AN INVESTIGATIVE STUDY INTO THE DIGITAL CUSHION AND ITS RELATIONSHIP WITH THE EXTERNAL HOOF

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Contents

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Abstract

Many farriers and hoof care practitioners are assuming digital cushion (DC) depth when externally assessing foot conformation on the horse. Various methods of measuring the depth of the DC to an assumed external reference point proximal to the heel bulb are being used in a belief that different farriery or trimming techniques can alter the depth, health and composition of the DC and thus improve the strength and depth of the horn in the heel area.

Aim: To determine whether external hoof conformation matches DC dimensions and also to determine if there is a reliable external reference point for assessing DC depth and position.

Materials and methods: Measurements of DC, heel and sole depth were taken on 100 cadaver limbs (52 front feet, 48 hind feet) using computed tomography (CT). Parameters were compared between front and hind to assess if there was a correlation between the depth of the DC and heel. Additionally, a measurement was taken externally with digital callipers to assess whether the assumed reference point being used by farriers and hoof care practitioners, would correlate with the DC measurement on CT.

Results: There was a strong, significant correlation between DC depth and heel/sole depth, and also between EHB depth and DC depth.

Conclusion: DC depth, to a certain degree, can be predicted accurately when assessing the external hoof. However, position rather than depth may be contributing to low heels. Using digital callipers to measure depth or position to the WBB proved to be statistically strong within the data set.

Declaration

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..................Signed by candidate.

Abbreviations

CC:	Collateral Cartilages
CT:	Computed Tomography
DC:	Digital Cushion
DIP:	Distal Interphalangeal
DDFT:	Deep Digital Flexor Tendon
DS:	Distal Sesamoid
DT:	Digital Torus
DP:	Distal Phalanx
EHB:	External Heel Bulb
GRF:	Ground Reaction Force
HPA:	Hoof Pastern Axis
H:	Hypothesis
MLB:	Medial Lateral Balance
MP:	Middle Phalanx
WBB:	Weight Bearing Border
RVC:	Royal Veterinary College

Introduction

Historically, lameness within the equine foot has been accredited to pathology associated with the horny external structures and their associated corium (O'Grady and Poupard, 2003), bone alignment and angles (Dyson *et al*., 2011), synovial structures (Smith, 2011), tendon lesions (Wilson *et al*., 2001), ligament desmitis (Dyson *et al*., 1995) and the lamina of the foot (Pollitt, 2010). However, limited attention has been given to the significance, health, depth or position of the digital cushion (DC).

The authors interest in DC depth and position, and how it correlates with external hoof shape, was the result of having limited success with low, weak heeled horses when shod with traditional open heeled horse shoes, fitted with length and width to offer support to the heels. Conventional open heeled shoes were invented 2000 years ago to protect hooves from wear and also for grip (Curtis, 2002). Low heels are categorised as being less than a 3:1 ratio with the toe from coronary band to weight bearing border (WBB) (Turner, 1992). Although studies on DC function (Dyhre-Poulsen et al., 1994; Bowker *et al*., 1998) and composition (Bowker, 2003) have been undertaken, the role of the DC as a supportive structure within the palmar foot is relatively overlooked and limited scientific research to date exists.

Digital Cushion Anatomy

Equine digital cushions are wedge shaped, highly specialised pads consisting of elastic subcutaneous adipose tissue (fat), fibrocartilage, collagen and modified skin glands. It has a poor blood supply and has gland ducts which exit through the corium of the frog. It is located proximally to the solar and frog corium and the palmar/distal surface is connected to the distal fibrous sheath of the deep digital flexor tendon (DDFT) and the abaxial surfaces of the collateral cartilages (CC) and the corresponding venous plexus. In addition to protecting the bony structures within the foot, it is an important structure in absorbing shock on impact with the ground (Murphy, 2002). This structure also distributes and reduces localised pressure under load which could cause damage to other singular structures of the foot, namely the horn tubules of the heel (Robert and Fails, 2011). Radiating from the connective tissue distal to the DDFT attachment within the DC are fibre tracts which form the digital torus (DT). Over time, and with the right amount of exercise, it is thought that this fibrous tissue and bundles of collagen fibre, will gradually become the fibrocartilage present in the DC which gives it its firm texture and mass in a "good footed" horse (Bowker, 2003). _See Fig. 1._

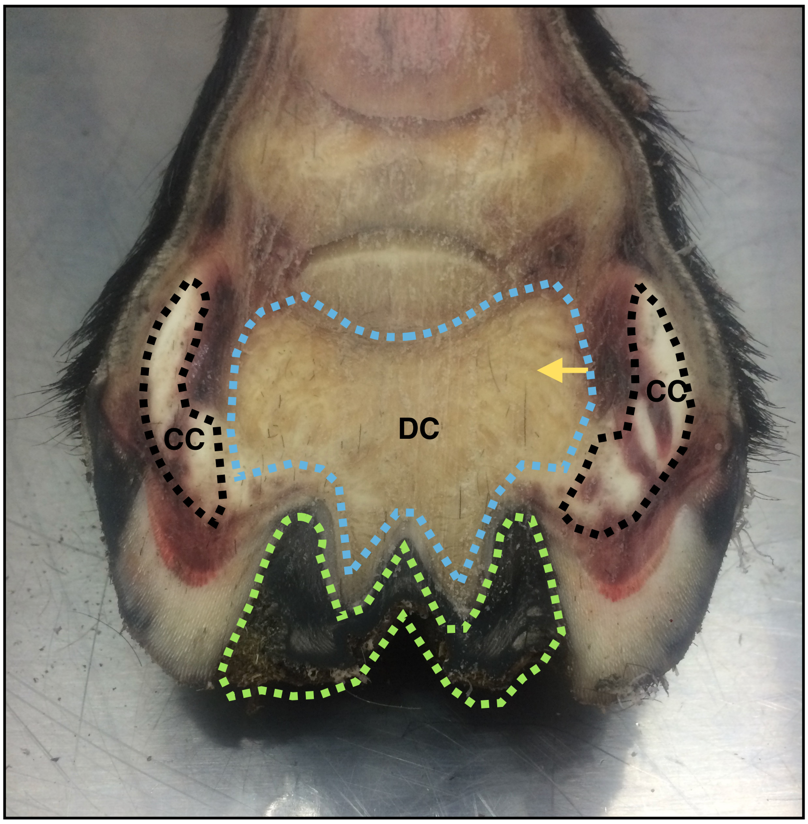

Fig. 1. Transverse section of the palmar aspect of a hoof showing DC outlined in blue with yellow arrow indicating horizontal fibrocartilage. Note the close relationship with the CC, outlined in black and external frog, outlined in green.

