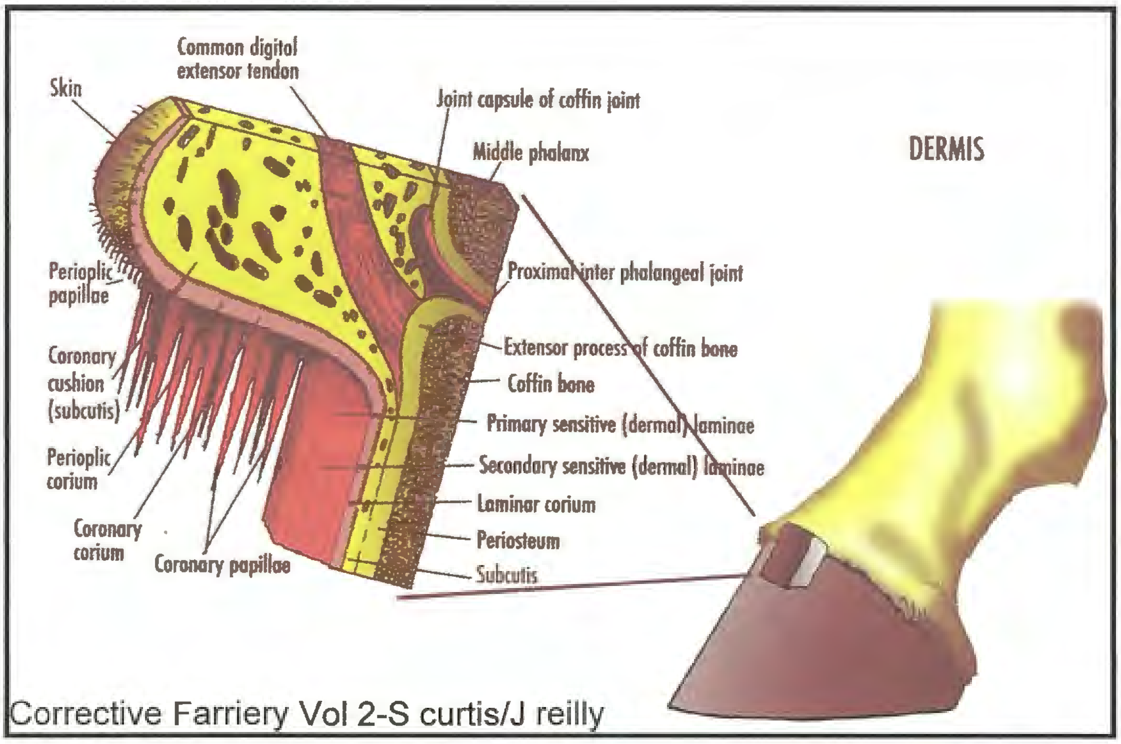


**Figure 2a.** *Section of coronary corium showing dermal papillae (illustration from Reilly edited by Curtis 2006 with permission).*

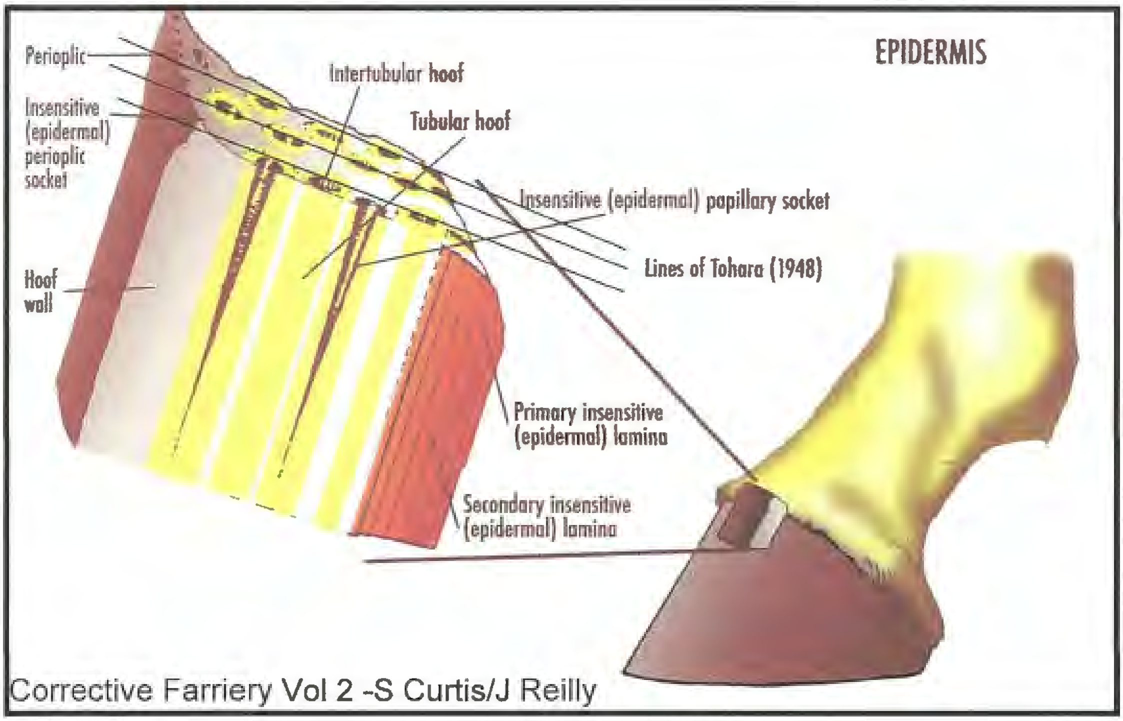


**Figure 2b.** *Section of hoof wall taken from the coronary band showing papillary sockets (illustration from Reilly edited by Curtis 2006 with permission).*

It is generally accepted within the farriery profession that the hoof wall does not vary in thickness from its origin at the coronary band to its conclusion at the distal border (Figure 1). The wall is thicker at the toe and becomes progressively thinner and more elastic toward the heels where it thickens again where it reflects dorsally as the bars (Baxter 2011) (Figure 3). This variation in hoof wall thickness is believed to be of importance in facilitating hoof function (Douglas *et al.* 1996, Hampson and Pollitt 2011, Pollitt 1996 and O'Grady 2009)

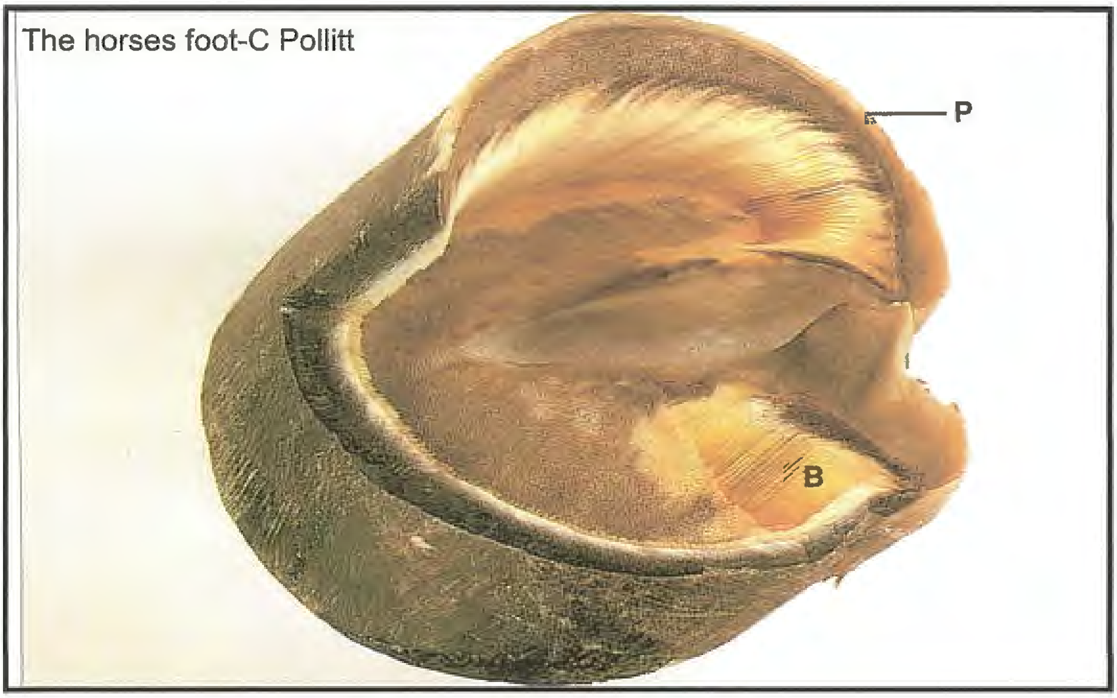


**Figure 3.** *The hoof capsule with all sensitive structures removed. Note the thickness of the dorsal wall and how it decreases as it reaches the quarters, then furthermore as it reaches the heel quarters (photo from Pollitt 1995 with permission).*

The external surface of the hoof wall is divided into three topographical regions: the dorsal region at the toe which blends medially and laterally into the quarters which blends into the heels.
There is no defined point where these regions start and end, they are used as a guide only.

The hoof wall can be classified into three layers:

1. *Stratum externum* - Outer layer referred to as the periople. It is produced from the papillae on the periopolic corium and is a continuation of the epidermis of the skin. The periople scales off at a variable distance down the wall to leave a thin layer of flat horn cells, *stratum tectorium* (Reilly 2006).
2. *Stratum medium* - Main body of hoof wall. It is produced from papillae on the coronary corium and consists of tubular and inter tubular horn. It has a distinct cellular architecture made up of keratinocytes that have undergone cornification and keratinisation (Reilly 2006).
3. *Stratum internum* - Inner non-pigmented wall and consists of primary and secondary epidermal lamella. Also referred to as the *Stratum Medium Zona Alba* (SMZA). Several studies have concluded that this region acts as a buffer zone thus allowing the load to be transmitted from the outer *stratum medium* to the more sensitive laminar surface, without inflicting damage (Wagner *et al.* 2001).

