An investigation into the use of hoof balance metrics to test the reliability of a commonly used foot trimming protocol and their association with biomechanics and pathologies of the equine digit.

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By

Mark Nathan Caldwell F.W.C.F.

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Abstract

The equine foot has a specific conformation (shape) that provides maximum biomechanical efficiency. Biomechanical efficiency allows the foot to withstand, accept, absorb, dissipate and transmit loading weight bearing forces in a manner that offers the greatest protection to the horse. This principle implies that there is some combination of foot size, foot shape, wall length and angles that make the foot an ideal shock absorbing, weight-bearing structure. It is the proper combination of these variables are said to constitute what has been described as the properly balanced foot. However, there are currently several conflicting hoof balance reference systems commonly utilised and what constitutes ideal balance has been the subject of great debate for many years. One goal of the research was to investigate the principle of equal geometric proportions and dependentcy on factors such as foot-type and environmental conditions. By utilising a standardised trimming protocol and a hoof mapping system to collect measurement data based on proportionality of the bearing border length the purpose of this study was, partly, to verify whether a commonly used theory of hoof balance, firstly described by Duckett, is achieved. Secondly to determine whether geometric proportions are equivalent following trimming, thereby achieving hoof balance.

Analysis suggested Currently accepted interpretations of static hoof balance including the achievement of an aligned phalangeal axis and a ground bearing border bisected by CoR are likely to be outmoded. This provides support to the hypothesis that feet should be managed on an individual basis rather than a “one-size fits-all” approach commonly applied and that implementing a prescriptive model may even be counter-productive to the functional integrity of the hoof.

Farriery technique have been shown to influence skeletal alignment within the foot. Standardised trimming and shoeing protocols were used to test the hypothesis that shoeing, over an extended period of time, would result in significant differences in static hoof balance proportions. Results showed that horses managed unshod had greater ability to manipulate bearing border length, re-align the heel angle and allow palmar heel migration than shod horses. Furthermore, proportional hoof balance measures were able to be altered in unshod feet and that equivalence of the proportional hoof measures were not present in either cohort (unshod/shod). The significant differences in hoof measures present in shod feet ie; flattening of the sole, heel contraction, reduction in dorsal hoof wall and heel angulation and dorsal migration of dorsal hoof wall and heel seemed likely to reflect the effect of the shoe over an extended period.

The application of a standard steel horseshoe appeared to influence hoof shape and is likely to both affect and be affected by mechanical forces acting on the foot. The affect of hoof shape and the mechanical forces experienced by the foot itself following the application of the standardised trimming protocol and the application of a shoe were investigated. Results highlighted significant post-shoeing statistical differences in all dynamic measurements between shod and unshod feet. Specifically post-shoeing reductions in peak pressure and the contact area resulting in differences in peak force and peak force time were noted. These results partially support the propersition of a difference in mechanical behavior of the foot under load and may reflect the differences witnessed in feet under different management regimes. Biomechanical analyses of this kind enable improved understanding of hoof function, and a rational, objective basis for comparing the efficacy of different therapeutic strategies designed to address hoof dysfunction and pathology.

There is considerable anecdotal information that poor foot conformation and balance are associated with an increased risk of foot-related lameness but foot imbalance may also result from lameness as an adaptation to chronic pain. Utilising MRI findings from a group of horses referred for lameness investigation bionominal logistic regression was used to test the hypothesis of risk of lameness associated with hoof measurement proportions. There is evidence to suggest a strong correlation between hoof conformation and the biomechanical inference on anatomical structures and foot-related pathologies.

Variation in key hoof measurement proportions resulted in significant differences in risk factors of specific common foot pathologies ie; navicular disease and degenerative joint disease of the distal interphalangeal joint.

It has been argued that the form of the solar arch was indicative the pathologies. Results from the current study appear to support his hypothesis by linking hoof morphology to the incidence of disease. Whilst the author recognises that hoof shape is influenced by any number of other factors, proportional values along the solar axis may well prove to be a good model for biomechanical efficiency either by trimming alone or form the basis of a more biomechanically sympathetic standardised shoeing model.

List of Abbreviations

ABRU	Australian Brumby Research Unit
ALDDFT	Accessory ligament of the deep digital flexor tendon
BB	Bearing border
BBL	Bearing border length
BM	Basement membrane
BO	Point of breakover
CB	Coronary band
CoP	Centre of pressure
CoP-CoR	Centre of pressure to centre of rotation
CoP-Heel	Centre of pressure to the heel buttresses
CoR	Centre of rotation
DDFT	Deep digital flexor tendon
DDTBB-CoR	Dorsodistal tip of the bearing border to the centre of rotation of the DIP joint
DHW	Dorsal hoof wall
DHWA	Dorsal hoof wall angle
DHWL	Dorsal hoof wall length
DIPJ	Distal interphalangeal joint
FRA	Apex of the frog
FRC	The Farriers Registration Council
GRF	Ground reaction force
HA	Heel angle
HEEL	Heel buttress origin
HPA	Hoof pastern axis
KDE	Kernel density estimation
KPa	Kilo pascal's
LANTRA	UK skill sector for land based learning
MCP	Metacarpophalangeal joint
MS	Milliseconds
N	Newton's
NB	Navicular Bone
PIP	Proximal interphalangeal joint
POF	Point of force
PTA	Podotrochlear apparatus
PVF	Peak force
PVP	Peak Pressure
SDFT	Superficial digital flexor tendon
SDL	Secondary dermal laminae
SE	Standard error
SEL	Secondary epidermal laminae
SEM	Standard error of the mean
SL	Suspensory ligament
STIR	Short tau inversion recovery
UST	Uniform sole thickness
WCF	Worshipful Company of Farriers

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to take this opportunity to express my gratitude to the people, whose help, encouragement and assistance have helped me complete this project.

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Chapter 1

Introduction

1.1 Background

The conformation of the equine hoof is considered an important factor affecting performance of the horse (Linford, 1993). Poor hoof conformation is a consequence of the anatomy of the horse and biomechanical function in high-performance activities and has been linked to risk of injury in horses (Kane et al., 1998). The equine hoof serves as the interface between the ground and the skeleton of the equine limb; its structure is capable of dissipating large forces associated with impact shock and loading. Hoof care professionals claim that the correct foot balance is critical in maintaining health and biomechanical efficiency (Johnston & Back, 2006), but the actual dimensions of the ideal hoof model have not yet been clearly defined. During the last century various models of hoof trimming and correct hoof balance, largely based on the historical works of Russell (1897) and others (Dollar & Wheatley, 1898) have been debated, yet to date there are little in the way of scientific data and agreement on the optimal model of hoof conformation (Thomason, 2007). Hoof conformation can be altered by human intervention, such as hoof trimming and the application of horseshoes (Kummer et al., 2006; van Heel et al., 2005). Empirical observation, personal experience, and pragmatism have sustained the activities of trimming and shoeing for thousands of years. Factors surrounding biomechanical dysfunction of the equine hoof and the relationship with balance and morphology have perhaps not been the focus for rigorous scientific investigation. By investigating these factors there is the potential to inform and influence equine hoof care, with the ultimate aim of preventing or limiting the likelihood of injury and disease in the equine hoof.

1.2 The rationale for shoeing horses

The equine hoof encapsulates and protects the bones and sensitive structures of the distal limb. The outer hoof capsule grows distally from the proximal border to the bearing border and is generally in balance with the amount of wear that naturally occurs as the horse travels over the ground (Pollitt, 1990). The growth rate of the hoof wall has been estimated at 7mm every 28 days taking on average 9 to 12 months for a hoof wall to renew itself (Pollitt, 1990). Domestication and continued work on abrasive terrain can compromise the delicate balance between growth and wear and may lead to lameness with economic implications associated with loss of animal performance. This has necessitated the need for professional foot care and protection in the form of a shoe.

1.3 A history of shoeing horses

There have been different opinions expressed on the origin of the horseshoe. Some historians have credited the Druids, although there is no hard evidence to support this claim, as the first to use iron shoes as a preventative measure against excessive hoof wear. Written records describing the use of nailed shoes are relatively late, first appearing around AD 900. There is very little evidence to suggest the existence of nailed-on shoes prior to AD 500 or 600, although there are archaeological examples: a horseshoe, complete with nails, dating to the 5th century A.D. has been discovered and evidence suggests that around 1000 AD, cast bronze horseshoes with nail holes became common in Europe. Commonly the design consisted of a scalloped outer rim and six nail holes.

By the time of the Crusades (1096–1270), horseshoes were widespread and frequently mentioned in various written sources (Encyclopædia Britannica, 2005)[1]. By the 13th century, shoes were forged in large quantities and could be bought ready-made. Hot shoeing, the process of shaping a heated horseshoe immediately before placing it on the horse, became common in the 16th century and in 1751 Bridges wrote his treatise titled "No Foot, No Horse" on the proper care and maintenance of hooves, a term in continued use to this day.

1.4 The current basis for farriery teaching in the UK

Hoof care professionals insist that correct foot balance is critical in maintaining health and biomechanical efficiency (Johnston & Back, 2006) but the actual dimensions of the ideal hoof model have not yet been clearly defined. The debate over the correct or desired proportions and angles associated with a 'normal' hoof capsule and what might constitute a balanced foot has been a source of contention for farriers and hoof care professionals over many years. It may be helpful to understand that farriery training in the United Kingdom is regulated by animal welfare legislation via the Farriers Registration Act (1975, amended 1977). The Farriers Registration Council (FRC) produces detailed guidelines for the standards of trimming and shoeing of Equids in the UK, from which competence is assessed for the purposes of qualification and legal registration. These strict guidelines outline foot balance and shoe fitting criteria for different styles of work and type of horse within critically acceptable tolerances of craftsmanship. These guidelines are based on a syllabus originally laid down by the Worshipful Company of Farriers (WCF) which has been mostly derived from the empirical knowledge from a range of authors dating from 1890.

[1] See - **https://www.britannica.com/topic/horseshoe** (accessed 15/05/2017)

The focus of current farriery teaching is based on maintaining correct geometric hoof balance. It is believed that geometric balance promotes the most efficient form and physiological function within the foot and therefore limits injury and disease to the foot and lower limb (Butler, 2005). When discussing balance, as it relates to the equine distal limb, however, the terms conformation and foot balance are often used interchangeably; more accurately conformation describes the size and shape of the musculoskeletal structures and the way in which they are spatially arranged. Foot balance though describes the way in which the hoof capsule relates to the skeletal structures of the limb. To understand the basis of foot balance in the horse a detailed understanding of form and function is required.

1.5 Anatomy and Physiology of the Equine Hoof

The hoof is a complex modification of the integument surrounding, supporting and protecting structures within the distal limb of the horse (Dyson, 2011). The hoof capsule encapsulates the structures of the foot including the distal interphalangeal joint (DIP joint), distal phalanx (P3), distal sesamoid (navicular) bone, dermal laminae, collateral ligaments, cartilages of P3, digital cushion, termination of the deep digital flexor tendon (DDFT) and a network of arteries, veins and nerves **(Figure 1.1)**. The external bearing surface is comprised of the horny sole, white line and frog (Stashak, 2002). The hoof wall consists of three layers; the stratum external, stratum medium and the stratum internum (Stump, 1967, Reilly et al., 1996) The inner layers of the hoof wall, the stratum internum, consists of around 600 non-pigmented keratinised, primary epidermal laminae, each of which bears 100-150 non-keratinised, secondary epidermal laminae (SEL) (Stump, 1967). Pollitt (2001) confirmed that the SEL dovetail with their adjacent counterparts of the secondary dermal laminae (SDL) of the laminal corium (**Figure 1.2**), which covers the parietal surface of P3, suspending P3 within the hoof capsule. Between the dermal epidermal laminae there is a thin epithelial cellular layer, described as the basement membrane (BM), which undergoes constant remodelling (Pollitt, 2001). As a result the SEL slide 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).

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 (CB) to the bearing border (BB). Its generation is from the epidermal basal cells of the coronary corium (Stump, 1967; Pollitt, 2001) and it is a non-homogenous and anisotropic material within which horn tubes run diagonally from the CB to the BB. The horn tubules are arranged into four zones of density (Reilly et al. 1996), the strongest and most densely populated zone being the outer layer. Intertubular horn is formed at right angles to the tubular horn, filling the void between the horn tubules (Bertram & Gosline, 1987). This construction achieves mechanical stability within the horn with the mechanical properties of the horn tubules being best suited to compressive force with the intertubular horn providing stability through tension (Bertram & Gosline, 1987). The equalisation of both compressive and tensile forces allows ground reaction forces to be dispersed within the structure without regional overload (Thomason, 2007).

The biomechanical function of anatomical structures within the foot is dependent on their ability to work in harmony. This harmonious relationship is commonly referred to as the foot mechanism (**Figure 1.3**) and the hoof acts to modulate irregularities in externally applied loads by attenuating the impact with the ground (Dyhre-Poulson et al., 1994). The hoof deforms differentially under the transfer of weight-bearing during the stance phase of locomotion, the dorsal wall of the equine hoof flattens (**Figure 1.3**). As the proximal dorsal wall rotates palmarodistally (or plantarodistally) about the distal border the palmar (or plantar) movement of the dorsal wall is accompanied by abaxial movement of the quarters and heels (Lungwitz, 1891; Colles, 1989; Roepstorrf et al., 2001).

Colles (1989) described the relationship between frog pressure and heel expansion supporting the pressure theory by concluding that the lateral movement of the heels is dependent on pressure to the frog. However Dyhre-Poulsen et al., (1994) measured the pressure within the hoof cushion and showed that the lateral movement of the heels is dependent on the lowering and backward rotation of the middle phalanx (known as Depression Theory). Similarly Roepstorrf et al., (2001) concluded that the middle phalanx rotates initially backward onto the palmar/plantar hoof and essentially pushes the palmar/plantar hoof into the ground. Since an equal and opposite force from the ground is applied through the supporting structures of the hoof, the hoof wall, frog and heel consequently deform to the pressure of the ground.

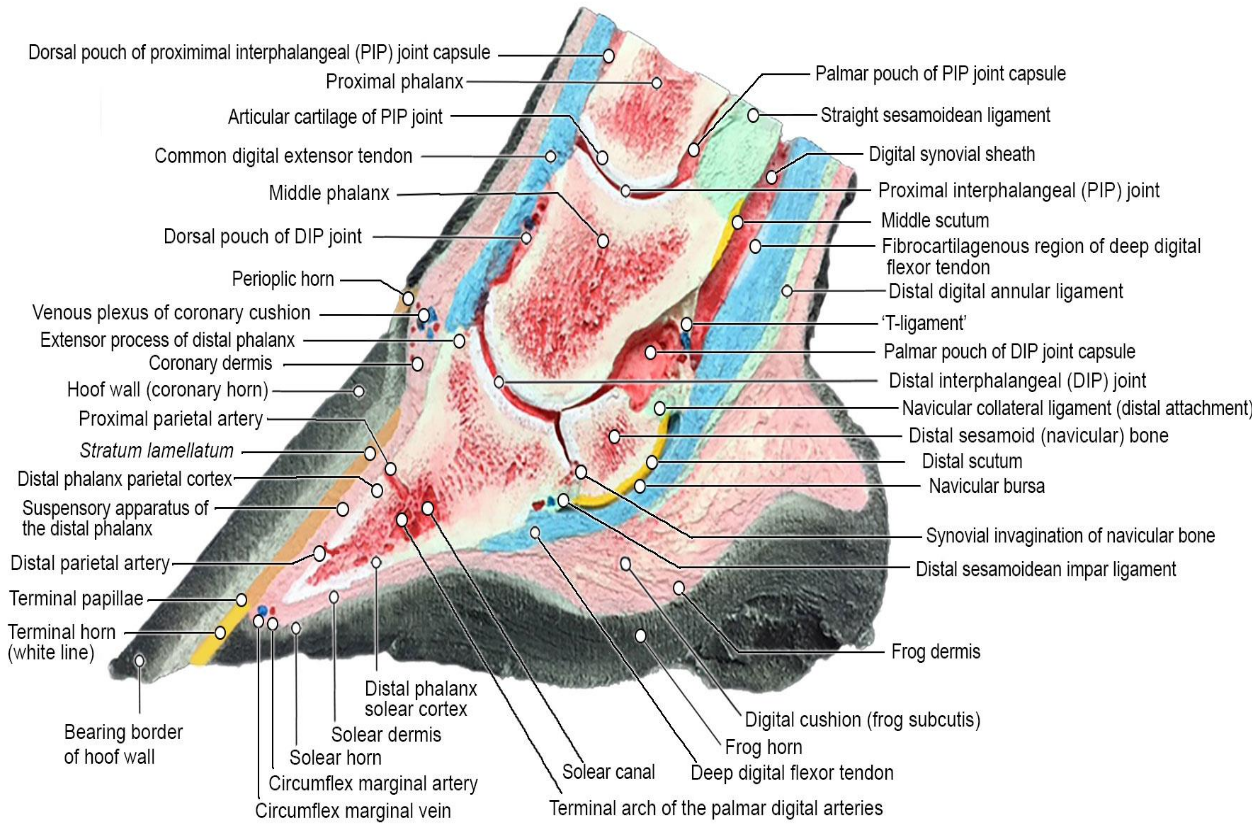

Figure 1.1 Schematic diagram showing the main anatomical structures of the equine foot in the midline sagittal plane. *Down loaded from http://3dvetanatomize.com/wp-content/uploads/2017/10/PU-cast-Sagittal-normal_-foot 11/17/1017*

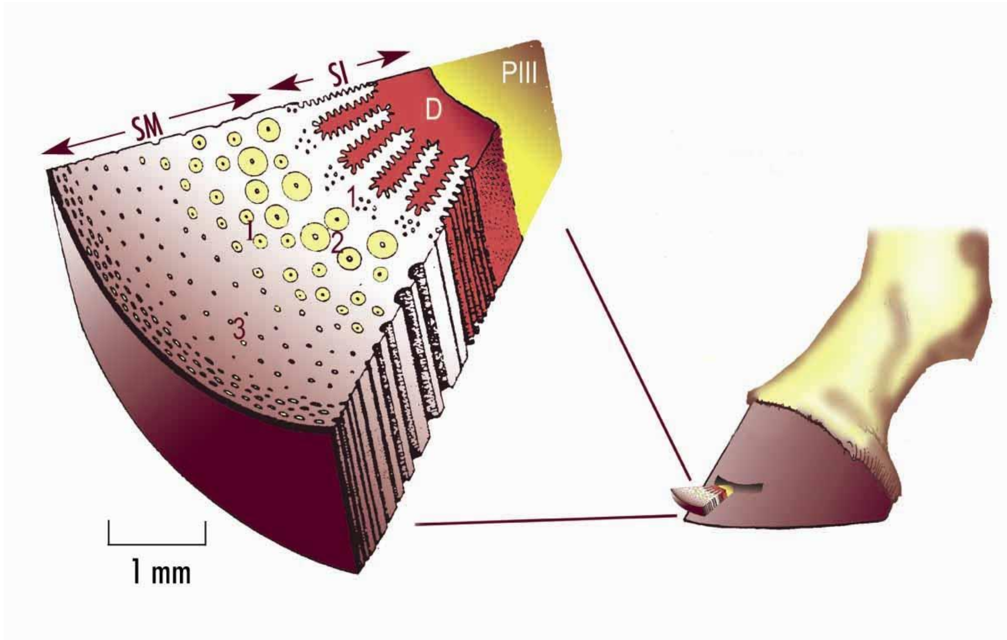

Figure 1.2 Schematic diagram of hoof growth. The inner layers of the hoof wall, including the stratum medium (SM), illustrating the differing layers of tubular density. The stratum internum (SI) consists of around 600 non-pigmented keratinised, primary epidermal laminae, each of which bears 100-150 non-keratinised, secondary epidermal laminae which dovetail with their adjacent counterparts of the secondary dermal laminae originating from the dermis (D) of PIII (distal phalanx, P3). *Illustration courtesy of J. Reilly*.

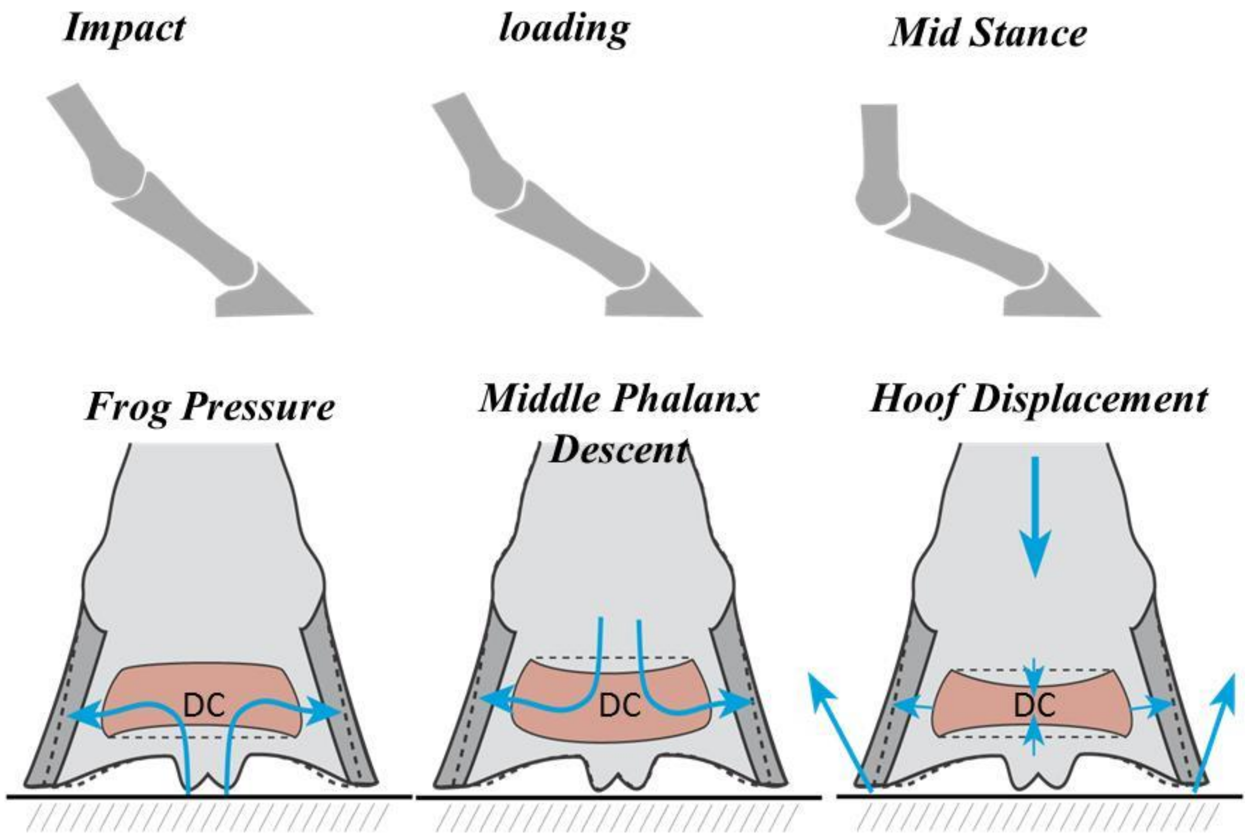

Figure 1.3 Schematic illustration of the transfer of forces through the hoof and the motion of the sole and frog during the stance phase. The solid line represents the shape of the unloaded hoof and the dashed line shows the change in shape which occurs during weight-bearing. *Illustration with permission from Dr. A. Parks.*

1.6 Static hoof balance

The debate over the correct or desired proportions and angles associated with a ‘normal’ hoof capsule and what might constitute a balanced foot has been a source of contention for farriers and veterinary surgeons over many years. The historical works of Lungwitz (1891), Dollar (1897) and Russell (1897) have largely informed and provided the basis for current conventional farriery teaching. In the resting horse, relationships between limb conformation and static foot balance are examined by viewing the foot from the lateral, dorsal and solar aspects and are based on the principal that the bearing border of the foot (BBL) should be trimmed perpendicular to the longitudinal axis. Furthermore there is much emphasis on the importance of achieving and maintaining correct hoof pastern axis (HPA), described as the parallel alignment the dorsal hoof wall (DHWA) and heel angle (HA), with the angle of the central axis of the phalanges. These angles are defined as being within the range of 50º to 55º (Stashak 2002). The correctly balanced hoof is then described as being symmetrical in outline with the proportions of the hoof capsule at any two points around lateromedial and/or dorsopalmar axial coordinates equal in height from the bearing border equating to Russell’s 1897 model of ideal foot balance (**Figure 1.4**).

Abnormalities in static foot balance are frequently described as deviations from this model. Current farriery teaching defines these deviations based on the descriptions of Turner (1992). Turner utilised a measurement system commonly referred to in farriery terms as coronary band mapping to define significant hoof balance abnormalities. These included broken hoof axis, under run heels, contracted heels, sheared heels and mismatched hoof angles.

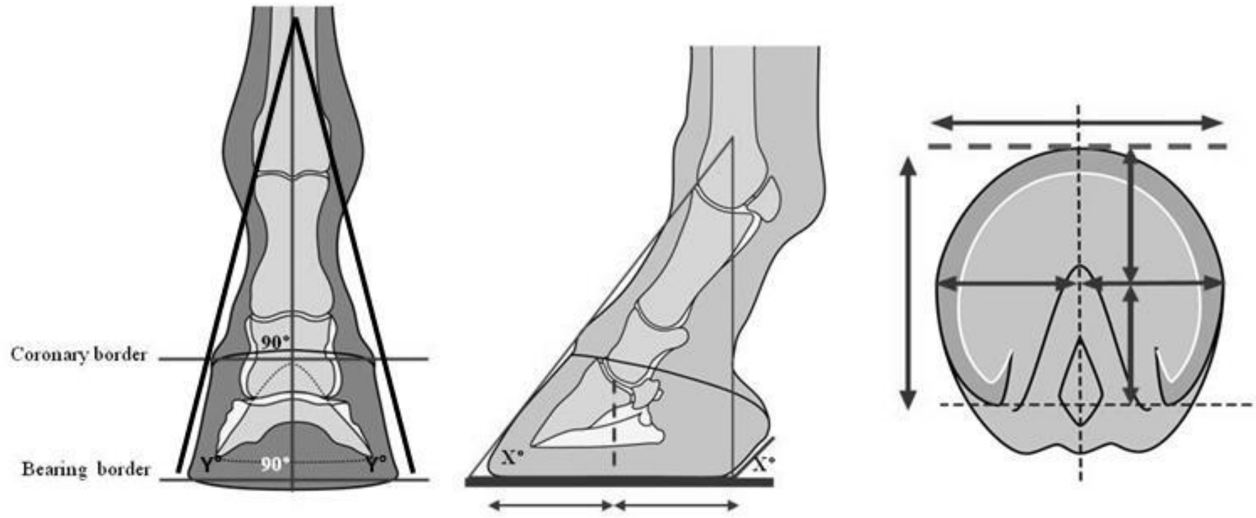

Figure 1.4 Schematic illustration of Professor William Russell's 1897 interpretation of ideal foot balance model. Russell suggested that coronary circumference was of equal height at any two opposing medial or lateral points and perpendicular to the sagittal axis of the limb (left) and that the ideal foot should exhibit heel / toe angle parallelism with the phalangeal axis. Russell further argued that the bearing border was symmetrical about its centre which he placed palmar of the frog apex. To this day Russell's (1897) model of symmetry within the equine foot remains the basis for current farriery teaching. *Illustrations courtesy of Dr. S. O'Grady.*

Broken hoof axis can be described in two ways: broken back - when the hoof angle is lower than the pastern angle; and broken forward - when the hoof angle is steeper than the pastern angle. Under run heels is defined as the angle of the heels being 5° less than the DHWA. Collapsed heels are defined as a toe length to heel length ratio of less than 3:1 whilst contracted heels are defined as the frog width presenting as less than two thirds of the frog length, whereas sheared heels are said to be a disparity between the medial and lateral heel lengths of 0.5cm or more (Turner and Stork. 1998, Turner, 1992).

Parks (2003) further describes foot balance as the way in which the hoof capsule relates to the skeletal structures of the limb further proximally in each plane. From the side, dorsopalmar foot balance is achieved when the angle between the dorsal hoof wall and dorsal pastern is straight, and when a line bisecting the third metacarpus intersects the ground at the palmar aspect of the hoof/ground interface (**Figure 1.4),** resulting in a right-angled triangle (Parks, 2012). From the front, mediolateral foot balance is achieved when the metacarpus and phalanges are equally bisected by a vertical line with the axis of the limb perpendicular to a horizontal line through coronary band or ground surface of the hoof wall. Finally from the solar view, both medial and lateral halves should be symmetrical about the central axis of the frog. According to Parks these proportions can be applied to any horse regardless of size. The maintenance of correct geometric hoof balance and a symmetrical shape are said to be essential in maintaining correct form and function of the foot. To this day Russell's (1897) model of symmetry within the equine foot remains the basis for recommendations for corrective farriery intervention and manipulation of the hoof.

1.7 Dynamic foot balance

In farriery terms a horse is said to be in dorsopalmar dynamic balance when the foot impacts the ground flat. Similarly a horse is said to be in mediolateral dynamic balance when the foot lands with both heels simultaneously as achieving uniform mediolateral impact and loading of the hoof through the stance phase of the stride (O'Grady, 2009)[2]. This approach suggests that the point of force (POF) follows a trajectory along the central axis throughout the stance phase of the stride. However van Heel et al., (2004) demonstrated that the lateral asymmetrical landing was the preferred way of landing in front feet and hind feet. Interestingly trimming (aimed at complete symmetry under static conditions) did not change this preference, but it did significantly alter the landing duration by up to 33% in the front feet, but not the duration of the stance.

The distal limb can be envisaged as a set of levers and pulleys which respond to force down the limb and an equal and opposite force from the ground on the limb - ground reaction force (GRF) (Parks, 2003). GRF is applied to the DIP joint through the hoof **(Figure 1.5)**, and *because* these two vertically opposed forces are not aligned, they create a moment (turning force) that rotates the phalanges, dropping the metacarpophalangeal joint towards the ground. An extensor moment is opposed by tensile force from the digital flexor muscles and associated accessory ligaments at their insertion/attachment of the tendons and through the suspensory ligament (Rooney, 2007). Contact force is transmitted from the ground to the hoof over the area of contact, which can vary with surface differences (Hobbs et al., 2011) and the balance or conformation of the hoof. The

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[2] See **- O'Grady, S. (2009). Guidelines for Trimming the Equine Foot: A Review. www.equipodiatry.com/article_equinefoot_trimming_guidelines.htm first downloaded 07/2012**

majority of the ground-hoof interaction force is transmitted from the ground to the wall and then to the distal phalanx, via tensile force, through the laminae which suspend the distal phalanx from the hoof (Thomason et al., 2001). Combining all the forces on the distal phalanx from the laminae produces a resultant force. The resultant vertical force on the distal phalanx is in the opposite direction and palmar to the GRF (**Figure 1.5**). Without any other forces acting on the foot both the orientation of the distal phalanx to the ground and morphology of the hoof capsule remain stable (Parks 2003). However in motion, the weight borne by the limb, the position of the foot, the joint angles of the phalangeal axis and the tension in the flexor tendons are constantly changing and this needs to be borne in mind when modifying the external parameters of the hoof through trimming or applying a shoe.

The stride can be divided into four main phases (Johnston & Bach, 2006) (1) impact phase, where the most common foot placement in the forelimbs has been shown to be 'lateral heel' in walk and 'lateral' in trot (Wilson et al, 2014). (2) support phase where the foot is flat on the ground; (3) breakover or rollover phase where the heel is no longer in contact with the ground, but the toe is; and (4) swing phase where the foot is off the ground. During the impact phase and the first part of the stance phase, the mass of the body is accelerating towards the ground. To decelerate the mass of the body as it descends to the ground as the foot lands and bears weight, several events occur: the metacarpophalangeal (MCP) joint hyperextends; the distal (DIP) and proximal interphalangeal (PIP) joints flex slightly, allowing the MCP joint to drop towards the ground as the tendons absorb and store energy; the distal phalanx is said to counter rotate within the foot about its dorsal solar margin so that the palmar processes move towards the ground; the articulation between the distal phalanx and navicular bone also widens (Parks, 2003) and the hoof expands; during the second half of the stance and breakover phase the horse is accelerated forwards and the limb lifted off the ground; And contraction of digital flexor muscles and release of stored energy in the tendon and accessory ligament of the deep digital flexor tendon (ALDDFT) flex the MCP joint and extend the DIP and PIP joints (Parks, 2003). The hoof therefore acts as an extension of the distal phalanx and so the leverage about the DIP joint may change. During the flight phase, the distal limb flexes and then extends to prepare for landing as it is protracted.

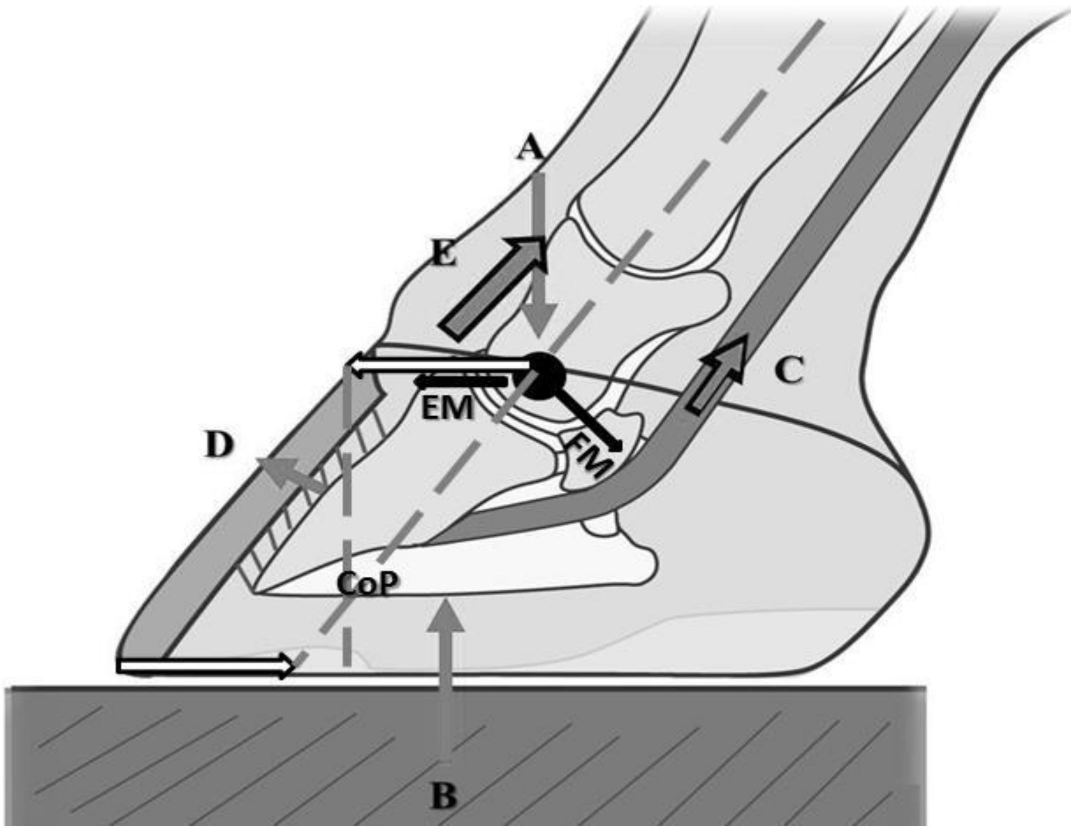

Figure 1.5 Biomechanical forces acting on the equine digit. The weight of the horse (A) is countered by ground reaction force (B). Other forces include the tensile forces of the deep digital flexor tendon (C), the laminae (D), and the common (or long) digital extensor tendon (E). Both the extensor moment (EM) and flexor moment (FM) and the dorsopalmar location of the centre of pressure (CoP) are also highlighted as discussed in Wilson et al., (2001). Arrows representing applied force are for illustrative purposes only and are not scaled according to magnitude of the force (*modified after O'Grady 2009).*

The initial impact of the horse's foot with the ground can be influenced by gait, speed, lameness and farriery (Clayton, 2004) with surface type and preparation recently determined to be of importance on dynamic loading (Mahaffey et al 2016). During the impact phase, (which occupies the first 50 milliseconds after contact) the hoof undergoes rapid deceleration in both horizontal and vertical directions, especially when the horse is travelling at speed or on a hard surface. During the stance phase, the vertical force increases as the limb accepts the horse's body weight and peaks at mid stance. In the first half of the stance, the negatively charged longitudinal force has a braking effect on the horse's forward motion before becoming positively charged in the second half of the stance providing forward propulsion. In the terminal part of stance, breakover occupies the time when the heels rotate around the toe which is still in contact with the ground. On hard surfaces the hoof remains flat until heel off but on a softer surfaces however, the toe may dig into the surface prior to heel off **(Figure 1.6)**.

Thomason & Peterson (2008) stated that of the main phases of the stance, the impact phase, can be further subdivided into two separate events: primary impact (approximately the first 7% of the stance duration) representing the first contact with the ground; and a second event of impact (5% to 30% of the total stance phase) representing the first stage of the collision of the horse's mass as the foot becomes firmly planted on the ground (**Figure 1.6)**. The rate of deceleration of the hoof in the first phase of impact is high as is the shock impact whereas in the second phase of impact the weight of the horse passes through the limb as the foot becomes firmly planted into the ground. The main support phase then lasts to approximately 80% of the total contact time before the final (breakover or rollover) phase when the hoof begins to lift off from the ground (**Figure 1.6)**.

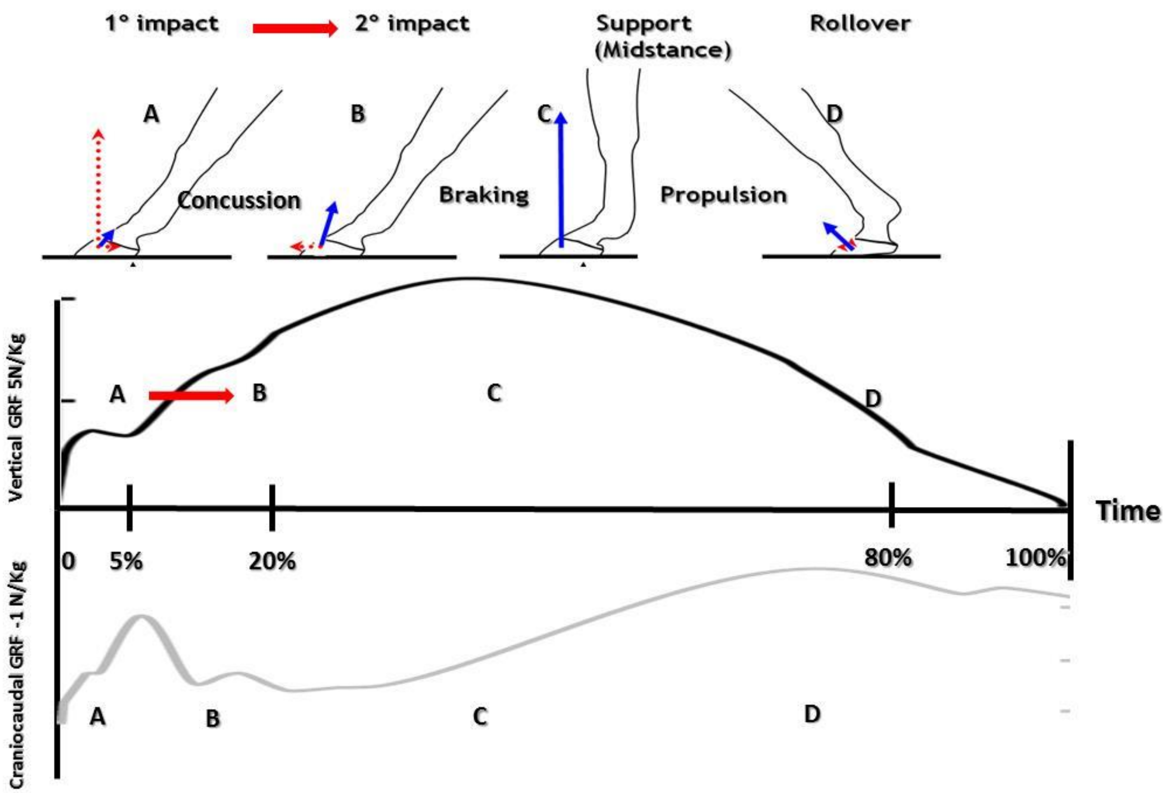

Figure 1.6 Stages of the stance phase of the stride. Relative amounts of vertical and horizontal acceleration (red dotted arrows) and ground reaction force (blue solid arrow) are shown drawn as a single vector to show its change in orientation with limb position. (A) In the first 7% of impact deceleration predominates, especially vertically as the hoof absorbs the shock of its own impact with the ground. (B) From 7-20%, the hoof slides forward then stops, while the weight of the body pushes forward (the arrow shown is the ground resisting this force). (C) At midstance (20-80%) vertical force predominates, exceeding bodyweight at the faster gaits. (D) At breakover (rollover) (80% of stance), acceleration resumes as the hoof rolls from the ground, while a residual force indicates the final thrust of propulsion (*modified after Thomason 2008).*

1.8 The biomechanical properties of the hoof

Integral to dynamic foot balance, and hence the movement of the horse, are the viscoelastic properties of the hoof. Viscoelasticity describes the different response of properties of a material under different stresses. When subjected to high or rapid stress deformation generally occurs in an elastic manner, whereas under constant stress deformation occurs slower in a viscous or fluid-like manner. The properties of these materials (e.g. the equine hoof) are as a direct result of their structure and function (Douglas et al., 1998). Changes to these properties may result in deviations from the elastic limits of a material (**Figure 1.7)** and then linked to alterations in the stride phases and lead to structural failure of the foot (Kane et al., 1998).

During weight-bearing and locomotion, the hoof wall deforms in a consistent pattern (**Figure 1.8).** The proximal dorsal wall rotates caudoventrally (Thomason et al., 2002) about the distal dorsal border whilst there is lateromedial flaring caudally (Colles, 1989; Thomason et al., 2002) with the principal forms of deformation experienced by the hoof capsule being bending and compression. Hood (1999) used transducers capable of discriminating between bending and compressive deformation and observed that the dorsal hoof wall was subject to either pure bending or compression and bending during static weight-bearing. Poor hoof balance increases the flexor moment (Wilson et al., 2001), altering the duration and or magnitude of stress on the hoof as the direction of force changes during impact, support and unrollement.

At trot, heel expansion is greater than the walk, whilst the movement characteristics are similar. Initially the heel undergoes an expansion during the first part of the support phase of the stride followed by heel contraction in the last 15-20% of stance from just before the time when the heel first becomes non weight-bearing to the time when the hoof is lifted up off the surface (Roepstorff et al, 2001) (**Figure 1.8**).