Digital Cushion Function

As with many structures within the horses foot, the actual function of the DC seems to be ambiguous. It is widely accepted due to its shape and structure that it has an anti-concussive function through energy dissipation (Robert and Fails, 2011). It is also largely accepted that it plays an important role in shock absorption (Murphy, 2002). Additionally, it is also hypothesised that it acts as a venous pump, assisting in returning the blood from the network of venous plexus in the foot, back up the horses distal limb once the joints are flexed (Ware and Colles, 2010).

Over the last century, three theories of energy dissipation within the DC have prevailed:

1. The pressure theory suggests, that at the landing phase of the stride, the frog and sole compress the DC, applying pressure to force the CC abaxially, which in turn would encourage venous blood from the hoof back up the leg during landing and loading. Once the limb enters the swing phase the DC decompresses (Lungwitz, 2015).

2. The depression theory is in essence a mirror image of the pressure theory. It is claimed that during landing and loading, the forces that are transmitted through the laminar attachments, are redirected and dissipated as the middle phalanx (MP) is lowered, which then causes depression of the DC, abaxial movement of the CC, and again, forces venous blood from the foot back up the leg. Decompression of the DC takes place during the unweighted swing phase of the stride (Williams and Deacon, 1999). However, a study using pressure inducers within the DC recorded a negative pressure upon landing and loading, which calls these two theories into question (Dyhre-Poulsen *et al.*, 1994).

3.The hemodynamic flow theory suggest that upon landing, energy from the ground reaction force pushes the heels and bars of the foot proximally, forcing the CC abaxially. This abaxial movement of the CC is claimed to be the mechanism which causes suction of the blood through the DC as it compresses, forcing blood through the network of venous anastomosis within the CC. The DC, again, decompresses through the swing phase. This movement of liquid (blood), based on a hydraulic fluid theory, is a very effective form of energy dissipation, and may also explain the negative pressure recorded within the DC. (Bowker *et al*.,1998)

Many farriers and professional hoofcare practitioners theorise that the mass of the DC may have a correlation to the external hoof shape, believing that under excessive compression from a long toe, low heel or broken back hoof pastern axis (HPA) type conformation, it will reduce in volume and depth (O'Grady, 2006; Ferrie, 2008; Gravelproofhoof.com, 2016). DC depth is also thought to be influenced by various trimming techniques, specifically the length of heel in relation to frog contact with the ground and discussion as to whether the DC can change in depth continues. A number of farriers and hoof care practitioners are beginning to use this assumed DC depth measurement using digital vernier callipers or more crudely, their thumb and finger, to decide upon a trimming and shoeing protocol (Varini, 2016). *See Fig. 2.*

Research in cattle has shown a strong correlation between thin DC's and lameness (Bicalho *et al*., 2009; Mülling and Greenough, 2006). However, there is limited data on the DC available in horses to date, due to minimal studies being undertaken other than Dyhre-Poulsen *et al*., 1994; Bowker et al., 1998 and Bowker, 2003.

Fig. 2. Image showing external measurement of the DC being used by some hoof care practitioners. With permission from gravelproofhoof.com

Aims and Objectives

Aims

The aim of this study is to determine whether external hoof conformation matches digital cushion dimensions and also to determine if there is a reliable external reference point for assessing DC depth and position.

Objectives

- To determine if there is a correlation between heel height and DC depth to the WBB
- To determine whether an external heel bulb (EHB) measurement with callipers can be used to measure DC depth to the WBB

Hypotheses

H1: There will be a correlation between heel height and DC depth to the WBB

H2: There will a correlation between the internal DC depth to the WBB and the EHB measurement with callipers.

Materials and Methods

Materials

This study included 100 cadaver limbs (*n=100*) randomly selected to reflect the general population of horses. A mixture of breeds, size, shod and unshod were selected from a freezer storage unit at The Royal Veterinary College London (RVC). The legs were from horses that had been euthanased for unrelated reasons to this study and the study was approved by the Ethics and Welfare Committee of The Royal Veterinary College.

Originally, 50 fronts and 50 hinds were to be used. However, after computed tomography (CT) scanning, 2 hind limbs had to be re-categorized into fronts. All of the limbs had been transected at the carpus/tarsus. If any signs of laminitis, severe hoof distortion, cracks or any noticeable foot pathology were present then these limbs were excluded from the study. Limbs were further organised into sides using proximal metacarpus and metatarsus recognition. There were 27 left fronts, 25 right fronts, 21 left hinds and 27 right hinds.

Measurements were taken post trim in millimetres for width (widest point), length (centre of toe to point of lateral heel) and width between the heels (each point of heel buttress) and each limb was weighed to give an indication of approximate size. The limbs were defrosted in warm water one hour prior to the study, shoes removed (*n=5*) and feet cleaned using a wire brush and a small amount of sole was removed to allow for the foot mapping process.

Methods

Foot mapping is a technique recognised by farriers but remains relatively unsupported scientifically. To standardise trimming, a foot mapping technique and trimming protocol was used within this *ex vivo* study. This was to allow repeatability in trimming all cadaver limbs. The same farrier (Jonathan Nunn FWCF) trimmed all of the feet following a standard protocol (configured by Grant Moon AWCF) *See Fig. 3.*