The hoof wall at the centre mid-line has four distinct zonal variations in tubule density (Figure 4). This arrangement of the 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 denoted, each comprising approximately 25% of the hoof wall (Figure 5). The zonal pattern appears to give the hoof wall a laminated, ply-like structure and in combination with the arrangement of the tubular and inter tubular horn, gives what engineers and material scientists would call a composite structure (Reilly 2006). Nature has given the horse a material capable of withstanding tremendous force and torsion, but also having the capability to replace itself on a continuous basis.

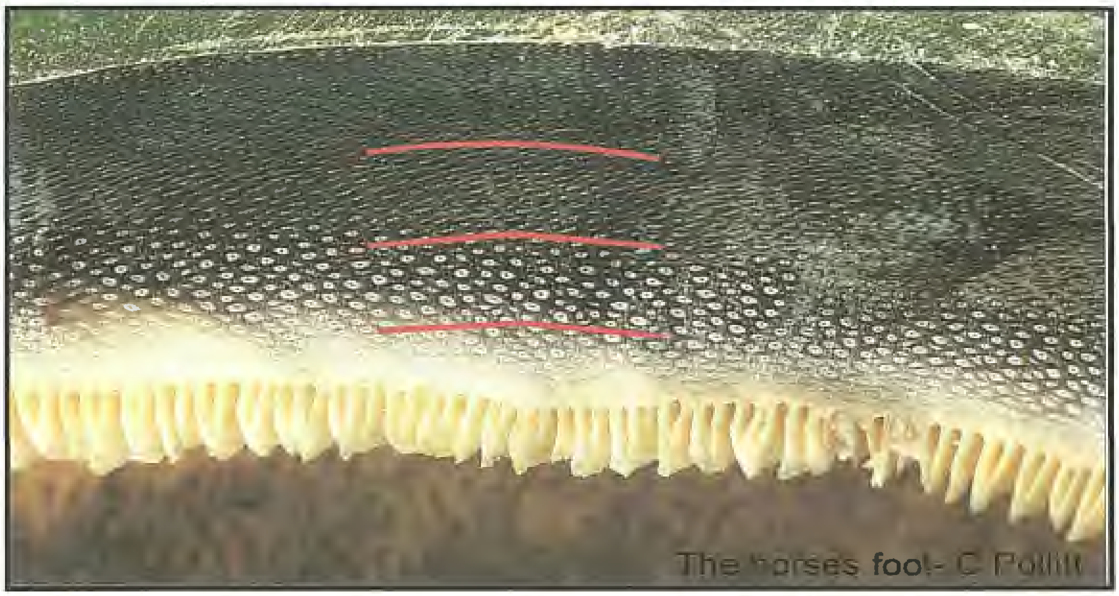


**Figure 4.** *A transverse section of the hoof wall showing four distinct zones of tubular density and size (red lines) (photo from Pollitt 1995 with permission).*

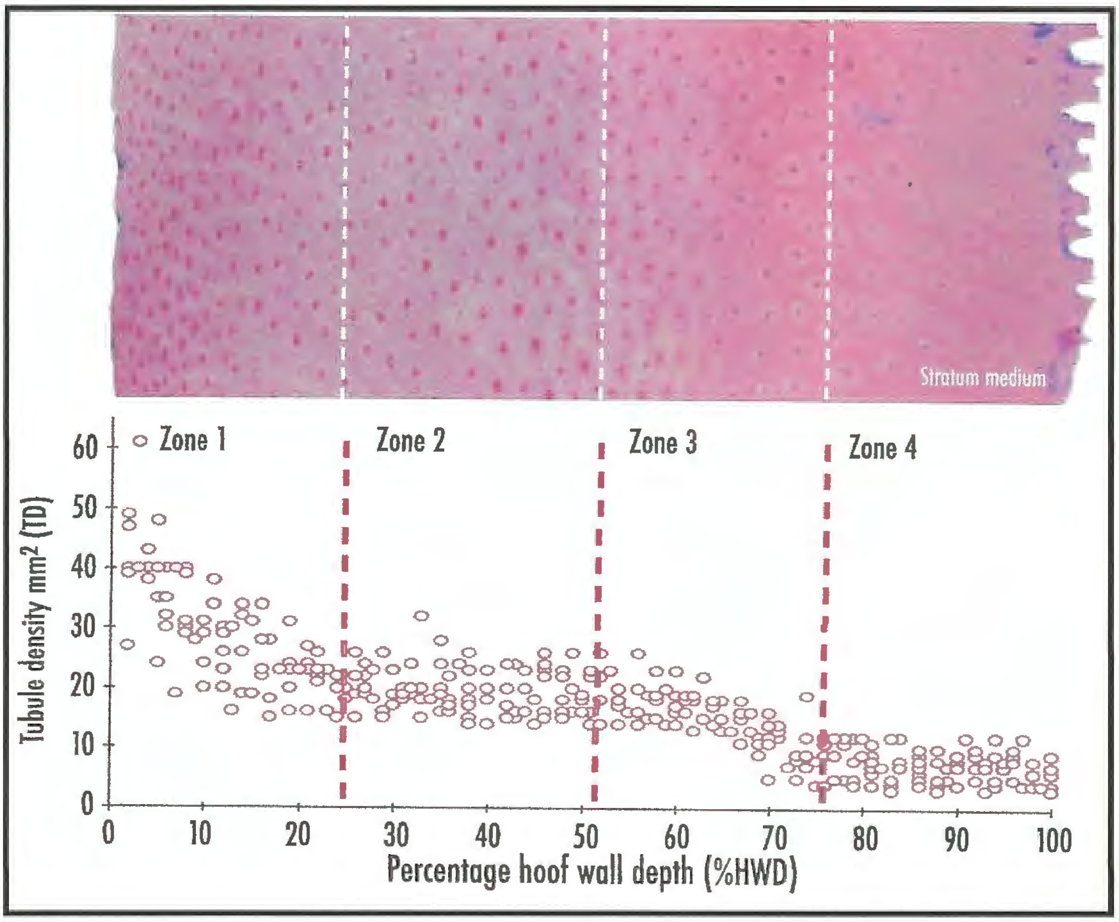


**Figure 5**. *Hoof wall zonation of the stratum medium.(illustration from Reilly edited by Curtis 2006 with permission).*

## Reasons for Performing this Study

When viewed from the solar surface the thickness of the hoof wall, around the foot's circumference, can be evaluated to determine how much 'foot' the farrier has to work with when trimming or shoeing. This view can be misleading as to the true thickness of the hoof wall because the wall has either been pared or worn parallel to the ground surface. This creates a misleading view and could lead to an inaccurate assessment (Figure 6a&b). The misleading view is greater at the toe as the angulation of the dorsal wall is between 50-55 degrees, in the ideally conformed foot (Baxter 2011) and the quarters are more vertical. It is reasonable to conclude that the lower the angulation, the thicker the wall at the toe will appear to be. This is because the wall has been pared or worn at a more acute angle, creating an oblique cross section through the hoof wall (Figure 6c). The only way to know the true thickness of the wall is to cut it at right angles to its outer surface. Only a foot with a vertical dorsal hoof wall would give a true reflection of the hoof wall thickness at the toe from the solar view.

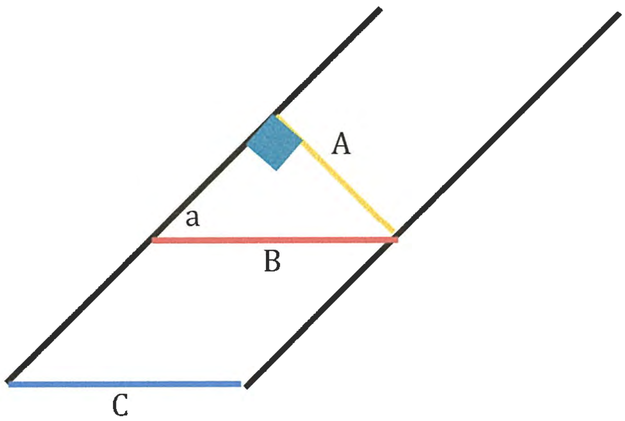


**Figure 6a.** *The two black lines are parallel to each other. The yellow line (A) is at a right angle to the black lines and represents the true distance between the lines. The red line (B) is parallel to the blue line (C). C represents the ground. The two lines A,B now make up a right angled triangle. The longest side of a right angled triangle is the side opposite the right angle, which in this case is B. This is called the hypotenuse. The hypotenuse (B) is the perceived thickness of the hoof wall when viewed from the solar surface, whereas the true thickness is line A, which will always be smaller than the hypotenuse. If the angle (a) is changed and becomes more acute, then the length of sides A and B also change. The smaller angle (a) then the shorter side A is in relation to side B.*