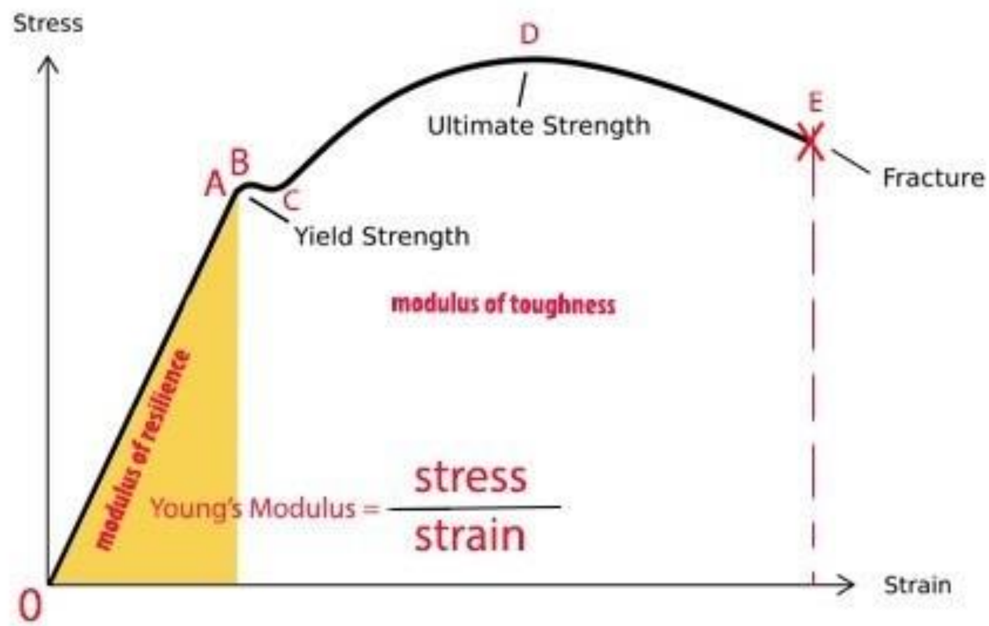

Figure 1.7 Representative tensile stress–strain curve. A material undergoes deformation (strain) in response to load applied (stress). The relationship is linear until yield strength is reached after which the material starts to deform in a non-elastic manner before eventually failing (red cross). Young's modulus can be calculated from the linear (elastic) slope of the relationship and hence is often referred to as Young's modulus of elasticity. (*Reprinted from School Physics/properties of matter/elasticity/Young's modulus. First viewed 11/01/2017).*

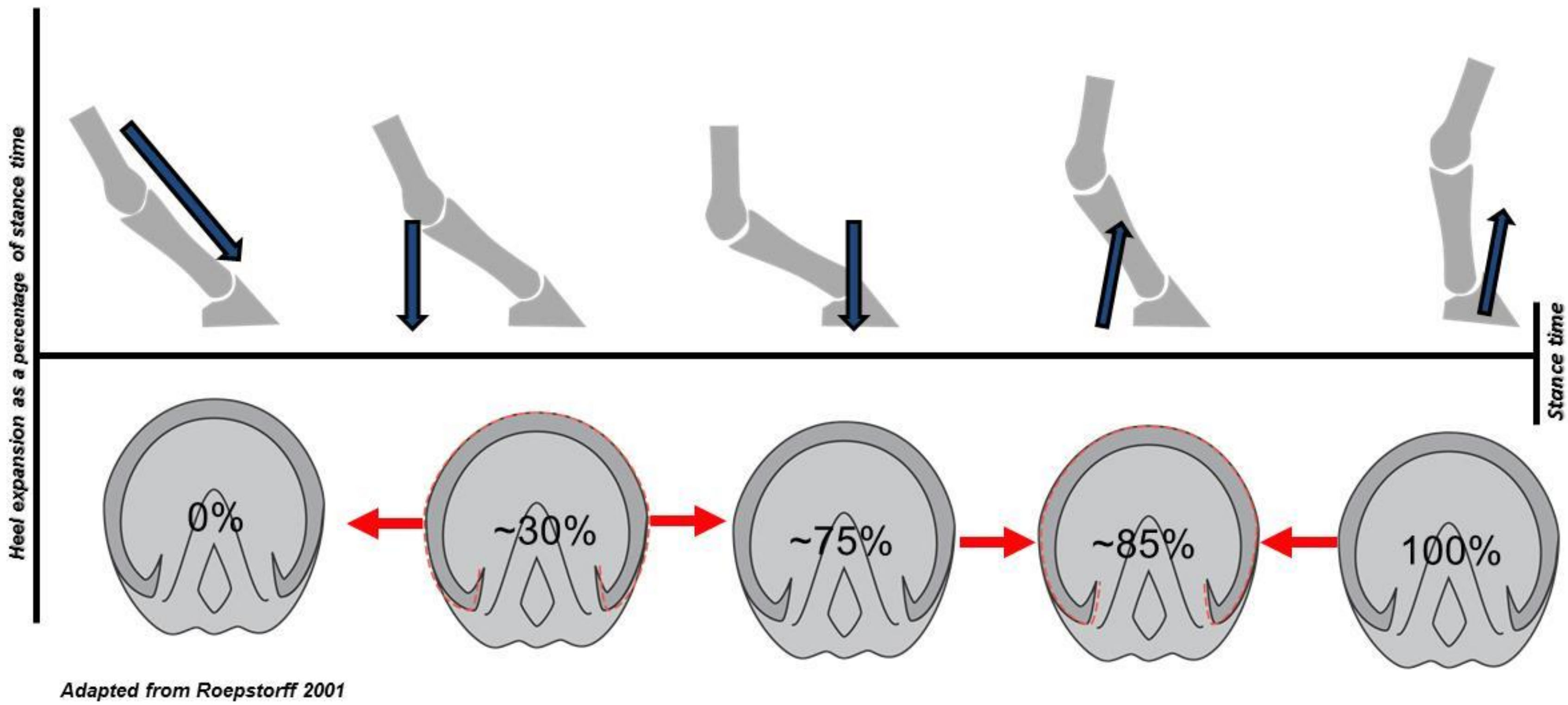

Figure 1.8 Schematic illustrations of palmar/plantar hoof expansion and contraction under load. Hoof expansion (red arrows pointing out) and contraction (red arrows pointing in) at different % stance time are demonstrated by the red dotted line in relation to direction of vertical force (blue arrows) created as the fetlock rotates under load (*Adapted from Roepstorrf et al., 2001reproduced with permission of A. Parks).*

Interestingly this heel contraction is reportedly greater in the un-shod foot. According to Thomason (1988) the hoof capsule during loading tends to compress the dorsal hoof wall (DHW) as the principle application of force moves toward the toe of the hoof. This compression of the dorsal hoof wall and subsequent expansion of its distal margin may tend to pull the heel forward and inward. In both *in vitro* and *in vivo* studies reported increased pressure on the sole and frog resulting in increased expansion of the heel (Roepstorrf et al., 2001). Similarly shoeing or elevating the hoof from the surface through support of the hoof wall resulted in less expansion of the palmar hoof. This appears to support the depression hypotheses. These authors conclude that the two mechanisms of frog pressure and digital cushion depression are inseparable, as downward loading of the limb on the palmar/plantar hoof would be supported by counter pressure on the frog resulting in deformation of the soft tissue of this area. Significantly manipulation of heel movement has been shown to be affected by farrier techniques which may have a subsequent relationship to health of the hoof (Roepstorrf et al., 2001). The palmar/plantar part of the hoof expands considerably greater distally compared to the proximal part (being wider and straighter in the unshod situation) and only slightly wider in the shod hoof condition. However in the shod foot the downward movement of the middle phalanx onto the palmar/plantar hoof tends to increase the deformation of the sole of the hoof downward.

1.9 Hoof trimming theories

Farriery technique has been shown to influence skeletal alignment within the foot (Kummer et al 2006; 2009) and the biomechanical hoof mechanisms involved in shock attenuation (Roepstorrf et al., 2001), therefore influencing the soundness of the horse but is often overlooked in the scientific literature. Several farriery texts (Emery et al., 1977; Hickman & Humphrey, 1987; Stashak, 2002; Butler, 2005) focus on specific aspects of the current foot balance model whilst offering contradictory advice on trimming methodology, most notably with regards to trimming of the heels, frog and sole. None however, make reference to evidence-based trimming protocols. A number of authors (Duckett 1990, 2008, Ovnicek et al., 2003a and Savoldi, 2007) however support an approach that uses specific external reference points to determine the position of the internal structures such as the distal tip of the P3 and the centre of articulation of the DIP joint. These authors also suggest that the morphological appearance of the sole indicates the orientation of the solar margin of P3 within the hoof.

1.9.1 The natural balance model

Alternative theories and practices have arisen concerning hoof trimming and to achieve static foot balance (Jackson, 1992; Ovnicek, 1993, 2003a, 2003b). Ovnicek (2003b), based on his interpretation of foot condition in feral horses advocating the natural balance trim where the wall depth is reduced to the level of non-exfoliating sole (a soft waxy type of horn which is referred to as the live sole margin), through to the heel buttresses which are trimmed to the ground bearing level of the frog at its widest point. The dorsodistal margin of the toe is rounded (replicating the so-called Mustang roll) to reduce leverage at enrolment. When the wall of the hoof is reduced in this way, the palmar to dorsal length of the frog represents approximately two-thirds of the length of the bearing border. In addition, a consistent 60:40 ratio about the centre of rotation (CoR) is maintained between the heel and the point of breakover. These morphological measurements are in sharp contrast to the widely accepted 50:50 geometric post-trim proportions of the bearing border around CoR advocated by Colles et al., (1983; 1989).

1.9.2 Duckett's dot and bridge

Duckett in the early 1990's has attempted to link the historical static foot balance model of hoof wall parallelism with the phalangeal axis to the dynamic interactions of the foot. He suggests trimming feet proportionately to specific external reference points (referred to as “Duckett’s dot” and “Duckett’s bridge”) **(Figure 1.9)**. According to Duckett (1990) these points are representative of two significant locations for biomechanical activity: the centre of pressure (CoP) and the centre of rotation of the distal interphalangeal joint (CoR) and as such the consistency of the “dot” and “bridge” as indicators of dynamic mechanical activity may partially explain the observations seen in feral feet by (Ovnicek, 1993). Duckett also stated that his model of static foot balance is proportionate across all horse and pony breeds. Duckett’s dot (relating to CoP) is defined as a consistent external reference point situated approximately 9.5 mm behind the apex of a trimmed frog in the averaged sized horse and that this point is vertically in line with the extensor process of P3 **(Figure 1.9)**. Furthermore the “bridge” (relating to CoR) is commonly within a range of 20–25mm palmar to the “dot”. Anecdotally, hoof care professionals often quote CoR as being positioned vertically at the intersection of the sagittal and frontal axis of the foot at its widest point of the bearing border (O’Grady & Poupard, 2003). Duckett (1990) stated that geometric foot balance could be assessed through three main foot balance indicators: (1) dorsal hoof wall (DHW) length; (2) the distance from the dorsodistal tip of the DHW to the widest point of the bearing border (Duckett’s bridge or CoR) and (3) the distance from a point 9.5mm palmar of the frog apex (Duckett’s dot) to the widest point of the frog. Duckett stated that all three of these measures were of equal length when hoof balance is achieved (Duckett, 1990).

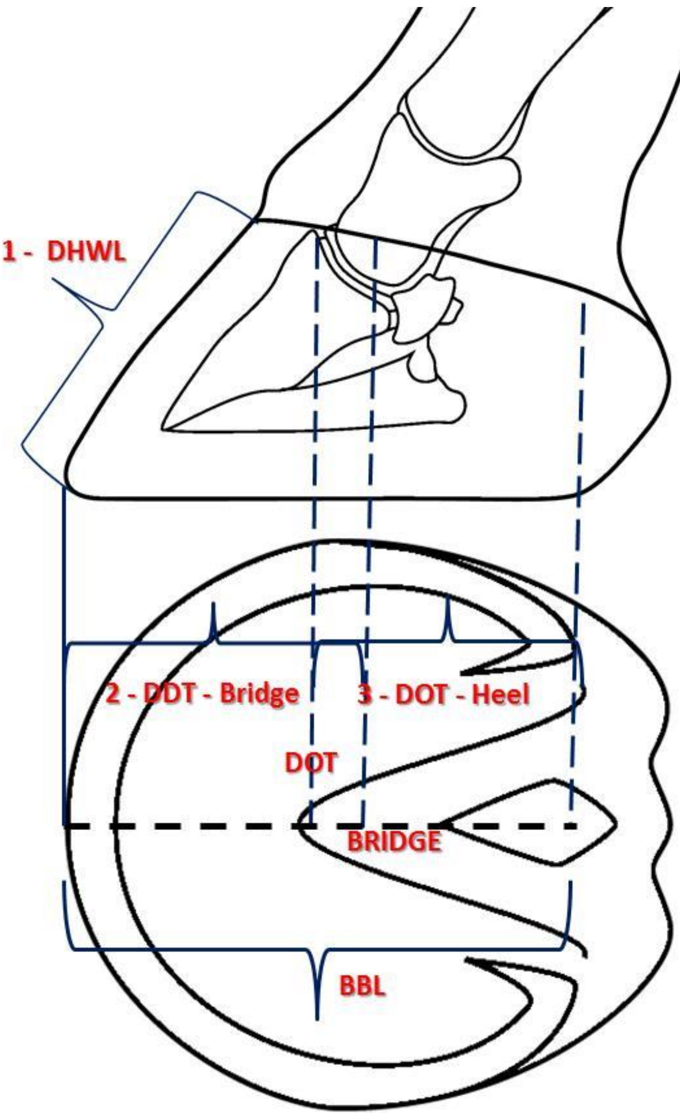

Figure 1.9 Duckett's 1990 external reference points Duckett's "Dot" and Duckett's "Bridge". Duckett suggested that to achieve static foot balance three measurement indicators: (1) dorsal hoof wall length (DHWL), (2) the distance from the dorsodistal tip of the toe (DDT) to the widest point of the bearing border (DDT - Bridge) and (3) the distance from a point 9.5mm palmar of the frog apex (DOT) to the widest point of the frog (DOT-Heel) were equivalent. (*Reproduced with permission of D. Duckett FWCF*).

1.9.3 Uniform Sole Thickness (UST)

Savoldi (2007) proposed a trimming protocol based on uniform sole thickness (UST) as a method of achieving both static and dynamic foot balance. UST defines the plane of the hoof capsule with the sole at its junction with the hoof DHW being of equal thickness from heel to toe. Since the form of the external hoof is directly related to the form and function of the internal structures it is suggested that UST can be used to quantify orientation of internal structures, specifically P3, in both sagittal and frontal planes (Savoldi, 2007). The author has also suggested that morphological differences within the solar arch are an indicator of specific foot pathologies. Whilst UST may be a useful theoretical method in cadaver feet of achieving a reference-based trim it may not be suitable on welfare grounds for use in practice. This is because of the difficulty in achieving a horizontal bearing border hoof and sole plane in those feet exhibiting gross distortion, particularly where the subsequent application of a level shoe may be required.

1.10 Effects of foot balance on hoof function

Several studies have demonstrated the possible effects of mechanical overload on the hoof function demonstrating that foot shape and biomechanical function can be influenced to some extent by trimming and shoeing (Wilson et al., 2001; Viitanen et al., 2003; Eliashar et al., 2004; Moleman et al., 2006). There is limited information however, on the orientation of the skeletal structures within the hoof capsule and their relationship with the external conformation of the foot. Kummer et al., (2006; 2009) investigated the effects of trimming on hoof conformation parameters such as hoof angle, height and P3 orientation using radiographs pre- and post-trimming on a single occasion. This approach whilst emphasising the importance of HPA and hoof symmetry however failed to account for individual biomechanical variation or the horse's capability for postural adaptation (Moleman et al., 2006).

Hood et al., (2001) investigated the effects on solar loading patterns with the hoof's interaction with its surface. These results suggested that hoof shape adapts to loading patterns which differ according to footing where the sole shares a greater load on softer substrate. These authors surmised that the concavity of the solar surface may play an important role in foot biomechanics and that its domed shape should be viewed as a weight-bearing structure that allows maximum load distribution across the surface of the foot. This idea is supported by Clayton et al., (2011) who in a study of bare foot warmblood dressage horses trimmed on a six weekly cycle noted consistent changes to the length of the DHW and an increase in DHWA. Continued maintenance of the trim resulted in a palmar/plantar migration of the heels, with increases in support length, heel angle and the solar angle of P3. Both Hood et al., (2001) and Clayton et al., (2011) concluded that significant morphological changes can take place in the hoof in response to the barefoot trim. Importantly palmar migration of the heels resulted in an increase in heel angle and support length with an increase in solar angulations of P3 identified as being potentially beneficial to the health of the foot.

Researchers in Australia investigated morphological and pathological variation between individuals from feral populations in different environmental areas (Hampson et al., 2011). By studying over 200 feral feet they concluded that environmental considerations such as substrate, availability of grazing and water strongly influenced geometric form of the hoof.

1.11 Hoof balance and the relationship to foot pathology

The idea that foot conformation is linked to foot pain, lameness or lower limb pathology has been in existence for a number of years. Kane et al., (1998) compared dorsopalmar and mediolateral hoof measures of a control group with racehorses with catastrophic musculoskeletal injuries. Horses with larger differences between dorsal hoof wall and heel angulation were associated with these injuries. This study has been widely cited as evidence of the connection between hoof conformation and lameness; however catastrophic injuries in racehorses is not a useful measure of the more common foot pathologies often associated with lameness and are linked to other factors such as surface and fatigue (Parkin et al., 2004; 2005). Interestingly the hoof angles in the study by Kane et al., (1998) fall within the normal range used in other studies (O'Grady et al., 2003; Stashak, 2002; Butler, 2005).

In support of the concept that foot balance affects forces in the lower limb, Willeman et al., (1999) demonstrated that a change in the heel: toe height ratio (by elevating the heels) changed the angle of inclination of the DDFT and thereby reducing compressive forces on the distal sesamoid bone and this concept has influenced how injuries to the DDFT and/or navicular apparatus are often managed clinically. However the decrease in force applied by the DDFT can result in a concomitant increased load on the superficial digital flexor tendon (SDFT) and suspensory ligament (SL). Dyson et al., (2011) in a retrospective study of 300 feet investigated whether hoof shape (based on digital photographs and radiographs) and injury (using high-field MRI to categorise injury group) were correlated. Despite the large number of horses evaluated in this study, there were no significant associations between angles and measurements and injury, although it is to be recognised that the authors limited their evaluation to the lateral aspect only (digital photographs/radiographs). In a recent study using MRI only, Holroyd et al., (2013) demonstrated that lame horses with a smaller sole angle (as taken from mid-sagittal plane on MRI) were more likely to have a DDFT or navicular bone lesion, but no correlation between heel and toe angle and pathology was found.

The accepted dogma on equine hoof conformation concludes there is a relationship between poor static foot balance and lower limb pathologies but this conclusion appears to be based on a rigid interpretation of values that are considered normal whilst assuming that the static model optimises the dynamic efficiency of the foot and reduces the risk of lameness and catastrophic injury. Trimming and shoeing to the currently accepted foot balance model are thought to play an important role in both the prevention and the treatment of numerous common foot pathologies despite there being no universally acceptable trimming protocol. The current foot balance models do not take into account the influences on hoof morphology and foot pathology of individual biomechanical variations or environmental considerations yet it is well recognised that a large range in hoof conformation dimensions exist in horses.

1.12 Hypothesis

It would be advantageous to hoof care professions if one universally accepted method of assessing common hoof proportions existed and if the effects of farriery intervention on static and dynamic foot balance could be accurately established. Static foot balance is defined as geometric proportions that would maintain stability with the minimum of postural sway, these proportions are dependent on factors such as foot-type (front and hind feet), foot management (unshod versus shod), environmental conditions (domestic versus feral) and are related to common foot pathologies. Dynamic foot balance, which observes the horse in motion, can be defined as a state of equilibrium of forces influencing the biomechanical function of the foot. In farriery terms this implies that a balanced foot should land symmetrically, i.e. the foot should land flat with the hope that this places force uniformly over the bearing surface of the hoof throughout the stance phase of the stride.

Such a study could also form the basis for establishing a quantifiable and predictive model for gross foot pathology.

This project will address the hypothesis that a standardised trimming protocol results in static and dynamic foot balance based on the principle of equal geometric proportions and that these proportions are dependent on factors such as foot-type (front and hind feet), foot management (unshod versus shod), environmental conditions (domestic versus feral) and are related to common foot pathologies.

1.13 Aims

The aims of this study are:

(1) To validate a standardised trimming protocol and measure reproducibility of the trim and relate external hoof reference points to key internal anatomical landmarks in the equine digit

(2) To measure static and dynamic foot pressures following a standardised trimming protocol

(3) To determine whether repeated trimming using the standardised trimming protocol results in equal geometric proportions and hence foot balance based on the widely accepted model of Duckett (1990)

Chapter 2

Materials and Methods

2.1 Ethical approval

Approval for this project was provided by Research Ethics and Safety Committee, Myerscough College, University of Central Lancashire (KK/RH/VN-Farr//Caldwell-M; 15th October 2009) and Veterinary Research and Ethics Committee, University of Liverpool (VREC209, 1st April 2014) with owner consent obtained for horse usage.

2.2 Sample collection

2.2.1 Cadaver material (UK domestic horses)

Equine fore and hind cadaver limbs were collected from a local abattoir in the North-West of England. Since samples were collected as a by-product of the agricultural industry, the Animal (Scientific Procedures) Act 1986 (Schedule 2) does not define collection from these sources as scientific procedures and therefore ethical approval was not required for collection. Limbs were from a mixed population horses typical to the region with unknown history. Limbs from horses with gross evidence of distal limb injury and/or severe conformational abnormalities were excluded from the study limiting the sample size, particularly of fore limbs. **Table 2.1** summarises the samples used in this study.

2.2.2 Cadaver material (Australian feral horses)

To study the influence of environment on hoof morphology, digital photographs of 89 feral horses from 5 different regions were obtained with permission from the Australian Brumby Research Unit (ABRU). Cadaver feet from ABRU were obtained during annual cull of feral horses and unrelated to the present study. Only images of the left fore feet were available for analysis. **Table 2.1** summarises the feral horse groups. Details relating to topography, rainfall and average temperature were recorded for each region.

Cadaver material					
Total number	Description	Region (long. & lat.)	Environment (rainfall; temp.)	Management details	Thesis chapter(s)
217	Domestic mixed-breed	NW England, UK (-3.86; -53.19)	Pasture (800-1000mm; 11-21^{o}C)	Domestic	3
20*	Brumby	Musslebrook, Aus. (18.67; 138.35)	Rock/shale (800-1000mm; 18-21^{o}C)	Feral	3
12*	Brumby	Cliffdale, Aus. (17.45; 138.35)	Soil/sand (600-800mm; 21-24^{o}C)	Feral	3
20*	Brumby	Kings Series, Aus. (24.50; 133.10)	Desert (200-300mm; 27-30^{o}C)	Feral	3
17*	Brumby	Palparara, Aus. (24.49;140.32)	Grassland (500-600mm; 18-21^{o}C)	Feral	3
20*	Brumby	Babbiloora, Aus. (25.18; 147.49)	Sand/shale (400-500mm; 27-30^{o}C)	Feral	3
Live cohorts					
36	IDxTB	NW England, UK (-3.86; -53.19)	Pasture (800-1000mm; 11-21^{o}C)	Domestic	4,5
65	Domestic mixed-breed	NW England, UK (-3.86; -53.19)	Pasture (800-1000mm; 11-21^{o}C)	Domestic	6

Table 2.1. Summary table of samples used in the study. Total numbers used with thesis chapters are shown. Further details of study samples are presented at the beginning of each results chapter. **digital photographs of left fore only.*

2.2.3 Live cohorts

Two main groups of live horses were used for this study (**Table 2.1**), descriptive data is provided for each group within the methods section of chapter 4, 5 and 6 respectively. The first group were riding horses belonging to Myerscough College, University of Central Lancashire managed under similar conditions. Myerscough College is a large equine teaching establishment where a number of horses are working liveries as such sample sizes were restricted by availability, teaching demand, term time access and owner consent. The second group were client-owned horses presenting to the Philip Leverhulme Equine Hospital, University of Liverpool for low-field MRI of the fore feet as part of clinical work-up for lameness. Lameness had been previously localised to the digit following anaesthesia of the lateral and medial palmar digital nerves at the level of the collateral cartilages, local analgesia of the DIPJ and/or local analgesia of the navicular bursa (Bassage and Ross 2011).

2.3 Digital photographic protocol

Dorsal, lateral and solar digital photographs were taken of each foot pre- and post-trim, (apart from the Australian feral samples where lateral only digital photographs were available). For the digital photographs, the camera was positioned perpendicular to the plane in which measurements were taken (**Figure 2.1**). For the dorsal and lateral views, the camera was centred in the midline of the hoof whereas for the solar views the camera was centred at the point of the frog. Each image had a reference measure included in the photograph at the time of acquisition (White et al., 2008). Digital photographs were then transferred to measurement software (OnTrack™ Equine Software, Lameness Solutions, Minnesota, USA).

2.4 Foot mapping protocol

Data were initially collected to validate the trimming protocol using a hoof mapping system (**Figure 2.2**). Twelve external hoof measures were chosen for this study based on measures used in previous work (Colles 1983; Kummer et al 2006; Dyson et al., 2011). A number of these measures are considered to be related to important biomechanical aspects of the foot and included a point 9.5mm palmar to the apex of the frog known to hoof care professionals as Duckett's dot and considered to represent the theoretical position of COP. The GRF matches the weight the limb bears, but it is exerted in the opposite direction. When a horse's foot stands on a flat, firm surface, the GRF distributes around the perimeter of the hoof capsule. COP is a calculated single given point where GRF is said to be at its greatest. At mid stance COP is said to be at its greatest approximately in the centre of the foot and dorsal of the DIPJ. In motion the peak vertical GRF occurs at around $50 - 55\%$ of stance, differences in the position and timing of COP are thought to adversely affect the mechanical behaviour of the hoof directly contributing to plastic deformation and distortion (Wilson et al., 1998; Thomason, 2007; Parks 2012b).

The bearing border reference points of COR and BO are considered important anatomical points in the biomechanics of the foot. COR, is the centre of rotation of the distal interphalangeal joint (DIPJ) which is a complex joint with three articulations: (1) between P2 and P3, (2) between P2 and the distal sesamoid bone and (3) between P3 and the distal sesamoid bone. The DIPJ is a ginglymus joint, however, because the sagittal groove on P2 is very shallow and the opposing ridge on P3 very low, this permits significant rotation and movement in the frontal plane (Parks 2012b). Breakover (BO) can be defined as a moment in the stance phase of the stride between the in time the horses heel lifts off the ground and the time the toe lifts off the ground and is thought to relate anatomically to the vertical orientation of the dorsodistal tip of P3 (Page et al., 2002). The toe acts as a fulcrum around which the heel rotates under the influence of the deep digital flexor tendon. Morphological changes in DHWL length and DHWA increasing the tensile forces on the deep digital flexor tendon and pressure on the heels and anatomical structures within the palmar/plantar aspects of the foot (Willeman et al., 1999; Wilson et al., 2001; Eliashar, 2004; 2012).

The bearing border reference points of CoR and BO were marked out along the sagittal axis of the frog using a grid mapping system. For this two parallel lines were projected dorsally along the bearing border from the centre of each heel buttress at the widest part of the frog to the toe area at the solar white line interface. Two additional lines were projected diagonally from the heel buttress intersecting with the previous parallel lines terminating in the toe area. A horizontal line perpendicular to the sagittal axis of the frog was drawn through the intersection of the diagonal lines corresponding to the widest part of the ground bearing hoof. The intersection of the diagonal lines was considered to be representative of CoR at this intersection (*diagonal arrows in* **Figure 2.2)**. The point of breakover (BO) was identified an additional line perpendicular to the sagittal axis of the frog through the intersections of the previous parallel and diagonal lines terminating at the solar white line junction in the toe area.

For validation of the trimming protocol, i.e. the ability of the trim to provide reproducible measures, referred to hereon in as "trim validation measures", specific external reference points were chosen. These included the point of breakover (BO), centre of rotation (CoR), centre of pressure (CoP) and the apex of the frog (FRA). Each reference measure was recorded as a raw value and then calculated as a proportion of the sagittal length (SL) before (pre-) and after (post-) trimming.

Following validation of the trimming protocol, geometric hoof balance was analysed pre- and post-trim using measures (hereon in referred to as "hoof balance measures") of dorsal hoof wall length (DHWL), dorsodistal tip of the bearing border to the centre of rotation of the DIP joint (DDTBB-CoR) and centre of pressure to the heel buttresses (CoP-Heel) each as a proportion of the bearing border length (BBL). Geometric hoof balance is achieved when each proportional hoof measure is equal, as described by Duckett (1990).

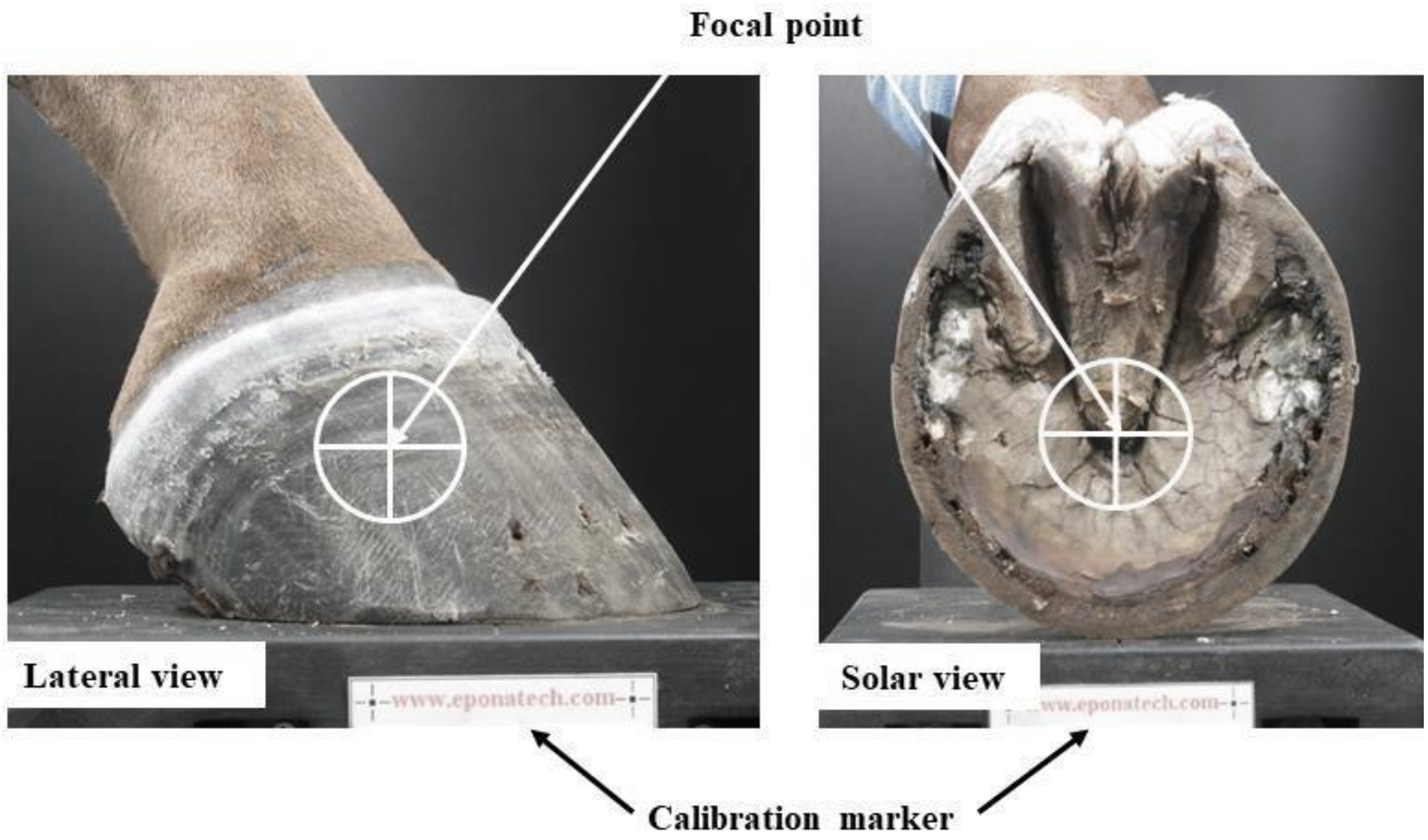

Figure 2.1 Lateral and solar photographic views of demonstrating the standardised digital photographic protocol. For the lateral view the camera was centred in the midline of the hoof whereas for the solar views the camera was centred at the point of the frog. Each image has a reference measure included in the photograph at the time of acquisition (*White et al., 2008*).

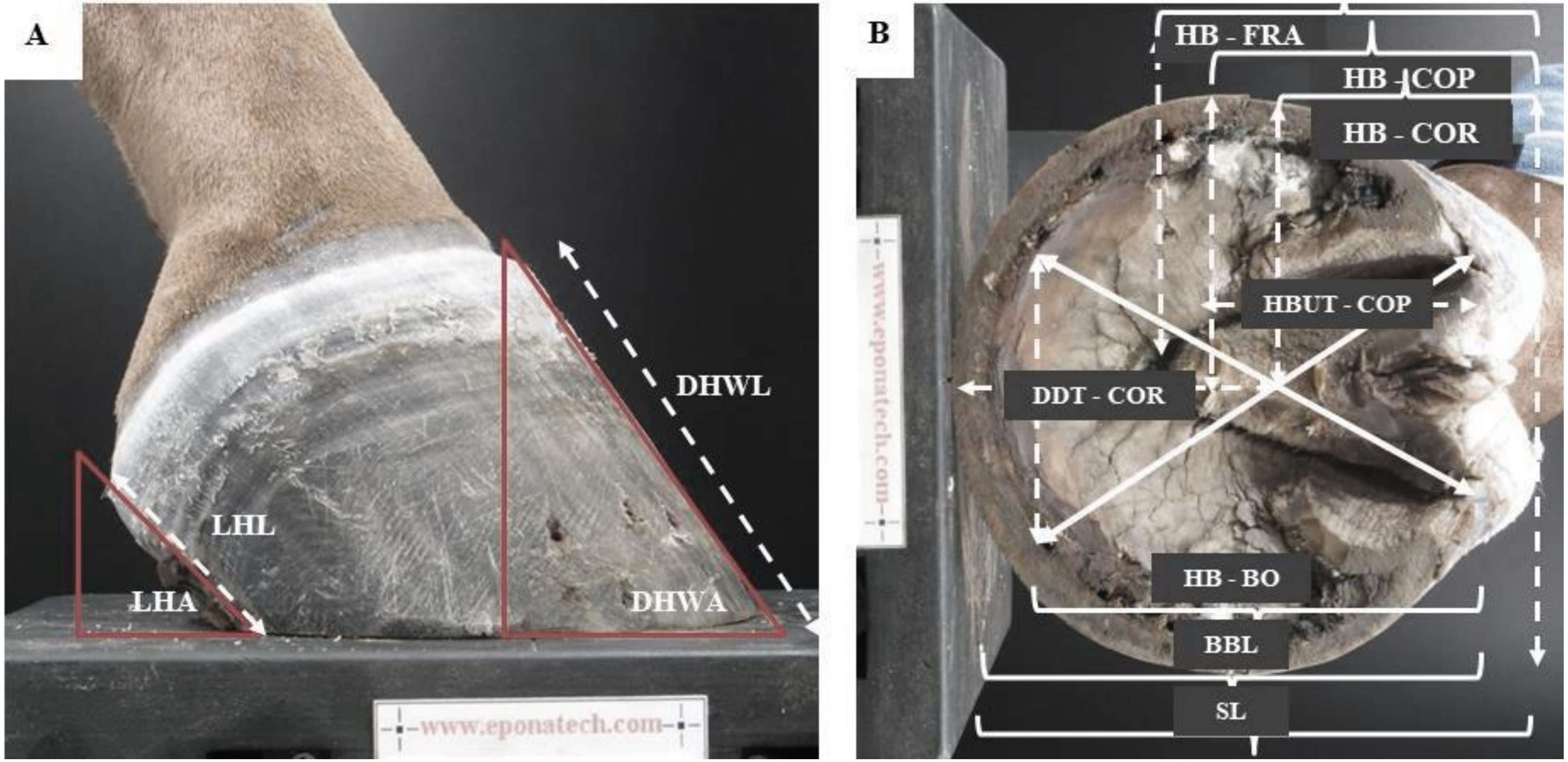

Figure 2.2 Schematic views of the external reference points from lateral (A) and solar aspects (B). BBL = length in the sagittal plane between the heel buttresses and dorsal toe; COP = point 9.5mm palmar to the apex of the frog; COR = point formed by the intersection of the heel buttresses and opposite breakover point (dotted lines); DHWA = angle between the dorsal hoof wall and horizontal ground; DHWL = length in the sagittal plane from the coronary band to the dorsal toe; DT-COR = length in the sagittal plane from the dorsal toe to COR; HA = angle between the heel bulb and horizontal ground; HB-BO = length from the heel bulb to the point of breakover (BO); HB-COP = length from the heel bulb to COP; HB-COR = length from the heel bulb to COR; HB-FRA = length from the heel bulb to the apex of the frog; HBUT – COP = length in the sagittal plane from heel buttresses to a point 9.5mm palmar to the apex of the frog; HL = length from the coronary hair line to the bearing border of the heel; SL = sagittal length from the heel bulb to the dorsal toe .

2.5 Standardised foot trimming protocol

The trimming protocol used was developed under UK Farriery National Occupational Standards[3] and based on Caldwell and Savoldi[4]. This trim addresses the frog, sole and white line first, followed by the bearing border and dorsal hoof wall. The trim relied on the initial assessment and identification of anatomical landmarks.

Initially the collateral margins of the frog were trimmed along its entire length forming an angle of about 55-60° with the bars such that the collateral sulci were clearly visible to their full depth and the true apex of frog (where the frog horn blends into the solar horn) could be identified **(Figure 2.3a)**. Perioplic horn that envelops the heel buttresses was removed to expose the collateral sulci to their full depth at the origin of the heel. The ground bearing surface of the frog was trimmed, removing only damaged and diseased tissue, proportionate to the foot with the caudal aspect of the bearing border of the hoof wall and level with the horizontal plane of the wall and sole to allow ground contact post trim **(Figure 2.3a)**.The white line was exfoliated **(Figure 2.3b)** by removing flaky solar horn and by trimming out the area to reveal yellow flexible horn at the true interface with the sole **(Figure 2.3a)**. The exfoliating solar horn was then removed, exposing confluent solar horn, identifiable by the waxy horn at the sole-white line interface at the soles leading edge. Trimming did not extend to an area commonly referred to as the sole callus, a flat area of sole approximately 8mm wide and found at the toe area dorsal to the dorsodistal margin of P3. The bars were trimmed removing only damaged or weak horn **(Figure 2.3a)**. Excess wall at the bearing border was removed to the level horizontal with the plane with the trimmed sole.

[3] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

[4] See: http://www.forgemagazine.co.uk/site/index-1newsarchiveapr10.html (accessed 27 August 2015)

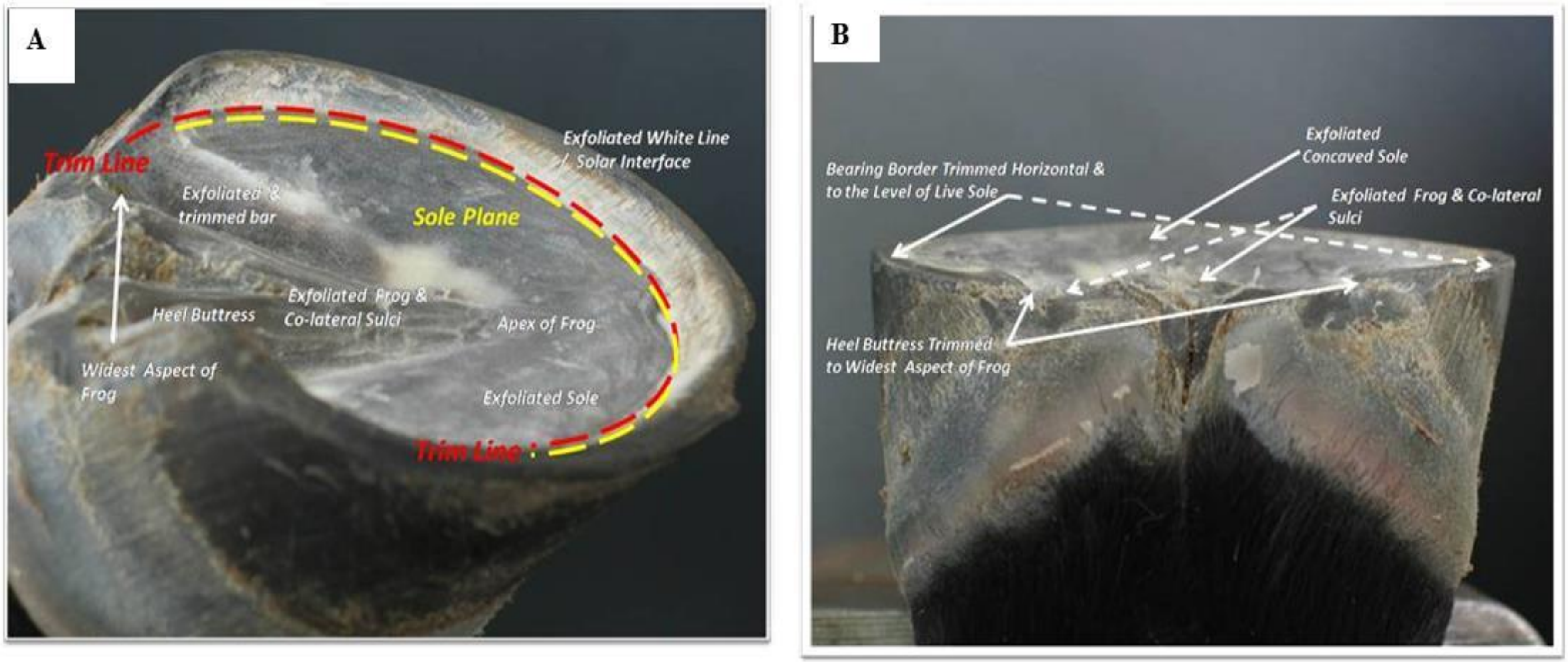

Figure 2.3 Annotated solar and palmar photographic views of demonstrating the standardised foot trimming protocol. (A)The frog was trimmed and sole and white line was exfoliated in preparation for trim. The white line was exfoliated to reveal the sole and horny wall interface. Removal of the remaining exfoliating solar horn revealed the true solar plane to which, removing only damaged or weak horn, the bars were trimmed to normal proportions. (B) The bearing border of the DHW was trimmed and excess wall at the bearing border was removed to a horizontal plane at the level of the sole plane. The heels were reduced in height to approximately to the widest part of the trimmed frog or the palmar / plantar aspect of the exfoliated central sulci.

Care was taken not to trim the bearing border of the hoof wall below the level of the previously trimmed sole. The heels were trimmed (reduced in height) to extend the bearing border to approximately the widest aspect of the trimmed frog or the palmar / plantar aspect of the trimmed central sulci **(Figure 2.3b)**. The hoof was then rasped from heel to toe by maintaining even pressure over the rasp to create a flat level surface on the ground surface of the foot. With the foot extended into the farrier position flares were removed from the dorsal hoof wall DHW, maintaining an equal amount of hoof wall around the bearing border of the hoof wall from quarter to quarter. DHW thickness was determined by the width of the wall from solar aspect of the white line interface at the quarters and DHW flares were only dressed when there were deviations in symmetry and to correspond to the phalangeal axis.

2.6 Shoeing protocol

All horses that were shod were fitted with handmade shoes from fullered concave material in a section suitable to each individual horse over three shoeing periods every 35 days **(Figure 2.4)**. Shoes were fitted to a competition style fit, designed to suit a shoeing cycle of no more than five weeks. As defined within the UK Farriery National Occupational Standards[5] this type of shoe should have symmetrical branches and be fitted to the heel buttress with additional 5mm length in a palmar direction. Nail-hole placement was confined to the dorsal half of the shoe. All front feet were shod with toe clips, with no additional traction devices added.

[5] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

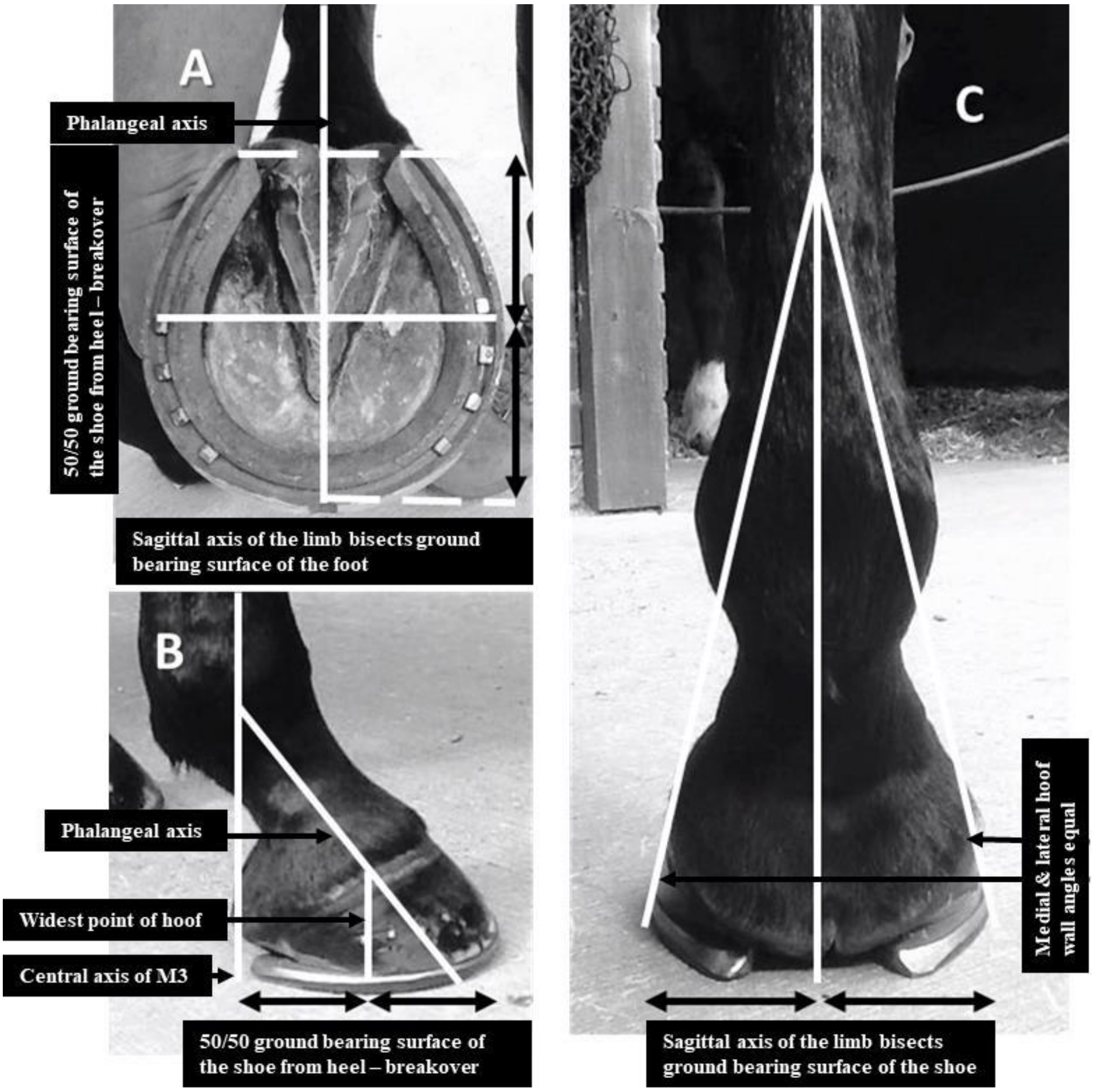

Figure 2.4 Photographs showing shoe fitting from solar (A), lateral (B) and palmar (C) aspects. The illustration highlights the main criteria of the shoeing protocol. Horses were trimmed and shod to a competition style as defined in the UK National Occupational Standards for Farriery.