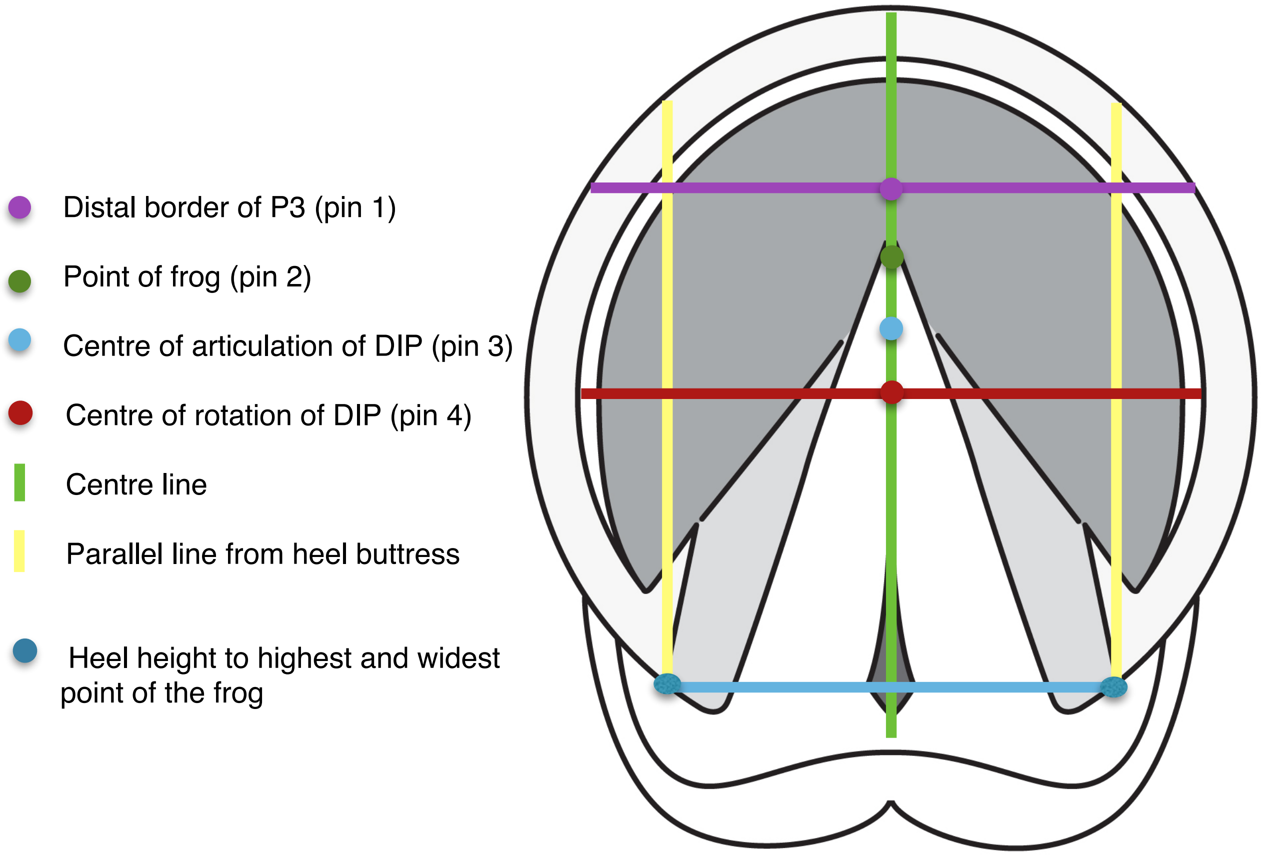

Fig. 3. Schematic diagram of the foot mapping protocol used in this study.

The exfoliating sole was removed to the level of the white line and the frog had any loose material trimmed away but no depth was reduced. The peripheral wall was removed down to the level of the sole in the toe area and the heels were trimmed down so that the heel buttress terminated at the widest and highest part of the frog. This allowed the frog to be weight bearing at the same level as the heels once ground bearing. Any hoof wall flares were removed achieving foot symmetry and a parallel dorsal hoof wall from coronary band to WBB.

Computed Tomography (CT)

All feet were scanned in a CT scanner using the same protocol (kV 80, mA150, slice thickness 1.25mm). All scans were performed proximal to the fetlock joint and distal to the ground bearing border of the hoof wall. A 16 slice CT scanner was used, all images were stored in DICOM format and transferred onto Osirix (medical image viewer) to be measured. CT produces a stack of image slices that allow the reconstruction of the foot and its components in 3D. Manipulation of CT studies also allows the viewer to mimic radiographs with which farriers are familiar.

Measuring Protocol

Measurements on CT images were taken by a qualified vet experienced in both the program and in measuring from CT scans (E. Fitzgerald MVB MRCVS Cert.EqSports Med (RVC). Each measurement was taken 3 times. The mean of the last two measurements were used for further analysis to minimise measuring error. All data was recorded onto a data spreadsheet (excel) to analyse.

Measurement A was taken from the most proximal point of the DC to the point of the WBB at 90 degrees. *See. Fig 4.*

Measurement B was taken from the most distal point on the distal sesamoid bone (DS) to the WBB at 90 degrees to give a heel/sole depth measurement. *See Fig. 4 and 5 a,b,c,d.*

Measurement C was taken from the most proximal point of the sole to the most distal point of the sole, directly distal to the DS to show that if DC compression was present this was not due to a thin sole. *See. Fig. 4.*

Fig. 4.
Two CT slices taken in the mid sagittal plane. The left picture shows an example of a horse with a relatively upright foot, the image on the right an example of a horse with a relatively flat foot.