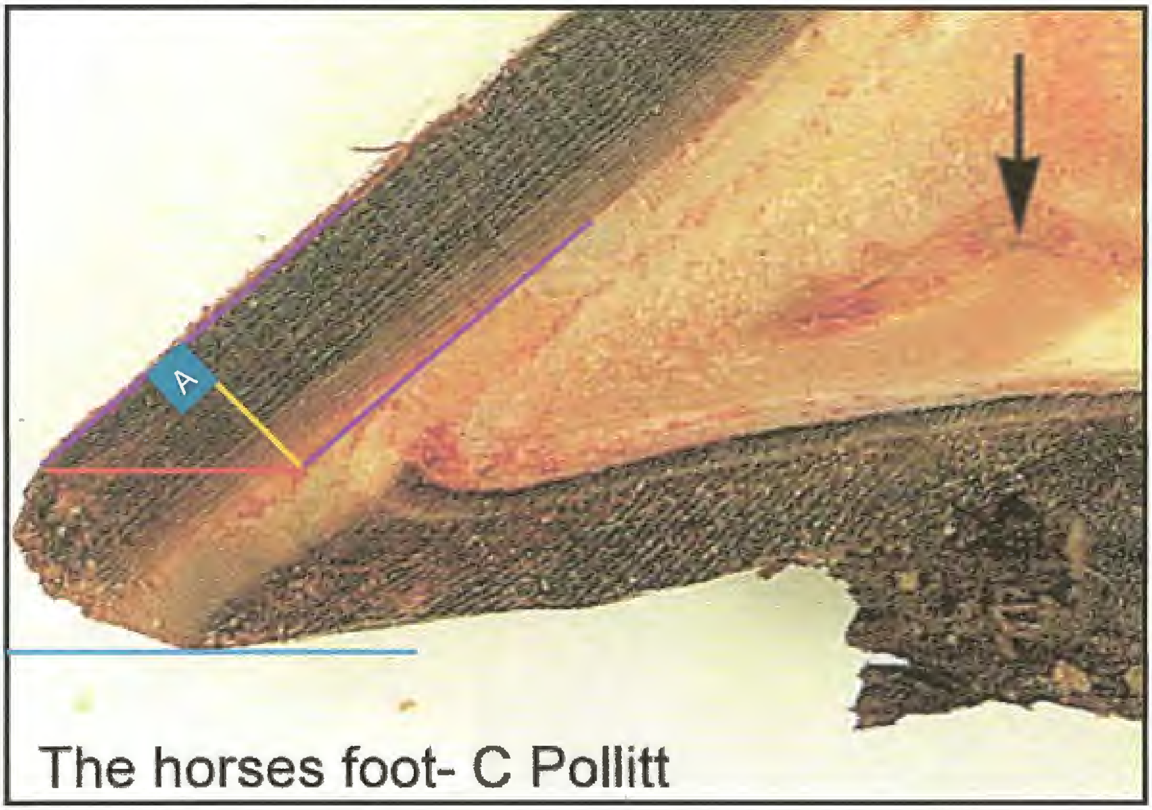


**Figure 6b.** *A sagittal section of a foot showing a right angled triangle. The right angle (A), the true hoof wall thickness (yellow line) and the hypotenuse (red line), make up the triangle. The purple lines are parallel and indicate the true hoof wall thickness. The red line (hypotenuse) and the blue line (ground) are also parallel (Photo from Pollitt 1995 with permission).*

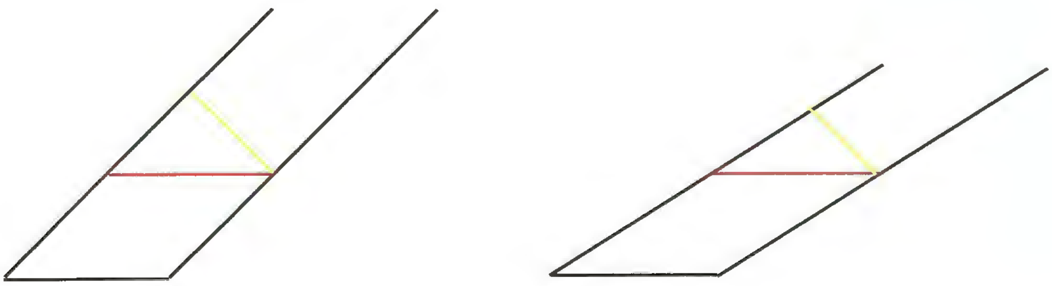

**Figure 6c.** *The diagrams show the misleading hoof wall thickness due to hoof wall angulation. The more angled the dorsal wall the greater the difference in length between the red and yellow lines. Yellow line represents the true hoof wall thickness, whereas the red line represents the misleading hoof wall thickness.*

The hoof wall is thicker at the toe and reduces in thickness by on average 50% when it reaches the heel quarters (Hampson & Pollitt 2011) (Figure 3). The author believes that this circumferential difference in hoof wall thickness, has a close resemblance to a leaf spring (Figure 7). It is this structural design and anatomical construction, as previously mentioned, that helps the foot to function and absorb concussion.

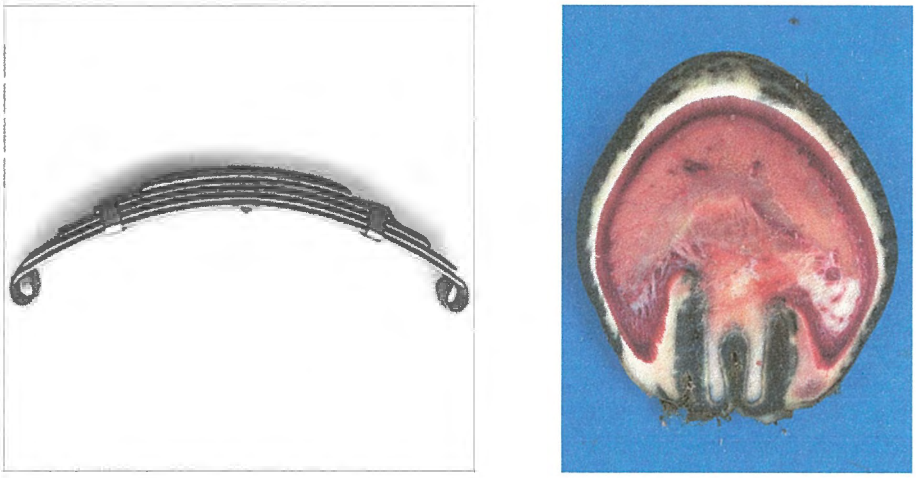

**Figure 7.** *A leaf spring turned upside down to show similarities of design to the hoof capsule. Note the thickness and multi layers at the centre of the spring and how it tapers of towards the ends. It is designed to flex and support weight but return to its original form when load is removed, similar to the hoof capsule.*

It is hypothesised that a smaller T:HQ ratio could result in a weaker hoof capsule and a bigger ratio could be stronger. If this is indeed the case then greater care and thought would be necessary before farriers artificially alter the T:HQ ratio by dorsal wall rasping.

## Aims

The aims were:

1. To measure the thickness of the wall at the circumferential points.

2. To categorise horses into breeds, feet into shapes and soles into planes and compare the T:HQ ratios.

## Objectives

The objectives of this study were:

1. To test the hypothesis that the hoof wall is approximately, twice as thick at the toe than at the heel quarters. i:e 2:1 (T:HQ) ratio.

2. To determine if breed, foot shapes and sole planes influences this ratio.

3. To compare left and right feet for differences in hoof wall thickness at the toe and overall hoof wall thickness.

## Materials and Methods

Before this study could commence three factors were considered:

1. Where on the hoof capsule was the best place to make a transverse cut to minimise the effects of natural hoof wall wear or farriery hoof wall rasping?
2. At which points around the transverse hoof section, should measurements be taken, to ensure that there was a consistency across all the differing hoof sizes and shapes?
3. How should feet be categorised into foot shapes and sole planes?

To ensure accuracy and consistency across all the different size feet, it was decided to measure the dorsal wall from its origin at the coronary band, to its conclusion at the distal border. This measurement was then divided by 4, with the calculation representing 25% of the total length of the dorsal hoof wall. The first 25% of the hoof wall distance from the coronary band was measured and marked parallel to the coronary band, and a line was drawn, indicating where the transverse cut will be made (Figure 8).

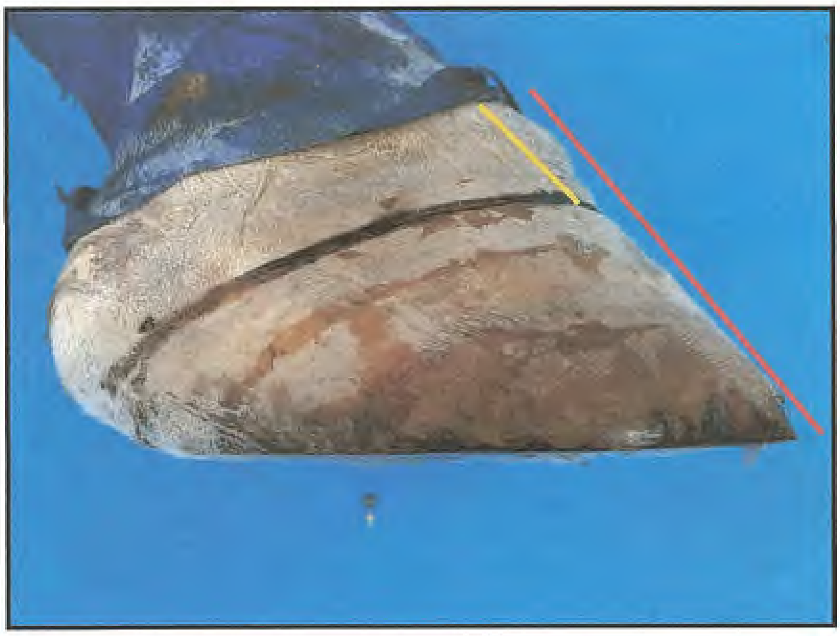

**Figure 8**. *The transverse cut was measured and marked.*
*Red line represents the total dorsal hoof wall distance (100%)*
*Yellow line represents the proximal 25% of the dorsal hoof wall.*
*Note the black line is parallel to coronary band.*

This method was repeated across all the feet in the study. Taking the measurements from this point minimised the effects of both natural and artificial hoof wall wear and by keeping the cut parallel to the coronary band would also make sure that the same age of hoof wall is measured around the circumference of the hoof.

To ensure the thickness of the hoof wall was measured at the same points regardless of size and shape, the foot was divided in to seven areas (Figure 9).