Key characteristics are A) the shoe should not interfere with the natural functions of the foot. B) The shoe should be of the correct weight and size for the horse and the work the horse is engaged in. C) The shoe should be of adequate length so that there is no loss of bearing surface and fitting to the heel buttress with additional 5mm length in a palmar direction with symmetrical branches. D) The excess hoof growth should be removed ensuring that correct balance is maintained and according to the horses conformation. E). No daylight should show between the shoe and the foot, necrotic feet being the exception to this rule. F) The right number and size of nails should be used in relation to the foot, and the nails driven so as to fill the nail holes. G) The clenches should be in regular line and flush with the wall. H) Clips should be well formed low and broad, and flush with the wall.

2.6 Radiographic protocol

Lateromedial and dorsopalmar radiographs were obtained to determine the relationship between the external reference points CoP and CoR to internal anatomical landmarks (extensor process of P3 and the centre of rotation of the DIP joint), (**Figure 2.5)**. The radiographic centre of rotation of the distal interphalangeal joint was identified based on Eliashar et al. (2002). Measurement data was collected using Ontrack™ and COP-COR distance was calculated and COR mapped onto the image, using the dorsal hoof wall marker for correction of magnification by beam divergence.

Cadaver limbs were placed in a custom-built press with the superficial digital flexor tendon (SDFT) and deep digital flexor tendon (DDFT) secured into the limb retaining socket at the head of the press (**Figure 2.6)**. Limbs were loaded at 8.9 kg/cm^2 to approximate the mid stance position presenting a parallel hoof pastern axis with the third metacarpal perpendicular to the bearing border of the foot (Turner, 1992). A radiodense marker of known length (60 mm) was fixed to the dorsal hoof wall and a radiodense drawing pin placed 9.5 mm palmar to the dorsal tip of the frog approximating the location of Duckett's dot (COP). Images were generated using an Ultra Power 100 xray machine set to 1.5 mAs, 58kV and a focal-film distance of 80cm in all cases.

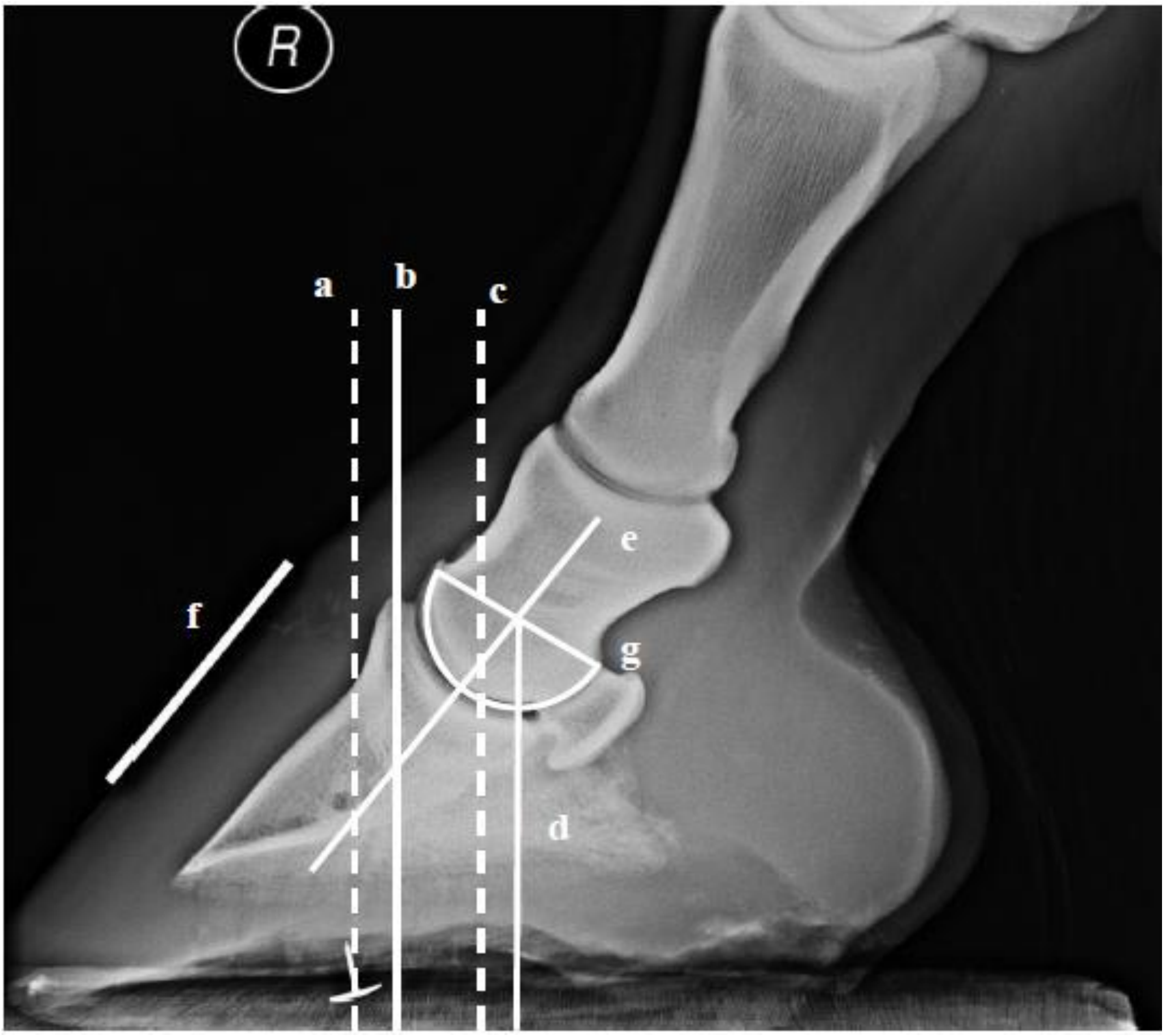

Figure 2.5 Lateromedial radiographic projection of the equine digit showing external hoof measure centre of pressure (COP) (*dashed line a*), vertical line through extensor process of P3 (*solid line b),* external measure of centre of rotation (COR) (*dashed line c)* and vertical line through centre of rotation of the distal interphalangeal joint (DIPJ) (*solid line d).* The centre of rotation of the DIPJ was located as the intersection of a line (*e*), parallel to the dorsal hoof wall marker (*f*), midway through the DIPJ at the chord of the arc (g) of the surface of the DIPJ. External hoof measure COP *(dashed line a)* was located at the entry point of a metallic pin 9.5mm palmar to the point of the frog and external hoof measure COR *(dashed line c)* was calculated from the COP-COR distance and mapped onto the image after correction for magnification (*taken from Caldwell et al., 2016)*.

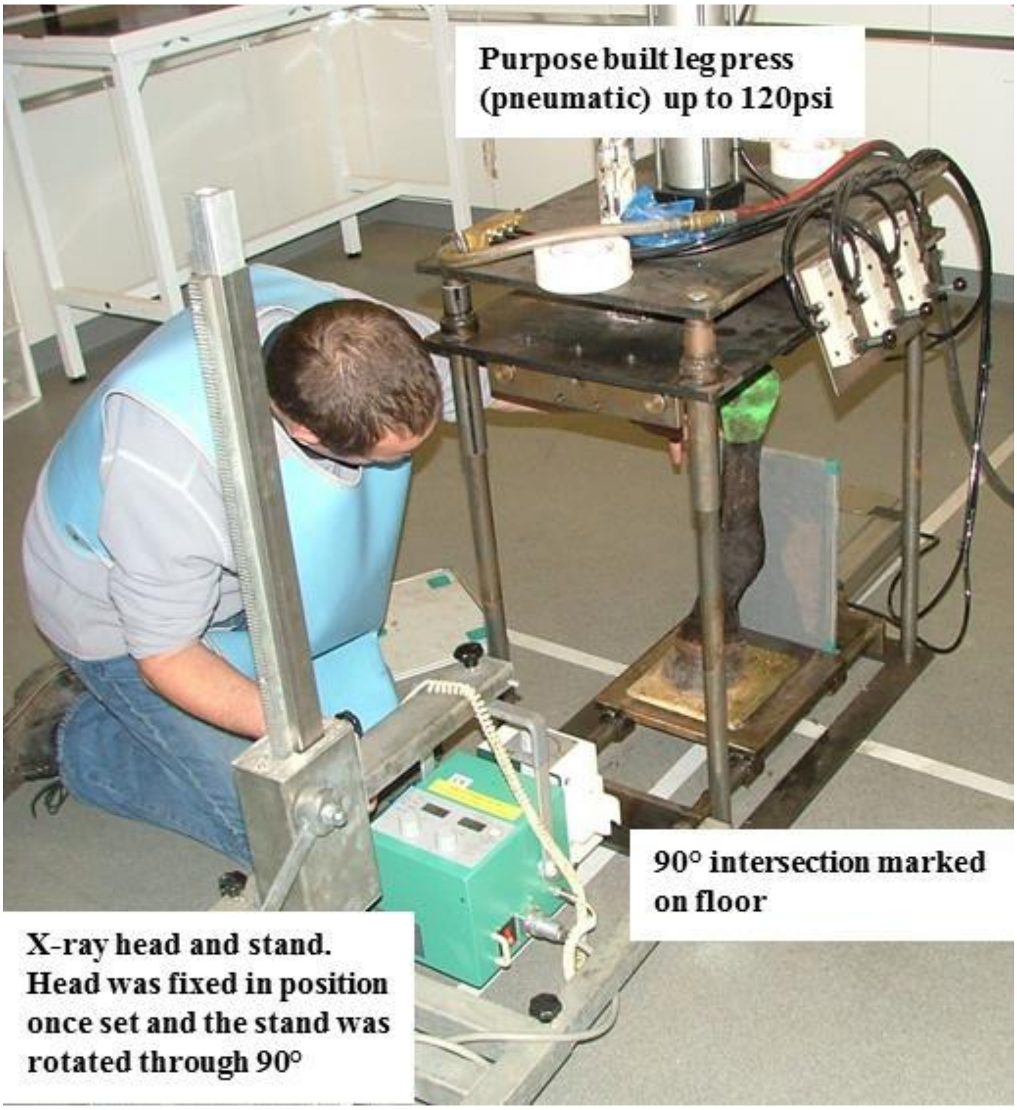

Figure 2.6 Custom-built press to mount cadaver limbs prior to radiography. The superficial digital flexor tendon (SDFT) and deep digital flexor tendon (DDFT) secured into the limb retaining socket at the head of the press. Limbs were loaded at 8.9 kg/cm^2 to approximate the mid stance position presenting a parallel hoof pastern axis with the third metacarpal perpendicular to the bearing border of the foot.

2.8 Foot pressure protocol

For collection of pressure data of the horse's hoof a commercial pressure mat system was used (Matscan ® XL, Tekscan, Mass. USA). This involved a 0.18mm tactile pressure mat sensor composed of 8448 sensels (pressure sensing elements) arranged for a spatial resolution of 3.9sensels/cm^2. The mat was calibrated prior to use and set on a flat concrete surface with a protective rubber cover. Data were collected at a sampling frequency of 100Hz and transferred for analysis. Custom software was used to calculate total contact area, pressure, and force and peak contact pressure and force for each horses hoof. To standardise the centre of pressure location and allow for accurate comparison a consistent coordinate system was created with the horizontal x-axis defined by a line connecting the heels (Cerfogli 2009). The axis origin was located at the medial heel of the right foot and lateral heel of the left foot. From the data obtained, the initial x and y coordinates for the centre of pressure were determined and converted to the standard coordinate system (**Figure 2.7**).

2.8.1 Static pressure measurements

To validate the pressure mats ability to record pre and post trim difference and to investigate any possible effect of preferential limb loading and hoof asymmetry on the data static pressure mat data was collected from group A (un-shod) only. Horses undergoing static pressure measurements were evaluated pre- and post-trim. Feet were thoroughly cleaned prior to the foot being positioned squarely with the horse fully weight bearing on the pressure mat. Measurements were taken for 8 second periods at a sampling frequency of 100Hz and repeated for two sequential data sets.

2.8.2 Dynamic pressure measurements

Data for each horse undergoing dynamic pressure measurements were collected at the walk pre- and post-trim. Data for each fore foot from 5 consecutive horse passes were recorded Parameters were set so that data recording was triggered from time of impact to lift off. A trial was considered valid if: (1) the horse moved at a constant pace; (2) it looked straight ahead; (3) the gait velocity was within the pre-set range 0.8–1.4 m/s at the walk; and (4) the hoof of at least one forelimb fully contacted the plate surface. For validity and consistency of data collection a total number of five valid measurements were collected for both forelimbs *as per* Oosterlinck et al., (2010).

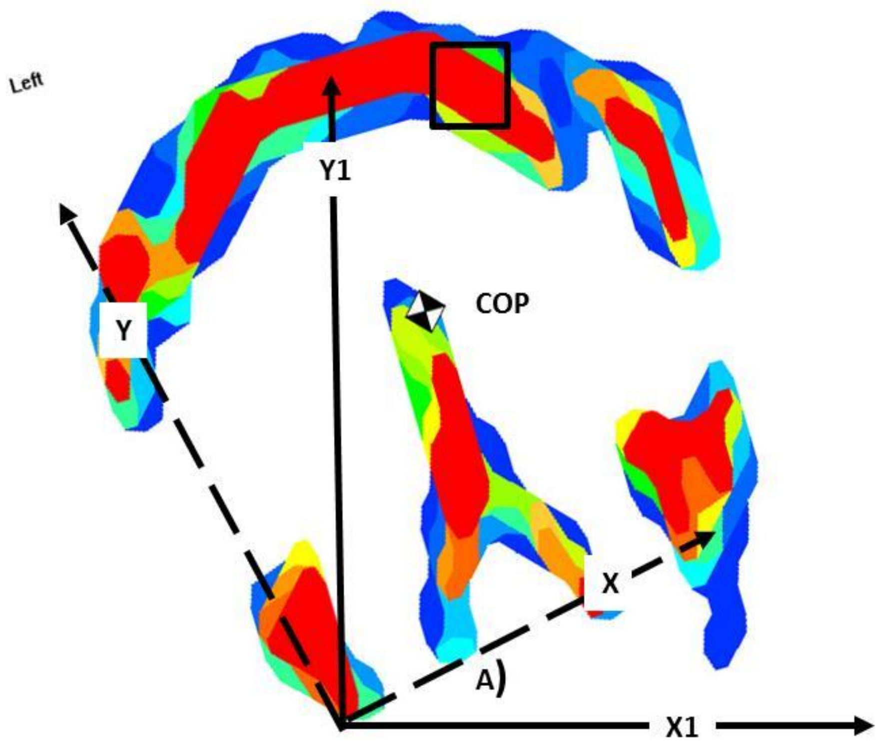

Figure 2.7 Example of a static pressure mat reading. COP is represented by the black/white diablo icon whilst peak pressure is highlighted by the black square. Angle A denotes the calculated angle of rotation of x, y from standard axes x1, y1 required to calculate COP. Colour schemes arbitrarily show areas of low (blue) to high (red) pressure.

2.9 Clinical MRI study

Horses undergoing low-field MRI as part of clinical investigation of fore limb lameness localised to the digit are detailed in Table 2.1. Lateromedial and dorsopalmar radiographs with radiographic markers were taken as standard practice following shoe removal to check for retained clenches or other artefacts prior to MRI. Horses underwent MRI evaluation using a 0.27T standing MRI unit (Hallmarq Veterinary Imaging, Surrey, UK) (**Figure 2.9)**. MRI sequences included T1-weighted 3D, T2*-weighted 3D, short tau inversion recovery (STIR) and T2-weighted FSE sequences in sagittal, frontal and transverse planes. MRI images were assessed by an experienced equine orthopaedic clinician. Injury groups based on MRI diagnosis were as follows: DIPJ and associated structures (collateral ligaments); navicular apparatus; and deep digital flexor tendon injuries.

Figure 2.8 Photograph of a low-field standing MRI unit. The sedated horse is stood with the limb inside a low-field open magnet. The radiofrequency coil is placed around the region of interest before sequence acquisition begins.

2.10 Statistical analysis

Unless otherwise stated all data were analysed using Minitab 16® (Minitab Ltd, Warwickshire., UK). Normal distribution for each data set was assessed using the Anderson-Darling test for normality. Wilcoxon paired sample tests and Mann Whitney U tests were used for non-parametric data post trim data. Statistical analyses were performed on all data sets and significant differences were determined by One-way ANOVA with Tukey HSD post-hoc correction. Repeated measures ANOVA were used to test significant differences between bare foot and shod groups in the prospective cohort studies chapters 6 & 7. Fiellers test for bioequivalence was used with equivalence intervals of 3.8% (Christley and Reid, 2003) to investigate hoof balance indicators: dorsal hoof wall length (DHWL); the distance from the dorsal toe to the centre of rotation (DDTBB-CoR); and the distance from the heel buttress to centre of pressure (HB-COP) as a proportion of bearing border length (BBL). The value 3.8% was calculated using a margin of error of 3.2mm (1/8 inch) of the mean BBL following trimming (114mm). Upper and lower P values were calculated for each comparison with a P value of <0.05 considered statistically significant. Results are presented as mean values ± standard error of the mean (SEM). Exact P-values are presented for all data sets as appropriate. Statistical significance for all data was set at the 5% level ($P<0.05$).

Chapter 3

Investigation of a commonly used foot balance protocol to achieve geometric proportions in the equine hoof

Aspects of this chapter have been published (see **Appendix A** for full article)

Caldwell, M.N., Allan, L.A.,. Pinchbeck G.L., Clegg, P.D., Kissick, K.E., and Peter I. Milner, P.I. (2015). A test of the universal applicability of a commonly used principle of hoof balance. *The Veterinary Journal*, Volume 207, January 2016, Pages 169-176, ISSN 1090-0233, http://dx.doi.org/10.1016/j.tvjl.2015.10.003.

3.1 Introduction

To understand the effect of trimming on hoof balance it is necessary to evaluate measures of balance and how these relate to external and internal features of the equine foot. There are many ideas around what constitutes hoof balance, mainly based on historical texts of Lungwitz (1891), Dollar (1897) and Russell (1897), as detailed in Chapter 1. The hoof balance ideal used in this study is based on Duckett's principles of geometric proportionality which are said to relate to internal anatomical landmarks (Duckett 1990). The basis of this idea is that hoof balance is achieved when specific hoof balance indicators, as a proportion of bearing border length, are equivalent. The advantage of this model is that it can be applied to all horse and pony breeds, irrespective of size which is why this theory is in common usage amongst hoof care professionals.

Evaluating the effects of a trimming protocol on hoof balance requires validation; this is lacking in many studies and often conventional farriery teaching is based on years of dogma without it being evidence based. Indeed it is astonishing to note that many studies do not even describe the trimming protocol despite inferring how important the trim was to the results. To assess the ability of a trimming protocol to achieve balance requires a measure of reproducibility and effectiveness of the trim. This could be done by measuring internal stresses on bone, ligaments and tendons in the loaded distal limb following trimming, whereas an alternative method would be to undertake a longitudinal study following cohorts of horses over several trimming cycles and measuring the effects of the trim on hoof measures and function. However there still requires trim validation and therefore the first part of this chapter evaluates the ability of a standardised trimming protocol to effect hoof measures in a cohort of cadaver limbs. In doing so it evaluates the behaviour of hoof measures in different (fore and hind) feet before and after trimming thereby establishing how well the trim achieves its goal in maintaining these hoof measures within defined boundaries and determines how these measures may be related to each other. Following this, the ability of the trim to achieve hoof balance as defined by geometric proportionality requires verification; measures of equivalence will determine whether two or more sets of results are equivalent which differs from statistical tests that determine when there is not a difference between results (Christley et al., 2003). In testing for equivalence between measures the assumption that geometric proportionality can be achieved following a standardised trim can therefore rigorously tested.

How the external hoof landmarks relate to internal anatomical landmarks, particularly ones through which critical forces or moments are deemed to occur, has often been used to explain how deviations from “normal hoof balance” can result in abnormal stresses on key structures within the digit (e.g. the navicular apparatus) (Wilson et al., 2001). Mapping how these external points refer to internal landmarks and whether these alter during trimming in achieving hoof balance will begin to bridge the gap between how external morphology of the hoof relate to the internal structures. In this chapter the extensor process of the distal phalanx and centre of rotation of the distal phalanx were chosen as these important internal landmarks relate to ground reaction forces and moment arms in the digit. If external measures map to these landmarks and more importantly, whether differences exist in different feet then this may help to explain how the external shape of the foot, and in particular key trim reference points, may influence the function of the hoof.

It is also important to appreciate the effects of environment on hoof shape and morphology. The determination of hoof quality and foot shape relies on a number of factors: diet, exercise, human interventions, and environment being a key determinant of many of these external factors. To do this a comparison is required of hoof morphology from horses kept in different environs. A suitable comparison here are feral horses who undergo “natural balance” in the wild (Ovnicek 2003) and are thought to represent the ideal hoof shape thus conferring optimum biomechanical advantages to sustain a healthy hoof. However variation in hoof morphology in the wild exists and this may be reflected by different environmental conditions (Hampson et al., 2013) and needs to be considered. Therefore in the final part of this chapter, cadaver samples from a number of different environmental conditions in a country with a large feral horse population (in this case Australia) were compared to UK domestic species to determine if geometric proportionality is achieved in a feral model and whether this is influenced by environmental factors.

3.2 Hypothesis

This chapter will address the hypothesis that a standardised trimming protocol results in static and dynamic foot balance based on the principle of equal geometric proportions and that these proportions are dependent on factors such as foot-type (front and hind feet) and environmental conditions (domestic versus feral).

3.3 Aims

The aims of this chapter were:

1. To test the reproducibility of a commonly used trimming protocol in relation to external hoof measures in fore and hind feet (trim validation).
2. To investigate the ability of a commonly used trimming protocol to achieve foot balance to achieve geometric proportionality.
3. To test the assumption that certain external hoof measures (defined by Duckett, 1990) equate to key internal anatomical landmarks following a commonly used trimming protocol.
4. To compare geometric proportionality following trimming to a feral horse population under different environmental conditions.

3.4 Study design

- **Sample collection**

UK samples were cadaver limbs collected from a local abattoir in the North-West of England (detailed in Chapter 2, 2.2.1). To test the reproducibility of the trim, 49 fore limbs were available. To evaluate whether the trimming protocol achieved geometric proportionality 49 limbs were available. To investigate differences between fore and hind feet, 68 fore limbs and 100 hind limbs were available.

For the comparison of UK limbs to feral population, UK samples were compared to digital images of 89 left fore feet from feral horses from 5 different regions in Australia as detailed in Chapter 2 (2.2.2).

- **Digital photographic and foot mapping protocol**

For the UK cadaver limb samples, digital photographs demonstrating the dorsal, lateral and solar views of the feet were used (as detailed in Chapter 2, 2.3). For the Australian feral horses, lateral only views of the fore feet were available for analysis. To test reproducibility of the trimming protocol, measures used included the point of breakover (BO), centre of rotation (CoR), centre of pressure (CoP) and the apex of the frog (FRA) with each variable measured from the heel bulb (HB). These are referred to hereon in as “trim validation measures”. To test the ability of the trimming protocol to achieve geometric proportionality, measures included dorsal hoof wall length (DHWL), dorsodistal tip of the bearing border to the centre of rotation of the DIP joint (DDTBB-CoR) and centre of pressure to the heel buttresses (CoP-Heel) each as a proportion of the bearing border length (BBL). These are hereon in referred to as “hoof balance measures”.

Geometric hoof balance is thought to be achieved when each proportional hoof measure is equal, as described by Duckett (1990).

- **Trimming protocol**

The trimming protocol used in this chapter was originally developed under UK Farriery National Occupational Standards[6] and based on Caldwell and Savoldi[7] and is detailed in Chapter 2 (2.5).

- **Radiographic protocol**

Lateromedial and dorsopalmar radiographs of 25 limbs were obtained as detailed in Chapter 2 (2.8). A radiodense marker of known length (60mm) was positioned on the dorsal hoof wall to calculate effects of magnification. A radiodense drawing pin was placed 9.5mm palmar to the dorsal tip of the frog to approximate the location of Ducket's dot.

- **Statistics**

Statistical methods are outlined in detail in Chapter 2, 2.10.

[6] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

[7] See: http://www.forgemagazine.co.uk/site/index-1newsarchiveapr10.html (accessed 27 August 2015)

3.5 Results

3.5.1 Reproducibility of the trimming protocol

Initially, 49 cadaver limbs were evaluated to test the reproducibility of the trimming protocol. **Table 3.1** details the results for the trim validation measures HB-CoR, HB-CoP, HB-FRA and HB-BO as a proportion of total sagittal length (SL) pre- and post- trimming.

Trim validation measurement	Pre trim	Post trim	P-value	95% CI
CoR / SL	0.46 ± 0.04	0.50 ±0.02	**<0.001**	-0.05, -0.03
CoP / SL	0.64 ± 0.03	0.65 ±0.03	0.46	-0.02, 0.01
FRA / SL	0.72 ± 0.04	0.71 ±0.03	0.55	-0.01, 0.01
BO / SL	0.85 ± 0.03	0.86 ±0.02	0.07	-0.02, 0.00

Table 3.1 Table of proportional hoof trim validation measures. Data are reported as mean ± sd. 95% confidence intervals are reported for pre-post trim differences. BO = point of breakover, CoP = centre of pressure; CoR = centre of rotation; FRA = frog apex; SL = sagittal length. Significant values ($P<0.05$) are represented in **bold**. n=49 cadaver limbs.

Following trimming, there was a significant increase in CoR only as a proportion of sagittal length. When differences between pre-trim and post-trim values for each trim validation measure as a proportion of pre-trim SL were ranked, there was a grouping in how the values changes post-trim across 49 cadaver limbs (**Figure 3.1**). In was noted that this pattern was linked to hoof morphology; for example, horses with a low dorsal hoof wall angulation (DHWA)/underrun heels had a reduced SL post-trim due to a reduction in the dorsal hoof wall thickness following minimal intervention required at the heels, resulting in an increase in the trim validation measures relative to the pre-trim values (*samples more to the left* in Figure 3.1).

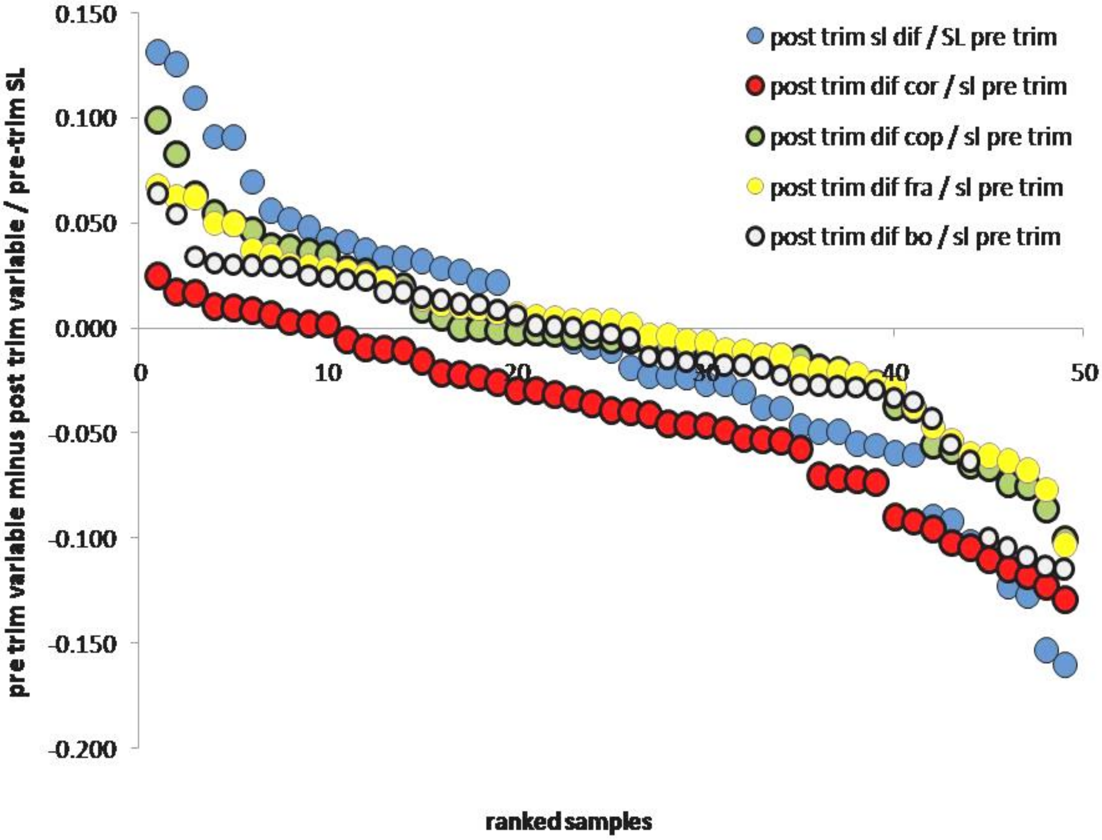

Figure 3.1 Ranked plot of pre-post trim differences in trim validation measures as a proportion of pre trim SL. Horses with a low dorsal hoof wall angulation (DHWA)/underrun heels had a reduced SL post-trim due to a reduction in the dorsal hoof wall thickness following minimal intervention required at the heels, resulting in an increase in the trim validation measures relative to the pre-trim values. Conversely horses with a steeper DHWA had both the DHWL and LHL reduced, leading to a relative lengthening of the SL and hence a reduction in post-trim values. n=49 cadaver limbs.

Conversely horses with a steeper DHWA had both the DHWL and LHL reduced, leading to a relative lengthening of the SL and hence a reduction in post-trim values (*samples more to the right* in Figure 3.1).

For further analysis of these results, differences in each trim validation measure pre- and post-trim were calculated as a proportion of pre-post trim SL and plotted against the difference in SL (pre-post trim) as a proportion of pre-trim SL (**Figure 3.2)**. This showed that for each variable, most samples showed little variation within themselves (70-80% within proportional spread of ± 0.5). Those that markedly deviated away from this range were ones that required removal of excessive heel depth and thus led to marked differences in the proportional value of the difference of the parameter measured (i.e. large y-axis values demonstrated), without actually significantly altering pre- and post-trim sagittal length (SL) (i.e. x-axis values close to zero intercept). These results showed that there was variation between different feet (likely to reflect differences in hoof morphology encountered) but variation within each foot pre- and post-trim, in the main, was low reflecting reproducibility of the trim.

Following on from this initial work 68 fore and 100 hind feet were compared to investigate whether there were differences after trimming between fore and hind limbs. **Table 3.2** shows that after trimming there were significant differences between fore and hind feet for the trim validation parameters CoR/SL, BO/SL and FRA/SL.

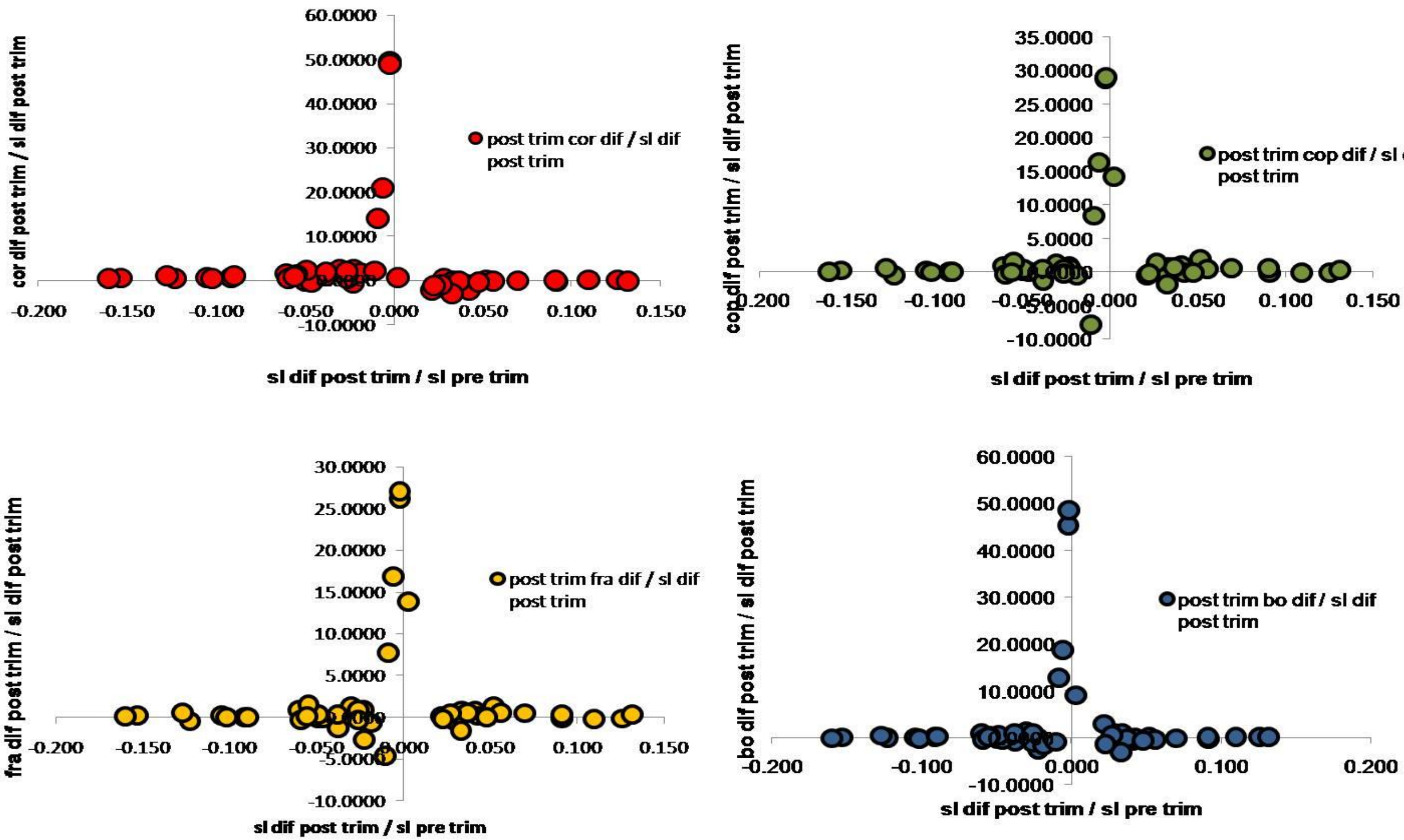

Figure 3.2 Scatter plots showing pre- and post-trim differences for CoR, CoP, FRA and BO each as a proportion of SL. The data for each variable illustrates most samples exhibited little variation within themselves (70-80% within proportional spread of ± 0.5). Those that markedly deviated away from this range were ones that required removal of excessive heel depth and thus led to marked differences in the proportional value of the difference of the parameter measured (i.e. large y-axis values demonstrated), without actually significantly altering pre- and post-trim sagittal length (SL) (i.e. x-axis values close to zero intercept). n=49 cadaver limbs.

Trim validation measurement	Post-trim fore limb (n=68)	Post-trim hind limb (n=100)	P-value
CoR / SL	0.48 ± 0.04	0.49 ±0.02	**0.01**
CoP / SL	0.64 ± 0.04	0.64 ±0.03	0.47
FRA / SL	0.69 ± 0.06	0.71 ±0.03	**<0.01**
BO / SL	0.86 ± 0.05	0.84 ±0.02	**0.02**

Table 3.2 Table of proportional hoof trim validation measures. Data are reported as mean ± sd. BO = point of breakover, CoP = centre of pressure; CoR = centre of rotation; FRA = frog apex; SL = sagittal length. Significant values (P<0.05) are represented in **bold**.

3.5.2. Geometric proportionality following trimming

To test whether the trimming protocol leads to geometric proportionality and hence foot balance as stated by Duckett (1990), hoof balance measures DHWL, DDTBB-CoR and CoP-Heel as a proportion of bearing border length (BBL) were compared pre- and post-trim and then tested with Fiellers test of equivalence.

Table 3.3 shows the results of these measures pre- and post-trim in 49 cadaver fore limbs. Significant differences were noted between pre- and post-trim in all three proportional measures showing that the trim protocol altered all hoof balance measures, decreasing DHWL/BLL and DDTBB-CoR/BBL whilst increasing CoP-Heel/BBL post-trim.

Hoof balance measurement	Pre trim	Post trim	P-value	95% CI
DHWL/ BBL	0.71 ± 0.07	0.62 ±0.03	**<0.001**	0.06, 0.10
DDTBB-CoR / BBL	0.66 ± 0.05	0.59 ±0.02	**<0.001**	0.05, 0.08
CoP- Heel / BBL	0.56 ± 0.04	0.58 ±0.03	**<0.05**	0.002, 0.029

Table 3.3.Descriptive statistics for pre- and post-trim hoof balance indicators. Data are presented as mean +/- sd. BBL = bearing border length; CoP = centre of pressure; CoR = centre of rotation; DHWL = dorsal hoof wall length. 95% confidence intervals are reported for pre-post trim differences. Significant values (P<0.05) are represented in **bold.** n =49 cadaver limbs.

Similar to what was seen with the trim validation measures, with the change between pre- and post-trim of each hoof balance measurement (as a proportion of pre-trim BBL) limbs showed distinct grouping effects within feet but also trends between feet when ranked (Figure 3.3).

Figure 3.4 shows the relationship of each of the hoof balance measurements/BBL pre-post trim differences with pre-post-trim BBL differences/pre-trim BBL. For pre-post differences in DHWL/BBL and DDTBB-CoR/BBL there was a negative relationship to pre-post BBL difference/pre-trim BBL ($r = -0.46$ and -0.47, respectively) whereas a positive relationship existed for CoP-Heel/BBL ($r = 0.30$).

For hoof balance to exist according the Duckett (1990) geometric proportionality of each of the three hoof balance measures should show equivalence. Initial evaluation of the data showed significant differences between each comparison (**Table 3.4**). Using Fieller's test of equivalence with intervals of 3.8% **Table 3.5** shows that following trimming, equivalence of geometric proportionality did not occur.

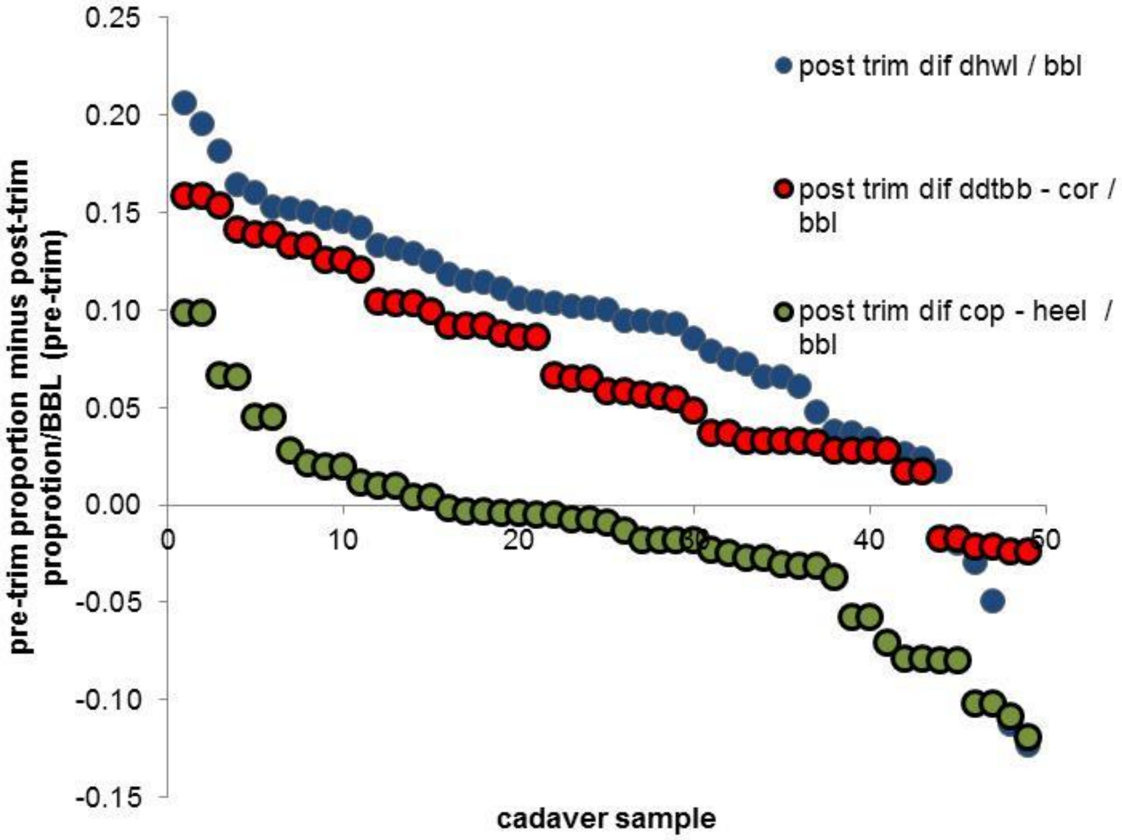

Figure 3.3 Ranked plot for difference in pre- and post-trim hoof balance indicators (DHWL/BBL, DDTBB-CoR/BBL and Heel-CoP/BBL) as a proportion of pre-trim BBL. n=49 cadaver limbs.

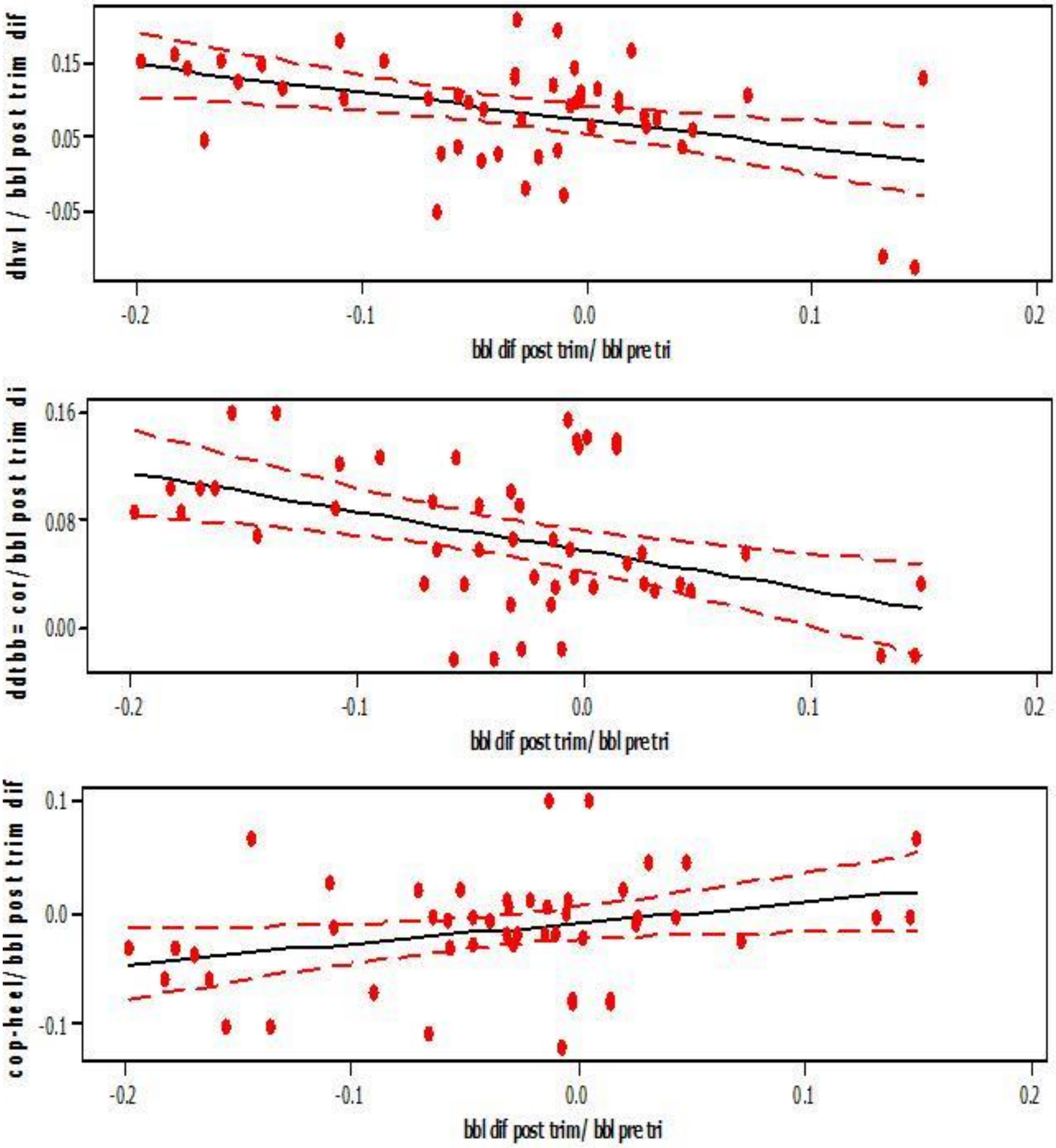

Figure 3.4 Scatter plots of pre-post trim differences for (a) DHWL/BBL, (b) DDTBB – COR/BBL and (c) Heel – COP/BBL versus pre-post trim difference for BBL as a proportion of pre-trim BBL. Black line represents trend line Red dashed lines represent 95% CI. n=49 cadaver limbs.