A. =Digital Cushion depth
B. =Heel/Sole depth at NB
C. =Sole depth

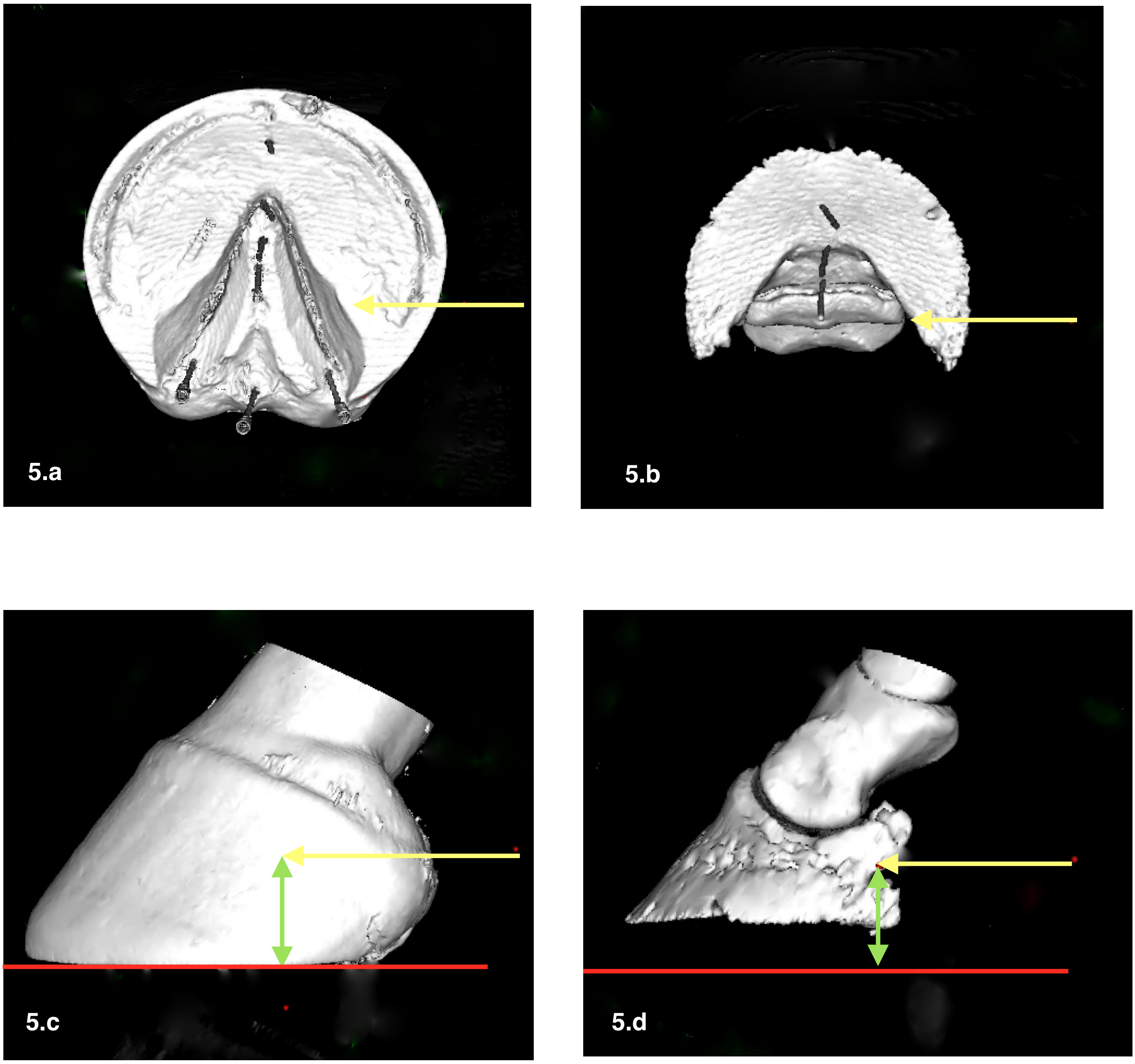

Fig. 5 a-d. CT scan of foot showing rendered image to establish measurement B:Heel/sole depth at DS. Yellow arrow indicates how the most distal point of the DS corresponds with the external heel area. Green arrow shows the most distal point on the DS corresponds with external heel depth from WBB to coronary band.

External Measurement

The external reference point was configured by a pilot study conducted by the author prior to the main study on a number of freeze dried limbs (Stromsholm). The proximal point of the DC was observed internally on a sagittally sectioned limb allowing observation as to where the external point of the DC would be. Each limb was recorded using digital photography. *See Fig. 6.*

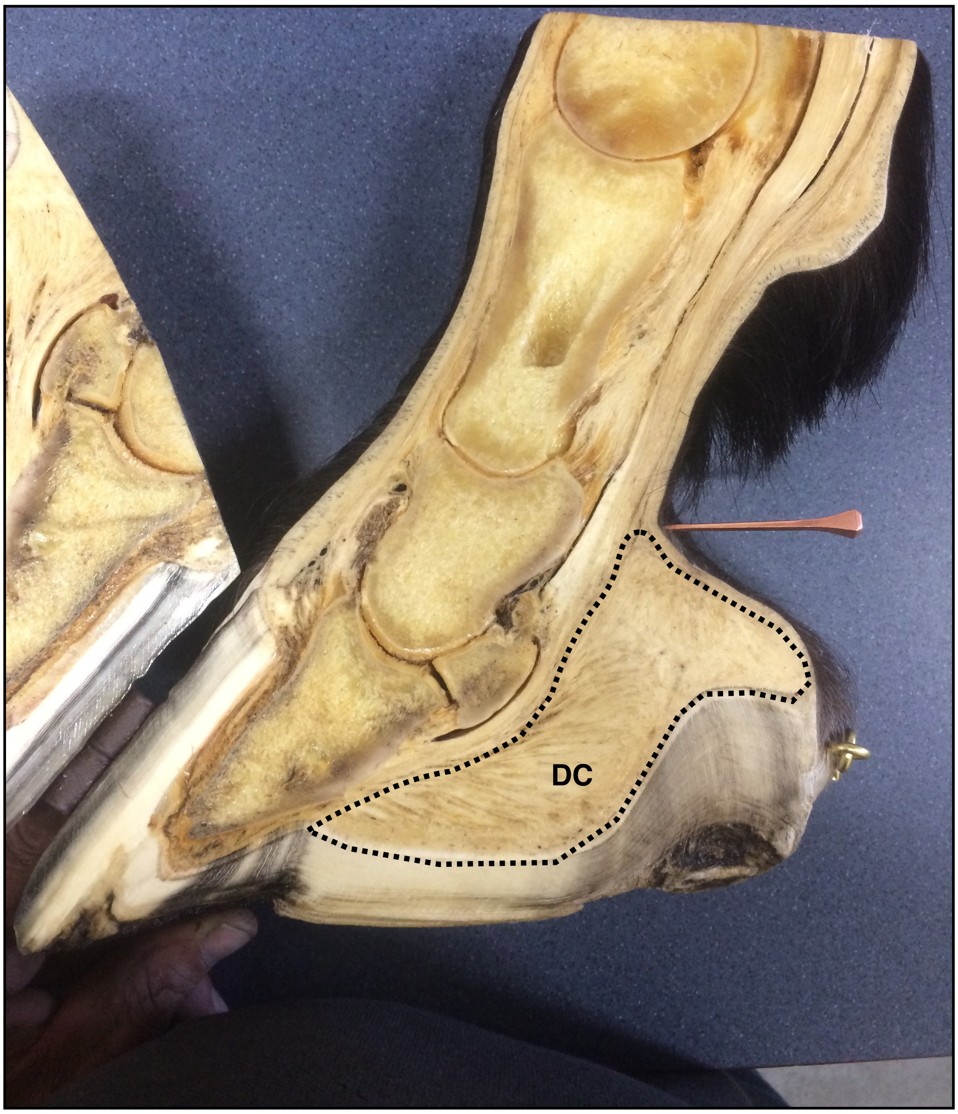

Fig 6. Freeze dried specimen courtesy of Stromsholm used for pilot study to establish the external reference point for the DC, outlined in black.

A subsequent 56 limbs (36 fronts, 20 hinds) were then randomly selected from the original study sample. A measurement was taken from the EHB reference point of the DC with digital vernier callipers to the WBB (measurement D). The WBB was recreated by the use of an aluminium plate being placed on the bearing border of the hoof wall and frog. All measurements were taken 3 times, with the first measurement being discarded and the mean of the second and third measurement used for further analysis. All data was stored in a lab book and transferred onto a data spreadsheet (excel). _See Fig.7._

Fig. 7. Image showing EHB measurement being taken using digital vernier callipers.

Data analysis

Data distribution was assessed by plotting histograms and by performing a Kolmogorov-Smirnov test and the data was found to be normally distributed. To compare front and hind feet a T test was used. To assess the relationship between the measured parameters a Pearsons correlation coefficient was calculated. All statistical analysis was performed in SPSS. P value was set at P=0.05.

Results

Horses bear weight approximately 60-40% in favour of the forehand (Back, E., *et al* 1995). Interestingly, the mean DC depth measurement A and D was greater in front feet than hind feet. A hind foot however showed the greatest amount of depth overall. All other parameters showed more depth within the hind feet and the standard deviation as a measure of spread was larger in the hind compared to the front feet. There was a significant difference in DC depth between fronts and hinds but in none of the other parameters. Table 1 A and B illustrate the measured foot parameters within the front and hind foot.