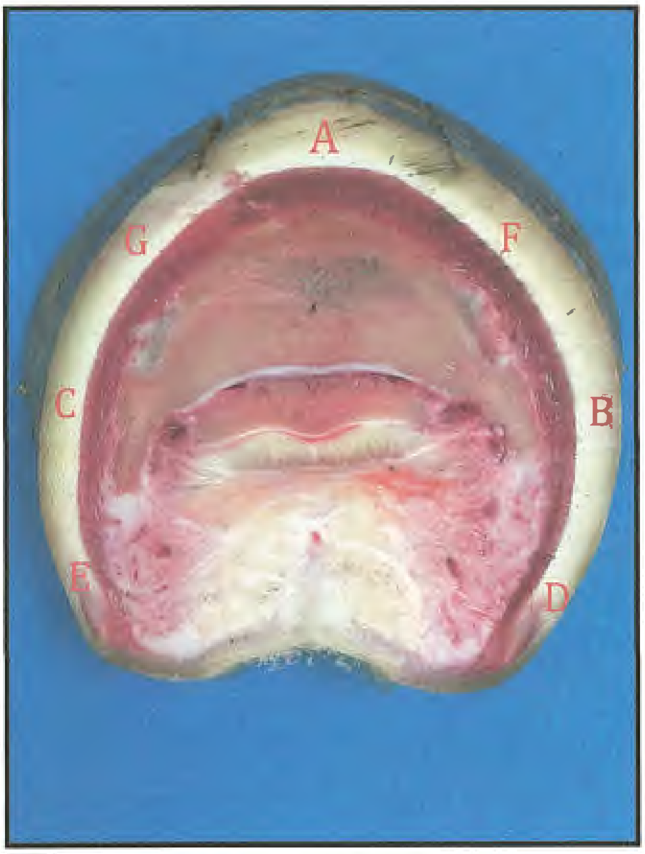


**Figure 9**. *The seven points where the hoof wall thickness was measured.*

1. *The centre of the toe (A) - the thickest part of the wall.*
2. *Lateral quarter (B) - the widest part of the foot.*
3. *Medial quarter (C) - the widest part of the foot.*
4. *Lateral Heel quarter (D) - the thinnest part of the wall.*
5. *Medial Heel quarter (E) - the thinnest part of the wall.*
6. *Lateral toe quarter (F) - the measurement was taken half way between the centre of the toe and lateral quarter.*
7. *Medial toe quarter (G) - the measurement was taken half way between the centre of the toe and medial quarter.*

It was decided to group the different foot shapes into four categories. Foot shapes were determined comparing the front half of the foot (solar view) only to the four commonly perceived toe shapes in horses and ponies.

1. Round
2. Oval
3. Square
4. Triangular

The sole plane was split into two categories:

1. Concave
2. Flat

The study was conducted on cadaver limbs of 20 domestically kept horses of various breeds and sizes (Table 1). A combination of both shod and unshod feet were used. For the purpose of this study, only front feet were used and both left and right feet were measured. This enabled a comparison of both feet to be made and establish if horses have a difference in hoof wall thickness between left and right feet.

Information was collected as to the various horses' age, breed and height. All the feet were evaluated and categorised into their various foot shapes and sole planes. Any feet showing visible signs of wear on the hoof wall, at the point of sectioning either natural or artificial, were discarded.

**Table 1** *Sample group of horses and ponies studied.*

| Horse | Age approx. (years) | Height h/h approx. | Breed | Shod(S) Unshod (U) | Foot shape | Sole plane | Foot width cm | Foot length cm |
|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 16.2 | W/B | U | T | C | 13.1 | 14.7 |
| 2 | 12 | 17.0 | I/D | S | R | F | 15.5 | 15.5 |
| 3 | 17 | 12.2 | W/P | U | SQ | C | 8.5 | 9.0 |
| 4 | 24 | 11.2 | W/P | U | OV | C | 8.0 | 8.2 |
| 5 | 22 | 13.1 | DART | U | OV | C | 9.6 | 9.5 |
| 6 | 22 | 15.2 | COB | U | R | C | 12.3 | 11.5 |
| 7 | 18 | 13.0 | W/P | U | SQ | C | 8.8 | 9.1 |
| 8 | 20+ | 10.0 | SHET | U | OV | C | 7.2 | 7.3 |
| 9 | 14 | 16.2 | TB | S | R | F | 13.0 | 13.0 |
| 10 | 15 | 15.3 | TB | S | OV | C | 12.3 | 12.6 |
| 11 | 21 | 16.3 | I/D | U | R | F | 16.0 | 15.2 |
| 12 | 12 | 16.1 | TB | S | R | F | 16.5 | 15.8 |
| 13 | 2 | 15.2 | TB | U | R | F | 12.8 | 12.6 |
| 14 | 8 | 16.0 | W/B | U | SQ | C | 13.5 | 13.0 |
| 15 | 1 day | Not known | CON | U | T | C | 5.5 | 5.0 |
| 16 | 12 | 16.1 | W/B | U | SQ | C | 12.1 | 13.5 |
| 17 | 20+ | 11.2 | W/P | U | SQ | C | 8.2 | 8.4 |
| 18 | 19 | 16.3 | W/B | S | T | C | 12.9 | 13.4 |
| 19 | 17 | 16 | TB | S | R | F | 14.5 | 14.3 |
| 20 | 9 | 17.0 | I/D | S | R | F | 15.6 | 15.6 |
| | | | | | | | | |

All the limbs were collected and frozen on the same day as the horses were euthanised over a 3 month period.

Once frozen (24 hours approx) each foot was measured and a parallel line was drawn around the hoof capsule (Figure 9). A transverse section was cut using a bandsaw (Charnwood-W730 14") along the line so to remove the distal part of the foot. The foot was still frozen at this point. The foot was allowed to thaw over 6 hours, before the measurements were taken (Appendix iv Table 2). Each measurement was repeated 3 times to limit error and obtain a consistent result.

The measurements were taken from the inner *stratum internum* to the outer *stratum externum*, at all the seven marked points using digital callipers (Hilka-Digital calliper 6"/150 mm) (Figure 10).

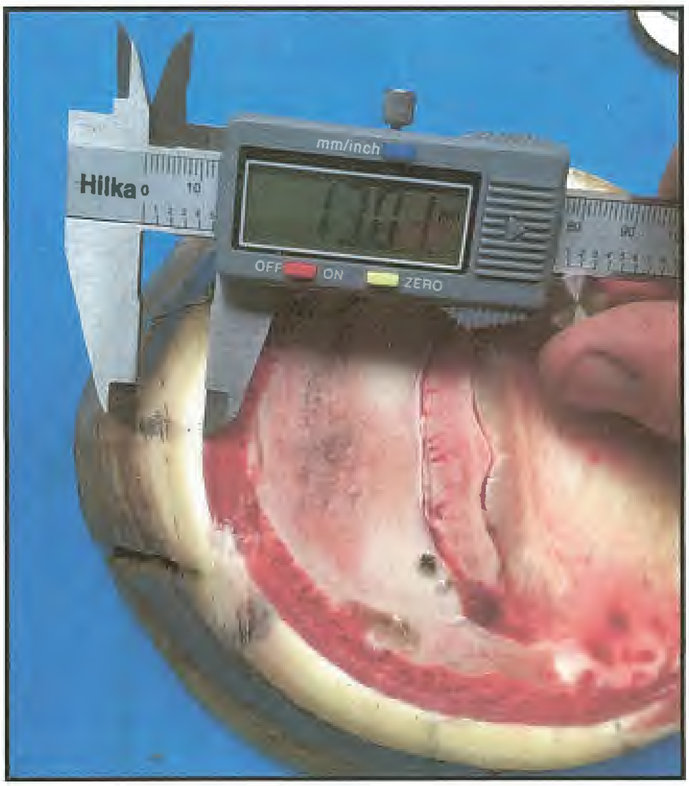


**Figure 10**. *The hoof wall was measured at all the 7 points using digital callipers.*

## Statistical Analysis

The hoof wall statistics were analysed using Microsoft Excel® and Minitab® version 17. The normality of data was established using the Anderson-Darling normality test. The data were summarised and are given as mean ± SD. Paired t tests were used to compare data for significant differences. For all analyses values of $p<0.05$ were considered statistically significant. Statistical differences were tested on left and right toe thickness, left and right total hoof wall thickness and hoof wall ratio in relation to breed, foot shape and sole plane. Hoof wall ratio, breed, foot shape and sole plane was compared with a normality of 2:1.

## Results

***Toe Thickness:*** Toe thickness differed significantly between left and right fore feet ($t_{19}$ =2.69;p<0.05). Mean ± SD (10.26 ± 2.72 mm) of the right toe thickness was significantly greater (p<0.05) than left (10.13 ± 2.58 mm). The results indicate that 85% (n=17) of the feet measured, had a thicker toe in the right fore than the left 15% (n=3) (Figure 11).