Comparison	Mean pre-post trim difference (95% CI)	P-value
DHWL/ BBL to DDTBB-COR /BBL	0.029 (0.019, 0.385)	**<0.001**
DHWL/ BBL to COP- HEEL / BBL	0.041(0.029, 0.054)	**<0.001**
DDTBB-COR /BBL to COP-HEEL/BBL	0.012 (0.002, 0.023)	**<0.05**

Table 3.4 Descriptive statistics for post-trim differences between hoof balance indicators. Data are presented as mean (+/- 95% confidence intervals). Significant values (P<0.05) are shown in **bold.** n=49 cadaver limbs.

Comparison	Post trim Variable / BBL	Lower & upper equivalence	Lower & upper T	Lower & upper P	Lower & upper 95% CI
DHWL / BBL; DDTBB - COR / BBL	0.62 ± 0.03; 0.59 ± 0.02	-0.017; 0.017	2.65; 9.88	**<0.001; 0.005**	-0.04; 0.02
DHWL / BBL; COP - Heel / BBL	0.62 ± 0.03; 0.58 ± 0.03	-0.016; 0.016	3.92; 9.18	**<0.001; <0.001**	- 0.05; 0.03
DDTBB - COR / BBL ; COP - Heel / BBL	0.59 ± 0.03; 0.58 ± 0.03	-0.016; 0.016	-4.51; 0.63	**<0.001;** 0.266	0.00; 0.02

Table 3.5 Statistical results from equivalence testing of the digitally mapped hoof balance indicators Data are reported as a proportion of post trim BBL at mean ± sd Results are displayed at both upper and lower limits. Significant values (P<0.05) are shown in **bold.** n=49 cadaver limbs.

Figure 3.5 shows the relationship between each geometric proportional measure. Post-trim differences in DHWL/BBL and DDTBB-CoR/BBL showed a positive relationship ($r = 0.517$, $P = 0.001$) (**Figure 3.5A**), whereas no relationship was found between DHWL/BBL and CoP-Heel/BBL (**Figure 3.5B**) and a negative relationship was noted between DDTBB-CoR/BBL and CoP-Heel/BBL ($r = -0.628$, $P = 0.009$) (**Figure 3.5C**) explaining the lack of equivalence between all three parameters.

After it was noted that equivalence of the three proportional measurements was not achieved, other indicators of hoof balance in common use were evaluated and compared to standard accepted values. These included achieving a 3:1 toe-heel height ratio and toe/heel parallelism. Deviations in these, particularly toe/heel parallelism are deemed important contributors to foot pathology. For example, differences between dorsal hoof wall and heel angulation of 5^{o} are classified as underrun heels. **Table 3.6** shows pre- and post-trim measurements of dorsal hoof wall and heel lengths and angles. Following trimming, significant differences in dorsal hoof wall length and angulation were achieved as well as heel length but not angle. When the frequency of 3:1 dorsal hoof wall/heel length ratio and dorsal hoof wall and heel angulations were plotted (**Figure 3.6)** it was noted that most of the trimmed feet lay outside the accepted normal values. For example, with DHWL and heel parallelism approximately two-thirds (33/49) of the samples (post-trim) would be classified as having underrun heels.

Measurement	**Pre-trim**	**Post-trim**	**P-value**	**95%CI (post-trim difference)**
DHWL	79.5 ± 9.61mm	72.13 ± 6.39mm	**<0.001**	-9.57, -5.22
LHL	32.57 ± 8.47mm	26.08 ± 6.35mm	**<0.001**	-8.07, -4.92
DHWA	50.69 ± 3.78^{o}	52.88 ± 2.79^{o}	**<0.001**	-2.97, -1.39
LHA	37.45 ± 10.56^{o}	38.42 ± 7.18^{o}	0.373	-3.14, -1.20
DHWL/LHL	2.44	2.77	**<0.001**	0.027, 0.07
DHWA/LHA	1.35	1.38	0.654	-0.031, 0.05

Table 3.6. **Summary table of other commonly used indicators of hoof balance.** DHWA =dorsal hoof wall angulation; DHWL = dorsal hoof wall length; LHA = lateral heel angulation; LHL = lateral heel length. Data are presented as mean ±sd. 95% confidence intervals are reported for post-trim differences. Significant values (P<0.05) are represented in **bold**. n=49 cadaver limbs.

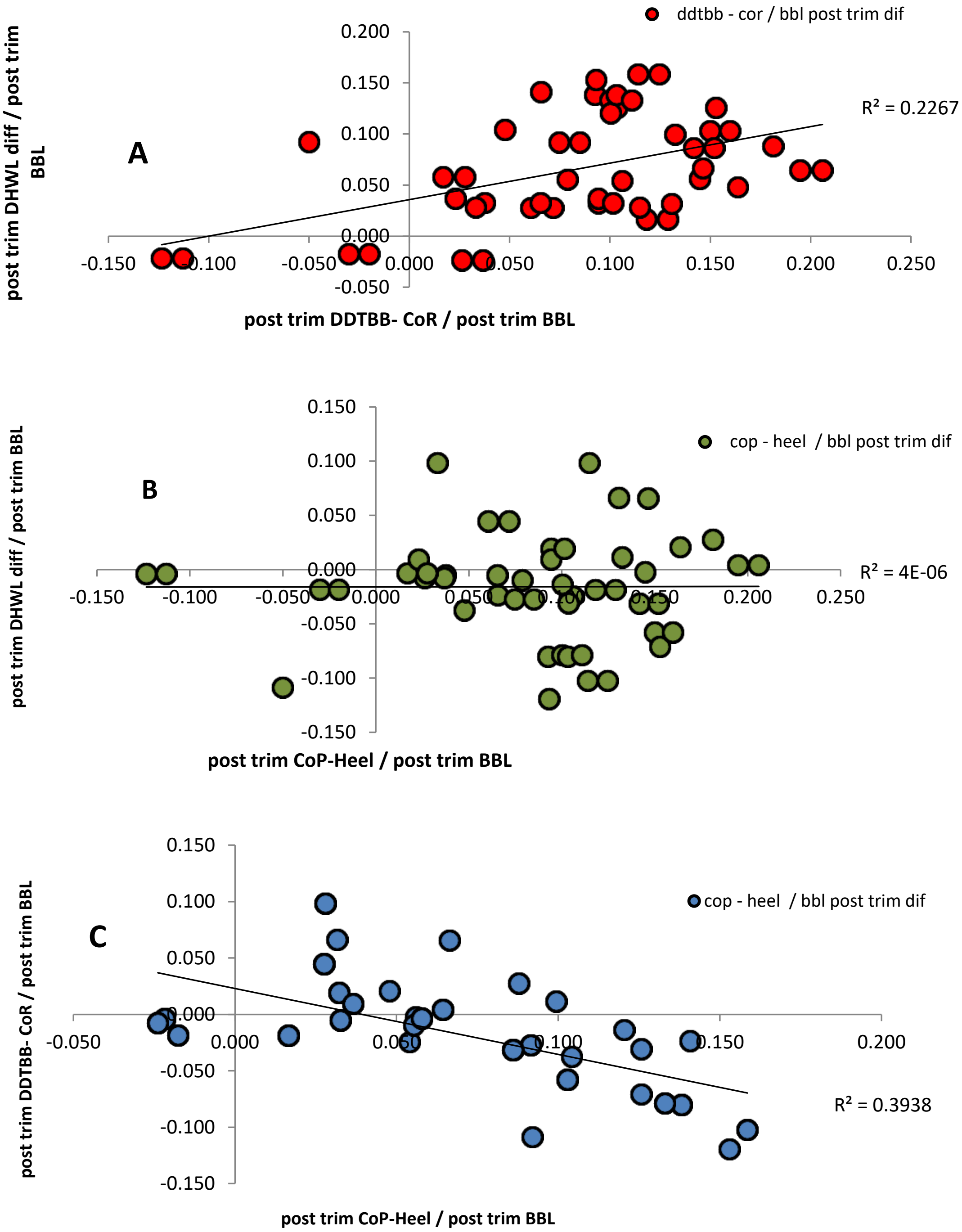

Figure 3.5 A-C Analysis of the relationships between each hoof balance indicator post trim, (A) DHWL / BBL and DDTBB – COR / BBL, (B) DHWL / BBL and Heel – COP / BBL and (C) DDTBB – COR / BBL and Heel – COP / BBL. n=49 cadaver limbs. *See List of Abbreviations piii for further details.*

3.5.3 Radiographic verification of internal landmarks to external hoof measures

For this part of the study, centre of rotation of the distal interphalangeal joint (COR-DIPJ) and the location of the extensor process of the distal phalanx (EP-COP) as two internal landmarks were compared to the location of the external hoof points CoR and CoP in 22 cadaver limbs after trimming. **Table 3.7** shows there was no significant difference between CoR and COR-DIPJ locations (P=0.12) but that the location of CoP significantly varied from the location of EP-COP (P<0.001).

Comparisons (post trim)	**Foot Mapped (mm)**	**Adjusted Anatomical (mm)**	**Adjusted difference (mm)**	**P-value**	**95% CI (adjusted difference)**
DDTBB – CoR and CoR-DIPJ	68.05±4.77	70.16 ±8.49	1.67± 6.02	0.11	0.53, 4.75
CoP - Heel and EP-CoP	66.06± 7.24	58.78± 7.42	-7.44± 6.80	**<0.001**	-10.40, -4.17

Table 3.7 Results from the radiographic comparison between the foot mapped locations of CoR and CoP with the adjusted anatomical location of CoR-DIPJ and EP-CoP (n = 22 cadaver limbs).

When DHWL was compared to internal landmark COR-DIPJ there was a good correlation between the two parameters (**Figure 3.6)**. This is supported by the findings that the location of external CoR post-trimming correlated well with DHWL (**Figure 3.7).** Therefore it can be concluded that the internal position of the centre of rotation of the DIPJ correlates well with the external location of CoR, and that CoR is related to the length of the dorsal hoof wall, whereas CoP does not relate to the extensor process and the main downward force of P3.

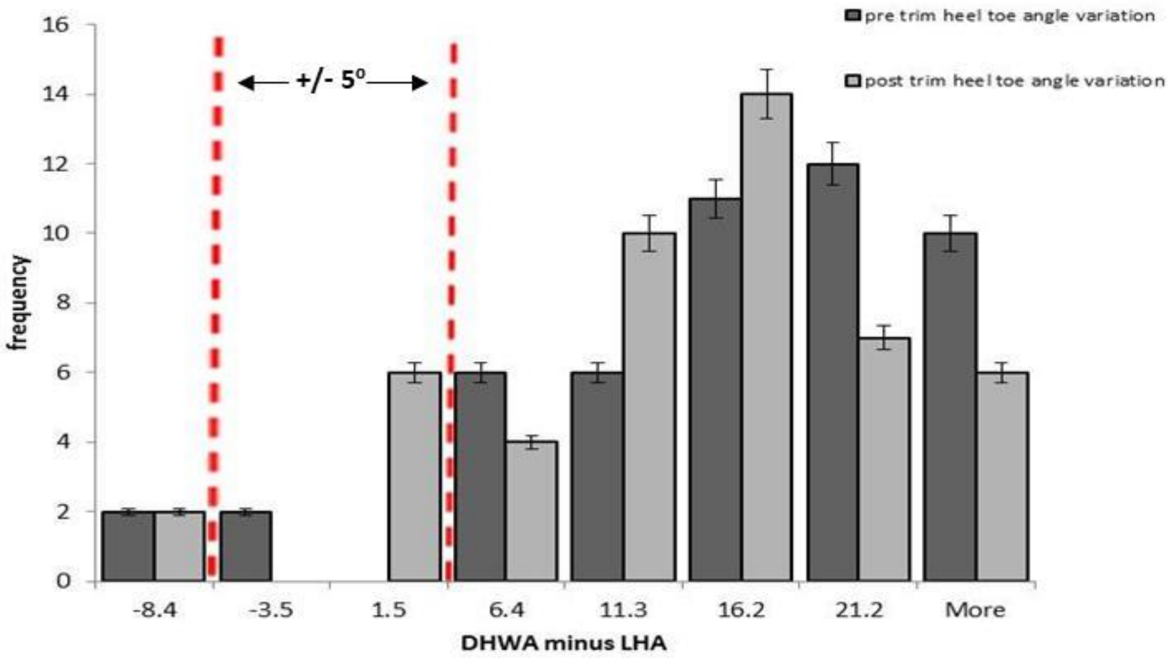

Figure 3.6 Frequency histogram illustrating the range of pre- and post-trim differences between heel and toe angle. Data are presented as mean difference ± sd between dorsal hoof wall (DHWA) and heel angulation (LHA). Dotted red lines show the commonly accepted margins of ± 5º.

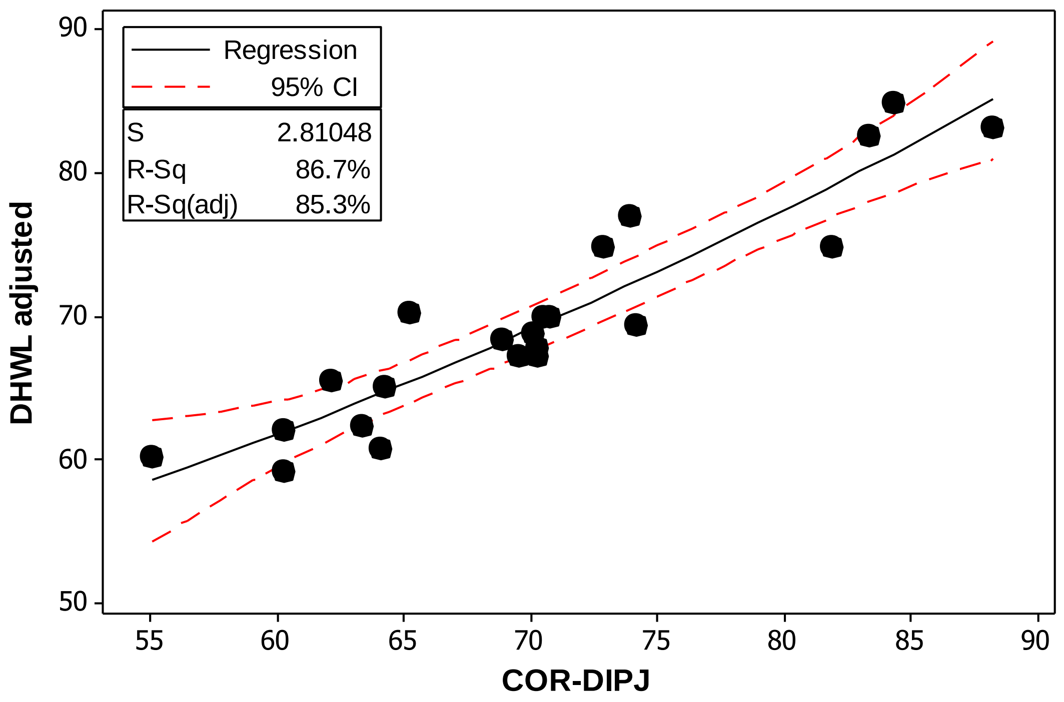

Figure 3.7 Fitted line plot with 95%CI plot shows post-trim regression between CoR-DIPJ and DHWL (adjusted) (n = 22 cadaver limbs). There is a strong post-trim morphological link between DHWL and CoR-DIPJ (R-Sq. Adjusted = 84.3%). Both values are adjusted for radiographic magnification. COR-DIPJ = centre of rotation of the distal interphalangeal joint; DHWL = dorsal hoof wall length.

3.5.4. Comparison of domestic UK feet to Australian feral hooves

In the final part of this chapter, hoof balance measures from UK feet were compared to a cohort of Australian feral hooves (n=89 cadaver limbs). Details of the environmental conditions for the Australian cohort in the 5 different regions as well as for the domestic cohort are presented in **Table 2.1**. Only digital photographs of the left fore foot of the Australian cohort were available for analysis.

Table 3.8 details the differences between the domestic and pooled feral cohorts. There were no significant differences between the two groups apart from CoP-Heel/BBL where CoP-Heel/BBL was significantly less in the feral group. When region and substrate types were evaluated, significant differences were present for CoP-Heel/BBL between the domestic region and all Australian regions (apart from Palparara, P=0.057) and between the domestic substrate and all Australian substrate types (**Table 3.9**). Further evaluation of toe-heel height ratio and angle differences are presented in **Table 3.10** by region and substrate-type.

	Domestic (UK)	**Feral (Aus.)**	**Mean difference**	**P value**
DHWL / BBL	0.71 ± 0.07	0.70 ± 0.04	-0.008 ± 0.015	0.602
CoP-Heel / BBL	0.56 ± 0.04	0.51 ± 0.045	-0.06 ± 0.01	**<0.001**
DDTBB-CoR / BBL	0.66 ± 0.05	0.66 ± 0.04	0.002 ± 0.010	0.821
Toe-heel height ratio	2.12 ± 0.33	2.20 ± 0.25	0.09 ± 0.07	0.222
Toe-heel angle difference	-13.28 ± 9.02	-16.55 ± 6.60	-3.28 ± 1.93	0.340

Table 3.8 Comparison of hoof balance measures between domestic (UK) (n=25) and Australian cohort (n=89). In addition, toe-heel height ratio and angle difference are also presented for the same cohorts. Data are presented and mean ± sd apart from mean difference (mean ± sem). Significant values are presented in **bold.**

Region	Comparison	DHWL/ BBL	P-value.	DDTBB–CoR/ BBL	P-value.	CoP - Heel/ BBL	P-value	CoP-CoR	P-value
Cliffdale	**Mussel**	0.026±0.011	0.525	0.008±0.009	0.983	0.050±0.009	**0.003**	0.059±0.015	0.082
	Kings	0.028±0.011	0.420	0.022±0.009	0.455	0.043±0.009	**0.016**	0.065±0.015	**0.036**
	Palparara	0.042±0.012	0.148	0.037±0.010	0.087	0.050±0.011	**0.014**	0.088±0.018	**0.008**
	Babbiloora	0.031±0.011	0.287	0.024±0.009	0.375	0.023±0.009	0.484	0.047±0.015	0.260
	Domestic	0.017±0.010	0.850	0.019±0.008	0.557	0.091±0.009	**<0.001**	0.110±0.015	**<0.001**
Mussel	**Kings**	0.002±0.010	1.000	0.014±0.008	0.857	0.007±0.009	0.994	0.007±0.015	1.000
	Palparara	0.016±0.012	0.926	0.029±0.010	0.290	0.000±0.011	1.000	0.029±0.017	0.847
	Babbiloora	0.006±0.010	0.999	0.015±0.008	0.791	0.027±0.009	0.293	-0.012±0.015	0.994
	Domestic	-0.0090.010	0.987	0.011±0.008	0.929	0.041±0.009	**0.015**	0.051±0.014	0.121
Kings	**Palparara**	0.014±0.012	0.962	0.015±0.010	0.876	0.007±0.011	0.997	0.022±0.017	0.944
	Babbiloora	0.004±0.010	1.000	0.002±0.008	1.000	0.020±0.009	0.633	-0.018±0.015	0.955
	Domestic	-0.011±0.010	0.963	0.003±0.008	1.000	0.048±0.009	**0.002**	0.045±0.014	0.241
Palparara	**Babbiloora**	-0.011±0.012	0.989	0.014±0.010	0.919	0.027±0.011	0.464	-0.041±0.017	0.567
	Domestic	-0.025±0.012	0.626	0.018±0.009	0.743	0.041±0.010	0.057	0.022±0.017	0.933
Babbiloora	**Domestic**	-0.015±0.010	0.891	0.005±0.008	0.999	0.068±0.009	**<0.001**	0.063±0.014	**0.027**
Substrate	**Comparison**								
Sandy	**Hard**	0.010±0.008	0.790	0.001±0.007	1.000	-0.027±0.007	**0.040**	0.028±0.012	0.350
	Mixed	0.015±0.010	0.676	0.009±0.008	0.843	-0.004±0.009	0.989	0.013±0.014	0.918
	Domestic	0.000±0.009	1.000	0.005±0.007	0.970	-0.071±0.008	**<0.001**	0.076±0.013	**<0.001**
Hard	**Mixed**	0.005±0.009	0.983	0.009±0.008	0.855	0.024±0.008	0.185	-0.015±0.014	0.865
	Domestic	-0.010±0.009	0.832	0.004±0.007	0.978	-0.044±0.008	**<0.001**	0.048±0.013	**0.042**
Mixed	**Domestic**	-0.015±0.010	0.718	-0.005±0.008	0.980	-0.068±0.009	**<0.001**	0.063±0.015	**0.018**

Table 3.9 Comparison of hoof balance measures as a proportion of BBL between different regions and substrate-types. Data are presented as mean differences (mean ± sem) between regions and substrate-types. In addition, mean difference between CoP-CoR is also presented. Significant values are presented in **bold** following ANOVA with tukeys post-hoc analysis.

Heel Toe angle by region	*Comparison*	Mean Diff.	SE	P-value.
Mussel	**Kings**	-7.535	1.396	**0.003**
	Babbiloora	-11.515	1.396	**<0.001**
	Cliffdale	-10.224	1.414	**<0.001**
	Palparara	-8.132	1.612	**0.007**
	Domestic	-4.116	1.324	0.247
Kings	**Babbiloora**	-3.980	1.396	0.340
	Cliffdale	-2.689	1.414	0.760
	Palparara	-0.597	1.612	1.000
	Domestic	3.419	1.324	0.454
Babbiloora	**Cliffdale**	1.291	1.414	0.987
	Palparara	3.383	1.612	0.675
	Domestic	7.399	1.324	**0.002**
Cliffdale	**Palparara**	2.093	1.628	0.943
	Domestic	6.108	1.344	**0.021**
Palparara	**Domestic**	4.016	1.550	0.450
Heel Toe angle by substrate				
Hard	**Mixed**	-7.748	1.279	**<0.001**
	Sandy	-5.647	1.118	**0.003**
	Domestic	-0.349	1.191	0.997
Mixed	**Sandy**	2.101	1.340	0.685
	Domestic	7.399	1.401	**0.002**
Sandy	**Domestic**	5.298	1.256	**0.018**
Heel Toe Height Ratio by region				
Mussel	**Kings**	0.048	0.059	0.993
	Babbiloora	-0.017	0.059	1.000
	Cliffdale	0.143	0.060	0.550
	Palparara	0.139	0.069	0.705
	Domestic	0.143	0.056	0.474
Kings	**Babbiloora**	-0.065	0.059	0.972
	Cliffdale	0.094	0.060	0.876
	Palparara	0.091	0.069	0.935
	Domestic	0.095	0.056	0.841
Babbiloora	**Cliffdale**	0.159	0.060	0.425
	Palparara	0.156	0.069	0.595
	Domestic	0.159	0.056	0.348
Cliffdale	**Palparara**	-0.003	0.069	1.000
	Domestic	0.000	0.057	1.000
Palparara	**Domestic**	0.004	0.066	1.000
Heel Toe Height Ratio by substrate				
Hard	**Mixed**	-0.041	0.051	0.943
	Sandy	0.117	0.045	0.251
	Domestic	0.119	0.048	0.294
Mixed	**Sandy**	0.158	0.053	0.163
	Domestic	0.159	0.056	0.188
Sandy	**Domestic**	0.002	0.050	1.000

Table 3.10 Comparisons of toe-heel height ratio and difference in angulation between region and substrate-type. Data are presented as mean difference (mean ±sem). Significant differences are presented in **bold** following ANOVA with tukeys post-hoc analysis.

3.6 Discussion

Poor hoof balance is a recognised contributor to lameness and lower limb pathologies (Kane et al., 1998, Eliashar et al., 2004) and therefore maintaining hoof balance is important in maintaining correct form and function of the foot. Despite there being commonly accepted trimming protocols and guidelines for trimming to an ideal model of hoof balance, most of these assumptions have been based on anecdotal practices passed on from generation to generation of farriers. This study used a standard trimming model based on National Occupational Standards for Farrier (LaNTRA) guidelines to investigate the effect of trimming on a number of external measures, with relation to commonly accepted hoof balance tolerances. Initial investigations are required to determine how the trim works by evaluating external parameters following trimming, to determine inherent differences between different feet, whether they are fore or hind feet or from domestic or feral horses, how they are likely to behave in response to the trim and how this then relates to key internal structures.

The main findings in this chapter were: 1) a standardised trimming protocol resulted in a consistent and repeatable trim but led to trends and groupings of measurements according to hoof morphology with differences between fore and hind feet present; 2) equivalence of geometric proportionality between key hoof measures did not occur thus challenging Duckett's definition of proportional foot balance; 3) other commonly accepted measures of hoof balance (toe:heel height ratio and parallelism) also did not commonly occur; 4) internal location of centre of rotation of distal interphalangeal joint correlated to external measure CoR but CoP did not relate to location of the extensor process of the distal phalanx; 5) Australian feral horses differed to UK domestic horses feet in some proportional hoof measures and this related to region and substrate-type.

These findings suggest that common accepted principles of foot balance in farriery may not hold true and therefore not be applicable to all feet in aiming to achieve the "ideal hoof". However results from this chapter show that mapping external hoof measures as proportional values has merit in evaluating hoof morphology, particularly around the location of the external measure CoR and its relationship to internal landmarks.

Trim validation measures

The first part of this chapter was to measure reproducibility of the trimming protocol used in the study and to determine how a sample cohort of limbs behave in response to the trim. Here, trim validation measures were used to look at overall shape and morphology. The trim mainly led to an increase in the distance between heel bulb and the point determined as the centre of rotation (intersection of diagonal lines from the heel buttresses to breakover, usually corresponding to the widest point of the foot) and tended to reduce variation between trim measures after trimming. Interestingly the trim validation showed that the trim measures clustered together and behaved similarly in individual feet but that inter-horse variation existed, i.e. there was variation in the shape of the foot between horses (as expected from a mixed sample), but the measures *within* that foot all behaved in a similar direction (Figure 3.1). This variation between horses was likely due to inherent differences in hoof shape; horses with low, underrun heels had little intervention at the heels but a reduction in dorsal hoof wall thickness which led to a reduction in post-trim SL and hence an increase in the post-trim differences for all external measures (positive values). Contrary to this, horses with a more upright conformation (high dorsal hoof wall length), have horn removal at both the toe and heel, leading to a relative lengthening of SL post-trim. This had the effect of reducing the proportional differences between pre- and post-trim measures. Most parameters post-trim (as a proportion of SL difference pre- and post-trim) had little variation about zero (± 0.5) as seen in **Figure 3.2**. In cases where large deviations occurred (generally high positive values) these were samples that required excessive heel removal; this led to marked differences post-trim in each parameter (measured along the x-axis) but resulting in little difference in SL pre- and post-trim, hence the values lying close to the y-axis. Where large deviations occurred in **Figure 3.2**, these were the sample outliers in **Figure 3.1**. This highlights the important effect excessive heel trimming has on hoof shape and proportionality.

Fore versus hind feet

Although the main anatomy of the distal hind limb is similar to that of the front, hoof loading characteristics of the hind limb differ and may contribute to the conformational differences seen. Hind feet tend to be more upright and narrower than fore feet (Spaak et al., 2012). Results from this chapter showed that trim measures, as a proportion of sagittal length, were significantly different to the fore limb in 3 out of 4 measures. Inspecting the data showed this was mainly related to position of the heel buttresses in relation to the sagittal length, consistent with a more upright conformation.

Geometric proportionality and other commonly accepted hoof balance measures

The foot balance theory chosen in this study is based on Duckett's theory of geometric proportionality (Duckett, 1990), which in itself is fundamentally based around Russell's interpretation of ideal foot balance (Russell, 1897). The advantage of this theory is that as a proportional measure it can be applied to all sizes of feet. For hoof balance to be achieved, Duckett's three key measures, as a proportion of bearing border length (BBL) show are equivalence. When the cadaver feet were trimmed using the trimming protocol, changes in proportional measures occurred with reductions in DHWL/BBL and DDTBB-CoR/BBL whilst CoP-Heel/BBL increased. This may be related to the relationship between each hoof balance measure and the difference in BBL pre- and post-trim since a positive relationship existed between DHWL/BBL and DDTBB-COR/BBL to BBL difference, and a negative relationship was present between CoP-Heel/BBL and BBL difference. Similar to the trim measures, individual feet showed similar behaviour with each hoof balance measure and a trend between different feet is likely to reflect differences in hoof morphology. Despite the clustering of the hoof balance measures within feet, equivalence of each proportional measure was not demonstrated post-trimming. When each hoof balance measure, as a proportion of BBL, was further scrutinised, no clear relationships existed between them (**Figure 3.5**) and this may explain the lack of equivalence found.

Common hoof balance indicators - heel toe angle and height measures

With the lack of equivalence highlighted using measures of proportionality, other hoof balance indicators in common use were evaluated. The notion of a 3:1 ratio between dorsal hoof wall and toe length and the concept of toe/heel parallelism is still taught in modern textbooks (Butler et al., 2005) with the conclusion that foot imbalance will be present if the hoof measurements do not fall within these defined parameters (Turner 1992, 1998). For example, feet are described as having underrun heels when there is a difference of $>5^{o}$ between toe and heel angulation. When toe:heel ratio and parallelism were evaluated the majority of the post-trim samples fell outside of these ideals. This therefore questions the usefulness of using these measures to prescribe foot balance in the equine digit and should probably be discontinued in their practice.

Relationship of external and internal landmarks

For external hoof measures to have increased meaning, their relationship (and how this changes) to internal structures is important to determine. Two external locations are thought to relate to two internal features. Firstly the location of the extensor process of the distal phalanx is thought to relate to the location of CoP whereas secondly the centre of rotation of the distal interphalangeal joint (DIPJ) relates to the position of CoR. For this chapter only, CoR relates to the centre of rotation of the DIPJ, whereas on average CoP was 7 mm from a vertical line drawn down from the extensor process. Since the centre of rotation of the DIPJ is dependent on the flexor moment arm and initiation of breakover, mapping external CoR and how it changes in different feet may be an important to determine in relation to foot pressure and pathology.

Feral versus domestic feet

The final part of this chapter compared a cohort of feral feet to domestic equine feet, using samples from the Australian Brumby Unit, to assess the effect of region and substrate-type on hoof parameters. The study of feral hoof shape came into prominence in the 1990s to promote "natural balance" as a benchmark for foot health in horses to optimise care of domestic horse feet (Jackson 1992; Ovnicek 1995, 2001, 2003) with the value of their findings questioned by others (Florence & McDonnell 2006; Hampson et al., 2010; 2013). In feral horses the CoP-Heel/BBL proportion was significantly smaller than domestic species whereas DHWL/BBL and DDTBB-CoR/BBL did not alter in different environs. This suggests that the location of CoP is variable and more dependent in environmental conditions whereas CoR remains in a more consistent location. When region and substrate-type were evaluated separately, CoP-Heel/BBL was also different to domestic UK samples, with the exception of those from the Palparara region. The Palparara region of Australia is characterised by grasslands and a more temperate climate and likely more comparable to domestic UK environs and may explain the lack of difference. Hampson et al., (2013) suggested that both internal reference points should remain consistent in these feral feet but the findings in this chapter suggest that CoR may be the only reliable marker for this. Indeed when the distance between CoP and CoR were calculated, regional and particularly substrate-type differences existed. Since CoP-CoR distance is a measure of solar arch orientation and hence hoof shape this could be explain how environmental differences lead to different hoof shape. A reduction or increase in CoP-CoR distance, equating to solar arch contraction or flattening, is therefore likely due to the biomechanical effects on CoP (in particular) whilst CoR acts as a reliable geometric measure and fixed anatomical point. Earlier in the chapter a reciprocal relationship between DDTBB-CoR/BBL and CoP-Heel/BBL was shown and this may reflect the dynamic association between CoP and CoR and hence solar arch. The solar arch orientation is at its most vaulted between the vertical anatomical positions of the extensor process and the distal sesamoid bone suspended between the extensor and flexor moments. Indeed increases or decreases in extensor or flexor moment are known to affect position of CoP during the support phase (Moleman and van Heel, 2006) and therefore the CoP-CoR distance may prove to be a critical parameter in hoof capsule function and form.

Conclusion

To conclude this part of the study, this chapter detailed the investigations into the effects of a standardised trimming protocol on hoof measures and balance using cadaver limbs. It showed that the trim was consistent in maintaining the shape of the foot, as measured by clustering of trim validation measures, but that variation across different feet occurred such that different shapes existed across the feet, and that geometric proportionality as a measure of hoof balance did not occur. The relationship between internal and external landmarks showed the CoR was a reliable indicator of the centre of rotation of the distal interphalangeal joint but that CoP did not relate well to the extensor process and may be due to the more dynamic nature of CoP location. Since CoP-CoR distance reflects solar arch the location of CoP and CoR may determine the overall form of the foot orientation and factors such as the environment have in altering these locations (especially CoP) may be important in regulating hoof shape changes. Evaluation therefore of how these parameters alter in the live horse over a period of trimming cycles, what the effect of adding shoes has on these parameters, how they relate to the function of the hoof and how these alter in disease states will be investigated in subsequent chapters.

Chapter 4

The effect of repeated trimming and shoeing on the external geometric proportionality in the equine fore foot

Aspects of this chapter have been published (see **Appendix A** for full article)

Caldwell, M.N., Allan, L.A.,. Pinchbeck G.L., Clegg, P.D., Kissick, K.E., and Peter I. Milner, P.I. (2016). A test of the universal applicability of a commonly used principle of hoof balance. The Veterinary Journal, Volume 207, January 2016, Pages 169-176, ISSN 1090-0233, http://dx.doi.org/10.1016/j.tvjl.2015.10.003.

4.1 Introduction

Domestication of the horse and increased demands in relation to work has compromised the delicate balance existing in the feral animal between growth and wear. This has resulted in the need for protection in a form of a shoe to reduce the loss of performance associated with abnormal wear and hence lameness, both on a military and domestic front. This change towards domestication has also come through breeding, particularly horses for sports purposes. Despite interventions with breeding (i.e. faster, stronger animals) and changes in work-pattern (i.e. speed and ability to jump rather than bear loads at lower pace) possibly resulting in a compromise to foot structure, the basic rationale of protection, enhanced performance and management of pathologies still remain true today.

The dynamic effects of shoeing have been studied at length (Dyer et al., 1994; Back and Clayton, 2001). The findings from these studies indicate that the use of horseshoes involves some potentially harmful effects on foot and limb pathology and this has stimulated an interest in maintaining feet without shoes (Jackson, 1997; Strasser, 2000). Protagonists of bare foot maintenance have provided anecdotal observations to support keeping horses barefooted and trimming the hooves in a manner that is believed to replicate the feral hoof (Ovnicek 1995; 2003). However the feral horse is not a domesticated athlete and replicating the feral foot model in domesticated horses has its limitations: it is unknown if this type of balance allows maximum functional hoof strength; it fails to account for the athletic activities of individual horses; and it is largely incompatible with traditional horseshoeing techniques (Hood, 2001).

In Chapter 3, a detailed investigation was performed into the effects of a standardised trimming protocol on external hoof balance measures and internal anatomical landmarks with comparisons between fore and hind feet and feral horses in different environments. It showed that key external measures may reflect internal positions and that shape of the foot appears to be related to these measures. The effects over time and the presence or absence of a shoe are likely to influence the behaviour of these key measures and therefore influence the shape of the foot. This chapter will therefore study the effects of the standardised trim in the live horse, unshod and shod over a number of trimming/shoeing cycles.

4.2 Hypothesis

This chapter will address the hypothesis that both standardised trimming and shoeing protocols results in significant differences in static hoof balance, based on the principle of equal geometric proportions, over an extended period of time and that these proportions are influenced by the application of a standard steel horseshoe over a number of shoeing cycles.

4.3 Aims

The aims of this chapter were:

1. To compare the effects of a trimming protocol on the hoof balance measures and geometric proportionality in horses trimmed over a number of trimming cycles
2. To investigate the effects of shoeing on hoof balance measures and geometric proportionality in horses trimmed over a number of trimming cycles
3. To investigate the effects of environment and management on hoof balance measures and geometric proportionality in horses trimmed over a number of trimming cycles

4.4 Study design

- **Cohort details and management**

Two groups of unrelated horses were used for this part of the study. Both groups were trimmed every 35 days on three consecutive occasions to the trimming protocol as described in Chapter 2 (2.5). Group A consisted of 20 TBx (6 mares; 14geldings, mean age 11 ± 3 yrs (range 6 -16 yrs) , mean weight 587 ± 30 kgs (range 490-610kgs) and median height 16hh (range 15.3 – 17.1hh) and remained unshod for the duration of the study. Group A horses were prepared for grass turnout and remained un-stabled for the duration of the study. Grazing was rotated over three separate 20+ acre paddocks during the study period. Grazing was supplemented with *ad lib* hay. All horses had access to field shelters and access to water was available throughout

Group B consisted of 6 TBx geldings mean age 8 ± 1 yrs (range 6-10 yrs), mean weight 510 ± 10 kgs (range 496 – 528 kgs) and median height 16.2hh (range 16.1 – 16.3 hh) and remained shod for the duration of the study. Group B horses were stable managed with routine daily exercise of a minimum 1 hour's road fitness work and a controlled diet according to individual need

- **Digital photographic and foot mapping protocol**

Digital photographs demonstrating the dorsal, lateral and solar views of the feet were taken as detailed in Chapter 2 (2.3) before and after each trimming cycle. Shod horses were photographed after shoe removal and before trimming (pre-trim) and then after trimming but before shoeing (post-trim).

Hoof balance indicators, each as a proportion of the bearing border length (BBL) included: dorsal hoof wall length (DHWL); dorsodistal tip of the bearing border to the centre of rotation of the DIP joint (DDTBB-CoR); and centre of pressure to the heel buttresses (CoP-Heel). Other hoof measures included toe: heel ratio and parallelism, as measured in Chapter 3. In addition, heel migration between trimming cycles was calculated from the difference between pre- and post-trim DDTBB-CoR and pre- and post-trim CoP-Heel from the pre- and post-trim bearing border difference, with a positive value reflecting dorsal heel and a negative value reflecting palmar heel migration.

- **Trimming and shoeing protocol**

The trimming protocol used in this chapter was originally developed under UK Farriery National Occupational Standards[8] and based on Caldwell and Savoldi[9] and is detailed in Chapter 2 (2.5). Horses in Group B were shod in standard fullered concave steel riding style horseshoe of the type typically used in the UK. Trimming and shoeing was conducted by the lead researcher and two other qualified farriers familiar with the trimming protocol. For consistency all feet were assessed pre and post trim by the lead researcher prior to data collection. All shoes were made and fitted by the lead researcher.

- **Statistics**

Statistical methods are outlined in detail in Chapter 2, 2.10.

[8] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

[9] See: http://www.forgemagazine.co.uk/site/index-1newsarchiveapr10.html (accessed 27 August 2015)

4.5 Results

4.4.1 Effect of trimming cycles and shoeing on hoof measures

The effect of the standardised trimming protocol on toe:heel ratio over the course of 3 trimming cycles (every 35 days) in group A (unshod) and group B (shod) is presented in **Table 4.1**. One way ANOVA results showed that there were significant differences between each group at each time point ($P<0.05$) with differences within group A only at pre-post-trim for the second and third trimming cycles. There were no significant differences within group B at pre-post trim at any of the trimming cycles. Further analysis showed that by the third trimming cycle, 29/40 (74%) feet in group A and 11/12 (91%) feet in group B were below the reported ideal of 3:1 ratio. In group A (unshod) there was a positive trend towards an increased toe:heel ratio over time (r = 0.69) whereas no trend was evident in group B (shod) (**Figure 4.1)**. **Table 4.2** shows the difference in dorsal hoof wall (toe) and heel angulation over the 3 trimming cycles in each group. Both groups showed wide range in toe:heel angle differences and despite trimming in both groups, mean differences often remained $>5^{o}$, with little difference between trims in group B (shod), particularly with the heel angulation. Group A (unshod) however did show a reduction in the range of differences towards the second and third trim suggesting the presence of a shoe may be restricting the ability of the heel to re-align. When dorsal hoof wall and heel angulation were correlated the angulation of the heels were moderately correlated to the dorsal hoof angulation in shod horses whereas a poor correlation existed in the unshod horses (**Figure 4.2)**.

Trim cycle (day)	**1 (day 0)**		**2 (day 35)**		**3 (day 70)**	
	Pre-trim	***Post-trim***	***Pre-trim***	***Post-trim***	***Pre-trim***	***Post-trim***
GP A (unshod) *n=40*	2.56±0.51	2.65±0.30	2.71±0.34	2.87±0.31*	2.65±0.36	2.82±0.38*
GP B (shod) *n=12*	2.50±0.29†	2.51±0.29†	2.42±0.25†	2.57±0.24†	2.58±0.29†	2.47±0.26†

Table 4.1 Toe-heel ratio pre- and post-trim for groups A and B at each 35 day trimming cycle. Data are presented as mean ± SD, n=12-40. * P<0.05 pre-post trim within each group; †P<0.05 between groups

Group	Trim cycle (day)		Mean difference (Θ°)	Range (Θ°)
A (unshod)	1 (day 0)	Pre-trim	-9.5 ± 6.0	-20.0: -15.0
		Post-trim	-9.0 ± 7.0	-18.0: -14.0
	2 (day35)	Pre-trim	-12.4 ± 6.0	-23.0: -2.0
		Post-trim	-13.4 ± 5.0	-26.0: -1.0
	3 (day 70)	Pre-trim	-9.9 ± 6.0	-20.0: -2.0
		Post-trim	-10.3 ± 4.0	-19.0: 0.0
B (shod)	1 (day 0)	Pre-trim	-14.7 ± 5.0	-21.0: -5.0
		Post-trim	-17.1 ± 6.0	-24.0: -6.0
	2 (day 35)	Pre-trim	-15.6 ± 3.0	-19.0: -8.0
		Post-trim	-15.7 ± 3.0	-19.0: -8.0
	3 (day 70)	Pre-trim	-15.3 ± 3.0	-19.0: -7.7
		Post-trim	-15.7 ± 3.0	-19.0: -8.0

Table 4.2 Descriptive statistics for toe:heel angle differences for groups A(unshod) and B (shod). Data are displayed as toe minus heel angle differences. Data are reported as mean ± SD degrees pre and post - trim at each study point. n=12-40 feet.

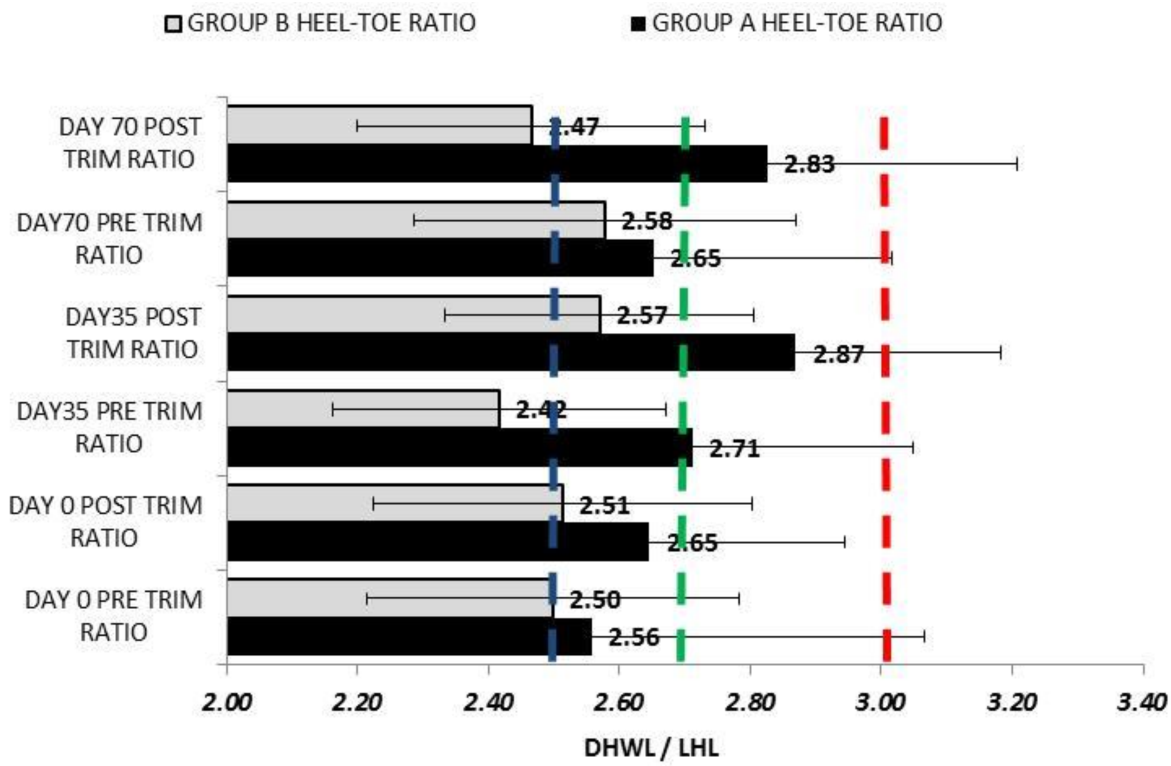

Figure 4.1 Histogram showing toe: heel ratio for group A (unshod) and group B heel before (pre) and after (post) trimming during 3 x 35 day trimming cycles. Note: the dotted red line represents the ideal ratio of 3:1 whereas the dotted blue line represent the mean post-trim ratio for group B over three trimming periods (2.5:1.± 0.3) and the dotted green line represents the mean post-trim ratio for group A (2.7:1 ± 0.4). Data are presented as mean ±SD. n=12-40 feet.