Table 1 A Front foot measurements

	Mean (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
Digital cushion depth	57.4	7.7	41.0	74.8
Heel/sole depth	32.5	4.3	23.8	43.6
Sole depth	7.9	3.4	2.0	15.2
External heel bulb depth	53.5	8.2	38.2	74.0

Table 1 B Hind foot measurements

	Mean (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
Digital cushion depth	53.8	10.4	41.1	76.1
Heel/sole depth	35.2	6.1	27.2	46.6
Sole depth	8.8	3.5	3.6	15.9
External heel bulb depth	50.2	10.9	36.6	73.6

There was a strong, significant correlation between DC depth and heel/sole depth throughout the data set (P=0.762, P<0.0001) *See Fig. 8*. There was also a strong statistical correlation between EHB depth and DC depth (P= 0.915, P<0.0001) *See Fig. 9*. When looking at the DC depth of the front feet only (P=0.822, P<0.0001) and when examining the hind feet only (P=0.853, P<0.0001) *See Fig. 10.* When examining the EHB depth on the front feet only (P=0.895, P<0.0001) and when examining the hind feet only (P=0.930, P<0.0001) *See Fig. 11.*

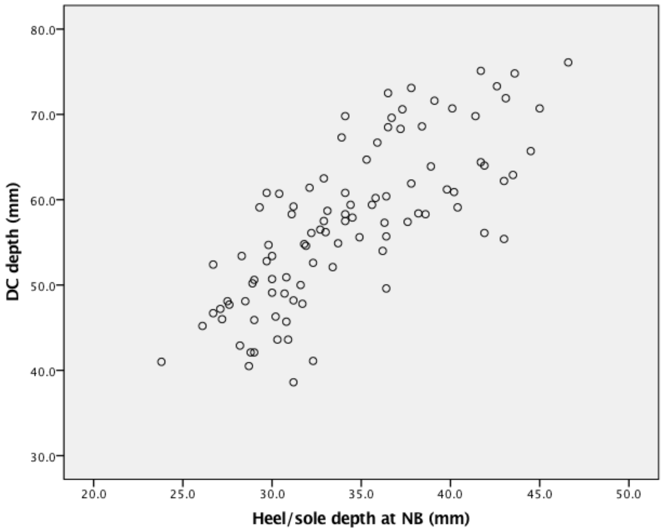

Fig. 8. Scattergraph showing a strong correlation between DC depth and heel/sole depth at the navicular bone.

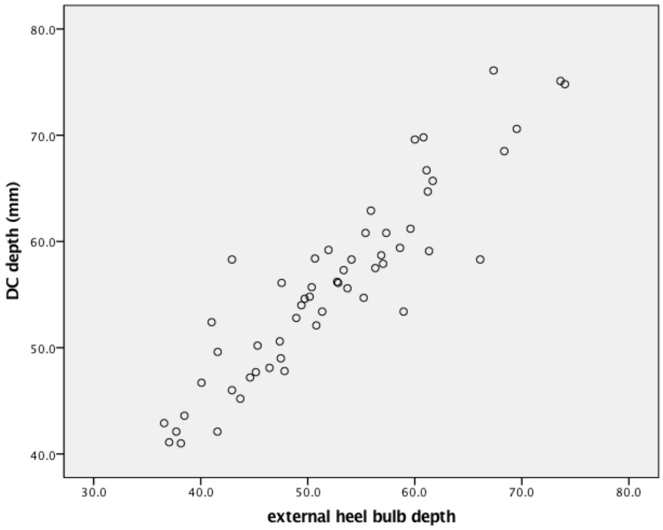

Fig. 9. Scattergraph showing a strong correlation between DC depth and external heel bulb depth.

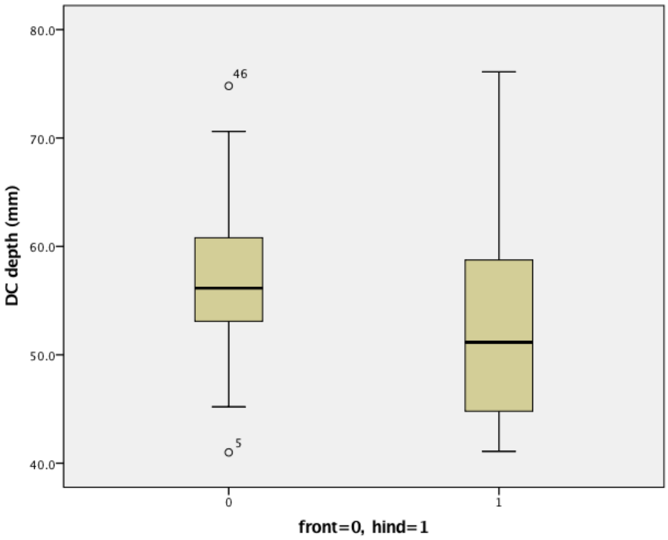

Fig. 10. Box plot showing a comparison of digital cushion depth between front and hind feet. The middle line represents the median value, the box the interquartile range and the whiskers maximum and minimum. The circle represents an outlier.

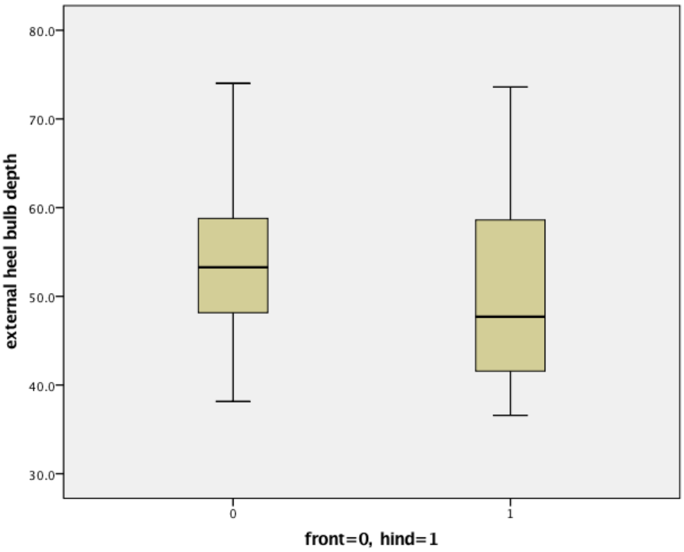

Fig. 11. Box plot showing a comparison of EHB depth between front and hind feet. The middle line represents the median value, the box the interquartile range and the whiskers maximum and minimum.