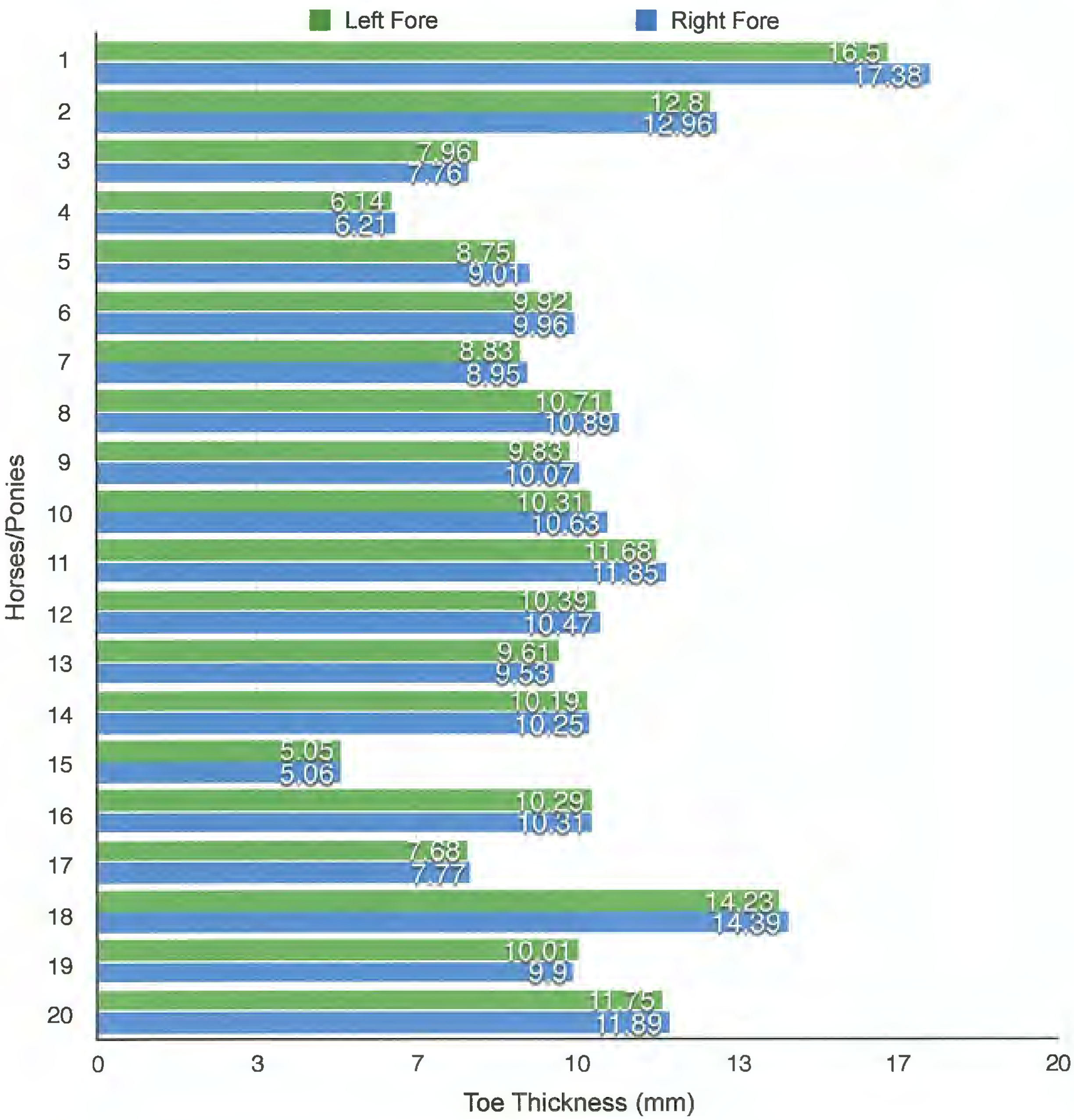


**Figure 11.** *A comparison of the toe thickness between the left (green) and the right (blue). Mean ± SD of the left fore (10.13 ± 2.58 mm) and the right fore (10.26 ± 2.72 mm). The right fore was significantly thicker than the left (p<0.05).*

***Total Hoof Wall Thickness:*** The THWT of the left and right feet were compared (Figure 12). This was achieved by adding all the 7 points measured on each foot together. The results showed a significant difference ($t_{19}$=4.23;$p<0.001$) between left and right fore THWT. The mean ± SD (57.35 ± 11.10 mm) right fore THWT was significantly thicker ($p<0.001$) than the left (56.36 ± 11.03 mm).

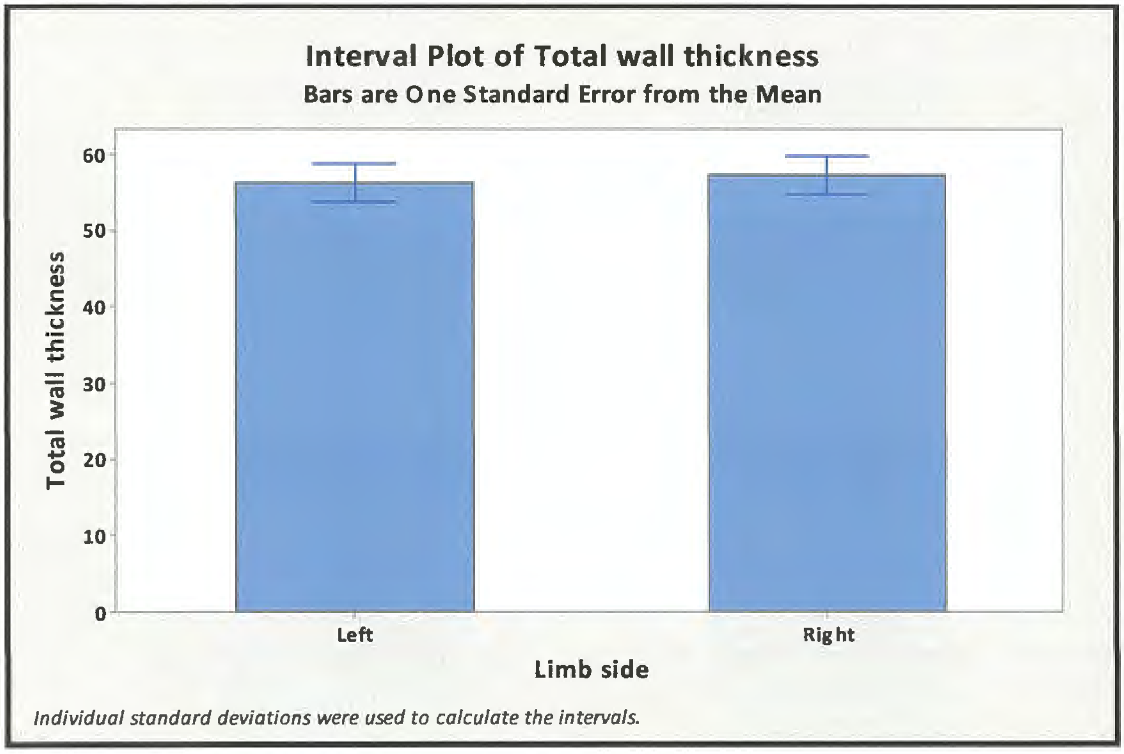


**Figure 12.** *Mean ± SD of the total hoof wall thickness between the left (56.36 ± 11.03 mm) and right (57.35 ± 11.10 mm) fore feet of all the horses measured. The right fore was significantly thicker than the left (p<0.001).*

***Hoof Wall Ratio:*** The data were collected for both left and right feet (n=40). A mean was taken between left and right feet of all horses and ponies (n=20). The mean toe thickness and heel quarter thickness were calculated for each pair of feet (Figure 13). A mean T:HQ ratio was calculated using the two measurements (Figure 14). The results showed that the T:HQ mean ± SD (1.77 ± 0.66 mm) hoof wall ratio was 1.77 ($t_{39}$=2.19;$p<0.05$). This differed significantly ($p<0.05$) to the hypothesised ratio of 2:1 (Hampson and Pollitt 2011).

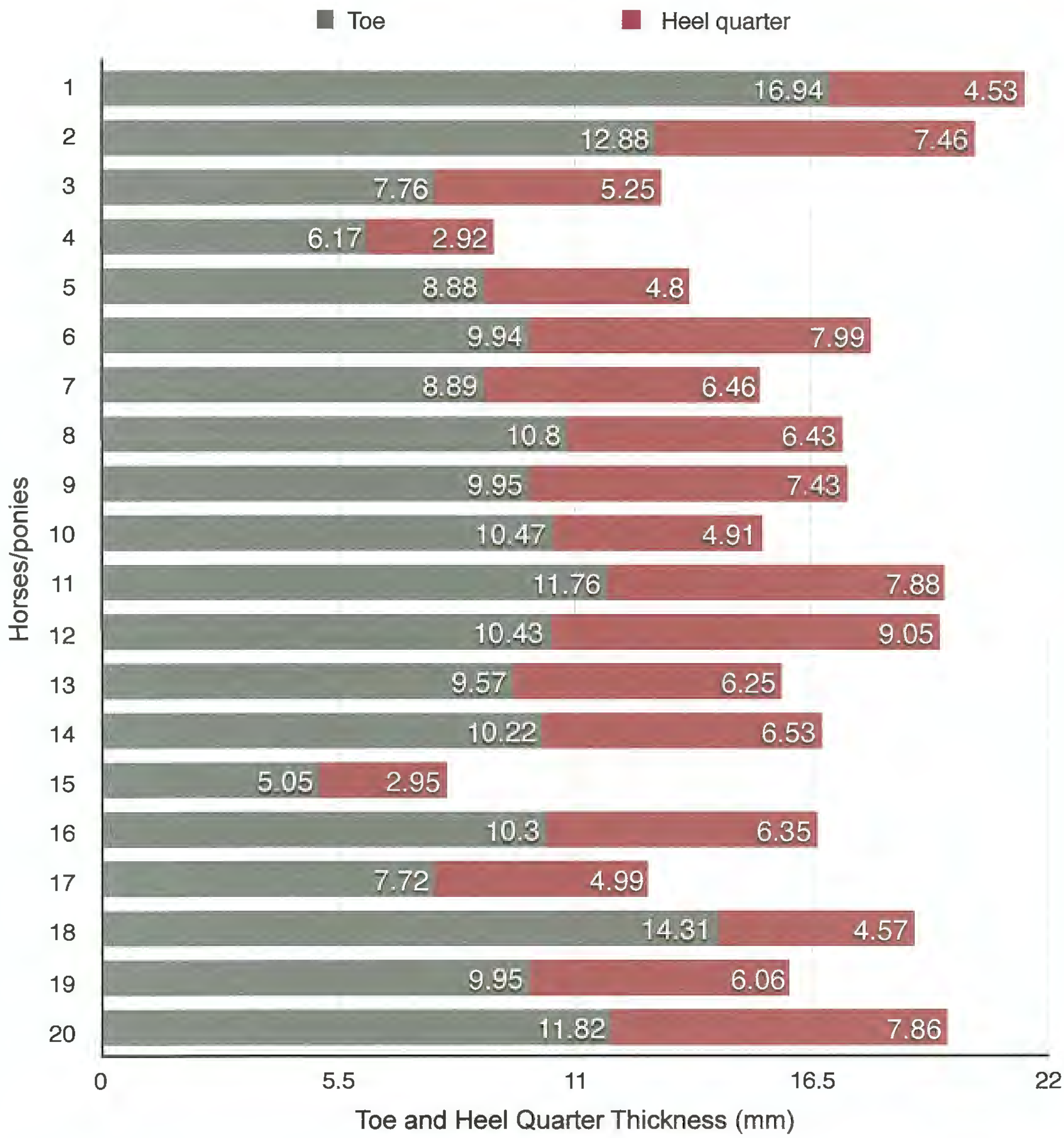


**Figure 13.** *The mean hoof wall thickness of the toe (Grey) and the heel quarter (red). Note the mean was taken between the left and right feet.*