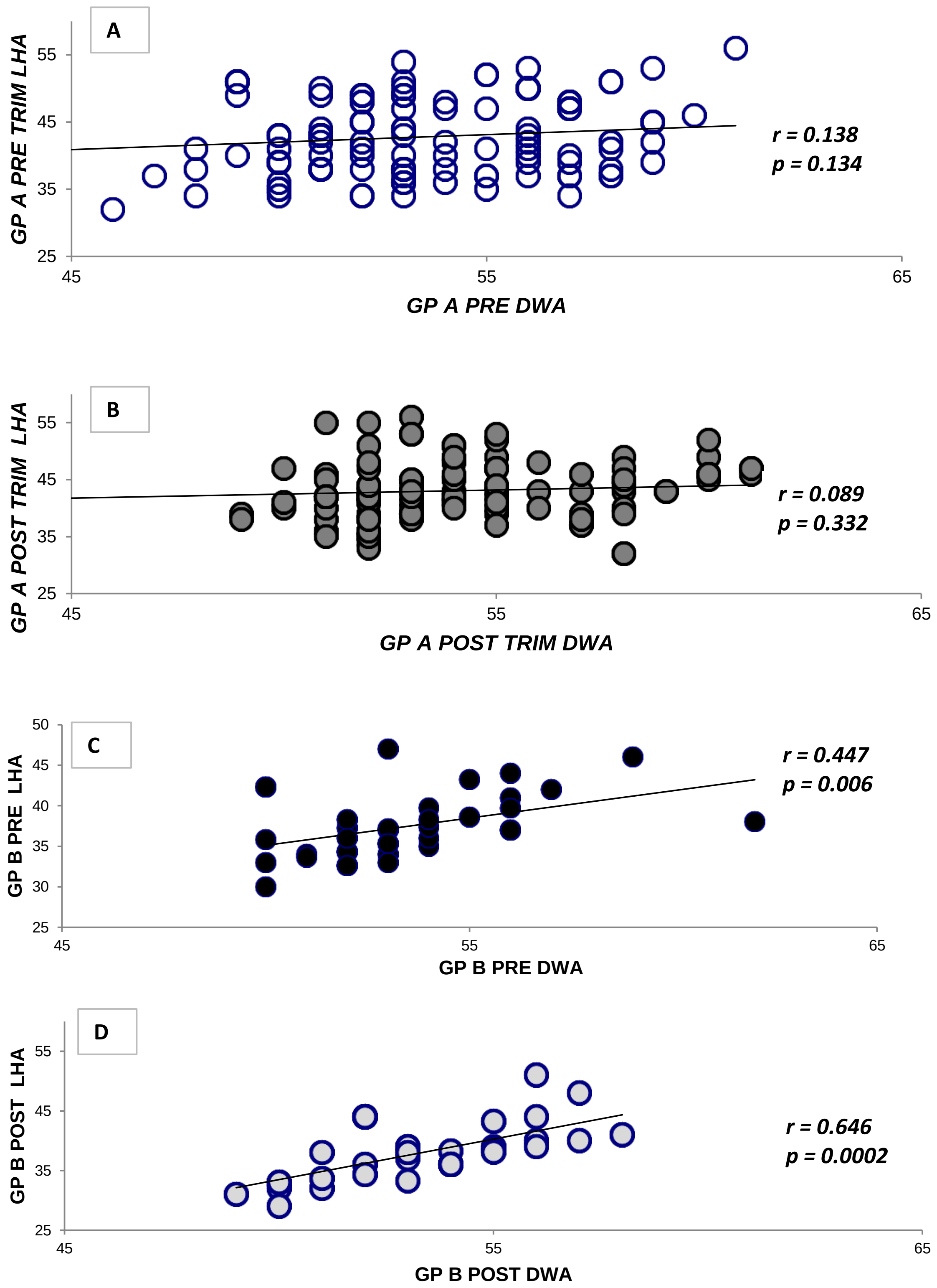

Figure 4.2 (A-D) **Simple linear regression analyses of dorsal hoof wall and heel angulation in groups A (unshod) and B (shod).** There is no significant relationship between LHA and DHWA in group A pre and post trim (A and B). There was a positive relationship group B post-trim r = 0.65 (D). Data points show combined values for each trimming cycle.

Similar to the cadaver limbs in Chapter 3, the majority of limbs fell outside of the ideal of toe:heel parallelism (± 5^{o}) with 31/40 (74%) of group A (unshod) and 10/12 (83%) of group B (shod) horses not within this model. In the presence of a shoe, there appeared to be no real change in the relationship between the toe and the heel whereas without a shoe there appeared to be the ability to affect the angle. This is borne out where palmar heel migration occurred in group A (unshod) but not group B (shod) by the end of 3 trimming cycles (**Table 4.3**).

Group	ΔBBL (mm)	Δ CoP-Heel (mm)	Δ DDTBB-CoR (mm)	CoP-CoR distance	Net heel migration (mm) [(ΔBBL)- Δ(CoP-CoR)]
A (unshod)	-4.93	-1.90	4.03	2.13	-7.06
B (shod)	-2.92	-5.75	2.83	-2.92	0.00

Table 4.3 Net heel migration in group A (unshod) and group B (shod) horses at the start (pre-trim, 1st trimming cycle) and end (post-trim, 3rd trimming cycle) based on difference between bearing border length (BBL) and difference in CoP-CoR distance as calculated through CoP-Heel and DDTBB-CoR difference. For net heel migration a positive values indicates dorsal migration whereas a negative value indicates palmar migration. n=12-40 feet.

Figure 4.3 demonstrates that at each trim cycle the bearing border (BBL) difference in group A (unshod) consistently reduced post-trim (around 5mm), whereas the Cop-CoR difference (as calculated by pre-post trim difference in DDTBB-CoR and CoP-Heel at each trim cycle) initially increased before plateauing. In group B (shod) there was no real change in BBL following trimming despite a similar increase in CoP-CoR difference again before plateauing. This ability to consistently alter the base of support (BBL) in the hoof is the likely responsible component to allow the heels to migrate in a palmar direction as seen in Group A (**Table 4.3**). **Figure 4.4** shows a negative correlation between pre- and post-trim BBL and CoP-CoR distance in group A. In group B a negative correlation also exists but a distinct clustering effect appears to occur, particularly at the second (day 35) and third (day 70) trim.

A possibility is the reported "left-right handedness" of horses although when the data were evaluated for this there was no difference between left or right feet (P>0.05).

Table 4.4 summaries the hoof measures from pre-trim at the first trim cycle to the post-trim 3rd trimming cycle, representing the 70 day study period in both groups. From this summary it appears that hoof measures and hence shape can be influenced more in the unshod foot than in the presence of a shoe, which migrates dorsally, apart from heel:toe angulation.

Group	**DHWL (mm)**	**LHL (mm)**	**Toe:heel ratio**	**Toe:heel angulation (degrees)**	**Heel migation (mm)**
A (unshod)	-6.8	-3.8	2.6:1 to 2.8:1	9.5° to 10.38°	-7.1
	<0.01	**<0.001**	**<0.01**	ns	**<0.01**
B (shod)	-3.1	-0.4	2.5:1 to 2.5:1	14.7° to 15.7°	0
	<0.01	ns	ns	ns	ns

Table 4.4 Summary for group A (unshod) and group B (shod) hoof balance measures at the beginning of and end of 3 trimming cycles. Data represent mean differences for each measure between pre-trim (1st trimming cycle) and post-trim (3rd trimming cycle) except for toe:heel ratio and angulation difference which represents value at pre-trim (1st cycle) and post-trim (3rd cycle). Significant values represented in **bold.** NS = not significant. n=12-40 feet.

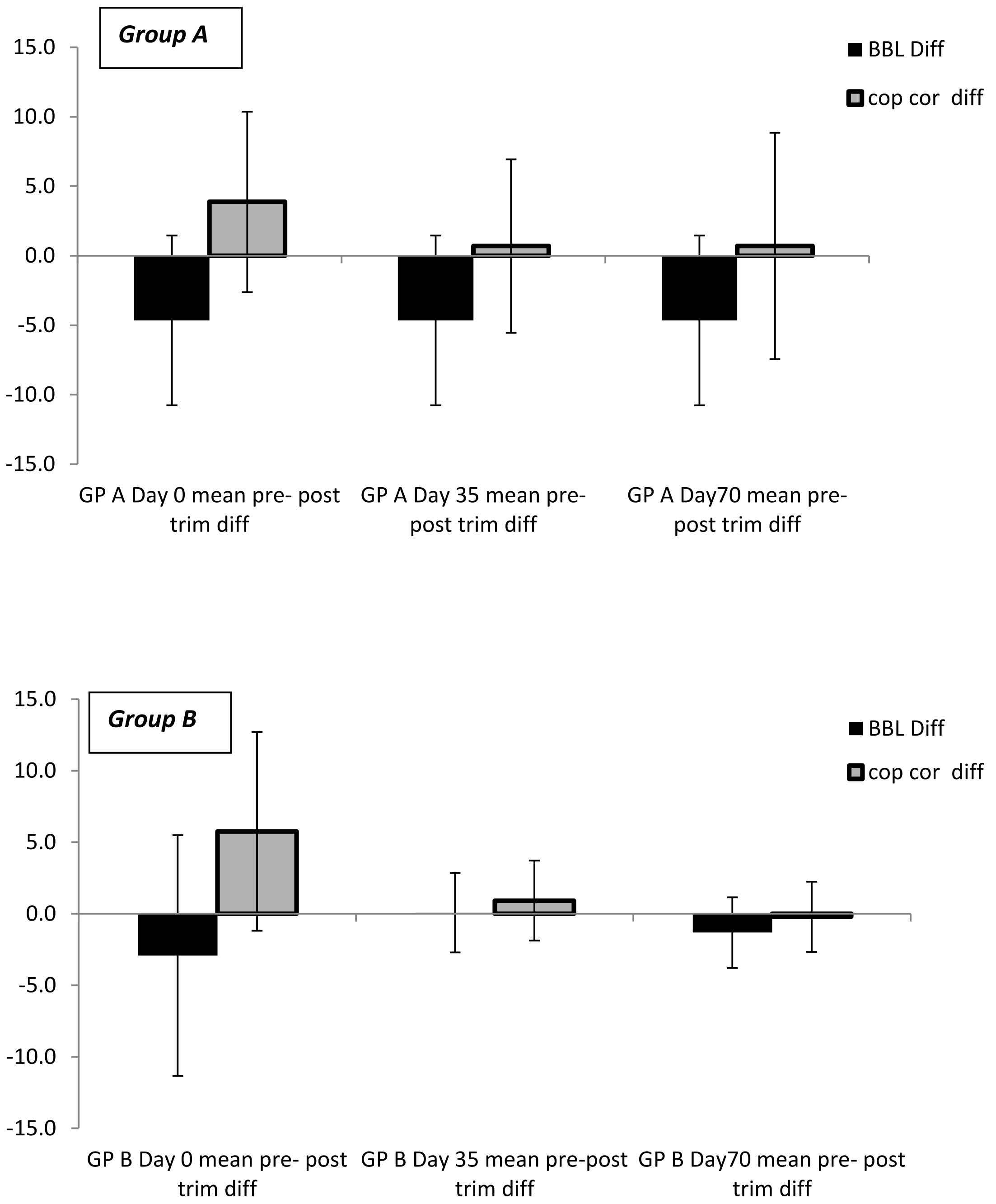

Figure 4.3 Histograms showing pre- and post-trim differences for bearing border length (BBL) and CoP-CoR at each trimming cycle in group A (unshod) and B (shod). Data are displayed as mean ± standard deviation. n=12-40.

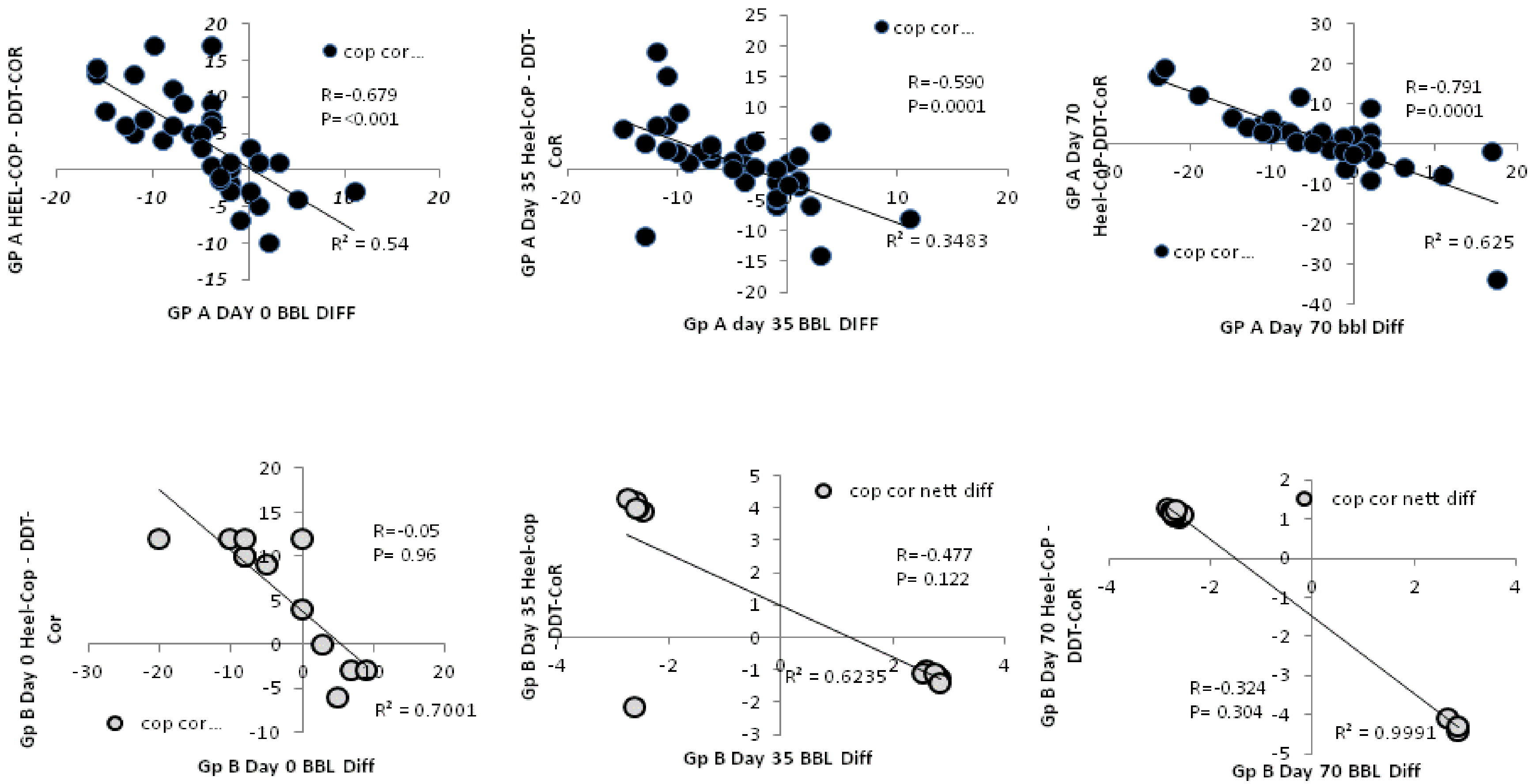

Figure 4.4 Scatterplot demonstrating the relationship between post-trim BBL and CoP – CoR differences for group A (unshod) and B (shod) at each trim cycle (day 0, 35 and 70). n=12-40

4.4.2 Effect of trimming cycles and shoeing on proportional hoof balance measures

The effect of trimming cycles in group A (unshod) and B (shod) on proportional hoof balance indicators is presented in **Table 4.6**. Over three trimming cycles post-trim values of all proportional hoof measures significantly reduced in group A but did not significantly change in group B. When groups A and B were directly compared, significant differences in DHWL/BBL and DDTBB-CoR/BBL but not CoP-Heel/BBL were evident over the 3 trimming cycles (**Table 4.7**).

Group	Proportional hoof balance indicator	Trim no.			P-value
		1	2	3	
A	DHWL/BBL	0.58 ± 0.07	0.53 ± 0.03	0.54 ± 0.02	**<0.001**
	CoP-Heel/BBL	0.58 ± 0.05	0.56 ± 0.05	0.53 ± 0.05	**<0.001**
	DDTBB-CoR/BBL	0.57 ± 0.04	0.54 ± 0.03	0.53 ± 0.05	**0.001**
B	DHWL/BBL	0.58 ± 0.03	0.57 ± 0.03	0.57 ± 0.02	0.257
	CoP-Heel/BBL	0.57 ± 0.04	0.57 ± 0.04	0.55 ± 0.05	0.591
	DDTBB-CoR/BBL	0.57 ± 0.04	0.56 ± 0.06	0.59 ± 0.03	0.234

Table 4.5 The effect of trimming cycle on each proportional hoof measure in group A (unshod) and group B (shod). Data are reported as mean ± SD post - trim at each study point. Significant values are presented in **bold** (n=12-40 feet).

Proportional hoof balance indicator	Group A	Group B	P-value
DHWL/BBL	0.55 ± 0.04	0.57 ± 0.03	**0.003**
CoP-Heel/BBL	0.56 ± 0.05	0.56 ± 0.04	0.761
DDTBB-CoR/BBL	0.55 ± 0.04	0.58 ± 0.05	**<0.001**

Table 4.6 Comparison of each proportional hoof balance indicator between group A (unshod) and B (shod). Data are reported as mean ± SE post-trim proportional measure over 3 trimming cycles. Significant values are presented in **bold**. n=12-40.

4.4.3 Testing for equivalence of proportional hoof balance measures

The hoof balance measures DHWL, DDTBB-CoR and Cop-Heel as a proportion of BBL were then compared for group A (unshod) and B (shod) following trimming (post-trim) at each of the 3 trimming cycles. **Table 4.7** shows descriptive statistics whereas **Table 4.8** details results of equivalence testing between the three proportional measures.

When the post-trim difference in DHWL/BBL was plotted at each trim cycle versus post-trim differences between hoof balance indicators, data in group A and B showed different relationships (**Figures 4.4**).

Group A - comparison	Trim no.	Mean pre-post trim difference (95% CI)	P-value
DHWL/ BBL to DDTBB-COR /BBL	1	0.01 (-0.01; 0.03)	0.312
	2	-0.03 (-0.05; -0.01)	0.252
	3	0.002 (-0.02; 0.02)	0.261
DHWL/ BBL to COP- HEEL / BBL	1	-0.03 (-0.05; -0.01)	0.489
	2	-0.01 (-0.03; 0.01)	**0.005**
	3	0.009 (-0.01; 0.02)	0.792
DDTBB-COR /BBL to COP-HEEL/BBL	1	-0.01 (-0.02; 0.01)	**0.01**
	2	0.018 (0.01; 0.03)	**<0.001**
	3	0.006 (-0.00; 0.02)	0.209

Group B - comparison	Trim no.	Mean pre-post trim difference (95% CI)	P-value
DHWL/ BBL to DDTBB-COR /BBL	1	0.02 (-0.15; 0.18)	0.164
	2	0.01 (-0.02; 0.05)	**<0.001**
	3	0.02 (-0.01; 0.06)	**<0.001**
DHWL/ BBL to COP- HEEL / BBL	1	0.02 (-0.02; 0.03)	0.305
	2	0.00 (-0.02; 0.02)	**<0.001**
	3	-0.02 (-0.05; 0.00)	**<0.001**
DDTBB-COR /BBL to COP-HEEL/BBL	1	0.00 (-0.02; 0.03)	0.875
	2	0.01 (-0.01; 0.04)	**<0.001**
	3	0.04 (0.01; 0.08)	**<0.001**

Table 4.7.**Descriptive statistics for comparison of pre-post trim differences between hoof balance indicators as a proportion of BBL**. Date are presented as mean with 95% confidence intervals. Significant P-values are shown in **bold**. n=12-40

Group A - comparison	Trim no.	Post trim variable / BBL	Lower & upper equivalence	Lower & upper T	Lower & upper P	Lower & upper 95% CI
DHWL / BBL; DDTBB - CoR / BBL	1	0.58 ± 0.07; 0.57 ± 0.04	-0.017; 0.017	-0.47; 2.09	**0.020**; 0.319	-0.04; -0.01
DHWL / BBL; CoP - Heel / BBL		0.58 ± 0.07; 0.58 ± 0.05	-0.017; 0.017	-1.73; 0.64	0.263; **0.044**	-0.03; -0.02
DDTBB - CoR / BBL; CoP - Heel / BBL		0.57 ± 0.04; 0.58 ± 0.05	-0.017; 0.017	-3.24; -0.15	0.440; **0.001**	-0.04; 0.00
DHWL / BBL; DDTBB - CoR / BBL	2	0.53 ± 0.03; 0.54 ± 0.03	-0.017; 0.017	-3.00; 0.71	0.240; **0.002**	-0.03; -0.01
DHWL / BBL; CoP - Heel / BBL		0.53 ± 0.03; 0.56 ± 0.05	-0.017; 0.017	-0.25; 3.36	**0.001**; 0.400	-0.03; 0.00
DDTBB - COR / BBL; CoP - Heel / BBL		0.54 ± 0.03; 0.56 ± 0.05	-0.017; 0.017	-3.10; 0.22	0.414; **0.001**	-0.04; 0.00
DHWL / BBL; DDTBB - CoR / BBL	3	0.54 ± 0.02; 0.53 ± 0.05	-0.017; 0.017	-0.96; 3.20	**0.001;** 0.171	-0.02; -0.01
DHWL / BBL; CoP - Heel / BBL		0.54 ± 0.02; 0.53 ± 0.05	-0.017; 0.017	-1.61; 2.21	**0.015;** 0.055	-0.02; -0.01
DDTBB - CoR / BBL; CoP - Heel / BBL		0.53 ± 0.05; 0.53 ± 0.05	-0.017; 0.017	-2.01; 0.91	0.184; **0.024**	-0.03; -0.02

Group B -comparison	Trim no.	Post trim variable / BBL	Lower & upper equivalence	Lower & upper T	Lower & upper P	Lower & upper 95% CI
DHWL / BBL; DDTBB - CoR / BBL	1	0.58 ± 0.03; 0.57 ± 0.04	-0.017; 0.017	-0.36; 2.04	**0.023**; 0.333	-0.02; -0.04
DHWL / BBL; CoP - Heel / BBL		0.58 ± 0.03; 0.57 ± 0.04	-0.017; 0.017	-0.36; 2.04	**0.023**; 0.333	-0.02; -0.04
DDTBB - CoR / BBL; CoP - Heel / BBL		0.57 ± 0.04; 0.57 ± 0.04	-0.017 ; 0.017	-1.07; 1.10	0.141; 0.149	-0.03; -0.03
DHWL / BBL; DDTBB - CoR / BBL	2	0.57 ± 0.03; 0.56 ± 0.06	-0.017; 0.017	-0.22; 1.49	0.075; 0.415	-0.03; -0.06
DHWL / BBL; CoP - Heel / BBL		0.57 ± 0.03; 0.57 ± 0.04	-0.017; 0.017	-1.23; 1.26	0.110; 0.116	-0.03; -0.03
DDTBB - CoR / BBL; CoP - Heel / BBL		0.56 ± 0.06; 0.57 ± 0.04	-0.017; 0.017	-1.34; 0.20	0.420; 0.097	-0.06; -0.03
DHWL / BBL; DDTBB - CoR / BBL	3	0.57 ± 0.02; 0.59 ± 0.03	-0.017; 0.017	-3.79; -0.60	0.276; **0.001**	-0.04; 0.00
DHWL / BBL; CoP - Heel / BBL		0.57 ± 0.02; 0.55 ± 0.05	-0.017; 0.017	-0.27; 2.54	**0.009**; 0.394	-0.01; 0.05
DDTBB - CoR / BBL; CoP - Heel / BBL		0.59 ± 0.03; 0.55 ± 0.05	-0.017; 0.017	-1.71; 3.96	**0.00; -0.05**	0.01; 0.08

Table 4.8 Statistical results from equivalence testing of the digitally mapped hoof balance indicators Data are reported as a proportion of post trim BBL at mean ± SD. Results are displayed at both upper and lower limits. Significant values ($P<0.05$) are shown in **bold.** n=12-40 feet.

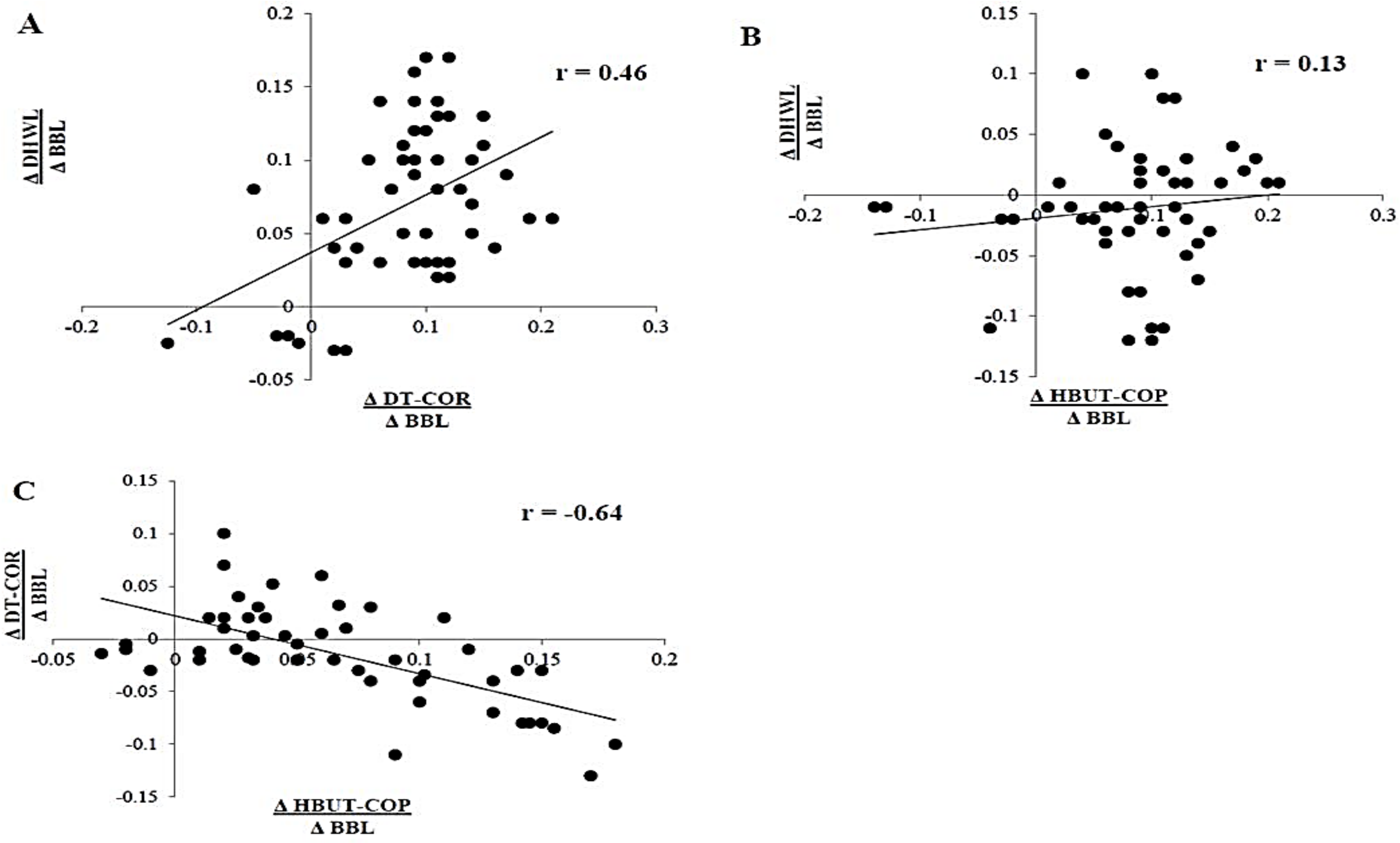

Figure 4.5 A-C Scatter diagrams representing the relationship between the differences before (pre) and after (post) trimming group A using the standardised trimming protocol, fully described in chapter 2 (2.5), of three hoof measures (DHWL, DT-COR and HBUT-COP) as a proportion of the pre and post trimming difference of BBL for each fore foot in unshod in-vivo (n=40, *dark grey circles*). For the cadaver group the differences were measured before and after one trim whereas for the *in-vivo* groups the differences were between pre trim 1 and post trim 3. DHWL = length in the sagittal plane from the coronary band to the dorsal toe; DT-COR = length in the sagittal plane from the dorsal toe to COR (identified as the intersection of the heel buttresses with the opposite breakover point); HBUT-COP = length in the sagittal plane from heel buttresses to a point 9.5mm palmar to the apex of the frog; BBL = length in the sagittal plane between the heel buttresses and dorsal toe.

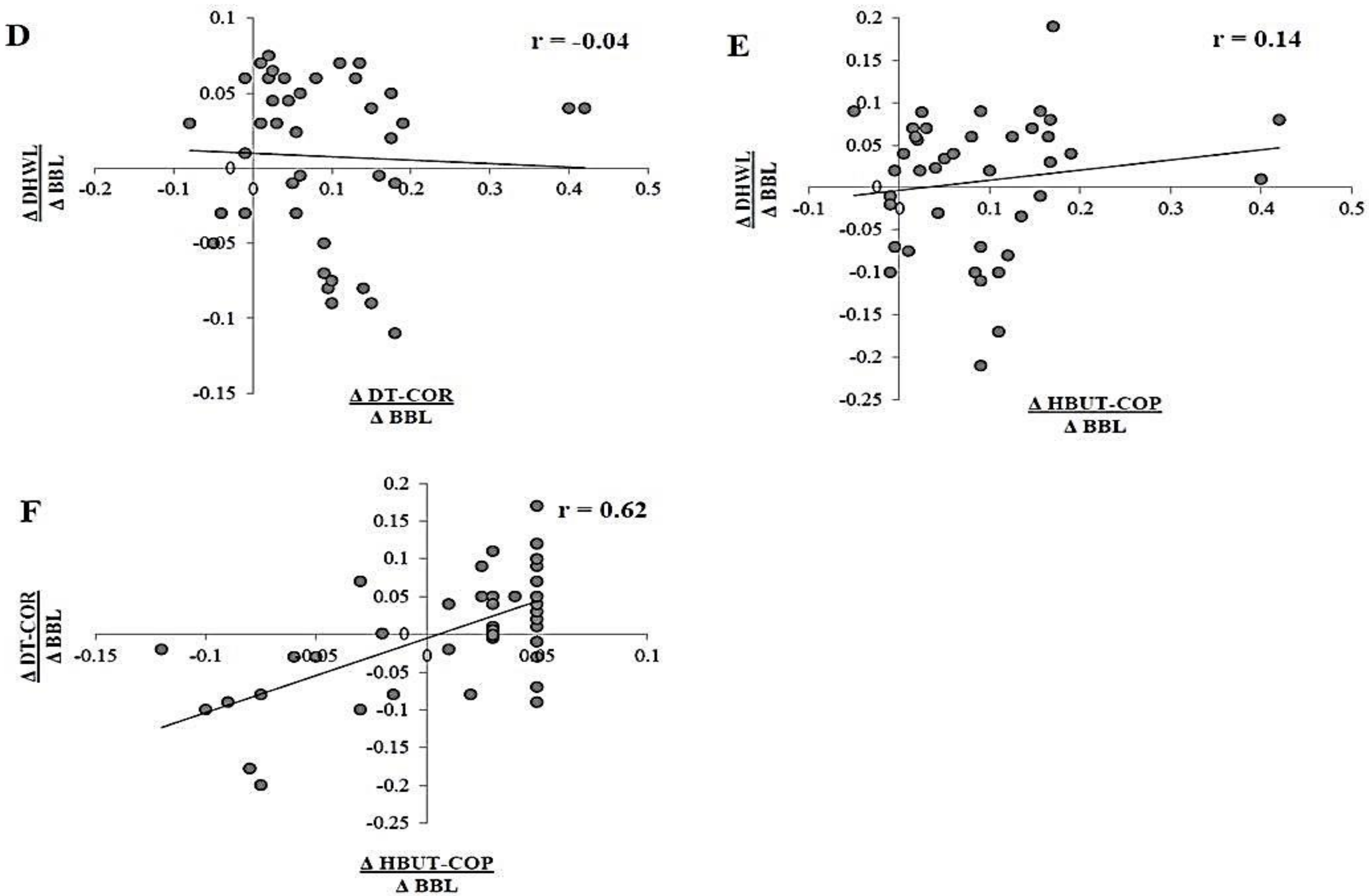

Figure 4.5 D-F Scatter diagrams representing the relationship between the differences before (pre) and after (post) trimming group A using the standardised trimming protocol, fully described in chapter 2 (2.5), of three hoof measures (DHWL, DT-COR and HBUT-COP) as a proportion of the pre and post trimming difference of BBL for each fore foot in shod in-vivo groups (Fig 4.5 D-F, n=12, *light grey circles*). For the cadaver group the differences were measured before and after one trim whereas for the *in-vivo* groups the differences were between pre trim 1 and post trim 3. DHWL = length in the sagittal plane from the coronary band to the dorsal toe; DT-COR = length in the sagittal plane from the dorsal toe to COR (identified as the intersection of the heel buttresses with the opposite breakover point); HBUT-COP = length in the sagittal plane from heel buttresses to a point 9.5mm palmar to the apex of the frog; BBL = length in the sagittal plane between the heel buttresses and dorsal toe.

3.1 Discussion

The presence of shoes on horses feet is a product of human intervention resulting from domestication. As such horses are able to work longer, harder and potentially run faster in line with the changing requirements on Equids as they fit in with modern society. However, the domestication and breeding of horses to undertake these human-imposed demands may come with a cost; changes to the wear pattern, shape and the ability of the hoof to adapt to these new stresses may be compromised and lead to differing hoof quality and thus eventually failure and pathology. To understand the effect of shoeing on foot shape it is important to undertake longitudinal studies. This chapter evaluated the effect of the presence of a shoe on the foot over a number of trimming/shoeing cycles on foot shape using hoof balance measures investigated in Chapter 3.

The main findings in this chapter were: 1) common hoof measures were not achieved in both groups (unshod/shod); 2) unshod horses had greater ability to manipulate bearing border length, re-align the heel angle and allow palmar heel migration than shod horses; 3) proportional hoof balance measures were able to be altered in unshod feet; 4) equivalence of the proportional hoof measures was not achieved in both groups (unshod/shod) after 3 trimming cycles.

The effect of repeated trimming on commonly accepted hoof measures

Similar to Chapter 3, commonly accepted hoof measures, such as 3:1 toe:heel ratio and parallelism were not able to be achieved within the 3 trimming cycles using a standardised trimming protocol. This questions whether these ideals are still valid in modern hoof care (Stashak, 2002; Dyson, 2002; Butler et al., 2005). Despite this it did appear that there were differences in the ability of the feet of unshod horses to alter in response to the trim compared to when feet were shod.

The application of a shoe led to a relative increase in dorsal hoof wall length and reduction in heel growth between trimming periods whereas the unshod group appeared to behave more like those reported with barefoot trimming (Hood et al., 2001; Florence et al., 2006; Hampson et al., 2011). The lowering of heels to engage the frog, bars and sole into the weight-bearing apparatus and shortening the foot by bevelling the toe can stimulate palmar/plantar migration of the heels, with increase in support length, heel angle and solar angle, whilst maintaining dorsopalmar foot balance was found in unshod horses in a study by Clayton et al., (2011).

In addition in the unshod group, the bearing border length was able to be manipulated at each trim such that the change in the length of the base of support could influence the CoP-CoR distance and allow the heels to migrate in a palmar direction. Controlling bearing border length is performed by reducing the hoof wall length and rasping the outer dorsal hoof (colloquially known as "backing up the toe"). Improving heel orientation and allowing heel migration leads to improved health and strength of the heel horn (Curtis, 1999). By improving the CoP-CoR distance in relation to the bearing border length, Ovnicek et al., (2003) this will lead to improved mechanical advantage at unrollement through reduced extensor moment during the propulsive stage of the stride.

Moleman and van Heel (2006) demonstrated that the horse is capable of compensating for changes in hoof morphology over time through postural adaptation. By engaging the frog and solar margin in weight sharing the contact area is increased and the resultant contact pressure per cm^2 is reduced. It therefore seems reasonable to assume that the maintenance of dorsopalmar foot balance witnessed by Clayton et al., (2011) and, to some degree, in the current study are a result of postural adaptation through an increase in support length of the bearing border.

The importance of CoP-CoR distance in the shod and unshod horse

What has become apparent in this study so far and in particular this chapter is the importance of the CoP-CoR measurement. A reciprocal relationship exists between BBL and CoP-CoR distance (as measured by difference between CoP-Heel and DDTBB-CoR), particularly in group A (unshod, **Figure 4.6**). The reduction in wall height following trimming lengthens the CoP-Heel distance whilst reducing the DDTBB-CoR distance. The re-orientation of the hoof capsule in this manner may alter the effects of loading, likely through reduction in both flexor and extensor moments by shifting CoP dorsally.

In group B (shod) the dorsal migration in CoP-CoR distance suggests flattening of the solar arch over time. This may be due to a change in mechanical behaviour during loading and support stage of the stance phase following the application of a shoe preventing palmar heel migration. Therefore the changes seen in group B, i.e. flattening of the sole, heel contraction, reduction in dorsal hoof wall and heel angulation (and hence dorsal migration of dorsal hoof wall and heel) are likely to reflect the effect of the shoe.

The application of a shoe influencing foot shape is probably not just a physical matter but through the alteration in dynamic forces acting through the foot. Hood et al., (2001) in a study on hoof interaction with different surfaces, showed that, in an unshod state, the epidermal structures of the sole frog and bars are weight sharing during the stance phase in addition to the dorsal hoof wall. The application of a shoe to the bearing border of the wall elevates the sole and frog away from ground contact. With the shoe holding the development and migration of heels in check, (through limitation in the ability to manipulate BBL, reduction in CoP-CoR distance and limited change to dorsal hoof wall length) may lead to an exacerbation of the compression of the heel under load from increased torque of the extensor moment, and increased solar loading through dorsoventral migration of the dorsal hoof wall (Thomasson 2009). This scenario mimics that which is commonly encountered in practice.

Influence of repeated trimming and shoeing on equivalence of hoof balance indicators

A measure of hoof balance using geometric proportionality of key hoof measures is based on the work by Duckett (1990). In Chapter 3 it was shown that equivalence of these geometric proportions was not achieved in cadaver limbs, and with the lack of correlation between these proportions demonstrated, questions its use as a measure of hoof balance.

In unshod horses, significant changes in proportional hoof balance measures could be achieved over the three trimming cycles but not in shod horses (Table 4.5). Due to the ability to consistently manipulate bearing border length in the unshod horse at each trim this is will likely explain this difference between unshod and shod horses. Despite this ability to be able to alter proportional hoof balance measures, particularly in unshod horses, the theory of geometric proportionality resulting in hoof balance by Duckett (1990) could not be achieved over the time course used in this study in either group. It is possible that extended time may have shown equivalence, but it was clear that even after 3 trimming cycles, the presence of a shoe resulted in different behaviour of the hooves. This is borne out by the correlations between the proportional hoof balance indicators in unshod and shod horses (Figure 4.7 and 4.8) and again likely due to the restriction by the shoe to influence bearing border length resulting in migration of the toe and heels dorsally with CoP-CoR distance leading to flattening of the solar arch.

Cohort samples and study design

This study used two prospective live cohorts to study the effects of repeating trimming and the presence or absence of a shoe on hoof measures. Previous studies have tended to concentrate on immediate effects following one or two trims (Kummer et al., 2006, 2009) whereas the present study extended observations over three trimming/shoeing cycles. However, it is to be appreciated that this still represents a relatively short time in hoof adaptation and a longer study time may have allowed further observations to be recorded. Despite this, clear differences in the behaviour of unshod versus shod feet were noted in this short period of time.

Horses were used from a general riding population as opposed to specific disciplines (e.g. racing) to allow applicability of findings to a wider population. There was, however a potential confounding effect on the study groups in that horses were pre-selected to be shod or left unshod and ideally a cross-over cohort study would have removed some of this effect. To achieve this, the study would have to have been repeated on the same horses the following season but it was not possible to secure these groups for the following season. A sample size that is too small reduces the power of the study and increases the margin of error, which can render the study open to misinterpretation of the results and accepting the hypothesis when in fact it may not be proven.

Conclusion

This chapter demonstrated that unshod and shod feet in horses behave differently over time with repeated trimming and shoeing. Some hoof measures which have been traditionally thought to be key measures of hoof balance do not hold up in this study and others, such as CoP-CoR distance, appear to be importance indicators of hoof capsule behaviour. This latter measure is also likely to relate to internal landmarks, as demonstrated in Chapter 3. To qualify whether these measures affect the function of the foot it is important to investigate how they relate to the mechanical forces experienced by the foot itself. This will form the basis of the next chapter.

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Chapter 5

A preliminary investigation of the effects of a standardised trimming protocol on the static and dynamic pressure mat data recordings in a cohort of riding school horses.

5.1 Introduction

Findings from Chapter 3 and 4 suggest that the CoP-CoR distance is an important indicator of hoof shape and may relate to internal parameters. This influence on hoof shape is likely to both affect and be affected by mechanical forces acting on the foot. Since the health and function of the foot is interrelated, the relationship between the shape and mechanical forces are also likely to be interrelated - this in itself will form a feedback mechanism into the hoof's internal structures.

It is widely accepted that differences in hoof balance proportions will alter the distribution of weight leading to morphological changes in hoof form. Stashak (2002) states that dynamic imbalance in weight bearing can be altered through the manipulation of the trim and or the application of shoes; by raising, lowering or extending the pertinent side of the hoof, the centre of pressure (COP) can be moved closer to the centre of the hoof. Normal hoof conformation (**Figure 1.1**) is therefore thought to optimise dynamic balance. In farriery the term dynamic balance implies that a balanced foot should land symmetrically, i.e. land flat and place forces uniformly on the bearing surface of the hoof wall (Parks 2007, O'Grady and Parks, 2008).

There is a paucity of studies on the dynamic effects of trimming and shoeing. Van Heel et al., (2004), investigated pressure measurements for the detailed study of the dynamic effect of trimming on hoof balance by instructing two farriers to trim the feet of nine horses towards a static hoof balance. The trim was aimed towards hoof symmetry, as advocated by Stashak (2002), yet the researchers failed to record pre- and post-trim morphometric measures casting doubt over the reliability and validity of their study. The standardised trimming protocol used in the present study (Chapter 2, 2.5) allows for repeatable measurement of external and internal measures of COR and BO (Chapter 3). In particular, the externally hoof mapped location of CoR proved to be an accurate indicator of the centre of rotation of the distal interphalangeal joint, and may therefore enable a relationship between the position of geometric hoof balance indicators, dynamic hoof balance measures such as ground reaction forces (GRF) and bearing border pressure in individual horses to be determined.

Using two cohorts of riding school horses the aim of this chapter was to investigate the effects of a standardised trimming/shoeing protocol on dynamic forces in relation to the externally mapped hoof measures.

5.2 Hypothesis

This chapter will address the hypothesis that both standardised trimming and shoeing protocols results in significant differences in dynamic foot balance and that mechanical behaviour of the hoof under load is influenced by the application of a standard steel horseshoe.

5.3 Aims

The aims of this chapter were:

1) To compare the effects of a trimming protocol on the contact force, pressure and contact area in horses whose normal foot management is barefoot over the duration of a trimming cycle
2) To investigate the effects of shoeing on the contact force, pressure and contact area in horses whose feet are normally managed with shoes over the duration of a shoeing cycle

5.4 Study design

- **Sample collection**

Two groups of general purpose riding school horses with no history of lameness were initially trimmed using a standardised trimming protocol previously described in detail in Chapter 2. (2.3). Horses in both groups were selected on the basis of availability from a cohort of riding school horses and soundness. Horses were allocated to groups based on work regime. Group A consisted of 5 Irish draft cross Thoroughbred (ID x TB) riding horses (3 mares, 2 geldings), mean age 10 ±3 yrs (range 7-14 yrs), mean weight 596 ± 9kgs (range 585 - 610 kgs) and median height 16hh (range 15.3 – 17.1hh). Group A horses were prepared for grass turnout and remained un-stabled for the duration of the study. Group B consisted of 5 TBx geldings, mean age 8 ± 2 years (range 6 - 10 yrs), mean weight 505 ± 6 kgs (range 496 - 510 kgs) and median height 16.2hh (range 16.1 – 16.3hh). Group B horses were stable managed with routine daily exercise of a minimum 2 hour's riding school work and a controlled diet according to individual need. Group B remained shod for the duration of the study and formed part of a pool of horses available to The School of Farriery Science apprentice training programme. As horses in group B had previously been shod by a range of farriers and to ensure uniformity and validity of data, horses (n=5) were trimmed and shod utilising the standardised shoeing protocol (Chapter 2. 2.6) thirty five days prior to pre-/post - trim hoof measurement data, together with static and dynamic pressure mat data being recorded.