Discussion

Methods

With regard to foot mapping, although standardised and repeatable, no consideration for conformation, HPA or hoof distortion could be accounted for within the cadaver sample and many of the limbs, once CT scanned, presented broken back HPA's and low palmar angles of the DP which may have influenced results. Various hoof maps advocate trimming the heel buttress to the highest and widest part of the weight bearing frog (O'Grady, 2011; Caldwell *et al.,* 2016). It could therefore be questioned that the foot map and trimming protocol, although effective on a majority of feet, may well have caused the heels to be lowered on certain feet in an attempt to try and bring the point of heel back to the widest point of the weight bearing frog, thus influencing measurement A. If a foot presented with any distortion, such as a long toe low heel, and the heels had been left to migrate dorsally before euthanasia, then trimming the heels to the widest point of the weight bearing frog can often take 2-3 shoeing cycles to achieve. If unachievable in one trim, then this point is extended with the use of a shoe (O'Grady, 2011). A more individual approach to conformation and foot morphology should be considered when transferring this, or any other foot mapping method and trimming protocol to the live horse or comparative *in vivo* studies.

Relating hoof mapping to everyday practice

The trim is a snapshot of a moment in time with a live horse. Frog contact is desirable (O'Grady, 2011; Caldwell *et al.,* 2016) but as natural growth of the peripheral hoof wall can exceed wear, depending on work and environment, the frog and DC may no longer be in contact with any bearing border (Hampson *et al.,* 2011). The frog, and also the DC, are rendered non weight bearing and the DC may not function efficiently (O'Grady, 2011).

However, feet with deep heels and no frog contact are generally healthy, therefore frog contact remains uncertain in relation to DC function. However, heel depth correlated strongly with DC depth, confirming H1 so the support internally and position within the palmer foot, rather than function seems to be influential to heel depth.

Influencing factors

A study conducted by Bowker, 2003 into “Good feet and Bad feet” found that although DC anatomy was identical amongst horses once dissected, the composition of the DC within weaker footed horses with low heels (thoroughbred types) contained a much higher percentage of adipose tissue than fibrocartilage. This was compared to horses with strong, upright heels (quarter horses, arab types) which contained a much higher percentage of firm supportive fibrocartilage and a lower percentage of adipose tissue. These corresponding DC’s varied greatly in texture, the DC of the weaker footed horses were very soft and yielded under pressure, as apposed to the DC from the good footed horse, that under the same pressure was firm and returned to its original shape (Bowker, 2003). Low heeled horses will generally have a less than ideal palmar angle. Combined with the centre of pressure being dorsal to the centre of rotation, a larger percentage of the horses weight will be concentrated over the palmar aspect of the foot (Barrey, 1990). With the addition of these thinner DC’s containing a higher adipose tissue content and less firm fibrocartilage, the DC will understandably compress in feet where the frog is on the same WBB as the heels or, if the frog is not on the same WBB, may vertically displace. This can occur more, than in a horse with more heel depth and a firmer DC which contains more supportive fibrocartilage.

Many factors are thought to contribute to DC health and composition and under development of the DC may well be a consideration within farriery. Lack of stimulation from the environment or surface is believed to effect the composition and density of the structure which may have consequences on its supportive role within the foot. Results showed that horses with low heels (thoroughbred types) possessed thin DC’s confirming H1. Many thoroughbreds will be shod from a young age due to their weaker feet becoming sore or shoes being required for traction in race training. Combined with standing for long periods in stables and only short periods of extreme exercise, their DC are largely rendered unstimulated (Bowker, 2003). This would correspond well to the results within this study.

Whilst genetics would seem to determine the conformation of the horse (Greet and Curtis, 2006), many people theorise that age, environment, hydration, type of exercise and farriery are also highly influential (Lungwitz, 2015). Being an *ex vivo* study, many of these influential factors could not be accounted for. However, dehydration could well have been a factor as some change in mass could have occurred in the DC from the thawing process. Despite moisture levels being proven to effect tissue properties (Kasapi and Gosline, 1999*)*, it was not possible to monitor for dehydration and using fresh specimens was unrealistic.

Establishing the true function of the DC could not be accounted for within this *ex vivo* study. As to whether the DC functions in accordance with either the pressure, depression or hemodynamic flow theory or actually a combination of all three, still remains ambiguous. However low heeled horses showed to have thin DC’s and combined with containing more soft adipose tissue than firm fibrocartilage, shock absorption and energy dissipation can be assumed to be inferior in these feet than horses with more heel depth and larger, firmer DC’s. Rather than the weight of the horse being dissipated through the DC, shock would instead be transferred to the bones, ligaments and lamina upon landing and loading (O'Grady, 2011).

Studies on cattle have shown a correlation between thin DC's and lameness (Bicalho *et al.*, 2009: Mülling and Greenough, 2006). Further studies to establish whether lameness correlates with thin DC's in horses would be warranted.

Results and measuring protocol

The measuring protocol used could be analysed further, as the DC, under more compression from the weight of the horse in front feet, rather than the DC compressing in a vertical direction, may well be displacing in a more palmar/plantar aspect (heel bulb area) under weight bearing. This would seem plausible taking into account its wedge shape and containing more soft adipose tissue towards the palmar aspect than the dense DT area directly under the DP (Murphy, 2002). This may have given a false reading of true DC depth. Taking this into account, a further measurement of the DC in the DT area, from a point beneath the most distal aspect of the DS, may show differing results. *See Fig. 12*. However, results did show that DC depth/position within the front feet and the hind feet, correlated strongly with heel/sole depth throughout confirming H1.