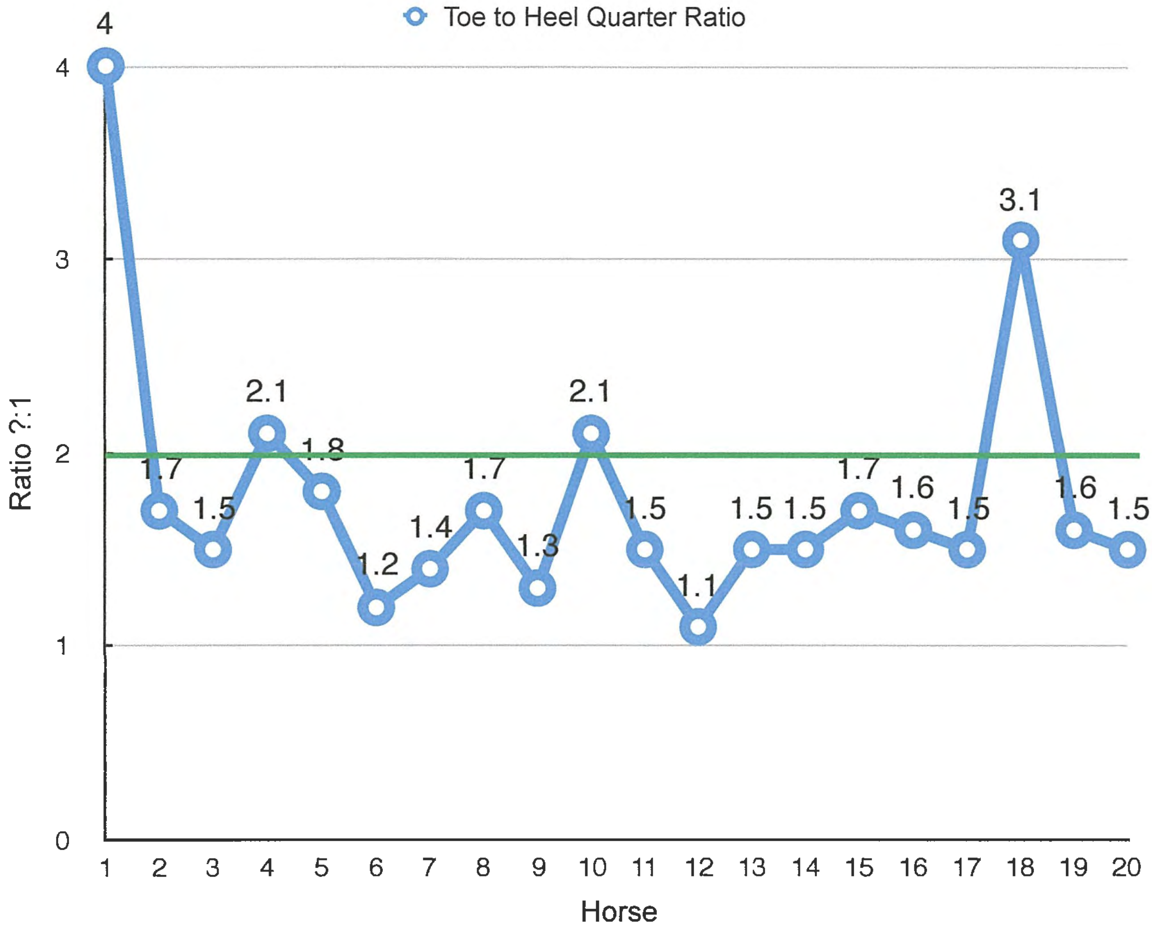


**Figure 14.** *The toe to heel quarter ratio. The green line indicates 2:1 ratio. Mean ± SD (1.77 ± 0.06 mm) of T:HQ ratio was significantly lower (p<0.05) than 2:1.*

***Breed Ratio:*** Statistical comparison between the toe and heel quarter ratio in relation to breed, was unable to be undertaken because the sample group did not have sufficient numbers in each breed group (figure 15).


**Figure 15.** *The mean toe to heel quarter ratio of the different breeds of horses/ponies studied. The blue line represents the largest T:HQ ratio in each group studied. The green line represents 2:1 ratio. The numbers in brackets indicate the total number of horse/ponies studied in each group.*

***Foot Shape:*** The mean ± SD (2.96 ± 1.20 mm) for triangular feet were not significantly different from 2:1 ($t_2$=1.39; p>0.05) (Figure 16). Round feet were significantly different ($t_7$=-7.92; p<0.001) with a mean ± SD (1.42 ± 0.20 mm) and square feet were also significantly different ($t_4$=-15.8; p<0.001) mean ± SD (1.50 ± 0.07 mm). Oval feet were nonsignificant ($t_3$= 0.73; p>0.05) mean ± SD (1.92 ± 0.20 mm).


**Figure 16.** *The mean toe to heel quarter ratio of feet in relation to foot shape. The blue line represents largest ratio in each group studied. The green line indicates 2:1 ratio. The numbers in brackets indicate the total number of horses/ponies studied in each group.* ***key ns*** *= non significant, * = p<0.05, ** =p<0.01, *** = p<0.001.*

***Sole Shape:*** The Mean ± SD (1.93 ± 0.78 mm) for concave soles were not significantly different from 2:1 ($t_{12}$=-0.28; p>0.05) whereas flat soles mean ± SD (1.45 ± 0.19 mm) showed a significant difference ($t_6$=-7.22; p<0.001) (figure 17).

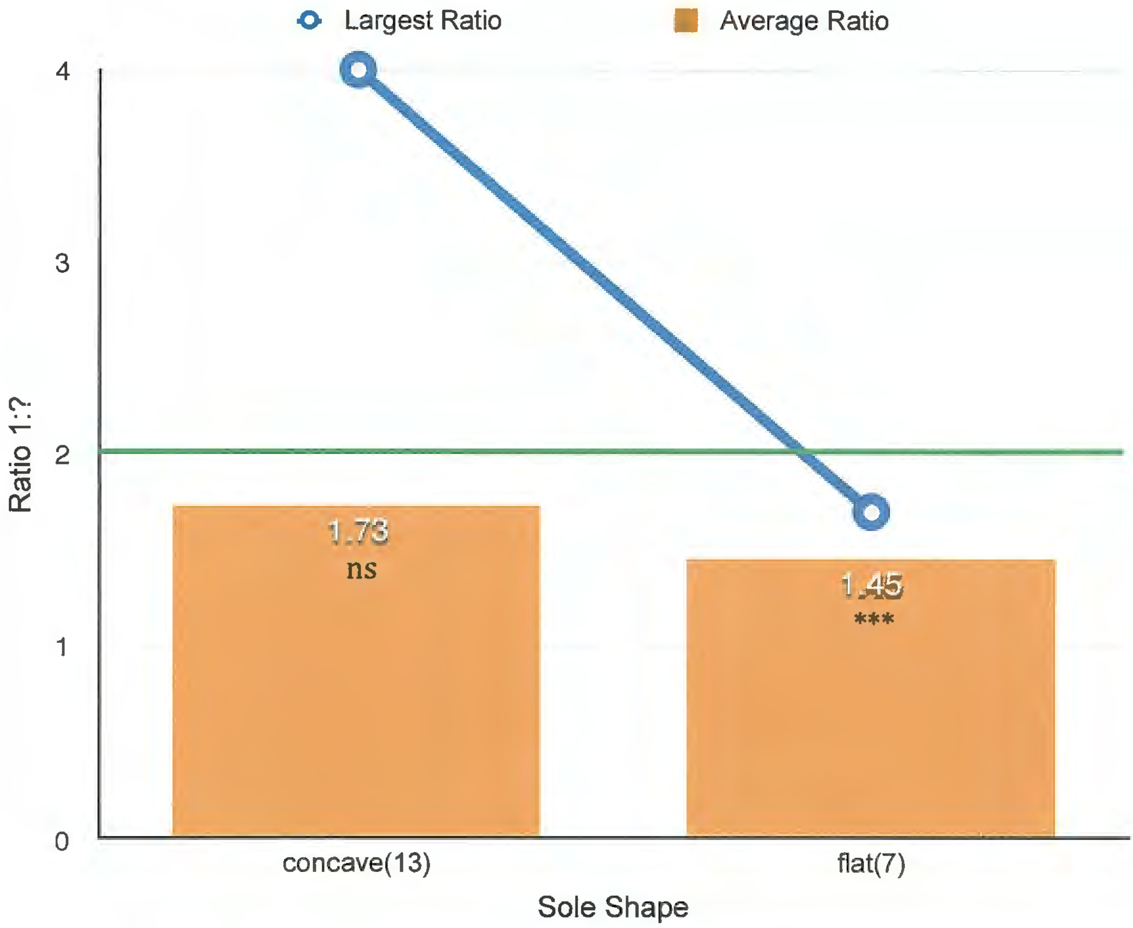


**Figure 17.** *The mean toe to heel quarter ratio in relation to sole shape. The blue line represents highest ratio in the each group studied. The green line indicates 2:1 ratio. The number in brackets indicates the total number of horses/ponies studied in each group.* ***key ns*** *= non significant, * = p<0.05, ** = p<0.01, *** = p<0.001.*

## *Summary of Results*

1. The left toe thickness was significantly smaller than the right ($p<0.05$).
2. The left THWT was significantly smaller than the right ($p<0.001$).
3. The mean T:HQ ratio of all the feet was 1.77:1. This was significantly different ($p<0.05$) when compared to a 2:1ratio.
4. The T:HQ ratio in relation to breed was unable to be compared due to the small sample numbers.
5. Round and square feet were significantly different ($p<0.001$) when compared to the 2:1 T:HQ ratio, whereas triangular and oval feet were not ($p>0.05$).
6. Concave soles were not significantly different when compared to the 2:1 T:HQ ratio ($p>0.05$) whereas flat soles were ($p<0.001$).