- **Digital photographic and foot mapping protocol**

Digital photographs demonstrating the dorsal, lateral and solar views of the feet were taken as detailed in Chapter 2 (2.3) before and after each trimming cycle. Shod horses were photographed after shoe removal and before trimming (pre-trim) and then after trimming but before shoeing (post-trim).

Trim validation external hoof measures of the sagittal length (SL) to the centre of rotation of the DIP joint (CoR/SL) and centre of pressure (CoP/SL) were recorded to investigate the relationship of these key anatomical points, with the timing of peak force and pressure pre- and post-trim. Sagittal length (SL) was used instead of bearing border length since pressure mat hoof contact data best reflects sagittal length. Hoof balance indicators including dorsal hoof wall length (DHWL), dorsodistal tip of the bearing border to the centre of rotation of the DIP joint (DDTBB-CoR) and centre of pressure to

- **Standardised trimming and shoeing protocol**

All feet were trimmed and shod to the national standards of competence with shoes fitted to a competition style fit described in detail (Chapter 2. 2.5 & 2.6). All horses that were shod were fitted with new handmade shoe from fullered concave material in a section suitable to each individual horse on each occasion. For consistency all horses were trimmed and shod by the lead researcher and two qualified farriers familiar with the same trimming protocol and shoeing style. Inter operator reliability was visually assessed during the trim, shoe fitting and attachment stage by the lead researcher using standardised assessment criteria for the Farriery National Occupational Standards (LaNTRA)[10].

- **Foot pressure protocol**

To validate the pressure mats ability to record pre- and post-trim difference and to investigate any possible effect of preferential limb loading and hoof asymmetry on the data static pressure mat, data were collected from group A (un-shod) only as detailed Chapter 2. (2.9.1). Group A had previously been managed bare foot by the lead researcher and two

[10] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

qualified farriers familiar with the same trimming protocol. Pre- and post-trim static pressure mat data for group A were recorded. Initial static data were not collected from group B as those horses had previously been shod by a range of farriers.

Pre-trim dynamic pressure mat data including contact surface area, total contact pressure, total contact force, peak contact force and pressure were collected from both groups at the walk pre-/post – trim group A in addition to pre-/post – shoeing from group B. Calibration was initially performed following the manufacturer’s instructions with a person of a known weight. To assess accuracy after these adjustments, a static measurement was made with a person standing on the pressure plate on one limb. Gain and offset were fine-tuned until the vertical force measured was equivalent to the BW; this was done once and all subsequent measurement sessions were calibrated to that file. Five consecutive left foot strikes and five consecutive right foot strikes were recorded. For each set of five trials, left fore (LF) and right fore (RF) measurements were averaged and PVP, PVF and contact area were calculated. Data files were trimmed so that each hoof strike was recorded from impact to lift off. A trial was considered valid if complete hoof prints of both forelimbs were recorded and if the velocity of the pony was within a preset range of 1.1–1.5 m/s at the walk and a full solar impression image was clearly visible on screen. Data collection was repeated 24 hours post-trim / shoeing.

- **Statistics**

Data were prepared for analysis using spreadsheet software (Microsoft Office Excel 2010) and statistical analysis was performed using Minitab 16®[11]. Normal distribution for each data set was assessed using the Anderson-Darling test for normality. Statistical analysis was performed on all data sets and significant differences were determined by Students t-test and one-way ANOVA with Tukey HSD post-hoc correction. Non parametric data was tested using Mann Whitney.

Results are presented as mean values ± standard error of the mean (SE) unless specified. Exact P-values are presented for all data sets as appropriate. Statistical significance for all data was analysed at $P<0.05$.

[11] Minitab 16: Minitab Ltd: Brandon Court, Unit E1-E2, Progress Way, Coventry CV3 2TE. United Kingdom

5.5. Results

5.5.1. Static measurements

Table 5.1 highlights significant increases between pre- and post–trim contact area for horses after trimming. Differences between the pre-trim/post-trim data for total contact force and maximum contact pressure were not significant, although total contact force almost reached significance (P=0.053). When analysed for differences between right and left fore (**Table 5.2**) data showed there were significant pre-trim differences in the mean force and contact area. Four horses appeared to display left foot preference showing a larger contact area whereas two horses appeared to display right foot preference. **Figure 5.1** shows a representative pre-trim vertical force output from a static pressure mat reading for an unshod horse. The force output pattern demonstrates the postural sway, evident by the reduction in vertical force in the right fore (green line) and increased force in the left fore (red line) over the duration of the stance.

	Pre trim	**Post trim**	**Difference**	**P-value**
Total Force (N)	2264.8 ± 237.2	2449.2 ± 271.5	183.3 ± 84.3	0.053
Contact Area (cm²)	109.3 ± 14.8	121.1 ± 14.4	11.8 ± 4.7	**0.028**
Max Contact Pressure (KPa)	77.1 ± 7.4	86.9 ± 31.2	9.2 ± 8.7	0.312

Table 5.1 Descriptive statistics for pre and post-trim differences in static pressure measures. Results are displayed as mean ± standard deviation (SD) for pre and post trim data whereas mean difference is displayed as mean ± standard error (SE). Significant values are presented in **bold**. n=10 feet

	Left Fore	**Right Fore**	**Difference**	**P-value**
Pre-trim				
Force (N)	2053.1	2075.6	380.2 ± 287.1	**0.023**
Contact Area (cm²)	102.6	98.1	11.3 ± 6.1	**0.006**
Peak Pressure (KPa)	229	233	4.0 ± 0.03	0.540
Post-trim				
Force (N)	2467.7	2433.3	3.0 ± 14.8	0.847
Contact Area (cm²)	123.8	118.4	5.8 ± 0.9	0.389
Peak Pressure (KPa)	234	225	9.2 ± 8.7	0.410

Table 5.2 Descriptive statistics for left and right fore pre and post-trim differences. Results are displayed as mean ± standard deviation (SD) for pre and post trim data whereas mean difference is displayed as mean ± standard error (SE). Significant values are presented in **bold**. n=5 horses.

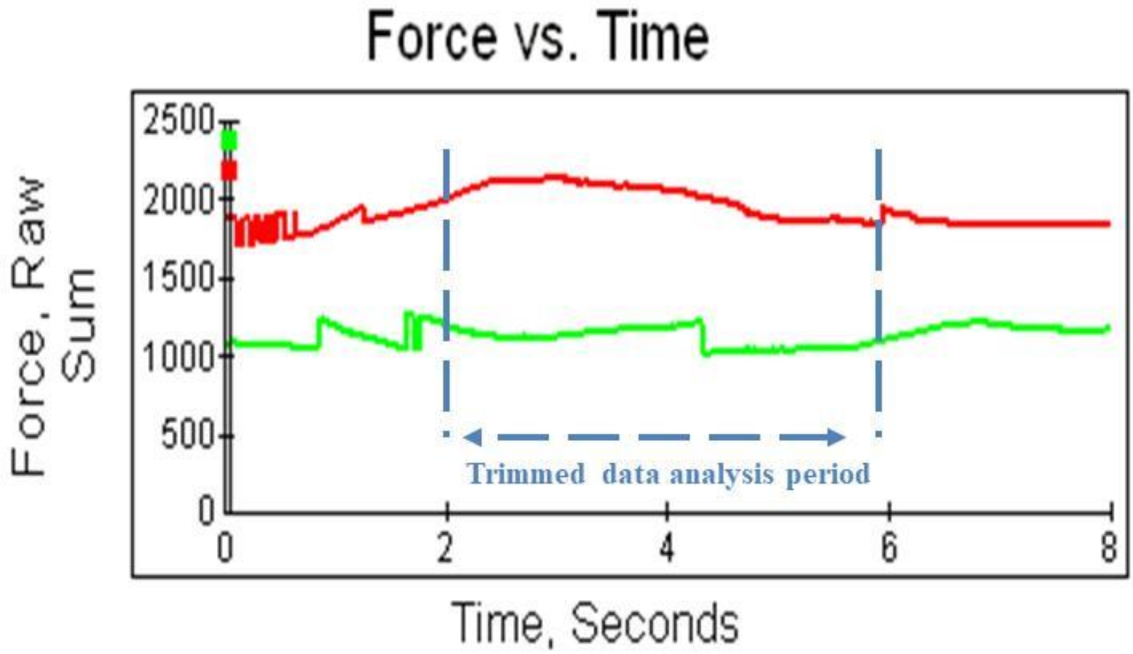

Figure 5.1 Representative trace of a static pressure measurement from an unshod horse. Data were collected to validate the pressure mats ability to record pre- and post-trim difference and to investigate any possible effect of preferential limb loading and hoof asymmetry. The left hoof is indicated in red and the right hoof in green. n=1. Data on the y-axis are in Newtons (N).

5.4.2 Dynamic measurements (group A - unshod horses)

Table 5.3 shows the dynamic measure peak force, stance duration, peak vertical force, peak vertical pressure and contact area pre- and post-trim. Peak force, stance duration and peak vertical force were significantly increased post-trim whereas peak vertical pressure was reduced. This latter finding is likely related to the changes in duration and peak force experienced by the foot. There were no differences observed between left or right fore feet.

Dynamic measure	Pre Trim Mean	Post Trim	P-value
Peak Force time (MS)	0.39 ± 0.03	0.71 ± 0.02	**< 0.001**
Stance Duration (MS)	0.79 ± 0.06	0.83 ± 0.06	**< 0.001**
Peak Force (N)	128.01 ± 2.94	146.7 ± 3.6	**0.002**
Peak Vertical Pressure (KPa)	131.90 ± 3.31	123.13 ± 3.08	**0.029**
Contact Area (cm²)	65.01 ± 3.03	69.64 ± 3.016	0.296

Table 5.3 Dynamic measures for pre-post - trim measures in group A (unshod). Data are displayed as mean ± standard error (SE). Significant values ($P<0.05$) are shown in **bold.** n=10 feet

When peak vertical force (PVF) was expressed as proportion of total stance time, there was a significant increase post-trim. **Figure 5.2** shows how the measures peak vertical pressure, peak vertical force and contact area behave over the total measurement period before and after trimming. With peak vertical pressure (**Figure 5.2B**) there appeared to be a reduction in the first third of stance time post-trim, whilst peak vertical force shifted towards the latter half of the stance after trimming (**Figure 5.2A**). No change in contact area was noted over the whole stance period before or after trimming (**Figure 5.2C)**. When the profiles of individual horses were inspected there was similar behaviour between horses suggesting low variation within the sample group (**Figure 5.3)**.

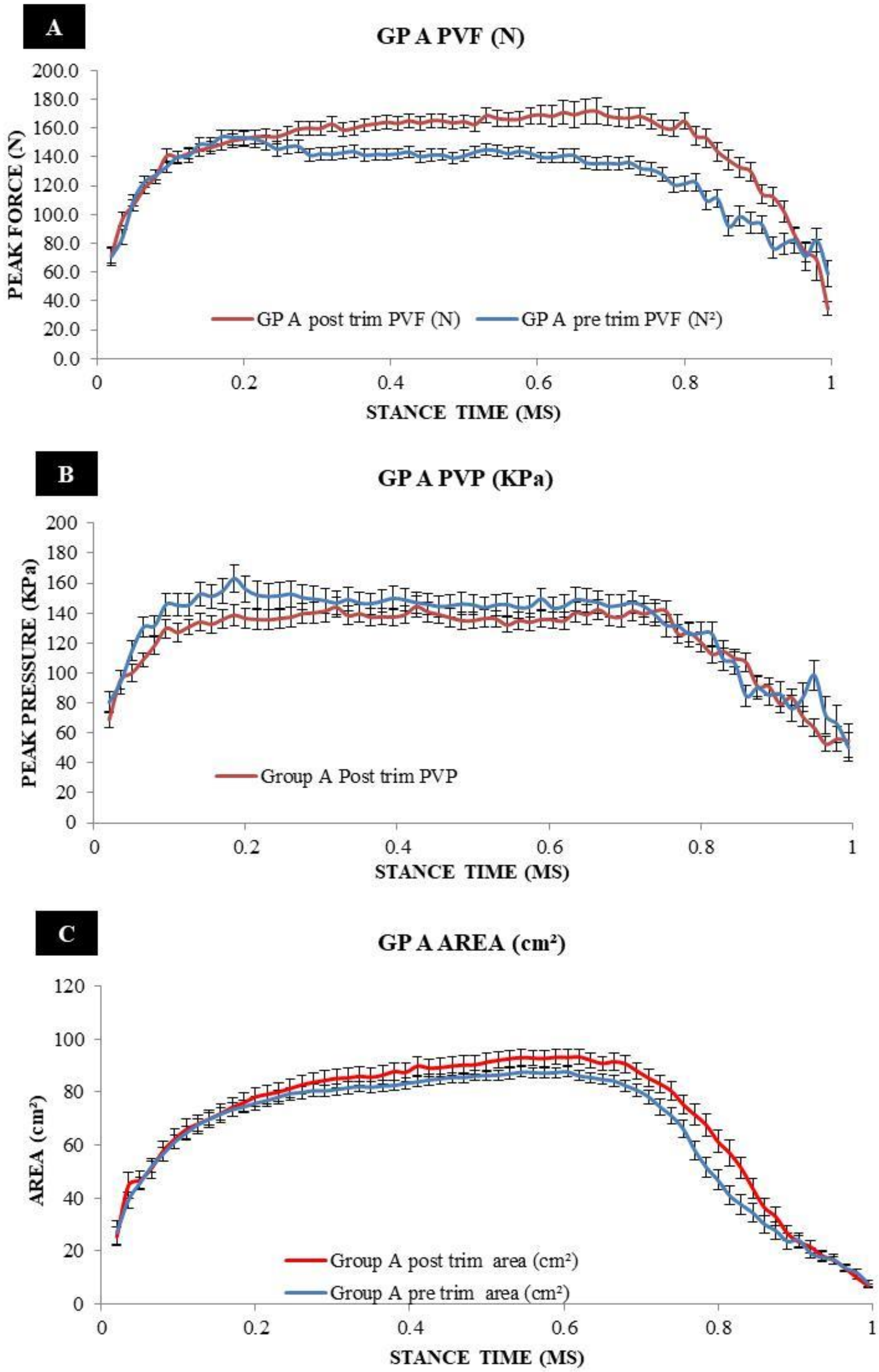

Figure 5.2 Pre- and post-trim values as a proportion of stance time in group A (unshod horses) for (A) peak vertical force (PVF), (B) peak vertical pressure (PVP) and (C) contact area. n=10 feet. *Error bars denote SEM.*

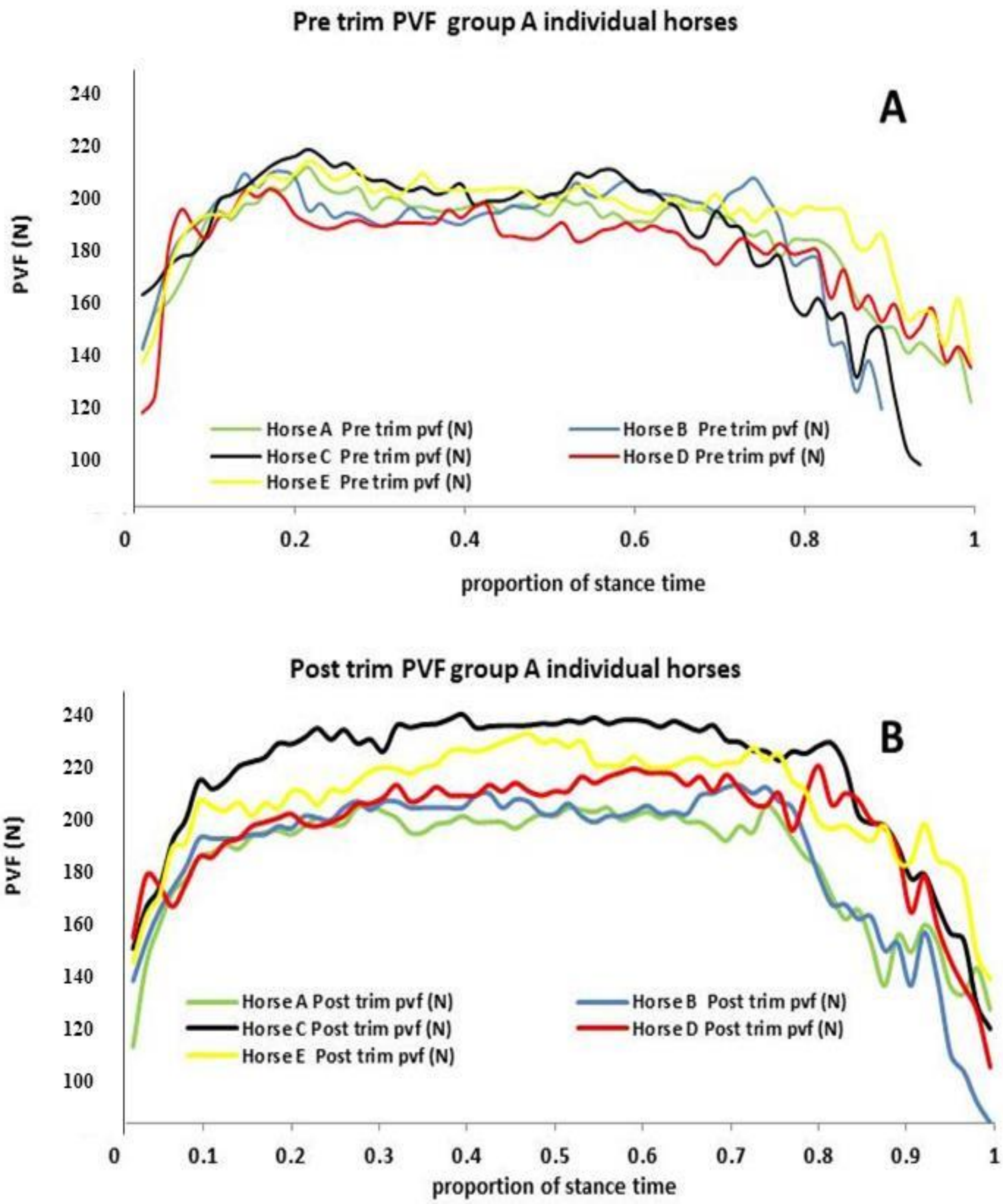

Figure 5.3 Pre- (A) and post–trim (B) peak vertical force (PVF) curves for individual horses in group A (unshod). Data are displayed as mean average of 5 passes both feet. The data illustrates suggests there was only minor variation within the sample group. Data on the y-axis are in Newtons (N). n=10 feet.

5.4.3 Dynamic measurements (group B - shod horses)

When the dynamic measures for the shod horses (group B) were analysed there was a significant effect of the presence of a shoe on all parameters (**Table 5.4**) at each shoeing session.

Dynamic measure	**Pre-trim**	**Post-trim**	**P-value (pre-/post-trim)**	**Shod**	**P-value (post-trim/ shod)**
Peak Force Time (MS)	0.36 ± 0.1	0.59 ± 0.1	**<0.001**	0.42 ± 0.1	**<0.001**
Stance Duration (MS)	1.15 ± 0.0	1.05 ± 0.0	**<0.001**	1.01 ± 0.0	**<0.001**
Peak Force (N)	234.1 ± 42.3	190.3 ± 43.6	**<0.001**	223.3 ± 5.7	**<0.001**
Peak vertical pressure (KPa)	244.3 ± 4.2	231.0 ± 4.3	**<0.001**	192.8 ± 4.5	**<0.001**
Contact area (cm^2)	84.9 ± 2.0	85.7 ± 2.3	0.786	61.0 ± 2.0	**<0.001**

Table 5.4 Dynamic measures for group B (shod) pre-trim, post-trim and shod at two trimming sessions. Data are displayed as mean ± standard error (SE). Significant values for pre-post trim and trim/shod differences (P<0.05) are shown in **bold.** n=10 feet

When each group was analysed for peak vertical pressure as a proportion of stance time, maximal pressure for each group occurred at different stages (**Figure 5.4**). Maximal peak force for the pre-trim group occurred late in stance (around 0.85ms) whereas after trimming this moved to just after 0.2ms of stance time. Following shoeing the maximal peak increased slightly to around 0.4ms. With contact force, pre-trim peak force occurred early in stance (around 0.3ms), moving post-trim to around 0.6ms stance time with shoeing moving this time slightly earlier to 0.45ms stance time (**Figure 5.5)**. **Figure 5.6** shows that trimming increased mean contact area but placement of a shoe led to an overall reduction over the stance period (pre-trim mean 84.9 ± 2.0 cm^2, post-trim mean 85.7 ± 2.3 cm^2 and post-shoe mean 61.0 ± 2.0cm^2). A strong positive correlation existed between both peak vertical force and peak vertical pressure with contact area (**Figure 5.7)**.

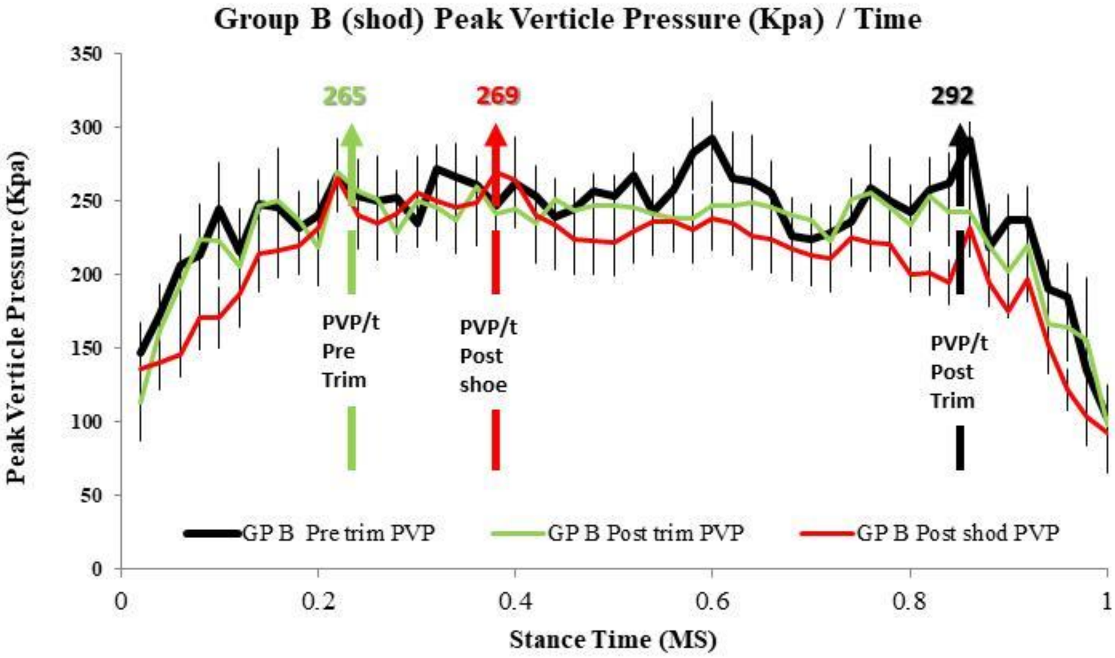

Figure 5.4 Mean peak pressure relative to proportional stance time in pre-trim (black line), post-trim (green line) and post-shoeing (red line) in group B. Maximal peak vertical force for each intervention is shown as a dotted line with maximal value shown (KPa). *Error bars indicate SEM.* n=10 feet

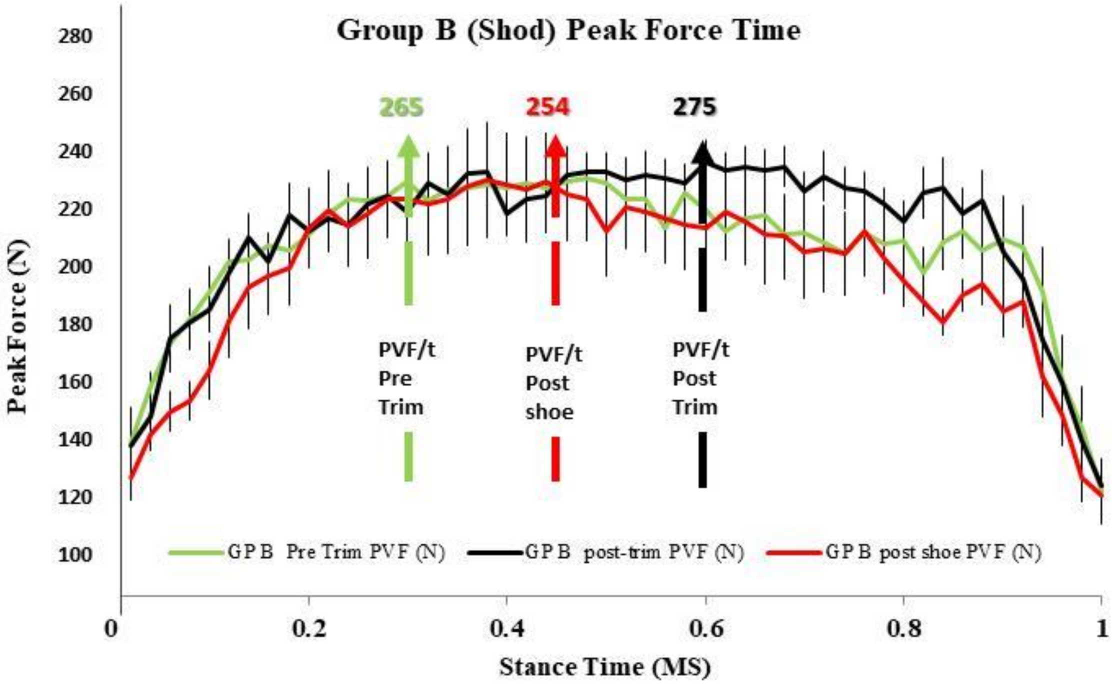

Figure 5.5 Mean contact force relative to proportional stance time in pre-trim (black line), post-trim (green line) and post-shoeing (red line) in group B. Maximal contact force (kg per cm^2) for each intervention is shown as a dotted line with maximal value shown. *Error bars indicate SEM.* n=10 feet

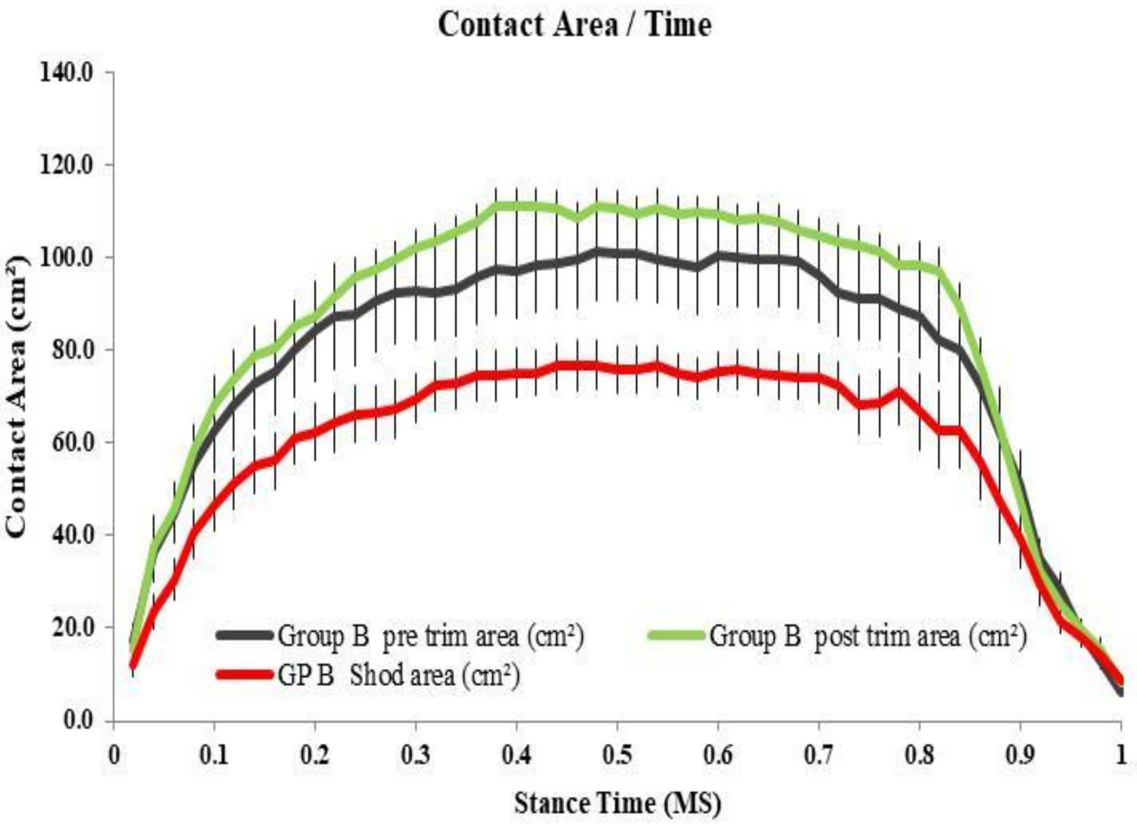

Figure 5.6 Mean contact area relative to proportional stance time in pre-trim (black line), post-trim (green line) and post-shoeing (red line) in group B. the data shows trimming increased the mean contact area but placement of a shoe led to an overall reduction over the stance period post-trim mean 85.7 ± 2.3 cm² and post-shoe mean 61.0 ± 2.0 cm²). *Error bars indicate SEM.* n=10 feet.

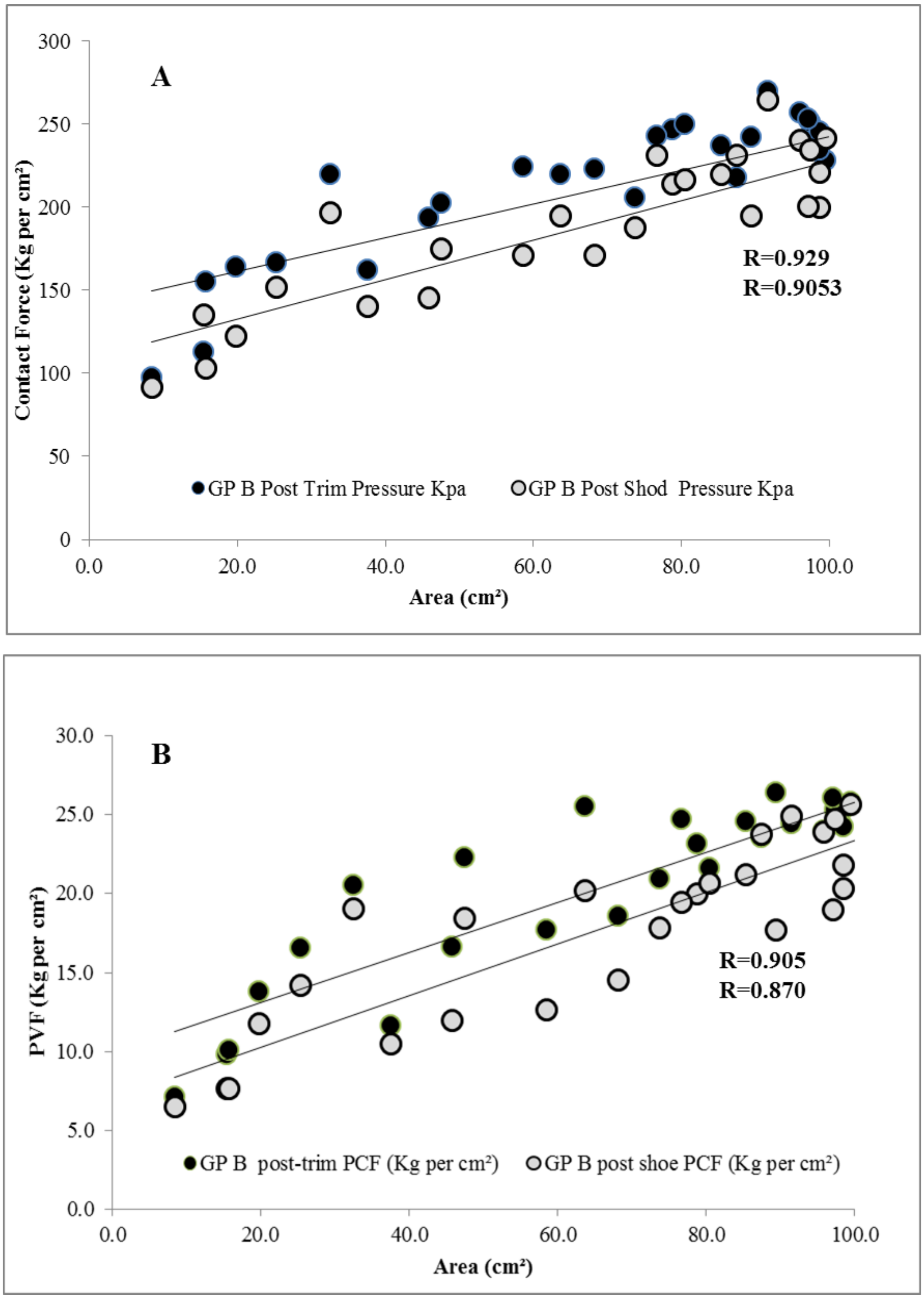

Figure 5.7 Scatterplots showing relationship between (A) contact force and contact area and (B) peak vertical force and contact area in Group B (shod) post-trim (*black circles)*and following shoeing *(grey circles)*. R-values are presented on the graphs for post-trim (*upper values*) and post-shoeing (*lower values).*

5.5.2. *External hoof measures for unshod (group A) and shod (group B) horses*

The previous chapter demonstrated that unshod and shod feet in horses behave differently over time. **Table 5.5** shows the pre- and post-trim external hoof measurements for both groups. No significant differences in pre- and post-trimming were present in this group but this may reflect that each group underwent the same trimming protocol as used in the current study at the previous trim (5 weeks earlier) prior to the measurements. **Table 5.6** shows the pre- and post-trim values for peak vertical force (PVF), peak vertical pressure (PVP) and contact area for proportional hoof group A (unshod) and B (shod) with proportion of stance time each hoof measure occupies. These measurements (PVF and PVP) were assumed to be dynamic representations of the anatomy of the

	Pre-trim	**Post-trim**	**Mean difference (95% CI)**	**P-Value**
Group A (unshod)				
BB / SL	0.863 ± 0.015	0.873 ± 0.014	0.010(-0.003, 0.022)	0.11
Heel / SL	0.160 ± 0.019	0.146 ± 0.021	-0.014(-0.031, 0.003)	0.09
COR / SL	0.475 ± 0.024	0.480 ± 0.019	0.005(-0.014, 0.024)	0.58
COP / SL	0.654 ± 0.037	0.632 ± 0.033	-0.023 (-0.052, 0.007)	0.131
BO / SL	0.903 ± 0.041	0.902 ± 0.032	-0.001 (-0.033, 0.030)	0.913
DHWL / BBL	0.694 ± 0.045	0.662 ± 0.035	-0.03 (-0.067, 0.002)	0.064
DDTBB - COR / BBL	0.648 ± 0.057	0.634 ± 0.043	-0.01 (-0.056, 0.030)	0.525
COP - HEEL / BBL	0.598 ± 0.043	0.582 ± 0.039	-0.016 (-0.051, 0.019)	0.359
COP - COR	0.208 ± 0.050	0.175 ± 0.037	-0.033 (-0.071, 0.004)	0.080
Group B (shod)				
BB / SL	0.880 ± 0.017	0.868 ± 0.019	-0.012 (-0.027, 0.004)	0.133
HEEL / SL	0.136 ± 0.024	0.153 ± 0.028	0.017 (-0.005, 0.038)	0.127
COR / SL	0.503 ± 0.030	0.488 ± 0.025	-0.016 (-0.039, 0.008)	0.174
COP / SL	0.564 ± 0.033	0.546 ± 0.029	-0.018 (-0.045, 0.008)	0.161
BO / SL	0.875 ± 0.038	0.888 ± 0.062	0.013 (-0.030, 0.057)	0.531
DHWL / BBL	0.584 ± 0.028	0.571 ± 0.028	-0.013 (-0.037, 0.01)	0.252
DDTBB - COR / BBL	0.565 ± 0.039	0.592 ± 0.035	0.027 (-0.005, 0.058)	0.094
COP - HEEL / BBL	0.504 ± 0.043	0.476 ±0.039	-0.028 (-0.063, 0.007)	0.106
COP - COR	0.067 ± 0.029	0.066 ± 0.027	-0.001 (-0.024, 0.023)	0.936

Table 5.5 Summary of pre- and post-trim hoof measures for group A (unshod) and B (shod). Data are displayed as the mean ± standard deviation (SD). Significant values (P<0.05) are shown in **bold.** (n=20 feet).

bearing surface of the foot and the orientation of the limb as the mass passes over the foot during the stance phase from first contact to unrollement into the swing phase. There were no statistical differences in group A (unshod) PVF, PVP or contact area in any of the recorded segments of the time line related to the external reference points as a proportion of SL.

	PROPORTION OF STANCE TIME (MS)		**PF (N)**		**PVP (KPA)**		**CONTACT AREA CM²**	
	Pre-trim	Post-trim	Pre-trim	Post-trim	Pre Trim	Post Trim	Pre Trim	Post Trim
Group A								
Heel / SL	0.160	0.146	152.9	152.9	151.22	134.06	71.72	69.89
COR / SL	0.475	0.480	141.3	163.3	144.92	135.02	85.52	90.28
COP / SL	0.654	0.632	141.8	170.1	147.12	140.34	84.22	89.35
BO / SL	0.903	0.902	93.1	114.5	85.91	79.27	24.05	23.40
Group B								
Heel / SL	0.136	0.153	213.9	226.2	248	247	73.0	78.8
COR / SL	0.503	0.488	261.4	268.1	253.79	246.70	100.91	111.02
COP / SL	0.564	0.546	238.8	271.5	257.37	238.16	98.74	110.78
BO / SL	0.875	0.888	224.6	261.1	190.40	166.82	62.38	63.58

Table 5.6 Peak vertical force (PVF), peak vertical pressure (PVP) and contact area for Group A and for each proportional hoof balance measure in relation to proportion of stance time (n=10 feet each)

Table 5.7 shows data for peak vertical force after shoeing in comparison to pre- and post-trim data for group B (shod). A significant increase in peak vertical force was measured in relation to breakover (BO) as a proportion of sagittal length (P=0.002). **Figure 5.8** shows a summated pressure mat readout from consecutive foot strikes with overall force related to time and areas mapping to peak vertical force and pressure illustrated.

Hoof measure	**PVF (pre-trim)**	**PVF (Post-trim)**	**PVF (Shod)**	**P-Value**
Heel / SL	213.9 ± 44.2	226.2 ± 56.0	196.0 ± 85.4	0.53
COR / SL	261.4 ± 44.2	268.1 ± 41.3	232.3 ± 91.2	0.36
COP / SL	238.8 ± 54.8	271.5 ± 45.2	237.7 ± 95.0	0.45
BO / SL	224.6 ± 55.6	261.1 ± 65.2	174.7 ± 27.1	**0.002**

Table 5.7 Peak vertical force at pre- and post-trim and post-shoeing in Group B. Data are displayed as mean ± standard error (SEM). Data were tested using two-way ANOVA with Tukey *post-hoc* corrections between pre-trim and post-shod and with significant values shown in **bold.**

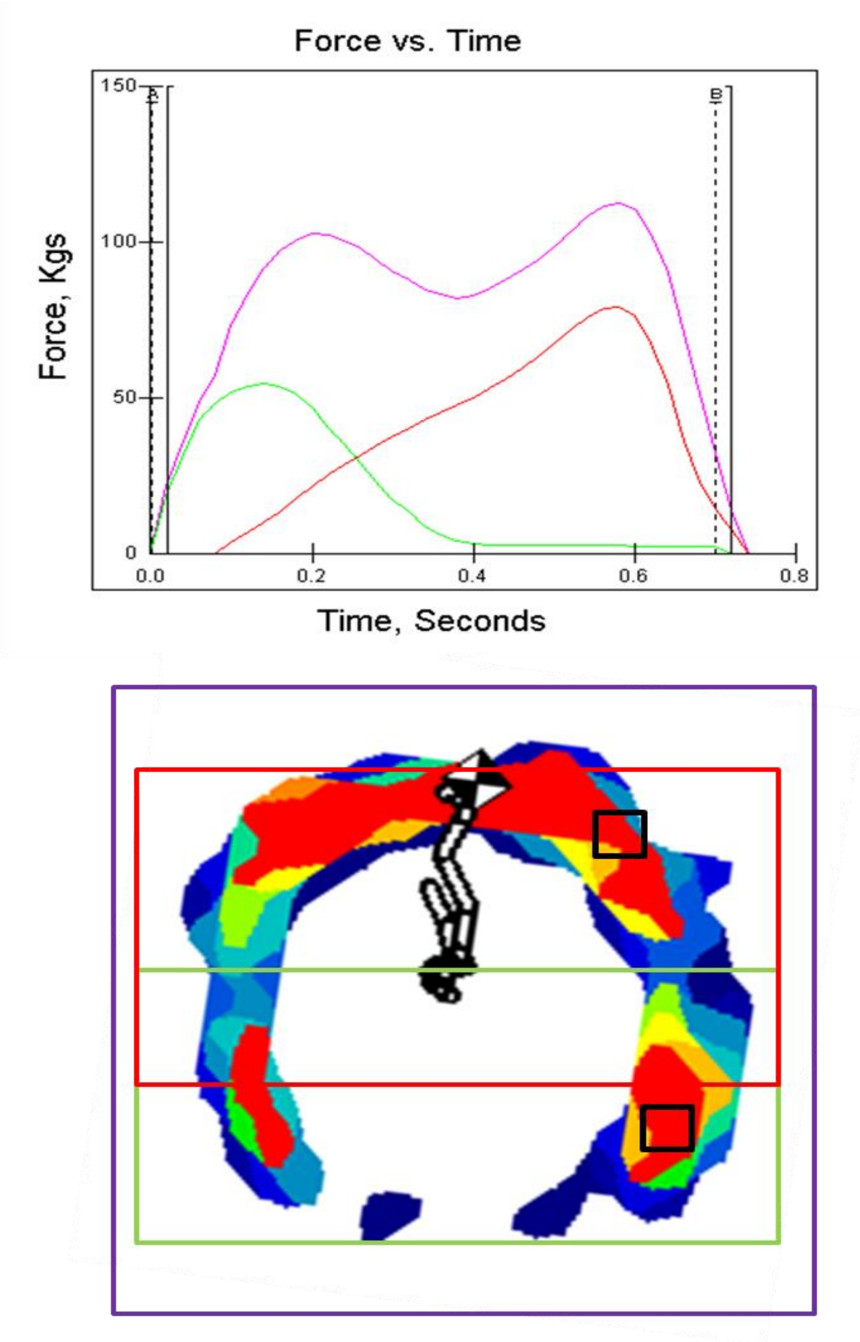

Figure 5.8 Summated pressure mat recordings from consecutive foot strikes. The force time curves illustrated (A) are colour-coded correspond with the individual segments of the foot print from which pressure mat data is recorded (B). The black square illustrates the area of sensels recording the peak reading.

5.5 Discussion

Ideal foot balance aims to establish the correct anatomical relationships in the distal limb and the hoof and is said to be essential for the forces in the foot and the distal limb to remain within physiological limits (Wright & Douglas 1993). The previous chapter demonstrated that unshod and shod feet in horses behave differently over time with repeated trimming and shoeing. Some hoof measures which have been traditionally thought to be key measures of hoof balance do not hold up whereas others, such as CoP-CoR distance appear to be important indicators of hoof capsule behaviour. This latter measure is also likely to relate to internal landmarks, as demonstrated in Chapter 3. Stashak (2002) states that dynamic imbalance in weight bearing can be altered through the manipulation of the trim and or the application of shoes. According to White et al, 2004 and others (Thomason and Peterson 2008) at the walk, the vertical force increases as the limb accepts the horse's body weight and peaks at approximately 60% of the stance phase immediately prior to heel off. Contact force is transmitted from the ground to the hoof over the area of contact however, the timing and location of peak vertical force may vary with changes in hoof balance or conformation (Hobbs et al., 2011). The increased strain increases the likelihood of plastic deformation and morphological changes within the hoof of the type typically associated with lower limb pathologies (Kane et al., 1998). It has been suggested that there is no ideal hoof balance model (Hampson et al., 2013) and for this reasons it is important to farriers and hoof care professionals to qualify how a trimming and shoeing plan might affect the function of the foot. For these reasons it is important to investigate how they relate to the mechanical forces experienced by the foot itself.

This study used a standard trimming and shoeing model based on UK Farriery National Occupational Standards[12] guidelines to investigate the effect of trimming and shoeing on a number of dynamic measures. These measures included the distribution of contact force and pressure pre-

[12] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 27 August 2015)

post trim and shoeing. The study evaluated external measurement parameters following trimming, to determine inherent differences between different feet and how they are likely to behave in response to the trim or application of a steel horseshoe and how this might then relate to key internal structures.

The main findings from this chapter were 1) pre-trim vertical force output from a static pressure mat reading (group A) demonstrated a postural sway, evidenced by significant pre-trim differences between right and left feet mean static vertical force with four horses displaying a larger contact area under their left foot; 2) there were no differences in both pre-/post– trim contact area and pre- and post-trim peak force time when expressed as a proportion of stance time, but there were significant differences in timing of peak vertical force in both groups pre-post trim; 3) there were post-shoeing statistical differences in all dynamic measurements in group B, specifically post-shoeing reductions (16.6%) in PVP, contact area per cm^2 (29.1%) and an increase in PVF (17.4%).