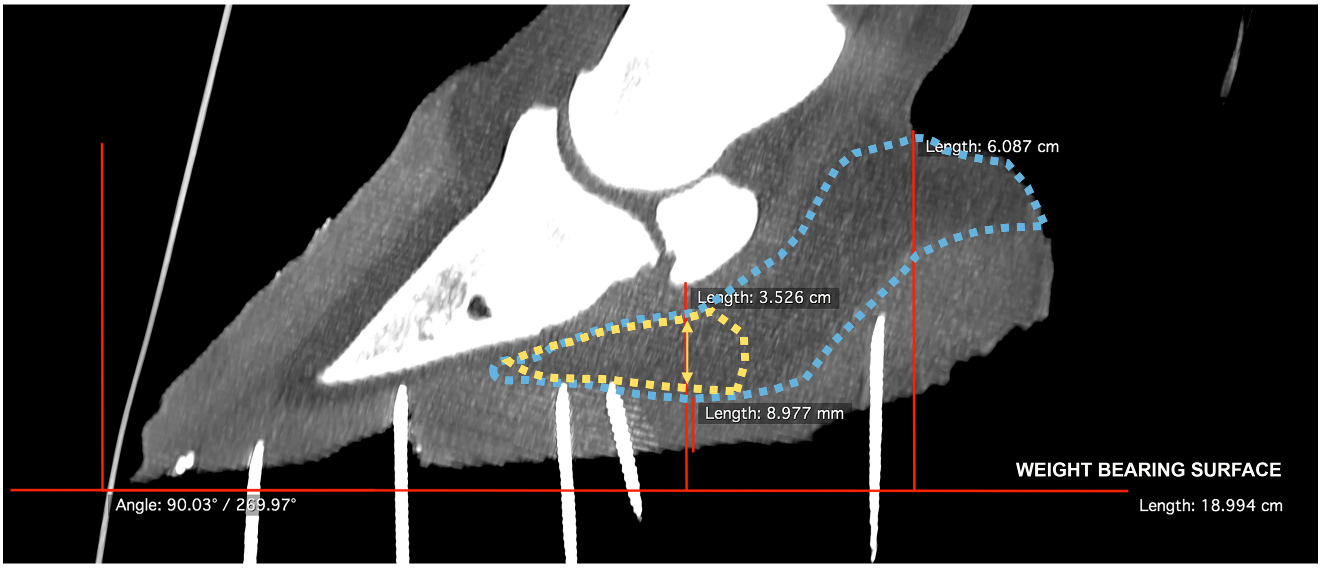

Fig. 12. Arrow indicating additional measurement of DT area outlined in yellow of DC which is outlined in blue.

Relevance to the external hoof

Vertical displacement of the DC (position), rather than compression, could be contributing to the horn tubules in the heel area becoming overloaded within these low heeled, weaker type feet. This compression, or vertical displacement, depending on the frog being in contact with the WBB, can be compounded once a traditional open heeled shoe, giving only peripheral support to the hoof wall is applied. The frog and DC have now further to travel distally as the bearing border is now further from the external frog by the depth of the shoe interface. The heel area may become compressed between the shoe and the descending weight of the horse against the ground reaction force (GRF), localised on the wall of the heels, which could be contributing to them becoming either crushed or low in comparison to the toe. Once the DC repositions distally, the coronary band can be seen to displace, divergent growth rings are apparent and horn tubules are now projected dorsally (Dyson et al., 2011). *See Fig. 13 a.b.c.*

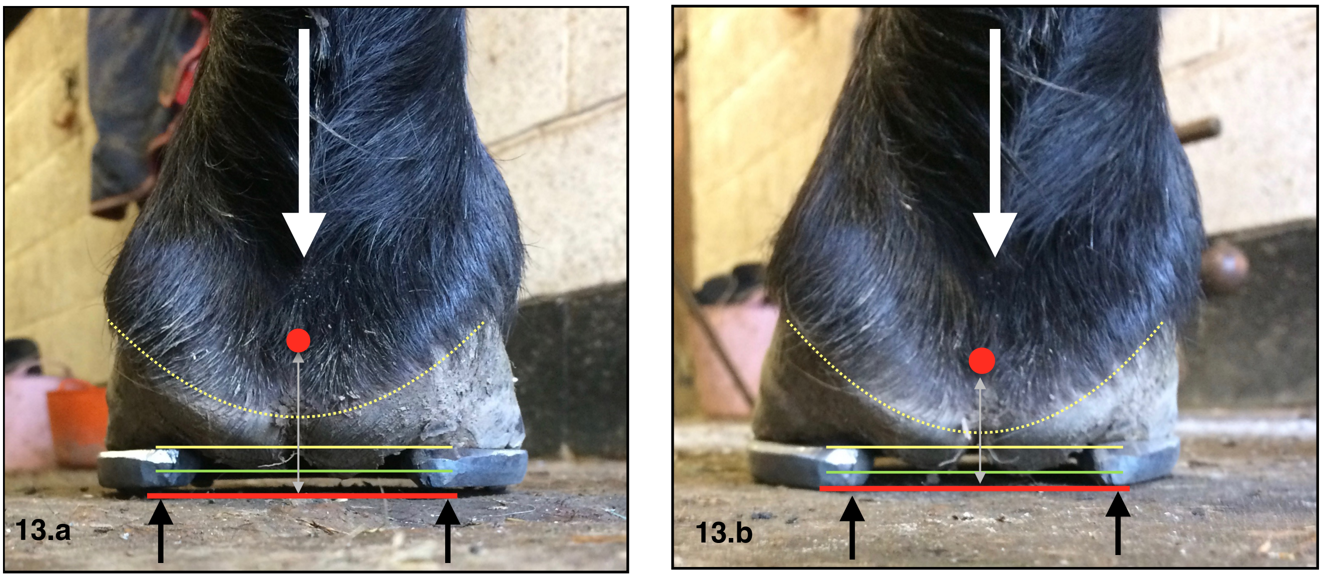

Fig. 13 a. A front foot with low heels shod in an open heeled shoe. Fig. 13 b. The same foot displaying an amount of vertical distal displacement of the DC using the EHB reference point (red circle) after 10 minutes of being shod. Yellow dotted line showing coronary band displacement. Yellow line indicating WBB of the heels, green line showing most distal point of the frog and red line showing WBB of the shoe. White arrows indicating the weight of the horse and black arrows represent GRF.

Fig 13. c. Showing the same foot with low heels and vertical displacement of the DC after 35 days of being shod in an open heeled shoe. Yellow dotted line showing coronary band displacement and blue arrows indicating the direction of the horn tubules in the heel area projecting in a dorsal direction.

Traditional farriery techniques

Horses are generally shod in open heeled shoes (Curtis, 2002). Although many feet will retain heel depth, many horses will consistently present with low heels at the end of a shoeing cycle (28-35 days approx). Low angles can be associated with lameness (Holroyd *et al*., 2012) and palmar foot lameness is a common cause within the equine industry (Dyson *et al*., 2002). The lower the angle of the hoof the larger the amount of weight is distributed in the heel area, creating a vicious cycle of a low heel, long toe conformation (Barrey, 1990). As the DC can be seen to vertically displace in open heeled shoes using the EHB reference point, support in this area prior to vertical displacement could be beneficial to improving horn tubule direction, heel depth and less acute angles.

Historically, horses would have shoes removed once they had ceased their work discipline or if their feet had become damaged (Lungwitz, 2015). This technique offered rapid results with hoof health and heel strength and feet could be seen to visually recover. The author hypothesised that this is because the thin DC within low heeled hooves were not being supported via the external horny frog once shod. Many feet would be rehabilitated in this method allowing the external frog, sole and internal DC to share the load put upon the peripheral wall and allow the DC to function as intended. The horny frog and dynamic DC would be repositioned proximally within the foot once the shoe was removed by the use of the horses weight and the GRF on the external frog. Additionally, increased vasculature in the palmar aspect of the foot may contribute to healthier horn growth in the heel area (Colles *et al*., 1980; Lungwitz, 2015). This technique seems to happen less frequently in modern day horse management and horses can be shod in the same manner for many years with little exercise or work which may contribute to lack of hoof health (Lungwitz, 2015; Bowker, 2003).