## Discussion

The results from this preliminary study have confirmed that the hoof wall at the toe is thicker than the heel quarters and there is a circumferential gradient from toe to heel (appendix iv). This was not unexpected, as the palmar aspect of the foot is designed to allow flexibility and expansion of the hoof capsule (O'Grady 2009) and when compared, the toe is significantly stiffer in both compression and tension than the quarters (Douglas *et al.* 1996).

The mean ± SD toe to heel quarter hoof wall ratio across all the horses feet studied (n=40) was 1.77:1 (1.77 ± 0.664 mm). This was significantly different ($P<0.05$) to Hampson and Pollitts (2011) finding, that Australian feral horses had a hoof wall thickness that was twice as thick at the toe than the heel quarter (2:1). This ratio could be because possibly the feet in the latter study were not cut parallel to the coronary band, so therefore were not cut at a right angle to the outer dorsal wall. The author of the present study has highlighted the importance of measuring the hoof wall at right angles to the outer hoof wall when assessing the true hoof wall thickness. A diagonal cut through the dorsal hoof wall would result in a misinterpretation of true toe thickness and lead to an appearance of a visually thicker toe. Hampson and Pollitts (2011) study did not indicate where the transverse cut was made so no comparison of the results can be made. Further consideration when comparing the two studies was that this study was conducted on domestic horses and ponies of various breeds and foot shapes, whereas Hampson and Pollitt's study were for one breed, the Australian Brumbie.

Douglas *et al.* (1996) found the hoof horn is stiffer in compression when compared to tension, indicating the hoof horn is a viscoelastic material. This was also suggested by Thomason, Biewener and Bertram (1992). When the hoof wall is under load at the loading phase of the stride, the outer dorsal wall would be under compression, as the dorsal wall would flatten or convex (Pollitt 1995) (Figure 1b). Alternatively, the inner hoof wall would be under tension, with a possible tendency to gape and widen due to structural flaws and micro cracks (Douglas *et al.* 1996).

During locomotion the toe receives the greater amount of biomechanical and physiological stress (Hampson and Pollitt 2011). The hoof capsule through evolution has been designed with a circumferential variation in thickness. The results from this study confirmed that the toe is thicker than the heel quarters (mean ratio 1.77:1), which helps to tolerate these stresses. It could be considered that a reduction in this ratio would reduce the functionality of the hoof capsule and contribute to possible hoof wall failure. Hampson and Pollitt (2011) questioned the removal of hoof wall at the toe when trimming feet and thus creating the same thickness of wall around the circumference of the hoof wall. The outer horn tubules are designed to bear weight and support the hoof capsule as it deforms during load and reducing the T:HQ ratio to 1:1 would remove this support. As the T:HQ ratio in this study (1.77:1) was smaller than previously suggested (2:1), then the tolerance for dorsal wall removal would be less as clearly the hoof wall at the toe is not as thick as previously thought.

When Reilly *et al.* (1996, 1998) examined tubular density a dorsopalmar decrease was found. The highest number of tubules were in the outer 25% of the hoof wall and the lowest number were in the inner 25%. This structural decrease in density would concur with Douglas *et al.* (1996) suggesting a gradient of stiffness across the hoof wall, with the outer wall providing rigidity and protection from outside forces and the inner wall flexibility and protection to the adjacent structures. Lancaster, Bowker and Mauer (2013) also identified a tubular density decrease across the hoof wall, but suggested that the tubular density was not the same in the medial and lateral quarters. They found the medial quarter had significantly higher tubular density than the lateral quarter, with the medial quarter closely resembling the toe in tubular density. The result could be due to the medial part of the foot receiving more load than the lateral side, as higher forces may result in a shifting or movement of tubules and intertubular horn within different regions, in order to reduce areas of peak stresses (Lancaster, Bowker and Mauer 2013). This concurs with Faramarzi, Thomason and Sears (2008) who also found that changes in hoof capsule thickness and the potential to remodel was a response to loading. This shifting of horn tubules and increase in density is worth considering in relation to the findings in this study regarding left and right THWT and toe thickness. Results showed that 85% (n=17) of the horses/ ponies studied had a significantly greater toe thickness in the right fore than the left ($p<0.05$) and the THWT was also greater in the right fore than the left ($p<0.001$). These horses and ponies could have been born with this difference or be a result of natural handedness. A study by McGreevy and Rogers (2004) found that domestic horses had a bias to standing on the right fore limb with the left fore limb outstretched when grazing, whereas a study on feral horses handedness concluded that no bias was found, suggesting that limb preferences present in domestic horse may be entrained (Austin and Rogers 2011). Horses and ponies often present with asymmetrical front feet of varying degrees and this study has shown that THWT could be a contributing factor. This interpretation is beyond the realms of this study.

It may be worth considering the study by Bidwell and Bowker (2006) who found that primary epidermal laminae at the toe significantly increased in density within a few weeks after birth. This was thought to be associated with increased hoof wall stress in high force areas in particular the toe region. Although the increase in tubule density and primary epidermal laminae in the same area could be considered an association and not a causation, it is reasonable to assume that high stress areas such as the toe, may contribute to this process. Consequently, does the hoof wall thicken with increased tubular density in line with increased primary epidermal laminae, as suggested by Bidwell and Bowker (2006) in the new born foal? Further study could be beneficial to elucidate this point.

The present author suggested the possible link in design of the hoof capsule and a leaf spring. The hoof wall has distinct areas of zonation (Reilly *et al.*

1996, 1998 and Lancaster, Bowker and Mauer. 2013) and it was suggested by Bertram and Gosline (1986), Reilly *et al.* (1996) and Kasapi and Gosline (1997), that these hoof wall zones, may be mechanisms for the controlled elimination of damaged wall segments by zonal delamination and where these zones meet acts as an inherent weaknesses. This suggests that the distinct layers of the hoof wall resemble the multi layers of a leaf spring and reducing these layers could compromise hoof wall function by reducing its residual strength and stiffness. A contributing factor to consider is the natural moisture gradient across the hoof wall. Douglas *et al.* (1996), Hampson *et al.* (2012) and Lancaster, Bowker and Mauer (2013) all found that the hoof wall has a gradient of moisture from the outside (lowest) to the inside (highest). This gradient is similar to the hoof wall zonation suggested by Reilly *et al.* (1996,1998) and Lancaster, Bowker and Mauer (2013). This moisture gradient would be expected as the outer wall is exposed to atmospheric conditions whereas the inner wall is adjacent to the soft tissue, with high moisture content. It was also suggested by Douglas *et al.* (1996) that the inner wall having a higher moisture content, could be prone to crack propagation and failure. Both Bertram and Gosline (1987) and Douglas *et al.* (1996) suggested the difference in stiffness between the toe and the quarters may be due to moisture. Bertram and Gosline (1987) manipulated the moisture content of the horn and found that stiffness was reduced at high moisture levels. This supports the causative relationship between moisture content and stiffness, rather than one which is merely coincidental (Douglas *et al.* 1996). Moisture seems to be important to the overall flexibility and fracture resistance of the hoof wall. When farriers trim horses dorsal wall rasping will inevitably occur. Excessive removal of the outer hoof wall could cause the inner zonal layers to lose moisture due to exposed atmospheric conditions. This loss of moisture combined with the decrease in tubule density and the reduction in the T:HQ ratio, could cause weakening of the hoof capsule and reduce the effectiveness of the leaf spring mechanism. A further study to investigate this possible link would be beneficial.

It was not possible because of insufficient sample numbers to test whether there is an association between breed and T:HQ ratio. Notwithstanding this, there was an indication that breed groups with higher sample numbers did show a reduced T:HQ ratio. Thoroughbreds (n=5) and Welsh ponies (n=4) had a mean T:HQ ratio of 1.52:1 and 1.62:1 respectively. Warmbloods (n=4) appeared to differ from these findings and showed a mean T:HQ ratio of 2.9:1. Clearly, a study involving a larger sample group would be essential to make any clear association regarding T:HQ ratio and breed.

Foot shapes were compared to a perceived normality of T:HQ ratio 2:1. This produced mixed results. Triangular and oval feet were not significantly different ($p>0.05$) whereas round and square feet were ($p<0.001$). This could be a result of a small sample group of triangular and oval feet (n=3, n=4 respectively) compared to round and square feet (n=8, n=5 respectively).These results also support the need for a larger sample group.

Sole planes were compared and tested for significant differences. They were also compared to a perceived T:HQ normality of 2:1 ratio. The results showed that concave feet were nonsignificant ($p>0.05$) whereas flat feet differed significantly ($p<0.001$).

An explanation for these inconsistent results regarding breed, foot shapes and sole planes, could be because horses 1 & 18 had a much larger T:HQ ratio (4:1, 3.1:1 respectively) than all the other horses and ponies studied and would influence the results. These higher ratios could be interpreted as unusual or could be normal within their breed, foot shape and sole plane.

## Limitations of Study

The study was conducted on a relatively small number of feet (n=40). To establish if there is a relationship between breed, foot shape and sole plane, a larger sample group would be needed. Increasing the number of feet measured would give a better indication on toe to heel quarter ratio in relation to breed, foot shape and sole plane and its possible relevance to foot function.

In this study only the dorsal wall was cut at a true right angle to the outer surface. The hoof capsule is a conical shape so therefore the medial and lateral quarters would have been cut obliquely through the hoof wall. This would increase the hoof wall measurement, depending on the angulation of the quarters. The more angled the wall the more oblique the cut. The author considered this, but felt that as the ratio was calculated using the heel quarter, which is more vertical than the quarters, the results would be close to a true reflection of heel quarter thickness.
If a future study were to be undertaken then consideration should be given to the difference in angulation between the medial and lateral sides of the hoof capsule. It is commonly accepted that the medial wall is more vertical than the lateral wall and only by cutting all the measured points at true right angle to the outer surface would an accurate data collection be attained.

## Conclusion and Clinical Relevance

The hoof wall encapsulates the internal structures of the foot and has a natural gradient in thickness from toe to heel, enabling it to withstand load, torsion and stress. This study has highlighted the importance of hoof wall anatomy and construction in facilitating foot function, with the natural gradient of tubule density and moisture, considered important in the hoof walls ability to absorb and dissipate load. The results concluded that the toe to heel quarter hoof wall ratio was significantly less (1.77:1) than previous suggestions (2:1). This smaller ratio should be considered as clearly there is less hoof wall at the toe which is able to be removed when trimming feet. The importance of maintaining the natural circumferential gradient of hoof wall needs to be considered as reducing the T:HQ ratio could cause the hoof wall to lose some of its integrity and strength when load is placed on the foot. Clearly further research is warranted.