The contrasting data between the pre-/post trim and post-shod PVP, PVF measures in the shod group strongly suggests that dynamic forces acting on the foot during the stance phase may also be influenced by the application of a shoe over time. The application of a traditional rim shoe to the bearing border of the wall elevates the sole and frog reducing contact area thus increasing the extensor moment changing the kinetics of solar loading (Thomason et al, 2008; Eliashar, 2012; Parks, 2012), this was further evidenced by the strong correlation between PVF and contact area (**Figure 5.7**).

The effect of trimming on static and dynamic pressure measurements

When analysed statically all horses in group A exhibited evidence of postural sway with significant pre-trim differences between right and left feet mean static vertical force. Four horses in group A (unshod) displayed larger contact areas under their left foot. As both groups spend a considerable part of their time stall rested these results may suggest a degree of handedness or preferential stance however, there was no evidence of dynamic asymmetry between left and right feet for PVP or PVF within both groups. Although left right hoof asymmetry has been reported (Wilson et al., 2009) the small number of horses sampled in group A, (n=5), preclude any specific conclusion.

The stance phase can be subdivided into different stages with distinct biomechanical characteristics (Thomason & Peterson, 2008): firstly the impact stage (the short period immediately following initial ground contact, when the hoof decelerates rapidly until vertical and subsequently horizontal velocity become zero) whose duration is roughly 20% of stance time; followed by the support stage (the period when maximal limb loading occurs) lasting the subsequent 60% of stance time; and finally the breakover or acceleration stage (the terminal part of the stance phase from heel-off to toe-off) during the latter 20% of the stance (**Figure 1.6**).

The current study demonstrates that changes in hoof conformation affect the timing of PVF (t). There was a significant post-trim increase in both overall stance time and peak force and pressure as a proportion of the stance phase (**Table 5.3**). The fact that PVF occurs significantly earlier in the stance phase as a result of increased foot growth may in part explain the link between dorsal migration of toe and morphological changes to heel and sole seen in witnessed in Chapter 4. As the DHW is increased in length and the corresponding DHWA reduced the PoF migrates palmar/plantar in the foot increasing both magnitude and duration of strain on the more juvenile structures of horn in heel area. An increase in the extensor moment has been shown to alter the position of CoP and CoR pin a palmar direction (Moleman, 2006) presumably changing the proportional time of dynamics within the stance phase, but not the overall time (van Heel et al., 2004). This would explain the increase in SL measurement and subsequent decrease on CoR as a proportion of SL. However, in the unshod horse this often negated by wear, particularly at the dorsodistal tip of the DHW resulting in a net palmar migration and reduction in the CoP-CoR distance as evidenced in chapter 4.

The effect of shoeing on static and dynamic pressure measurements

The current study demonstrates that changes in hoof conformation affect the timing of PVF (t). In group B, when expressed as a proportion of overall stance time, PVF (t) ranged between 36% pre-trim and 60% post-trim of total stance time. There were strong correlations between PVP (r=0.871), PVF (r=0.929) and contact area in group B (shod). Trimming significantly increases contact surface area -characterized by an increase in uniformity of wall contact, increase in contact of the peripheral sole, and a contact of the frog and bars. The application of a traditional rim shoe, of the type typically used in the UK, has the opposite effect (Table 5.5) reducing the contact area considerably. Results from the current study would seem to support the conclusions of both Hood et al., (2001) and Clayton (2011) investigated the effects on solar loading patterns with the hoof's interaction with its surface. These results suggested that hoof shape adapts to loading patterns which differ according to footing. In the unshod model the sole shares a greater load directly with the substrate however, the total load is deflected proximally along the DHW, except in footing where the sole shares a greater load on softer substrate, in the shod model. These authors surmised that the concavity of the solar surface may play an important role in foot biomechanics and that its domed shape should be viewed as a weight-bearing structure that allows maximum load distribution across the surface of the foot.

The results show a significant post shoeing mean reduction of 24.72 cm^2 (29%) of contact area and a mean 33.2N (17%) increase in PVF (Table 5.5). The relationship between PVF is thought to be reflected by changes in the form and function of the hoof structures (Parks, 2012). In the unshod foot, force (F) is dispersed across a combination of epidermal structures at various stages of the stance phase and GRF is concentrated around the peripheral bearing border. The differences in PVF (t) presumably alter the mechanical behaviour of those hoof structures, such as the sole and frog, and no longer engage in weight sharing during the support or mid stance phase. Eliashar (2007) suggested that, without a shoe, hoof wall compression at the toe and quarter is more constant and less in magnitude than with a shoe. Previous studies on the effects of shoeing on the orientation of hoof balance indicators (Chapter 4, **table 4.3**) highlighted an increase in the CoP-CoR distance due to dorsal migration of the DHW which appeared to be linked to solar arch shape. Presumably due to the reduction in contact area whilst the solar border and frog are elevated from the ground, the application of force with opposing GRFv concentrated on the bearing border of the wall the sole is subjected to increased load. In contrast the unshod hoof maximizes ground contact and deflecting GRFv over a greater surface area reducing deformation of the sole.

Study design

The two groups of horses used in this study represented sample populations of Irish draft cross thoroughbred riding horse type (Group A, n=5) and Thoroughbred cross eventers type (Group B, n=5). The exact environmental and management details of the study samples were not fully known but the sample was representative of the type and size of riding / leisure horse typically found within any farriery practice in the Northwest of England. There were limited numbers of animals in each group which limits opportunity to draw firm conclusions from this study. An extended study period over a number of thirty five day trimming and shoeing cycles was originally envisaged to produce a more comprehensive data set over time. A cross over trial with a larger sample size over an extended period would have produced a more comprehensive data set and enabled more meaningful conclusions on the effect of both the standardised trimming and shoeing protocols on peak force and pressure applications during the stance phase. It proved difficult to acquire two groups of sufficient numbers over an extended period. However, the collection of data from ten successful passes from each horse in both groups pre-/post – trim and post-shoeing (group B) ensured uniformity of the data.

The use of modern diagnostic imagery, digital motion sensors and strain gauges may well have produced more comprehensive data analysis on the effects of trimming and shoeing on mechanical behaviour of the foot. Funding prohibited this type of in depth study. The current farriery based field study was deemed more appropriate for a practical analysis of results.

The kinetic examination to measure the pressure forces between horseshoe and ground was carried out by using a high-resolution sensor foil based pressure measurement system (Tekscan™[13]). Pressure mat systems of this type have previously been demonstrated to have a high degree of accuracy and consistency throughout the mid stance phase (van Heel et al., 2004; 2006; Oosterlinck et al., 2010, 2012; Nauwelaerts et al., 2017). Although kinetic data is more normally collected at the trot the variations in PVF and PVP time curves between the walk and the trot have been shown to be negligible (Oosterlinck et al., 2012). As the current study focused on the stance phase, when both vertical and subsequently horizontal velocity become zero, the walk was determined to be a suitable gait.

[13] Tekscan, Inc. 307 West First Street. South Boston, MA. 02127-1309, USA

Conclusion

This chapter provides evidence that the timing of PVF and the hoof contact area appear particularly critical and are likely to influence the shape of the foot and internal forces acting on anatomical structures within the foot. The dynamics of the foot are clearly influenced by the trim and the application of a nail-on steel horseshoe. The results from the current study may influence further research on both the shoeing protocol and the optimum shoeing cycle, if any degree of mechanical congruency is to be maintained. The body of current scientific evidence strongly suggests a link between hoof conformation and lameness pathologies and injuries. The restoration of ideal foot balance is consistently prescribed as part of the treatment plan for a number of foot pathologies.

The results from the current and previous chapters has questioned the efficacy of the commonly accepted foot balance model suggesting that a model, based on proportional values might better account for individual biomechanical variation witnessed in practice. Investigating the difference between the common proportional values recorded following a standardised trimming protocol and those found in a cohort of diseased feet may contribute to an understanding of the effects of hoof conformation on common pathologies. This will form the basis of the next chapter.

Chapter 6

Are geometric hoof proportions associated with pathologies of the equine foot identified with MRI?

6.1 Introduction

The relationship between foot conformation and lameness is still unverified. There is considerable anecdotal information that poor foot conformation and balance are associated with an increased risk of foot-related lameness but foot imbalance may also result from lameness as an adaptation to chronic pain (Snow and Birdsall, 1990; Turner, 1992; Balch et al., 1993).

Foot balance is a subjective term but should take into the account the structure and function of the foot i.e. its size, shape and the way that it relates to the rest of the limb and the ground. Foot imbalance can therefore be defined as an alteration in this relationship where over a period of time, chronic changes can occur in an attempt to compensate for this imbalance. Changes in hoof shape can alter biomechanical function and the nature of the forces interacting between the hoof and the ground (Thomason et al., 1992) and if sufficient stress is induced by these changes, lameness may occur (Parks, 2005). For example, a long toe and a low, collapsed heel is still considered a risk factor in the development of foot-related lameness (Turner, 1992). However, Dyson et al., (2011), whilst supporting this, reported that only 10% of the unilaterally lame horses had a low, collapsed heel foot conformation in the lame limb and that there was no difference in the incidence of this conformation between lame and non-lame feet.

Pathology of the deep digital flexor tendon (DDFT), navicular apparatus and distal interphalangeal joint (DIPJ) are common causes of foot lameness in the horse (Dyson et al., 2005). Localisation of the lameness to the foot is commonly made by the response to diagnostic analgesia with a diagnosis made through radiological and magnetic resonance imaging (MRI) findings. Recent investigations into the relationships between pathologies and the angles and shapes of the hoof capsule and the P3 found no significant association between a variety of foot conformation parameters measured on radiographs and injury category (Dyson et al., 2011) and in a subsequent study Parker and Dyson (2014) found no associations between foot measurements, the duration of lameness or onset of disease and cause of foot pain. Often manifestations of foot pain are typically slowly progressive (Dyson et al., 2011), particularly in horses exhibiting lesions involving the navicular apparatus. Dyson et al., (2011) found that in feet with a combination of injuries of the DDFT and the navicular apparatus the angle of the coronary band, the hoof wall length: heel length and heel: toe height ratios were significantly larger compared with the non-lame feet (Dyson et al., 2011). This suggested that a low heel conformation may predispose to injury to the navicular apparatus or DDFT. However, it common that horses with 'navicular disease' will present with a range of conformational abnormalities, including upright, boxy feet through to a low, collapsed heel and a broken-back foot-pastern axis (Wright, 1993). Recently Holroyd et al., (2013) indicated that horses with a small angle of the concave solar border of the P3 to the horizontal may have an increased risk of DDFT or navicular lesions using sagittal images on MRI. This is supported by the anecdotal evidence of Savoldi (2007) who suggested that solar arch orientation was indicative of underlying pathologies. Work so far has concentrated on measurements through one plane (e.g. lateral or sagittal). However, results from previous chapters (3 and 4) show the importance of solar surface measurements in determining external hoof shape and internal landmarks, particularly when evaluated as a proportional measure. In this chapter the relationship between external hoof measures (primarily from the solar aspect) to primary causes of lameness in the foot (as determined by MRI) will be investigated.

6.2 Hypothesis

This chapter will address the hypothesis that variations in common hoof balance indicators could be associated with an increased risk of common foot pathologies.

6.3 Aims

The aims of this chapter were:

1) To investigate the relationship between a range of hoof balance indicators and common foot pathologies witnessed in MRI investigation.
2) To investigate the risk factors associated with hoof conformation in a cohort of cases presented for MRI investigation and the frequency of common foot pathologies.

6.4 Study design

- **Sample collection**

The standardized hoof mapping and trimming protocols have been shown to provide consistent and repeatable data (Chapter 3, paragraph 3.4.1). The hoof measurement data from 117 post trimmed cadaver feet (group C; 49 plus 68 feet as described in Chapter 3) were used to compare the equivalent data collected from 155 front feet of 78 client-owned horses (group L) presenting to the Philip Leverhulme Equine Hospital, University of Liverpool for low-field MRI of the fore feet as part of clinical work-up for lameness (detailed in Chapter 2, 2.2.3). All horses had forelimb lameness referable to the digit based upon positive response to anaesthesia of the palmar digital nerves (at the level of the ungulate cartilages), anaesthesia of the distal interphalangeal joint (DIPJ) and/or anaesthesia of the navicular bursa (Bassage & Ross 2010). All horses were examined by clinicians (at Lecturer/Senior Lecturer level) at the Philip Leverhulme Equine Hospital, University of Liverpool between January 2015 and December 2016. The clinic population comprises only horses with lameness, and represents a broad cross-section of breeds, work disciplines and ages.

The diagnosis for all foot cases was recorded separately and categorised at the time of patient examination as part of clinical work-up. For this study, records were evaluated and categorisation of the main MRI findings was carried out by an experienced clinician familiar with evaluating MRI images (Group 1: DIPJ and associated structures; Group 2: navicular apparatus; Group 3: deep digital flexor tendon injuries). Findings were grouped into mild, moderate or severe levels based on recorded MRI appearance. The current study makes no reference to lameness or pathology status of feet within group C as only hoof measurement data was used for analysis.

- **Digital photographic and foot mapping protocol**

Digital photographs demonstrating the lateral and solar views of the feet were used (as detailed in Chapter 2, 2.3). Twelve external hoof reference measures (detailed in Chapter 2, 2.4) were recorded as a raw value and then calculated as a proportion of the sagittal length (SL).

- **Radiographic protocol**

Lateromedial radiographs of all limbs were obtained as detailed in Chapter 2 (2.8). A radiodense marker of known length (60mm) was positioned on the dorsal hoof wall to calculate effects of magnification. A radiodense drawing pin was placed 9.5mm palmar to the dorsal tip of the frog to approximate the location of Duckett's dot.

- **MRI protocol**

Horses underwent MRI evaluation using a 0.27T standing MRI unit (Hallmarq Veterinary Imaging, Surrey, UK) (detailed in Chapter 2, 210). MRI sequences included T1-weighted 3D, T2*-weighted 3D, short tau inversion recovery (STIR) and T2-weighted FSE sequences in sagittal, frontal and transverse planes.

- **Statistics**

Unless otherwise stated all data was analysed using Minitab 16®[14]. Normal distribution for each data set was assessed using the Anderson-Darling test for normality. Statistical analysis was performed on all data sets and significant differences were determined by One-way ANOVA with Tukey HSD post-hoc correction. Non parametric data was tested using Mann Whitney.

Bionominal logistic regression using StataCorp V. 14.2[15] USA was used to test the hypothesis of risk of lameness associated with hoof measurement proportions. Proportions have been multiplied by 100 in order to ease interpretation of results. Measurement data for HB/SL was omitted from the model due to collinearity with BB/SL measurements. Kernel density estimation (KDE) was used to estimate the probability density function of a random variable for non-parametric data.

Results are presented as mean values ± standard deviation of the mean (SD) unless specified. Exact P-values are presented for all data sets as appropriate. Statistical significance for all data was analysed at $P<0.05$.

[14] Minitab 16: Minitab Ltd: Brandon Court, Unit E1-E2, Progress Way, Coventry CV3 2TE. United Kingdom
[15] StataCorp LLC, 4905 Lakeway Drive, College Station, Texas 77845-4512. USA

6.5 Results

Descriptive statistics

Data were obtained on 155 feet from 78 horses available for analysis of which 27 (35%) exhibited unilateral left fore limb lameness and 18 (23%) exhibited unilateral right fore limb lameness. 33 horses exhibited bilateral lameness of which 14 (18%) exhibiting increased levels of left fore limb lameness and 19 (24%) right fore limb lameness.

Table 6.1 lists both primary and secondary diagnostic lesions. Findings were combined since the aims of this chapter was not to comment on incidence of foot pathology but rather whether there is an association between the presence of abnormal findings (primary/secondary) and external hoof measures. Conditions involving the DIPJ and associated structures accounted for 102/155 (66%) limbs, with pathology of navicular apparatus seen in 97/155 (63%) limbs. DDFT lesions were present in 22/155 (14%) limbs with other lesions accounting for the remaining limbs.

To validate the accuracy of the mapped external hoof, measures were compared to the location of key internal anatomical reference points, as determined radiographically (**Table 6.2**). There were significant differences between CoP/SL and the extensor process of P3 measurements. Interestingly, however, there was no difference between the external mapped location of CoR and CoR-DIPJ. This supports earlier findings that the internal position of the centre of rotation of the DIPJ maps well to the external location of CoR.

Category	Primary	Secondary
DIPJ (mild)	41	31
DIPJ (moderate)	22	6
DIPJ (marked)	2	
DDFT (mild)	3	
DDFT (moderate)	8	9
DDFT(marked)	2	
Navicular (mild)	31	25
Navicular (moderate)	30	7
Navicular (marked)	4	
Hoof (chronic)	4	
Foot penetration (chronic)	2	
PIPJ	2	4
MCPJ	1	
P3 Bone	1	
NAD	2	

Table 6.1 Frequency and description of primary and secondary lesions recorded from MRI evaluation. Lesions were categorised into either distal interphalangeal joint and associated structures (DIPJ), lesions of the deep digital flexor tendon (DDFT) or navicular apparatus (navicular). Lesions were graded mild, moderate or marked Additional findings were also described including primary involvement of the proximal interphalangeal (PIPJ) or metacarpophalangeal joints (MCPJ), primary bony involvement of P3, chronic hoof conditions and foot penetrations. NAD = nothing abnormal detected. n = 155 limbs.

	Hoof mapped measure	Anatomical location	Mean difference (95% CI)	P-value
COR/SL	0.465 ± 0.052	0.468 ± 0.038	0.00 (-0.01, 0.01)	0.974
COP/SL	0.672 ± 0.049	0.656 ± 0.041	0.02 (0.01, 0.03)	**<0.001**
COP - COR/SL	0.206 ± 0.054	0.188 ± 0.034	0.01 (0.01, 0.02)	**0.002**

Table 6.2 Comparison between the location of the external hoof measure CoR and CoP (as a proportion of SL) and the centre of rotation of the DIPJ and the extensor process of P3. Data for each category are presented as mean ±SD whereas difference is presented as mean ±95% CI. Significant values ($P<0.05$) are shown in **bold.** n = 155 feet.

Foot conformation and lameness diagnosis

Table 6.3 shows the comparison of external hoof measures between the clinical group (Group L) and cadaver feet used in Chapter 3 (Group C). Significant differences between each group were noted (apart from DHWL/SL) suggesting significant dorsal migration of hoof measures.

Hoof measure	Group L (n=155)	Group C (n=117)	Mean difference (95% CI)	P-value
BBL/SL	0.825 ± 0.050	0.860 ± 0.022	0.031 (0.021, 0.041)	**<0.001**
Heel/SL	0.176 ± 0.051	0.139 ± 0.022	-0.031 (-0.042, -0.022)	**<0.001**
COR/SL	0.465 ± 0.052	0.492 ± 0.016	0.026 (0.018, 0.035)	**<0.001**
COP/SL	0.672 ± 0.049	0.645 ± 0.031	-0.032 (-0.041, -0.022)	**<0.001**
BO /SL	0.824 ± 0.048	0.852 ± 0.034	0.027 (0.017, 0.038)	**<0.001**
COP - COR/SL	0.206 ± 0.054	0.153 ± 0.033	-0.051 (-0.061, -0.042)	**<0.001**
DHWL/SL	0.474 ± 0.049	0.473 ± 0.043	-0.001 (-0.012, 0.009)	0.802

Table 6.3 Comparison between the external hoof reference points as a proportion of SL between group L (lame) and group C (cadaver). Data are presented as mean ±SD whereas differences are reported as mean ± 95% CI. Significant values ($P<0.05$) are shown in **bold** (n=117-155).

Table 6.4 shows comparisons of each proportional hoof measure in the lame horses versus control group. There were significant differences between control and horses in DDFT, DIPJ and navicular categories for BBL, HB and COR as a proportion of SL as well as for COP-COR distance. For COP and BO as a proportion of SL, there were significant differences between lame and control groups for DIPJ and navicular categories. There were no differences between DHWL as a proportion of SL between lame and control groups in any category. **Figure 6.1** illustrates the differences between individual measurements along the solar margin between the post-trim control group C and different injury categories within group L. The effects of a more palmar orientation of the heel buttress in the control group C highlights the differences in the orientation of Heel, COR, COP, BO and the CoP-CoR measures in feet categorised with DIPJ and navicular lesions whereas only the Heel, COR and CoP-CoR measurements appeared significant within the DDFT group of injuries. This is supported by earlier results highlighting the range of differences in pre- and post–trim measures (Chapter 3, **Figure 3.2**).

Results of logistic regression analysis are displayed in **Table 6.5** and indicate significant relationships between hoof measurement proportions and disease status. Proportions have been multiplied by 100 in order to ease interpretation of results and so odds ratios relate to 0.01 unit change. Apart from COP/SL with DDFT lesions, a change in each hoof measure was associated with either an increased or decreased odds of the lesion present. For navicular lesions, an increase of 0.01 in BB, COR and BO as a proportion of SL reduces the odds of the foot having navicular pathology by 0.59-0.87 whereas for every 0.01 increase in COP/SL increases the odds by 1.28 times. Similarly, with DIPJ pathology, an increase in BB, COR and CO as a proportion of SL.

SL reduces the likelihood of the foot having a DIPJ lesion by 0.59-0.82 whereas an increase in COP/SL increases the risk (OR 1.38, 95% CI 1.19-1.59). For DDFT lesions, increases in BB, COR and BO as a proportion of SL reduces the odds of associated DDFT pathology by 0.58-0.83 but there was no significant effect of COP/SL found.

Proportional hoof measure	Comparison	Mean difference	95% CI	T-Value	Adjusted P-value
BBL/SL	**DDFT-Cadaver**	-0.040 ± 0.111	(-0.069, -0.011)	-3.5	**0.003**
	DIPJ-Cadaver	-0.042 ± 0.006	(-0.057, -0.026)	-6.95	**<0.001**
	Navicular-Cadaver	-0.031 ± 0.006	(-0.047, -0.016)	-5.28	**<0.001**
	DIPJ-DDFT	-0.002 ± 0.012	(-0.033, 0.028)	-0.19	0.998
	Navicular-DDFT	0.008 ± 0.012	(-0.022, 0.039)	0.71	0.895
	Navicular-DIPJ	0.011 ± 0.007	(-0.007, 0.028)	1.53	0.422
Heel/SL	**DDFT-Cadaver**	0.040 ± 0.012	(0.010, 0.070)	3.42	**0.004**
	DIPJ-Cadaver	0.045 ± 0.006	(0.0293, 0.061)	7.3	**<0.001**
	Navicular-Cadaver	0.031 ± 0.006	(0.0158, 0.047)	5.16	**<0.001**
	DIPJ-DDFT	0.005 ± 0.012	(-0.026, 0.037)	0.44	0.971
	Navicular-DDFT	-0.008 ± 0.012	(-0.039, 0.023)	-0.69	0.901
	Navicular-DIPJ	-0.014 ± 0.007	(-0.032, 0.005)	-1.94	0.212
COR/SL	**DDFT-Cadaver**	-0.030 ± 0.012	(-0.060, -0.001)	-2.64	**0.042**
	DIPJ-Cadaver	-0.027 ± 0.006	(-0.042, -0.011)	-4.34	**<0.001**
	Navicular-Cadaver	-0.025 ± 0.006	(-0.040, -0.009)	-4.09	**<0.001**
	DIPJ-DDFT	0.004 ± 0.012	(-0.027, 0.035)	0.31	0.989
	Navicular-DDFT	0.006 ± 0.012	(-0.025, 0.037)	0.48	0.964
	Navicular-DIPJ	0.002 ± 0.007	(-0.016, 0.020)	0.28	0.993
COP/SL	**DDFT-Cadaver**	0.017 ± 0.012	(-0.014, 0.048)	1.39	0.507
	DIPJ-Cadaver	0.032 ± 0.006	(0.015, 0.048)	4.93	**<0.001**
	Navicular-Cadaver	0.023 ± 0.006	(0.007, 0.040)	3.67	**0.001**
	DIPJ-DDFT	0.015 ± 0.013	(-0.018, 0.048)	1.18	0.643
	Navicular-DDFT	0.006 ± 0.013	(-0.026, 0.039)	0.51	0.957
	Navicular-DIPJ	-0.008 ± 0.007	(-0.0275, 0.010)	-1.15	0.660
BO/SL	**DDFT-Cadaver**	-0.029 ± 0.012	(-0.061, 0.003)	-2.3	0.099
	DIPJ-Cadaver	-0.030 ± 0.007	(-0.047, -0.013)	-4.47	**<0.001**
	Navicular-Cadaver	-0.028 ± 0.007	(-0.044, -0.011)	-4.25	**0.000**
	DIPJ-DDFT	-0.001 ± 0.013	(-0.034, 0.033)	-0.08	1.000
	Navicular-DDFT	0.001 ± 0.013	(-0.032, 0.034)	0.07	1.000
	Navicular-DIPJ	0.002 ± 0.008	(-0.017, 0.021)	0.26	0.994
COP-COR	**DDFT-Cadaver**	0.047 ± 0.013	(0.013, 0.081)	3.58	**0.002**
	DIPJ-Cadaver	0.058 ± 0.007	(0.0404, 0.076)	8.34	**<0.001**
	Navicular-Cadaver	0.048 ± 0.007	(0.030, 0.066)	6.95	**<0.001**
	DIPJ-DDFT	0.011 ± 0.014	(-0.024, 0.047)	0.81	0.850
	Navicular-DDFT	0.001 ± 0.014	(-0.035, 0.036)	0.05	1.000
	Navicular-DIPJ	-0.010 ± 0.008	(-0.031, 0.011)	-1.3	0.562
DHW/SL	**DDFT-Cadaver**	0.012 ± 0.014	(-0.023, 0.047)	0.86	0.826
	DIPJ-Cadaver	0.004 ± 0.007	(-0.014, 0.023)	0.59	0.934
	Navicular-Cadaver	0.001 ± 0.007	(-0.018, 0.019)	0.11	1.000
	DIPJ-DDFT	-0.007 ± 0.014	(-0.044, 0.029)	-0.52	0.954
	Navicular-DDFT	-0.011 ± 0.014	(-0.047, 0.026)	-0.77	0.868
	Navicular-DIPJ	-0.004 ± 0.008	(-0.025, 0.018)	-0.43	0.974

Table 6.4 Comparisons of proportional hoof measures between lame horses and control (cadaver) feet. Horses in the lame group were categorised based on the primary lesion into DIPJ, DDFT or navicular groups. Data are presented as differences of the mean ± SE with 95% CI. Adjusted P-values are present following Tukeys post-hoc analysis. Significant values ($P<0.05$) are shown in **bold.** n=117-155 feet.

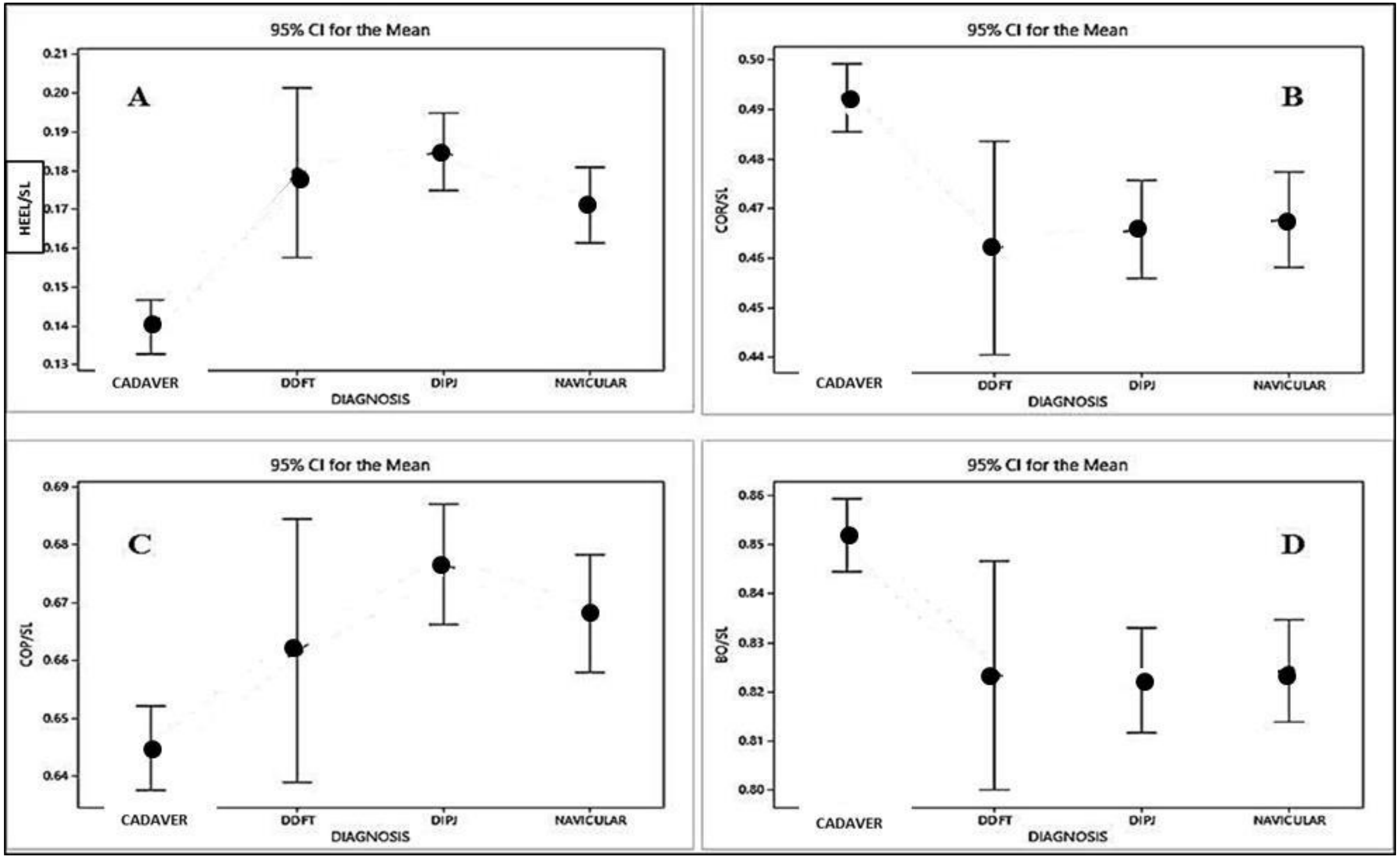

Figure 6.1 Individual interval plots for key solar border measurements Heel/SL (A), COR/SL (B), COP/SL (C) and BO/SL (D). (n=117 - 155).

Category	No.	Hoof measure	Odds Ratio (95% CI)	P Value
Navicular	**97**	BBL/SL	0.701 (0.609 - 0.808)	**<0.0001**
		COR/SL	0.585 (0.478 - 0.715)	**<0.0001**
		COP/SL	1.284 (1.132 - 1.457)	**<0.0001**
		BO/SL	0.873 (0.789 - 0.968)	**0.010**
DDFT	**22**	BBL/SL	0.577 (0.426 - 0.783)	**<0.0001**
		COR/SL	0.650 (0.479 - 0.881)	**0.006**
		COP/SL		
		BO/SL	0.833 (0.698 - 0.993)	**0.042**
DIPJ	**102**	BBL/SL	0.586 (0.487 - 0.705)	**<0.0001**
		COR/SL	0.592 (0.482 - 0.727)	**<0.0001**
		COP/SL	1.376 (1.190 - 1.591)	**<0.0001**
		BO/SL	0.824 (0.727 - 0.930)	**0.002**

Table 6.5 Logistic regression analysis of each hoof measure for the primary lesion categories DIPJ, DDFT and navicular. Measurement data for Heel/SL was omitted from the model due to collinearity with BBL/SL measurements; BBL/SL was selected for inclusion in the model as the variable was more significant to the model. Data are presented as odd ratios with 95% confidence intervals (CI). Odds ratio represent for each 0.01 change in proportional hoof measure. Significant values ($P<0.05$) are shown in **bold.** n=22-102.

Figures 6.2 – 6.4 illustrate the individual Kernel density distributions of the hoof measurement variables for Heel (HB)/SL, COR/SL, COP/SL and BO/SL in both the cadaver group (C) and a subset of navicular, DIPJ and DDFT lameness horses from group (L). The Heel/SL variable is shown in these figures to highlight the dorsal migration of the hooves from group L.

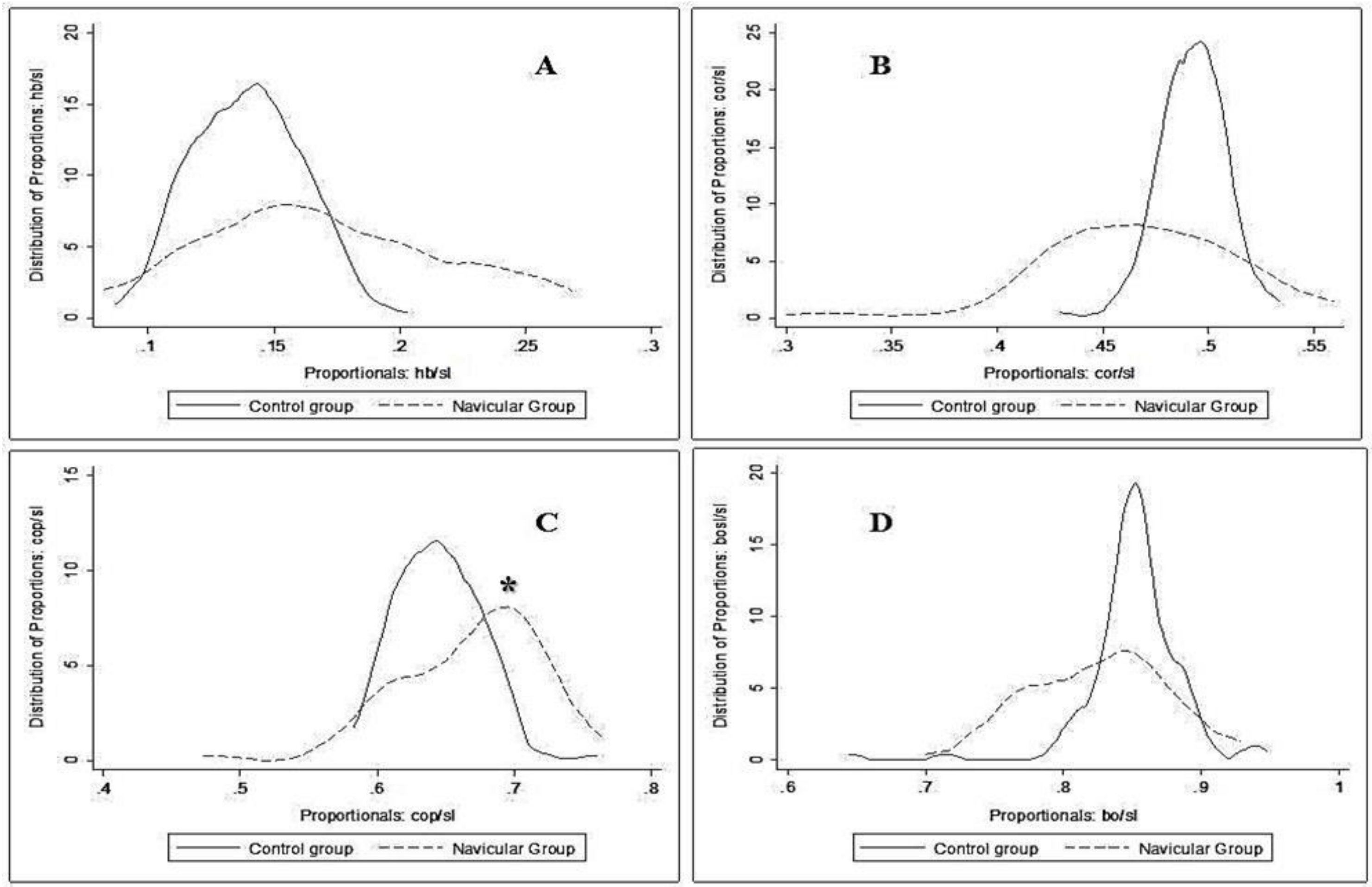

Figure 6.2 Individual Kernel density distribution plots for the control group and samples from the lameness group with navicular lesions. Data displayed are key solar border measurements Heel (HB)/SL (A), COR/SL (B), COP/SL (C) and BO/SL (D). *A one unit increase in the COP/SL proportion (C) will increase the odds ratio of the foot having navicular pathology versus no disease by a factor of 1.284 (p value <0.0001, 95%CI: 1.132, 1.457), indicating that as this hoof measurement proportion gets larger, the odds of navicular disease increases.

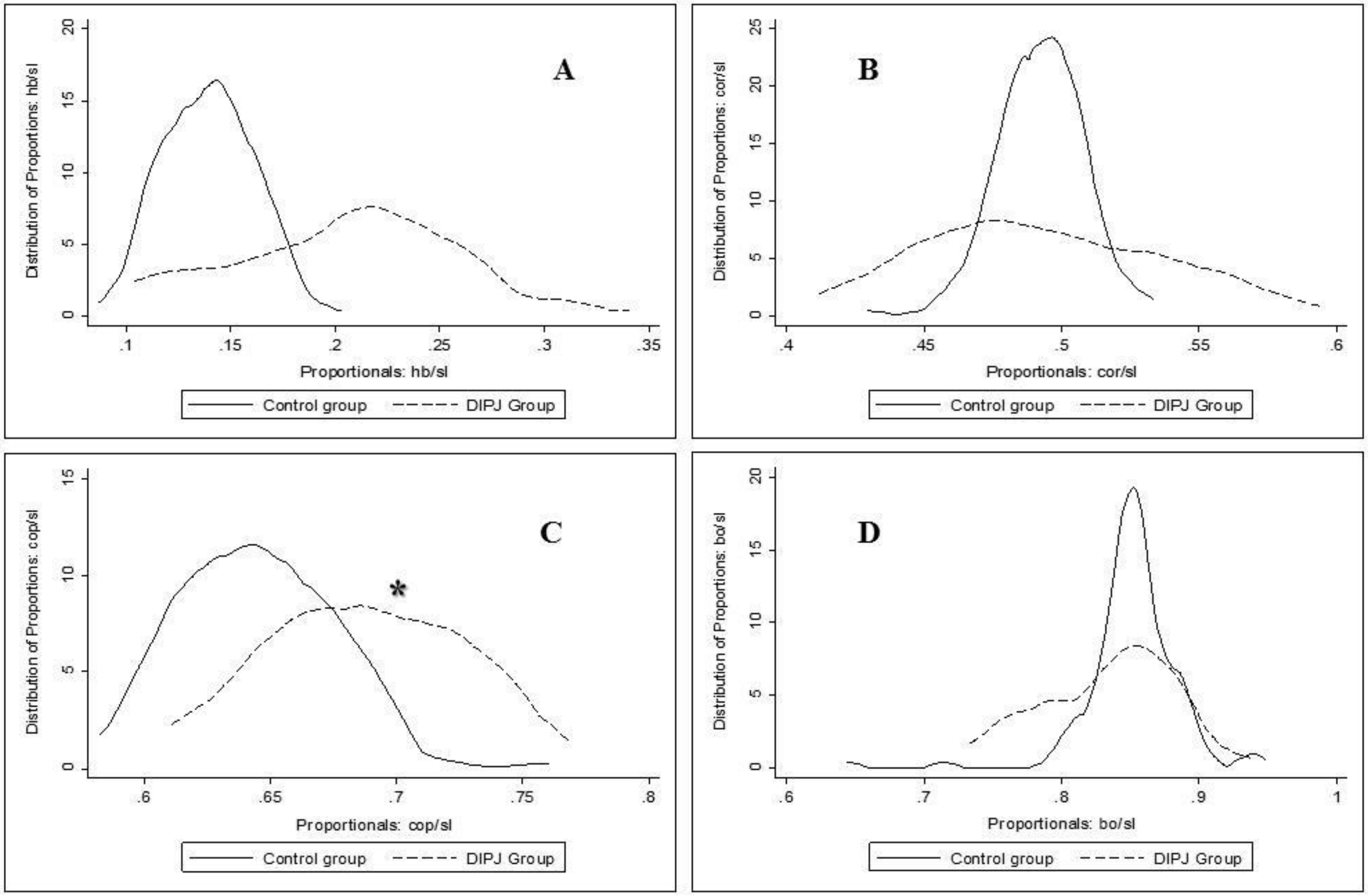

Figure 6.3 Individual Kernel density distribution plots for the control group and samples from the lameness group with DIPJ lesions. Data displayed are key solar border measurements Heel (HB)/SL (A), COR/SL (B), COP/SL (C) and BO/SL (D). * A one unit increase in the COP/SL (C) proportion will increase the odds ratio of the foot having DIPJ disease versus control group C by a factor of 1.376 (p value <0.0001, 95%CI: 1.190, 1.591), indicating that as this hoof measurement proportion gets larger, the odds of DIP disease increases.

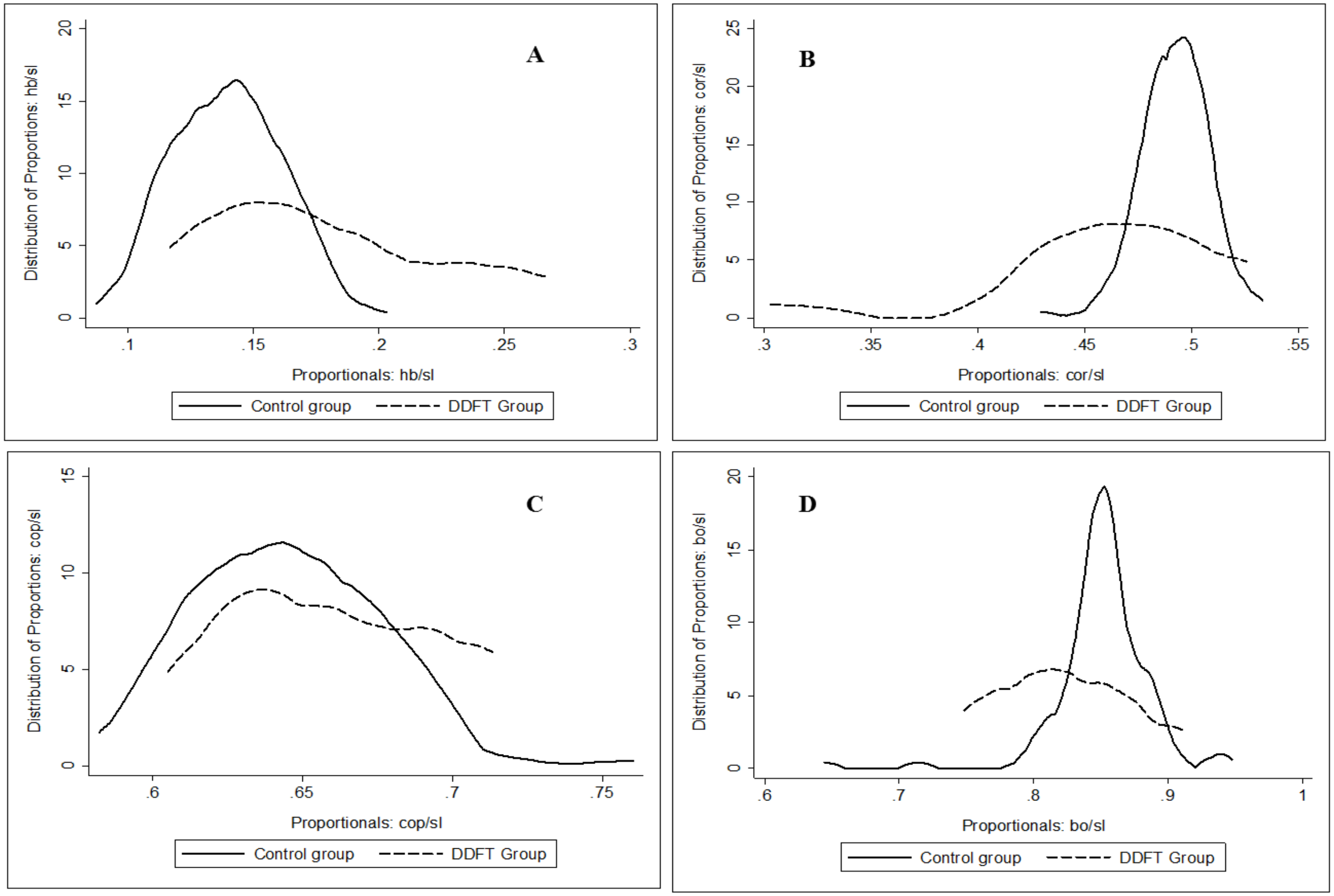

Figure 6.4 Individual Kernel density distribution plots for the control group and samples from the lameness group with DDFT lesions. Data displayed are key solar border measurements Heel (HB)/SL (A), COR/SL (B), COP/SL (C) and BO/SL (D). * A one unit increase in the COR/SL (B) proportion will increase the odds ratio of the foot having a DDFT lesion versus cadaver (control) group C by a factor of 0.65 ($p = 0.006$, 95%CI: 0.479 - 0.881), and that a similar increase in BBL/SL measure (p value <0.001, 95%CI: 0.425 - 0.783) will increase the odds factor by 0.58 indicating that as these hoof measurement proportions gets smaller, the odds of DDFT disease decreases.