Remedial methods of shoeing these low heeled horses in an attempt to support the low or under run heel include, but are not limited to, wide webbed shoes, fitted with length and width at the heel area; the straightbar shoe, egg bar shoe and heartbar shoe. These bar shoe variations are assumed to benefit the foot by offering a larger ground bearing surface (eggbar). Weight sharing by incorporating the horny frog, and decreasing excessive expansion and distal movement of the horny frog under weight bearing (straightbar and heartbar) (Williams and Deacon, 1999). Little consideration to the DC is given, as function will be inhibited by the use of a rigid bar shoe. To function correctly the DC must be allowed to compress under stance and decompress through the breakover and swing phase of the stride (Lungwitz, 2015; Williams and Deacon, 1999; Bowker *et al*., 1998).

However, with a rigid bar shoe fixed to the foot, the DC will be under pressure by partial compression of the external frog from the straight bar, and complete compression through the external frog from the heartbar in every phase of the stride, including the unweighted swing phase. This will allow the already compressed DC to only partially function through depression from P2, thus compromising function and health (Lungwitz, 2015; Williams and Deacon, 1999; Bowker *et al*., 1998).

One aspect to also consider is necrosis of the frog and thrush associated with the application of bar shoes (Williams and Deacon, 1999). Treatment necessitates the necrotic frog material to be trimmed away. This can cause the frog to be below the WBB of the heels, creating space for the DC to vertically displace.

Modern alternatives to rigid bar shoes are polymer packing materials that will offer load sharing benefits to the heels by utilising the sole, external frog and DC, preventing vertical displacement. However, it will also inhibit function through constant compression by the hard, non-breathable material, again producing necrosis and thrush. If barefoot is not an option for the individual equine with weak feet, then the author considers a soft natural packing material, which will offer movement and function to the horny frog and DC, combined with a frog support pad to prevent any repositioning of the frog and DC distally, optimal for DC and overall foot health and function. *See Fig. 14.*

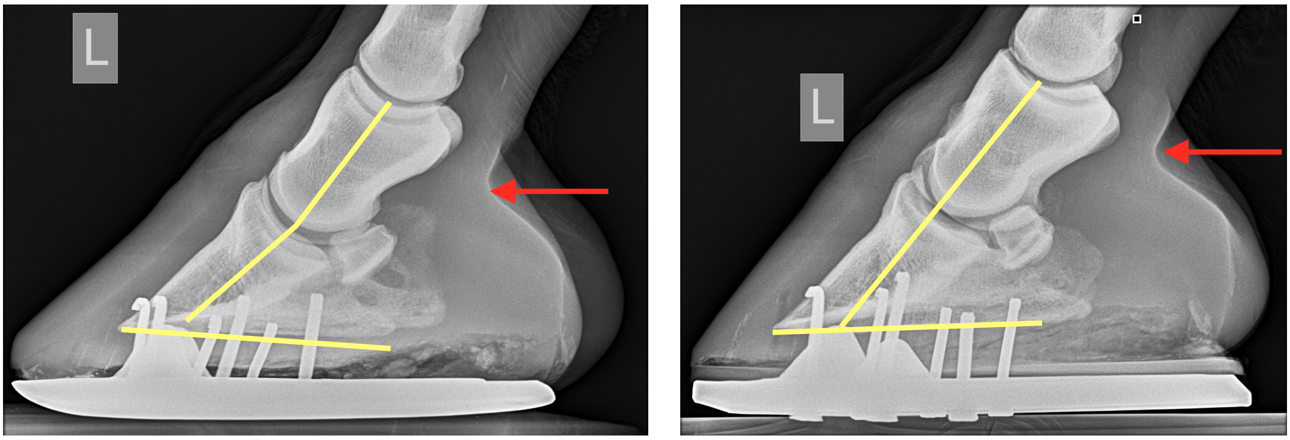

Fig. 14. Radiographs showing foot with low heels, before (left) and after being shod with frog support and a soft, medicated natural packing (right) to allow for DC function. Before radiograph on left showing signs of a negative palmar angle of the DP and broken back HPA. After radiograph on right showing improved palmar angle of DP and correct HPA. Red arrows show DC in a more proximal position once shod in this manner. Radiographs courtesy of J.Nunn FWCF

Conclusion

It is evident that the palmar foot is made up of a number of components including the DC that all work in unison to support the weight of the horse and protect vital internal and external structures. Externally, it is easy for a farrier or hoof care practitioner to visually evaluate if a horse has a low heel, long toe conformation. Hypothesis 1 was fully supported from the results in this study that DC depth/position from its most proximal point to the WBB strongly correlates with external heel depth, confirming that the DC depth/position within the foot is predictable from the external hoof. However, there were some feet in the dataset that externally had good heel depth that you would hence conclude a well-developed DC, and that was not the case. Equally there were horses that had low heels that possessed a DC of reasonably good depth.

As to whether a DC which lacks in depth or is positioned distally within the hoof is a primary cause for a hoof to have low heels, or whether the low heel actually causes the compression of the DC remains uncertain. However, data can now be externally obtained and further studies undertaken as correlation for Hypothesis 2 was significantly strong. Further studies as to whether the DC can decrease, or alternatively, increase in depth from environmental stimulation, diet, hydration or any differing hoofcare methods would be warranted. Taking these results into account, it could be further hypothesised that if the DC depth or its position within the foot was preserved from an early age, or repositioned proximally if vertical displacement occurs, then low heeled horses with the associated low angles and pathology associated, may be improved upon by utilising its supportive structure. *See Fig.14.*

The preliminary procedures of using an external reference point for the location of the DC being used by farriers and hoof care practitioners proved to be statistically strong with the internal DC. However, a more accurate measurement internally in the more supportive DT area, distal to the DP and DS to the most distal point of the DC, rather than the WBB may show differing results. Although the sample used in this study showed no radical palmar displacement of the DC, the author hypothesised that under extreme compression from the DP, thinner DC's containing more adipose tissue, may well be displacing and filling the heel bulbs showing a misleading amount of DC depth. Hence, using digital callipers externally to measure DC depth/position may not be accurate in extremely low heeled feet.

Manufacturers addresses

1. CT scanner. GE Lightspeed Pro 16, GE Healthcare, 352 Buckingham Avenue, Slough, UK
2. Digital vernier callipers. Halfords, St Johns Centre, 8 Rope Walk, Bedford MK42 0XE
3. Freeze dried specimens of equine limbs. Stromsholm Limited Wood Court Chesney Wold Bleak Hall Milton Keynes MK6 1NE
4. Iphone 5s (Photography). Apple, 26 Midsummer Blvd, Milton Keynes MK9 3GB
5. Osirix medical image viewer. Pixmeo SARL, 266 Rue de Bernex, CH-1233 Bernex, Switzerland. http://www.osirix-viewer.com
6. SPSS (version 23) IBM, Armonk, USA

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