The majority of right fore feet have a larger hoof wall thickness at the toe as well as overall hoof wall thickness, when compared to left fore feet. This could possibly suggest that horses have a tendency to be handed and whether this is congenital or acquired would need to be studied before any conclusions could be made. Future research into the significance of T:HQ ratio concerning breed, foot and sole shape and its possible influence on foot function is recommended.

*Farriery consideration:*

When viewed from the solar surface the hoof wall gives a false indication of true toe thickness. This is due to the angulation of wear or trim occurring across the dorsal hoof wall instead of at a right angle. It follows that the more sloping the hoof wall angle, the larger the toe thickness would appear to be, leading to a possible misinterpretation. Numerous authors have identified the importance of a hoof wall gradient from toe to heel, from both an anatomical and engineering prospective. It is clear from this study that the natural circumferential gradient is less than previously thought and consideration should be given before this gradient is reduced through dorsal wall rasping. With this in mind T:HQ ratio as well as hoof wall anatomy and structure, needs to be considered when assessing and trimming feet. Excessive dorsal wall rasping will remove the outer horn tubules and reduce the natural T:HQ ratio. This could weaken the hoof capsule and compromise foot function.

## Manufactures Addresses

Charnwood, Cedars Court, Walker Road, Hilltop Industrial Estate, Bardon, Leicestershire, England. LE67 1TU.

Hilka Tools (UK) Ltd, 1 Roebuck Place, Roebuck Road, Chessington, Surrey, England. KT9 1EU.

Microsoft excel®, Microsoft Corporation, One Microsoft way, Redmond WA 98052-6399, USA.

Minitab® 17, Minitab Ltd, Brandon Court, Unit E1-E2, Progress Way, Coventry, CV3 2TE, UK.

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## Appendices

***Appendix i***

Email communication from Simon Curtis FWCF, Hon AssocRCVS, granting permission to use photos From Corrective Farriery Vol 2 Chapter 17 (2006). Figures 2a&b and 5.

Dear Simon Moore
1/12/15
You have my permission, as copyright holder, to use the illustrations listed below:
Chapter 17 page 346 Figure 3a Modified view of the coronary region of hoof.
Chapter 17 page 347 Figure 3b Magnified view of coronary region of hoof.
Chapter 17 page 360 Figure 15 Graph of Reilly's zones
in your Fellowship thesis. These images can be subsequently published within any variations of this work.
Best wishes
Simon Curtis

***Appendix ii***

Email communication from Christopher Pollitt BVSc PHD, granting permission to use photos from Color Atlas of The Horse's Foot (1995).
Figures 1a&b, 3, 4, and 6b.

Hi Simon
You are welcome to use the pics listed
Have a look at my new book The Illustrated Horses Foot via Amazon - you may like them better
Cheers
Chris

## *Appendix iii*

**Key to table 1**

| Breed/type | Abbreviation |
|---|---|
| **Warmblood** | W/B |
| **Irish Draught** | I/D |
| **Welsh Pony** | W/P |
| **Dartmoor Pony** | DART |
| **Cob** | COB |
| **Shetland Pony** | SHET |
| **Thoroughbred** | TB |
| **Connemara** | CON |

**Key to table 1**

| Foot Shape | Abbreviation | Sole Shape | Abbreviation |
|---|---|---|---|
| **Round** | R | Concave | C |
| **Square** | SQ | Flat | F |
| **Triangular** | TR | | |
| **Oval** | OV | | |

## *Appendix iv*

**Table 2** - *(measured in mm)* Ratio (T:HQ) represents the average for horse/pony of both left and right feet.*

| Horse/ foot | Toe | Medial toe quarter | Medial quarter | Medial heel quarter | Lateral toe quarter | Lateral quarter | Lateral heel quarter | * Ratio T:HQ |
|---|---|---|---|---|---|---|---|---|
| 1L | 16.5 | 10.64 | 7.09 | 3.89 | 12.06 | 8.08 | 4.46 | 4:1 |
| 1R | 17.38 | 11.22 | 7.12 | 3.96 | 12.66 | 8.19 | 4.61 | 4:1 |
| 2L | 12.80 | 10.96 | 9.93 | 7.13 | 10.99 | 9.94 | 7.64 | 1.7:1 |
| 2R | 12.96 | 11.02 | 10.12 | 7.23 | 11.07 | 10.04 | 7.86 | 1.7:1 |
| 3L | 7.76 | 9.00 | 7.17 | 4.77 | 9.01 | 7.16 | 5.34 | 1.5:1 |
| 3R | 7.76 | 10.73 | 7.51 | 5.16 | 9.16 | 7.05 | 5.76 | 1.5:1 |
| 4L | 6.14 | 6.01 | 4.29 | 2.83 | 6.03 | 4.31 | 2.91 | 2.1:1 |
| 4R | 6.21 | 6.11 | 4.31 | 2.98 | 6.12 | 4.39 | 2.97 | 2.1:1 |
| 5L | 8.75 | 7.80 | 6.35 | 4.78 | 8.26 | 6.72 | 4.79 | 1.8:1 |
| 5R | 9.01 | 7.92 | 6.63 | 4.78 | 8.36 | 6.66 | 4.86 | 1.8:1 |
| 6L | 9.92 | 9.31 | 8.68 | 7.83 | 9.41 | 8.58 | 7.82 | 1.2:1 |
| 6R | 9.96 | 9.42 | 8.71 | 8.08 | 9.52 | 8.60 | 8.24 | 1.2:1 |
| 7L | 8.83 | 12.58 | 6.65 | 5.96 | 11.25 | 8.02 | 6.89 | 1.4:1 |
| 7R | 8.95 | 12.61 | 6.69 | 6.06 | 11.31 | 8.09 | 6.93 | 1.4:1 |
| 8L | 10.71 | 9.35 | 6.27 | 6.52 | 9.72 | 6.66 | 6.67 | 1.7:1 |
| 8R | 10.89 | 9.37 | 6.64 | 6.44 | 9.73 | 6.69 | 6.12 | 1.7:1 |
| 9L | 9.83 | 11.92 | 7.51 | 7.24 | 12.41 | 8.30 | 7.66 | 1.3:1 |
| 9R | 10.07 | 11.85 | 7.59 | 7.23 | 12.14 | 8.39 | 7.60 | 1.3:1 |
| 10L | 10.31 | 9.20 | 6.67 | 4.84 | 9.59 | 6.67 | 4.84 | 2.1:1 |
| 10R | 10.63 | 9.39 | 6.74 | 4.96 | 10.60 | 7.69 | 5.01 | 2.1:1 |
| 11L | 11.68 | 11.00 | 8.30 | 7.79 | 11.45 | 8.80 | 7.95 | 1.5:1 |
| 11R | 11.85 | 11.25 | 9.01 | 7.81 | 11.46 | 9.02 | 8.00 | 1.5:1 |
| 12L | 10.39 | 10.82 | 10.69 | 8.95 | 11.03 | 10.97 | 9.14 | 1.1:1 |
| 12R | 10.47 | 10.91 | 10.75 | 8.96 | 11.10 | 10.99 | 9.16 | 1.1:1 |

**Table 2 Continued-*** *Ratio (T:HQ) represents the average for horse/pony of both left and right feet.*

| Horse/ foot | Toe | Medial toe quarter | Medial quarter | Medial heel quarter | Lateral toe quarter | Lateral quarter | Lateral heel quarter | * Ratio T:HQ |
|---|---|---|---|---|---|---|---|---|
| **13L** | 9.61 | 9.65 | 7.27 | 6.09 | 9.66 | 7.36 | 6.13 | 1.5:1 |
| **13R** | 9.53 | 8.97 | 8.05 | 6.14 | 9.71 | 7.89 | 6.66 | 1.5:1 |
| **14L** | 10.19 | 9.63 | 7.16 | 6.01 | 9.68 | 8.03 | 6.59 | 1.5:1 |
| **14R** | 10.25 | 9.81 | 7.40 | 6.70 | 9.94 | 8.72 | 6.82 | 1.5:1 |
| **15L** | 5.05 | 4.75 | 4.25 | 2.92 | 4.76 | 4.27 | 2.99 | 1.7:1 |
| **15R** | 5.06 | 4.74 | 4.25 | 2.90 | 4.77 | 4.31 | 3.00 | 1.7:1 |
| **16L** | 10.29 | 11.12 | 5.62 | 5.40 | 11.80 | 7.73 | 7.25 | 1.6:1 |
| **16R** | 10.31 | 11.41 | 6.01 | 5.51 | 11.81 | 7.77 | 7.25 | 1.6:1 |
| **17L** | 7.68 | 8.43 | 7.31 | 4.92 | 8.51 | 7.32 | 4.99 | 1.5:1 |
| **17R** | 7.77 | 8.56 | 7.40 | 5.01 | 8.66 | 7.44 | 5.05 | 1.5:1 |
| **18L** | 14.23 | 9.99 | 7.11 | 4.51 | 10.00 | 7.08 | 4.46 | 3.1:1 |
| **18R** | 14.39 | 10.06 | 7.19 | 4.61 | 10.03 | 7.26 | 4.72 | 3.1:1 |
| **19L** | 10.01 | 9.87 | 7.36 | 6.08 | 9.92 | 7.44 | 6.11 | 1.6:1 |
| **19R** | 9.90 | 9.70 | 7.33 | 6.01 | 9.73 | 7.39 | 6.06 | 1.6:1 |
| **20L** | 11.75 | 10.99 | 8.98 | 7.91 | 10.92 | 8.90 | 7.84 | 1.5:1 |
| **20R** | 11.89 | 11.05 | 8.96 | 7.86 | 10.95 | 8.87 | 7.85 | 1.5:1 |