When analysing the subsets of lameness category of mild, moderate or severe in navicular lameness there were marked differences in the risk factors associated with specific hoof measurements. Results of the logistic regression indicated significant relationships between BB/SL and COR/SL hoof measurement proportions and mild navicular disease status.

A 0.01 unit increase in BB/SL and COR/SL proportions increase the odds ratio of mild navicular disease versus control group C by a factor of 0.494 ($P<0.001$, 95%CI: 0.384, 0.637) and 0.462 ($P<0.001$; 95%CI: 0.328, 0.649), respectively, indicating that as this hoof measurement proportion get larger, the odds of mild navicular disease decreases. However, a 0.01 unit increase in the COP/SL proportion will increase the odds ratio of moderate navicular disease by a factor of 1.296 ($P=0.001$, 95%CI: 1.112, 1.510), indicating that as this hoof measurement proportion gets larger, the odds of moderate navicular disease increases. Conversely a 0.01 unit increase in BB/SL and COR/SL proportions increase the odds ratio of marked navicular disease by a factor of 0.496 ($P=0.056$, 95%CI: 0.242, 1.018), indicating that as this hoof measurement proportion get larger, the odds of marked navicular disease decreases.

6.6 Discussion

From this chapter there is evidence to suggest a strong correlation between hoof conformation and the biomechanical inference on anatomical structures and foot-related pathologies. Therapeutic farriery is normally prescribed as an overall part of any treatment strategy, with trimming and shoeing usually directed at a specific diagnosis or at a symptom. However, there is often a common objective of imposing a rigid one size fits all geometric foot balance model (i.e. the restoration of HPA) in each occasion. To apply these objectives, it is important for farriers and hoof care professionals to know not only which structures are injured but how changes in hoof conformation might, over time, affect the stress on those structures and induced pain or impaired function. Previous chapters have shown not only significant differences in a wide range of hoof measures over the duration of a trimming / shoeing cycle of as little as 35 days (Chapter 4) but also a high degree of individual variation. Additionally, the previous chapters have demonstrated how environment and substrate play a part in managing biomechanical relationships if not form and shape (Chapter 3) calling into question the philosophy of a common geometric hoof balance model. The previous chapter (Chapter 5) investigated the differences in pre-/post-trim dynamic pressure mat data and provided evidence that the timing of PVF and the contact area hoof appear particularly critical and are likely to influence the shape of the foot and internal forces acting on anatomical structures within the foot. The dynamics of the pre-trim foot, 35 days post-trim, are clearly influenced by not only the standardised trimming protocol but also the application of a nail-on steel horseshoe. Specifically, there were significant differences in timing of peak vertical force pre-post trim and post-shoeing (Chapter 5, **Figure 5.7**).

To better understand the possible link between hoof conformation and disease this chapter investigated hoof measurement data and the causes of lameness. This was achieved by analysing the hoof measurement data from a cohort of diseased feet, diagnosed during MRI investigations, and comparing them with same measures from a cohort of post trim cadaver feet (from chapter 3).

The main findings in this chapter were: 1) pre-/post – trim in the position of hoof balance measures COR and COP as a proportion of the sagittal length were in line with those of previous chapters, and when external hoof measures were compared to internal anatomical positions there was no difference between the external mapped location of CoR and CoRDIPJ; 2) there were significant differences in all proportional measures with the exception of DHWL/SL between the lame group (group L) and control group (group C) highlighting the range of dorsal migration of the hoof measures within group L when compared to the group C; 3) there were significant differences in all hoof measures between group C and each injury type but no differences between injury type in group L; 4) logistic regression analysis between group L and group C indicated significant relationships between hoof measurement proportions and individual disease status where increases in key measurements such as COP increased the odds of navicular, DDFT lesions and DIPJ lameness; 5) analysis of the subsets of lameness category of mild, moderate or marked in navicular lameness revealed there was a noticeable difference in the risk factors associated with specific hoof measurements where, for example, a 0.01 unit increase in BB/SL *and* COR/SL proportions decreases the odds of mild navicular pathologies whilst a 0.01 unit increase in the COP/SL proportion increases the odds of moderate to severe navicular pathologies.

Relevance of the findings in this chapter

Lameness and degenerative pathologies such as navicular and DIP joint disease have often been linked with changes in foot size and shape without necessarily the data to support this. Farriers are in a unique position, with regular scheduled access, to monitor changes in hoof conformation. Historically hoof balance parameters have been linked with the bearing border (Colles, 1983) and hoof pastern axis (HPA), which includes an evaluation of heel toe parallelism and heel toe height ratio. Results from previous elements of the current study have conclusively demonstrated that these assumptions do not hold true (Caldwell et al., 2016).

The current study has adopted a unique approach to analysing hoof measurement data by referencing key anatomical reference points of the origin of the heel buttress (heel, HB), the centre of rotation of the distal interphalangeal joint (CoR), the centre of pressure (CoP) and the estimated position of the dorsodistal tip of P3 (BO) as a proportional value of the overall sagittal length of the foot including the heel bulbs. The standardised hoof mapping and trimming protocols utilised within these studies (Chapter 2) have proved both repeatable and highly accurate. Analysis of hoof measurement data between a control group of feet whose measurements were within this normal range (group C) and a group of horses presenting for low-field MRI of the fore feet as part of clinical work-up for lameness (group L) there were significant differences in all proportional measures with the exception of DHWL/SL. These results highlighted a broad range of variation within the data, from the so called ideal hoof balance model for all hoof measurement variables, and considerable dorsal migration of the hoof in horses within group L (**Table 6.3**).

Although lameness has been associated with the development a long-toe and low-collapsed-heel conformation (Turner, 1992; Eliashar, 2004; 2012; Dyson, 2011; Parks, 2012a) the findings of the current study do not wholly support this observation, Integral to dynamic movement of the horse are the viscoelastic properties of the foots anatomical structures. Viscoelasticity describes the different response of properties of a material under different stresses. When subjected to high or rapid stress deformation generally occurs in an elastic manner whereas under constant stress, deformation occurs slower in a viscous or fluid-like manner resulting in more permanent loss elasticity. The properties of these materials (e.g. cartilage, ligaments and tendons) are as a direct result of their structure and function (Douglas et al., 1998). Results from the current study appear to suggest a biomechanical relationship between the morphology of key anatomical points along the bearing border of the foot and its overall sagittal length. It is well documented that the mechanical properties of the hoof allow elastic deformation under load and that significant increases in strain can be affected by farrier techniques which may have a subsequent relationship to health of the hoof (Roepstorrf et al., 2001) resulting in more permanent deformation of foot shape as witnessed within group L. According to Thomason (2002) the hoof capsule during loading tends to compress the dorsal hoof wall (DHW) as the principle application of force moves toward the toe of the hoof. In the shod horse this compression of the dorsal hoof wall and subsequent expansion of its distal margin may tend to pull both the heel and toe forward and inward. The subsequent dorsal migration of the hoof increases the flexor moment (Wilson et al., 2001), altering the duration and or direction of stress on the hoof as the position of the limb over the foot perpetuating the cycle of deformation experienced by the hoof capsule under bending and compressive force. The mechanical effects of load on the structure of the solar margin of the hoof appear to be exaggerated with the application of a perimeter fit rigid horseshoe. In the shod foot the downward movement of the middle phalanx onto the palmar/plantar hoof tends to increase the deformation of the sole of the hoof downward (Roepstorrf et al., 2001). Loss of contact area reduces the capability of weight sharing across the epidermal structures of the sole, bars and frog (Chapter 5, 5.3.4) and may well contribute to the range of deformation of the hoof witnessed in group L; this is supported by earlier comparisons of the proportional hoof balance measurements between contrasting groups of shod and barefoot cohorts (Chapter 4, **Table 4.5**).

The results from this chapter strongly suggest that the hoof trimming protocol and the post-trim geometric proportions reported in previous chapters may reduce the risk factors associated with common fore foot pathologies including navicular lesions and DIP joint disease. Regression analysis shows that increases, in key proportional measurements along the solar axis such as COP, outside the normal range proportional value of 0.01 increase the incidence of an MRI diagnosis of navicular by a factor of approximately 1.3 and DIPJ lameness by a factor of 1.4 Conversely increases in BBL/SL and COR/SL decreased the odds of diagnosing pathology involving the navicular, DDFT or DIPJ region. There is evidence to suggest individual differences in hoof conformation, specifically the proportional length of BBL/SL and the orientation of the COP, are related to pathology with increased risks of lameness.

Study design

The current study was a prospective observational case–control study. This study had some limitations; the exact environmental and management details of the study samples were not fully known; the results were gained from a population of horses referred to a tertiary equine hospital for advanced diagnostics and may not necessarily typical of the entire equine population. However, the hospital caseload represents a mixed, general population predominately from the

North West of England and so sample was representative of the type and size of riding / leisure horse typically found within any farriery practice in this locality. In addition, a control group of sound horses was not available for MRI comparison but to accomplish this would likely require a Home Office licence. This limits the ability to draw positive conclusions a direct correlation between hoof metrics and the onset of disease.

One important aspect in this chapter is that it could not be stated that the feet from the control group were disease-free or without MRI abnormalities. If the study were to be repeated, then MRI of all the limbs in the control group would have been useful. Despite this, a subset of the limbs (n=25) were used in the radiographic study (Chapter 3) and although relatively insensitive did not show overt radiological signs of disease during analysis. In addition, trimming pattern in group L was not recorded it is to be recognized that some of these difference may reflect inherent variation present in live cohort studies. However, this investigation was to look at how external hoof measures following a standardized trimming protocol (group C) relate to horses with fore limb lameness localized to the digit with evidence of abnormalities on MRI (group L) rather than to provide a cause for common foot pathologies. Despite this, important relationships between key hoof measures and incidence of common foot problems were recognized and provide causal evidence between specific hoof shapes and conditions of the equine digit.

Conclusion

Farriery has linked geometric hoof balance indicators and solar arch morphology to poor horn quality, lameness and pathology. Savoldi (2007) argued that the form of the solar arch was indicative the pathologies he noted post mortem. Results from the current study appear to support his hypothesis by linking hoof morphology to the incidence of disease.

Whilst earlier results have shown that equivalence of Duckett's hoof balance model based on equal proportionality of the DHWL and external reference points along the solar axis did not exist, it is clear that the standardised hoof trimming protocol utilised in these studies could be related to the incidence of common conditions of the equine foot. Whilst the author recognises that hoof shape is influenced by any number of other factors, proportional values along the solar axis may well prove to be a good model for biomechanical efficiency either by trimming alone or the basis of a more sympathetic shoeing model.

Chapter 7

Summary

7.1 Introduction

Consideration of equine hoof balance relies on the existence of ideal hoof and digit conformation such that the function of the horse is not compromised and that the risk of lameness is minimised (Linford et al., 1993; Kane et al., 1998; Viitanen et al., 2003; Eliashar et al., 2004). As such, what constitutes ideal balance has been the subject of great debate for many years. Hoof abnormalities have been described in terms of deviation of height, angle or orientation of hoof measures from defined values, although this approach may fail to take into account biomechanical variations between breeds (Turner, 1992). To address this latter concern, the term geometric balance has been used to imply symmetry about the different axes of the static foot (O'Grady 2006). Feet which do not match this "ideal" are frequently recommended to undergo corrective farriery with the aim to achieving the ideal shape (Colles, 1983) yet it has been demonstrated that a wide range in hoof conformation dimensions exist between horses (Caldwell, et al; 2016).

It is important to stress from the outset that the body of work presented in this thesis is primarily concerned with the practical implications of farriery for hoof conformation and disease with the application of common trimming and shoeing protocols. Whilst the possible links between hoof conformation and common diseases of the foot have been investigated as part of the study, as a practicing farrier the author refrains from commenting on the pathogenesis of the diseases or non-farriery related diagnostics or treatments. However, it is the author's firm belief that farriers are uniquely placed, often attending to maintain feet regularly to identify changes in the health and form that may be indicative of the early onset of disease.

Existing studies fail to make reference to any specific trimming protocol that could be replicated in subsequent research and arguably the conclusions drawn from such studies are of limited practical use in applied farriery. The aims of this study were: 1) to validate a standardised trimming protocol and measure reproducibility of the trim and to relate external hoof reference points to key internal anatomical landmarks in the equine digit; 2) to determine whether repeated trimming using the standardised trimming protocol results in equal geometric proportions and hence foot balance based on the widely accepted model of Duckett (1990); 3) to evaluate whether geometric proportions are related to foot-type (front and hind feet), foot management (unshod versus shod), environmental conditions (domestic versus feral) and investigate the effect of the trimming protocol on dynamic foot measures of PVF and PVP; and 4) to investigate the links between variations in hoof conformation and frequency of common foot pathologies and lameness.

7.2 Recognising the importance of CoP-CoR distance

To validate the standardised trimming protocol a range of proportional values of common external reference points of cadaver feet of feral horses residing in different environmental regions with samples of front and hind cadaver feet from UK domestic horses were studied. The results conclusively demonstrated that the trimming protocol was consistent, providing accurate and repeatable measurement data. Subsequently, the effects of the standardised trim over time and the presence or absence of a shoe were investigated. Key measures from two cohorts of live horses, unshod and shod over a number of trimming/shoeing cycles were used to investigate whether or not the presence or absence of a shoe are likely to influence the shape of the foot. Results indicated that the mechanical behaviour of the hoof differed between unshod and shod feet. Specifically, that measures associated with the solar arch, DDBBT - CoR and Heel – CoP appeared to be influenced by the application of a steel horseshoe.

The results highlighted an increase in the CoP-CoR distance in the shod feet suggesting stretching and flattening of the solar arch over time. This may be due to a change in mechanical behaviour during the loading and support stage of the stance phase following the application of a shoe (**Figure 7.1** and **7.2**). This hypothesis is partially supported by the difference in palmar heel migration over the study period between groups. The spread of the CoP-CoR data may be a significant factor in the type of hoof morphology in shod feet commonly witnessed in practice.

7.3 Hoof risk factors and the likelihood of foot pathology

Results from the current study clearly demonstrate an increased likelihood of disease related to hoof conformation based on the proportional measurements of CoP/SL, CoR/SL and BO/SL, all of which may be key elements of a more definitive hoof balance model. The current study found increased risk factors between proportional hoof balance measurements and finding common foot pathologies on MRI. Significantly, when compared to the hoof balance measures of a cadaver group, a 0.01 increase in the CoP/SL measurement increased the risk factor of navicular lameness by around 1.3 and in DIPJ lesions by a factor of 1.4 indicating that as this hoof measurement proportion gets larger, the odds of DIPJ disease increases. Conversely a 0.01 increase in the BB/SL, COR/SL and BO/SL proportions increased the odds ratio of finding navicular and DIPJ pathology by a factor of 0.7, 0.6 and 0.9 (Chapter 6, **table 6.6**) respectively, indicating that as these hoof measurement proportions of the sagittal length get larger, the incidence of navicular and coffin joint being diagnosed on MRI decreases.

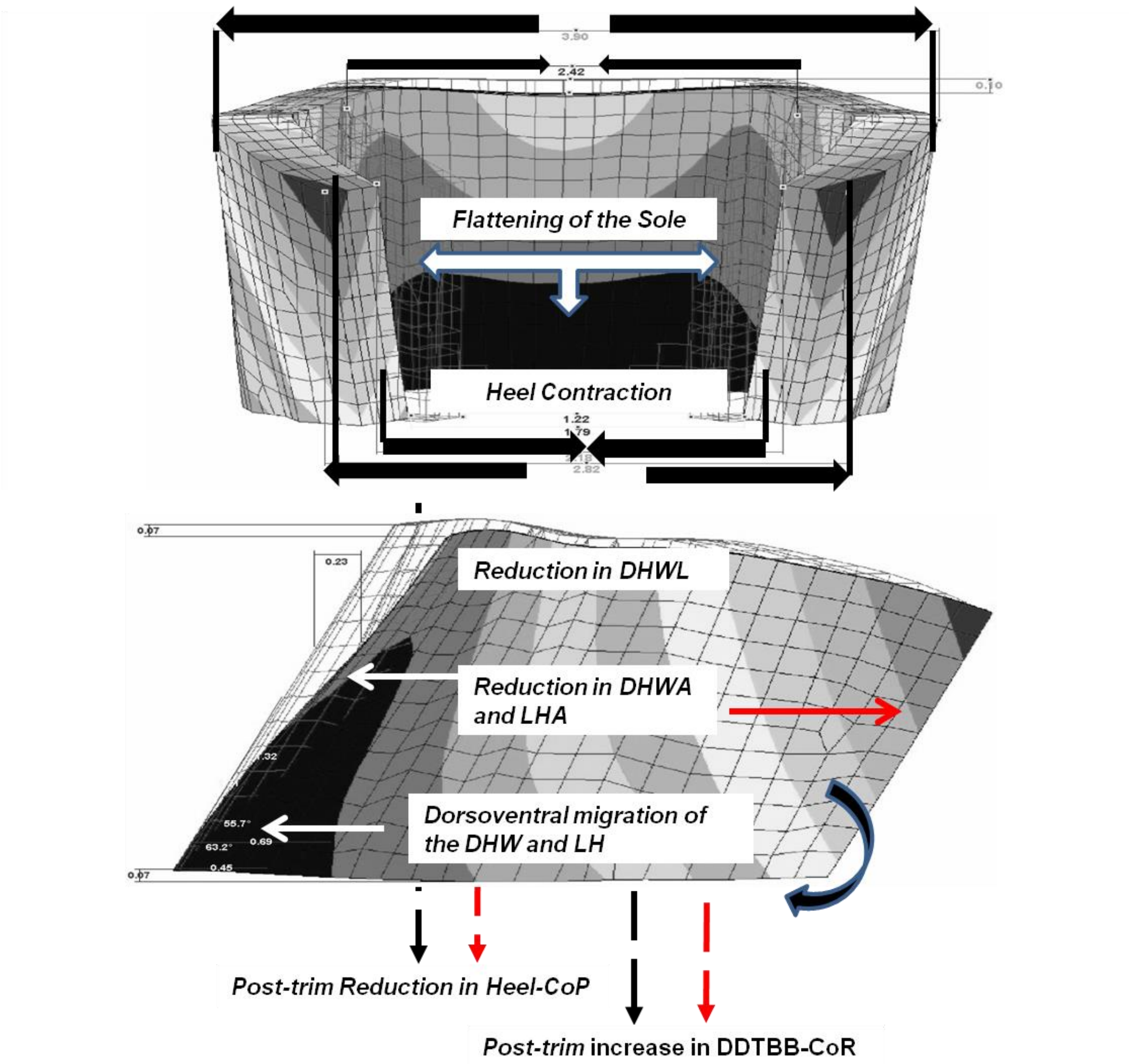

Figure 7.1 Schematic representation of the effects of changes in the CoP-CoR distance over the study period feet in group B. *Modified after Newlin, Collins and Reilly 1998*.

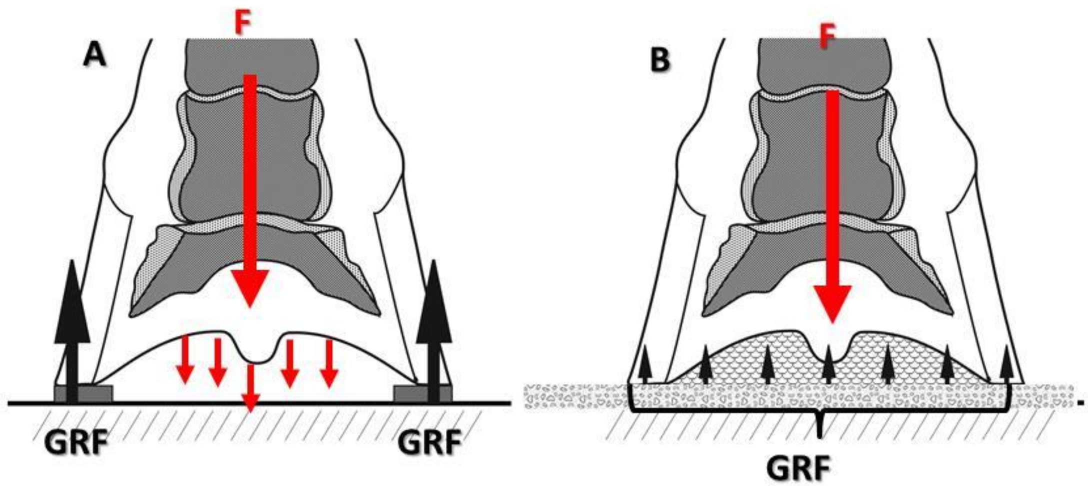

Figure 7.2 Schematic illustration of applied force to the shod foot (A) and unshod foot (B) and the implications of solar weight sharing. In the shod foot (A) the contact area is reduced whilst the solar border and frog are elevated from the ground the application of force with opposing GRFv concentrated on the bearing border of the wall the sole subjected to increased load. In contrast the unshod hoof maximizes ground contact and deflecting GRFv over a greater surface area reducing deformation of the sole. *Reproduced and modified with permission from S. O'Grady.*

Interestingly, hooves with DDFT lesions diagnosed on MRI showed a different pattern than cases with navicular pathology with regards to CoP/SL. Although both groups exhibited dorsal heel migration (Figure 6.2A and 6.4A), those with DDFT lesions the CoP/SL remained similar to control groups (i.e. heel height is maintained, Figure 6.4 C) whereas in the navicular group, there was a significant difference in the CoP/SL proportion between disease and control group (Figure 6.2C) relating to heel collapse. In the DIPJ lesion group changes in CoP/SL fell between DDFT and navicular groups where dorsal heel migration and flattening of the solar arch were both evident (Figure 6.3A, C). This may explain the different forces generated through the tendon and joint moment arms in feet with DDFT lesions and navicular changes i.e. increased tension in the tendon through increased dorsoflexion during the impact phase of the stride occurs as the heels are situated further dorsally but retain their strength. This can lead them to act as a fulcrum and hence often having the appearance of a "double-movement" at the heels in horse with DDFT pain.

7.4 Does using a standard static hoof balance model for all horses provide optimal biomechanical efficiency for the equine foot?

For each foot there is a specific conformation (shape) that provides maximum strength. Maximum strength means the foot's ability to withstand, accept, absorb, dissipate and transmit loading weight bearing forces in a manner that offers the greatest protection to the horse. This principle implies that there is some combination of foot size, foot shape, wall length and angles that make the foot an ideal shock absorbing, weight-bearing structure. It is the proper combination of these variables that we could recognize as the properly balanced foot (O'Grady, 2009).

When domestic horses are shod the hooves are trimmed to remove excess growth but the major consideration is often the geometry of the hoof. When a shoe is applied the normal growth rate exceeds their wear rate. During the trimming and shoeing process it is possible to change geometric relationship of the foot with the skeleton, and so some reference system is required to relate the shape of the capsule to the skeleton. The hoof is said to be balanced when certain geometric criteria are fulfilled.

There are currently several conflicting hoof balance reference systems commonly utilised. The most common of these is the aligned hoof-pastern axis (HPA) metric which requires that the dorsal surface of the fetlock, when viewed from the side, is parallel to the dorsal surface of the hoof. The HPA metric is the currently accepted best practice metric for dorsopalmar hoof balance (O'Grady and Poupard 2003), but the evidence supporting the idea that this is optimal is limited (Parks 2006). A modification of this method requires that the longitudinal axes of the first and second phalanges are parallel to the dorsal surface of the distal phalanx (Stashak et al. 2002, p 1090). However Balch et al. (1995) point out that true axial alignment of the phalanges does not occur because the proximal interphalangeal (PIP) joint is always slightly overextended regardless of hoof angle and this may not be possible to achieve in practice. It is possible to manipulate both the angle of the dorsal wall and the fetlock angle together because as the dorsal wall angle is increased the fetlock angle decreases and vice versa (Bushe, et al. 1987).

When the HPA is not aligned it is called either broken back or broken forward. The results of chapter six suggest that deviations in the HPA model increase the risk of navicular syndrome and support the conclusions of Parkes, et al; (2015) and others (Kane, et al; 1998; Wilson, et al; 2001 and Holroyed, et al; 2013).

It is generally accepted that abnormal weight distribution on the foot or disproportionate forces placed on a section of the hoof wall, over time, cause it to assume an abnormal shape (O'Grady 2013). The mechanical behavior of the hoof structures reflects a relationship between an applied forces or a stress, the hoof structures response to that stress is deformation or strain (Douglas et al 1996). The mechanical properties of hoof horn are such that the geometrical form of the hoof are often influenced by the effects of general skeletal conformation on loading parameters during the stance phase (Eliashar. 2012). The horn tubules are arranged into four zones of density (Reilly et al 1996), the strongest and most densely populated zone being the outer layer. This construction achieves mechanical stability within the horn with the mechanical properties of the horn tubules being best suited to compressive force whilst the Intertubular horn provides stability through tension (Bertram and Gosline 1987). The equalisation of both compressive and tensile forces allows ground reaction forces to be dispersed within the structure without regional overload (Thomason 2007). An increase in strain leads to plastic deformation of the horn and structural failure of the hoof such as low weak heels which has been associated with pathology (Eliashar. 2012).

Farriery technique have been shown to influence skeletal alignment within the foot (Kummer et al 2006; 2009), and the biomechanical hoof mechanisms involved in shock absorption (Roepstorrf et al 2001) and as such presumably is of consequence to the orthopedic health of the horse. In practice it is not always possible to manipulate DHWA to align with the phalangeal axis and maintain the integral strength of the DHW. Anecdotal evidence amongst farriers suggests a link between excessive thinning of the DHW, and the subsequent loss of integral strength, and a loss of solar arch depth. A standardised trimming methodology for retaining dorsal hoof wall (DHW) strength has been the subject of much debate between farriers for a number of years.

More recently a 50/50 ground bearing surface to the centre of articulation metric has been advocated. It has been suggested that these proportions would provide a greater degree of biomechanical efficiency. A 50/50 metric requires that, when viewed from the side, a line projected distally from the COR, should bisect the bearing surface approximately at its centre point. The apparent seminal source for this metric (Colles. 1983) gives no justification, but O'Grady (2009) attempts to provide a biomechanical justification that this allows the moments about the joint to be equal and therefore at equilibrium when the horse is standing, presumably causing the centre of pressure (COP) to be directly under the joint centre of rotation. The joint moment experienced by the DIP joint during locomotion (Clayton et al. 1998, 2000) causes the COP to be located cranially to the joint centre of rotation. Since the loads on the hoof are greater during locomotion than when standing, this justification seems weak. The hoof balance metrics results in chapters 3, 4 and 5 found no evidence to support a 50/50 bearing border metric in either domestic or feral samples, however they do suggest that any variation in a 50/50 metric is reduced when the entire sagittal length, from the most palmar aspect of the heel bulb to the trimmed DHW are considered.

Currently accepted interpretations of static hoof balance including the achievment of an aligned phalangeal axis and a ground bearing border bisected by CoR are likely to be outmoded. Previous work has shown that horses posturally adapt following changes in hoof's biomechanical configuration through the location of CoP and CoR (Moleman et al., 2006). Therefore this provides support to the notion that feet should be managed on an individual basis rather than a “one-size fits-all” approach commonly applied and that implementing this prescriptive model may even be counter-productive to the functional integrity of the hoof.

7.5 Does the application of a standard steel horseshoe have implications for biomechanical efficiency for the equine foot?

The results outlined in chapter four highlight significant differences in hoof balance metrics between feet manged with and without shoes. The significant differences in both COP and COR as proportional values of the post-trim SL strongly suggest changes in the mechanical behaviour of the hoof over time. This is supported by the results outlined chapter six which demonstrates that changes in hoof conformation affect the timing of PVF (t). In the shod group, when expressed as a proportion of overall stance time, PVF (t) ranged between 36% pre-trim and 60% post-trim of total stance time. According to White et al, 2004 and others (Thomason and Peterson 2008) at the walk, the vertical force peaks at approximately 60% of the stance phase immediately prior to heel off. Contact force is transmitted from the ground to the hoof over the area of contact. However, the timing and location of peak vertical force also varied with changes in pre-trim and post-trim hoof conformation and is supported by Hobbs et al., (2011). It seems reasonable to assume that the increased strain experienced by specific regions of the hoof may well increase the likelihood of plastic deformation and morphological changes within the hoof of the type typically associated with lower limb pathologies (Kane et al., 1998).

The fact that PVF occurs significantly earlier in the stance phase as a result of increased foot growth may in part explain the link between dorsal migration of toe and morphological changes to heel and sole seen in witnessed in Chapter 4. As the DHW is increased in length and the corresponding DHWA reduced the PoF migrates palmar/plantar in the foot increasing both magnitude and duration of strain on the more juvenile structures of horn in heel area. An increase in the extensor moment has been shown to alter the position of CoP in a palmar direction (Moleman, 2006) presumably changing the proportional time of dynamics within the stance phase, but not the overall time (van Heel et al., 2004). Both Hood et al., (2001) and Clayton (2011) investigated the effects on solar loading patterns with the hoof's interaction with its surface. They concluded that hoof shape adapts to loading patterns which differ according to footing. In the unshod model the sole appears to share a greater load directly with the substrate however, the total load is deflected proximally along the DHW, except in footing where the sole shares a greater load on softer substrate, in the shod model. The results within chapter 4 suggest that the concavity of the solar surface, highlighted by the CoP-CoR value, may play an important role in foot biomechanics and that its domed shape structure may be compromised by the timing of PVF distribution within the foot.

7.6 How might these studies influence common farriery protocols?

If a 50/50 COR metric does influence biomechanical efficiency of the foot during the stance phase and the maintenance of geometric form is beneficial these results strongly suggest that trimming and shoeing protocols should be tailored to the individual needs in order to best manage the biomechanical forces that influence hoof health. In particular the trim should not only maintain correct geometric proportions but should retain DHW strength. Where this is not possible as a result of anatomical variation or distortion shoe placement and modification of the shoe to reduce leverage at unrollement might be more beneficial than trimming the hoof wall to match the phalangeal axis.

The overwhelming weight of current scientific understanding of the biomechanical behaviour of the foot and the relationship to pathology and lameness supports the findings in chapter six of this study. The results clearly illustrate that variations in key hoof balance metrics such as COR are present in horses presenting with pathology. Science has long assumed that poor farriery management is a significant factor in the onset of such pathologies, whilst these results do not confirm or repudiate that they do suggest that a thorough and comprehensive analysis of current farriery protocols is warranted. These results and the available evidence suggest that a standardised shoeing protocol that maximizes a 50/50 COR metric between the point of breakover and the widest point of the frog, engages as much of the epidermal structures in weight sharing as is practical whilst eliminating shear during unrollement may reduce the hoof distortion and increase biomechanical efficiency.

Whilst it cannot be stated that the standardised trimming protocol achieves either geometric or dynamic hoof balance the results demonstrate it to be repeatable and that there are clearly effects on the mechanical behaviour of the hoof over time that might be considered desirable. Where the horse must be shod for welfare and economic reasons, this might best be achieved with a more mechanically sympathetic model. The current state of understanding suggests that weight sharing between the hoof wall, sole and frog reduce contact pressure and presumably shear force between the wall and sole. This might best be achieved initially, by the application of a broad thin shoe profile with the outer edges domed or bevelled from the ground surface and the application of proprietary pour in sole support materials that replicate more common substrate conditions evidenced within chapter 3 (3.5.4). These simple actions might lead to reduction in strain and facilitate a smoother transition into the swing phase.

7.7 Conclusion

The results from the current study enables farriers and hoof-care professionals to formulate a trimming/shoeing plan based on key hoof measures such as CoR on an individual basis and therefore tailored to the needs of the horse. It also enables veterinary clinicians to monitor the progress of individual farriery-related treatment plans and to prescribe active interventions aiming to optimise mechanical efficiency. The accuracy and repeatability of the trimming procotol also opens up the prospect of more comparative studies for other researchers in the field through a standardised approach. The results of this and previous works show the farrier industry needs to re-assess the relevance of currently accepted horse-shoeing practice.

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Digital Measurement software – Ontrack Equine Software, c\o Lameness solutions LLC, PO Box 152, Lake Elmo, Minnesota 55042, USA. www.ontrackequine.com

X-Ray machine – Porta 1030, Job corporation, 1-19 Shinyokohama, Koho Ku-Ku, Yokohama, Japan.

Plates & Film – Fuji Ltd, UK. Unit 10A St Martins business centre, St Martins way, Bedfordshire, MK42 OLF. www.fujifilm.co.uk

Microsoft Excel - Microsoft Corporation One Microsoft Way Redmond, WA 98052

Statistical software - Minitab Ltd - Progress Way, Coventry CV3 2TE

Pressure Mat - Tekscan 307 West First Street, South Boston, MA. 02127-1309. USA.

MRI Unit - Hallmarq Veterinary Imaging, Surrey, UK

Appendix A

Scientific Publications

The Veterinary Journal 207 (2016) 169–176

Contents lists available at ScienceDirect

The Veterinary Journal

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A test of the universal applicability of a commonly used principle of hoof balance

M.N. Caldwell [a,b], L.A. Allan [a], G.L. Pinchbeck [c], P.D. Clegg [b], K.E. Kissick [a], P.I. Milner [b,*]

[a] School of Veterinary Nursing and Farriery Science, Myerscough College, University of Central Lancashire, Bilsborrow, Preston, Lancashire PR3 0RY, UK
[b] Institute of Ageing and Chronic Disease, University of Liverpool, Leahurst Campus, Chester High Road, Neston, Cheshire CH64 7TE, UK
[c] Institute of Infection and Global Health, University of Liverpool, Leahurst Campus, Chester High Road, Neston, Cheshire CH64 7TE, UK

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ABSTRACT

This study used a UK trimming protocol to determine whether hoof balance is achieved (as defined by equivalence of geometric proportions) in cadaver limbs ($n = 49$) and two cohorts of horses (shod, $n = 6$, and unshod, $n = 20$; three trimming cycles). To determine equivalence, dorsal hoof wall length (DHWL), distance from the heel buttress to the centre of pressure (HBUT-COP) and distance from dorsal toe to centre of rotation (DT-COR) were calculated as a proportion of bearing border length (BBL) using digital photography. Geometric proportions were tested using Fieller's test of equivalence with limits of difference of 2.8%. In 22 cadaver limbs the location of external COR and COP was also mapped radiographically to the extensor process of the third phalanx and the centre of rotation of the distal interphalangeal joint.

Equivalence of geometric proportions was not present following trimming in cadaver limbs or in the two cohorts. Although the dorsal hoof wall to heel wall ratio improved in cadaver and unshod horses after trimming, dorsal hoof wall and lateral heel parallelism was absent in all groups and COP was not consistently in line with the extensor process. Increased COP-COR distance occurred in shod horses and may relate to solar arch flattening. Palmar heel migration, however, occurred more in unshod horses. The study shows that equivalence of geometric proportions as a measure of static hoof balance was not commonly present and widely published measures and ratios of hoof balance rarely occurred in this sample population of horses.

Introduction

Consideration of equine hoof balance relies on the existence of ideal hoof and digit conformation such that the function of the horse is not compromised and that the risk of lameness is minimised (Linford et al., 1993; Kane et al., 1998; Viitanen et al., 2003; Eliashar et al., 2004). As such, what constitutes ideal balance has been the subject of great debate for many years.

Present-day interpretations of ideal hoof balance (Stashak et al., 2002; Eliashar, 2012) are largely based on the historical work of Lungwitz (1891), Dollar (1898) and Russell (1897) with Russell's model of symmetry of the equine foot remaining the basis for corrective farriery intervention and manipulation of the hoof. Conventional farriery teaching is still based on the principal that the bearing border of the foot should be trimmed perpendicular to the longitudinal axis whilst emphasising the importance of achieving correct hoof pastern axis (HPA) and hoof symmetry (Turner, 1992; Stashak et al., 2002).

Hoof abnormalities have been described in terms of deviation of height, angle or orientation of hoof measures from defined values, although this approach may fail to take into account variation between breeds (Turner, 1992). To address this concern, the term 'geometric balance' has been used to imply symmetry about the different axes of the static foot (O'Grady, 2006). In the early 1990s a theory of hoof balance was developed by David Duckett[1] based on proportionality of external reference points that relate to internal anatomical features. This theory states that hoof balance is achieved when specific hoof balance indicators, as a proportion of bearing border length, are equal and that this can be applied to all horses and pony breeds irrespective of size. Primarily due to this latter feature, this theory is in common usage amongst hoof care professionals and hence chosen for this study.

Evaluating the importance of hoof balance is a challenge; one way would be to measure internal stresses on bone, ligaments and tendons in the distal limb following loading under different hoof balance arrangements whereas a comprehensive epidemiological

* Corresponding author. Tel.: +44 151 794 6041.
E-mail address: p.i.milner@liverpool.ac.uk (P.I. Milner).

[1] See: http://afj.americanfarriers.com/file_open.php?id=160 (accessed 8 September 2015).

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approach detailing the risk factors associated with injury using different balance protocols would provide an alternative approach to this problem. We adopt a different approach by taking a commonly used trimming protocol and use a system of measurements to verify whether hoof balance is achieved. The purpose of our study was to determine whether geometric proportions are equivalent following trimming (thereby achieving hoof balance as described by Duckett) by firstly using cadaver limbs and then applying the same question to the live animal by following a cohort of shod and unshod horses over three trimming cycles.

Materials and methods

Sample collection

For the cadaver study, 49 unshod forelimbs were collected from a licenced abattoir in the North-West of England. Limbs from horses with evidence of gross distal limb pathology/injury or obvious conformational abnormalities were excluded. All horses were euthanased for non-research, commercial purposes. For the prospective cohort study, two groups of unrelated horses kept in similar management conditions were used. Both groups were trimmed every 35 days for three consecutive cycles using a standardised trimming protocol. Group A (n = 20, Irish Draught [ID] × Thoroughbred [TB]) were kept unshod for the duration of the study whereas group B (n = 6, TBx) were shod in a standard fullered concave steel riding style horseshoe of the type typically used in the UK.

Approval for this project was provided by Research Ethics and Safety Committee, Myerscough College, University of Central Lancashire (KK/RH/VN-Farr/Caldwell-M; 15 October 2009) with owner consent obtained for horse usage.

Trimming and shoeing protocol

The trimming protocol used was developed under UK Farriery National Occupational Standards[2] and based on the work of NMC and others, published in the farriery journal *Forge*.[3] This trim addresses the frog, sole and white line first, followed by the bearing border and dorsal hoof wall. Briefly, the collateral margins of the frog were trimmed to form an angle approximately 55–60° to the bars. The ground bearing surface of the frog was then trimmed with the caudal aspect of the bearing border of the frog becoming level with the horizontal plane of the bars to be able to allow ground contact during loading prior to reducing the wall. The white line was then trimmed to the solar horn, identified by the waxy horn at the sole-white line interface. After this, excess wall was trimmed at the bearing border from toe to heel to produce a horizontal plane with the sole and the heels reduced in height to extend the bearing border onto either the widest or highest aspect of the frog. Following rasping the hoof flat, any flaring of the dorsal hoof wall was reduced from quarter to quarter, leading to a consistent hoof wall bearing border avoiding lowering the bearing border below the sole.

In shod horses, a handmade steel shoe with symmetrical branches was made and fitted in a competition style, terminating 5 mm from the heel buttresses. Nail placement was restricted to the dorsal half of the shoe and dorsal toe-clips were present. For the unshod cohort of horses, to avoid shearing and tearing of the hoof wall, the outer hoof wall was slightly bevelled.

Digital photography and foot mapping protocol

Hoof measurements were performed from digital photographs of solar and lateral views of the hoof (White et al., 2008). Photographs were obtained using Fuji Finepix and Kodak c875 digital cameras, placed on a fixed tripod at a distance of 70 cm. For lateral views the image was centred on the hoof wall, 1 cm distal to the coronary band, halfway between the dorsal hoof wall and palmar heel. For solar views, the image was centred at the point of the frog, with the sole positioned perpendicular to the camera. Images were calibrated using Invicta callipers (Findel Education) with measures performed at the time of image acquisition.

Twelve external hoof measures were chosen for this study based on measures used in previous work (Colles, 1983; Kummer et al., 2006; Dyson et al., 2011) and to answer the aims of this study (Fig. 1). A number of these measures related to a point 9.5 mm palmar to the apex of the frog (known to hoof care professionals as 'Duckett's dot'). This is an important external reference point and is thought to relate to a line running vertically from the extensor process of the distal phalanx, through the centre of the semilunar line and therefore considered to represent the centre of pressure (COP). It differs from another external reference point, the centre of rotation (COR) which is understood to relate to the widest point of the foot (O'Grady and Poupard, 2003) intimating the centre of articulation of the distal interphalangeal joint (DIPJ). In the present study, COR was determined as the intersection of lines drawn from the heel terminus to the opposing breakover point at the toe (Fig. 1). Measurements were taken from the dorsal toe (DT) to the heel bulb (HB) or heel buttresses (HBUT). These latter two points relate to the morphology of the heels (heel bulb) as well as accounting for the weight-bearing surfaces in the palmar heel region (heel buttress).

Measurements made to test the reliability of the trimming protocol (cadaver limbs only) included sagittal length from the heel bulb to dorsal toe (SL), heel bulb to breakover point (HB-BO), heel bulb to frog apex (HB-FRA), heel bulb to centre of pressure (HB–COP) and heel bulb to centre of rotation (HB–COR). Differences in HB-BO, HB-FRA, HB–COP and HB–COR following trimming were expressed as a proportion of SL difference. These differences were compared as a measure of reliability of the trimming protocol.

Dorsal hoof wall length (DHWL), distance from the dorsal toe to the centre of rotation (DT-COR), distance from the heel buttress to centre of pressure (HBUT-COP) and distance from the heel buttress to the dorsal toe, known as the bearing border length (BBL) were used to determine geometric proportions in this study, based on Duckett's theory of hoof balance. Since Duckett's theory is related to all horses and ponies regardless of size, differences in the hoof measurements DHWL, DT-COR and HBUT-COP were calculated as a proportion of BBL before and after trimming.

Inherent to the trimming protocol used in this study, reduction of heel height can extend the BBL in a palmar direction at the heels. Therefore, net heel migration was additionally quantified as a measure of the difference between the change in BBL and change in COP-COR before and after trimming where a negative value indicated palmar heel migration. The behaviour of the solar arch of the foot may be inferred by the COP-COR distance, where an increase in COP-COR indicates solar arch flattening and vice versa occurs with a decrease in COP-COR. Finally, dorsal hoof wall angles (DHWA), heel angles (HA) and heel lengths (HL) were also measured before and after trimming.

Radiography

To determine the relationship between the external reference points COP and COR to internal anatomical landmarks (extensor process of the third phalanx [P3] and the centre of rotation of the DIPJ), lateromedial and dorsopalmar radiographs of 22 cadaver limbs were obtained (Fig. 2). Limbs sectioned through the antebrachiocarpal joint were placed in a custom built press with the superficial digital flexor tendon (SDFT) and deep digital flexor tendon (DDFT) secured into the limb retaining socket at the head of the press.

Limbs were loaded at 8.9 kg/cm^2 with the bearing border of the foot in full contact with the ground with a straight hoof pastern axis and the third metacarpal perpendicular to the bearing border of the foot (Turner, 1992). A radiodense marker of known length (60 mm) was fixed to the dorsal hoof wall and a radiodense pin placed 9.5 mm palmar to the dorsal tip of the frog approximating the location of Duckett's dot (COP). Images were generated using a Porta 1030 digital X-ray unit (Job Corporation), processed using Vetray CR2430 digital reader (Sedacal) and converted to JPEG images with measurements performed using Ontrack digital measurement software (Lameness Solutions). The radiographic COR of the distal interphalangeal joint was identified based on the work of Eliashar et al. (2002). COP-COR distance was calculated and COR mapped onto the image, using the dorsal hoof wall marker for correction of magnification by beam divergence.

Statistical analysis

Unless otherwise stated, data are presented as means ± s.d. Data were tested for normality using the Anderson–Darling test. Significant differences were determined by Students t test and one-way analysis of variance (ANOVA) with Tukey post hoc corrections. For equivalence testing of the hoof balance indicators dorsal hoof wall length (DHWL), the distance from the dorsal toe to the centre of rotation (DT-COR) and the distance from the heel buttress to centre of pressure (HBUT-COP) as a proportion of BBL, Fieller's test for bioequivalence was used with equivalence intervals of 2.8% (Christley and Reid, 2003). The value 2.8% was calculated using a margin of error of 3.2 mm of the mean BBL following trimming (114 mm). Upper and lower P values were calculated for each comparison with a P value of <0.05 considered statistically significant. Analyses were performed using Minitab 16.

Results

Cadaver study

Of the external hoof measures HB-BO, HB-FRA, HB-COR and HB-COP as a proportion of sagittal length (SL), only HB-COR/SL showed a significant difference in proportion post trim (0.46 ± 0.04 pre trim to 0.50 ± 0.02 post trim, P < 0.05) (Fig. 3). Fig. 4 demonstrates the differences in each external hoof measure before and after trimming as a proportion of sagittal length ranked for individual feet

[2] See: http://www.lantra.co.uk/getattachment/fc228f7a-18de-479d-a91e-a57bab77b889/Farriery-NOS-%28Jan-2010%29.aspx (accessed 8 September 2015).

[3] See: http://www.forgemagazine.co.uk/site/index-1newsarchiveapr10.html (accessed 8 September 2015).

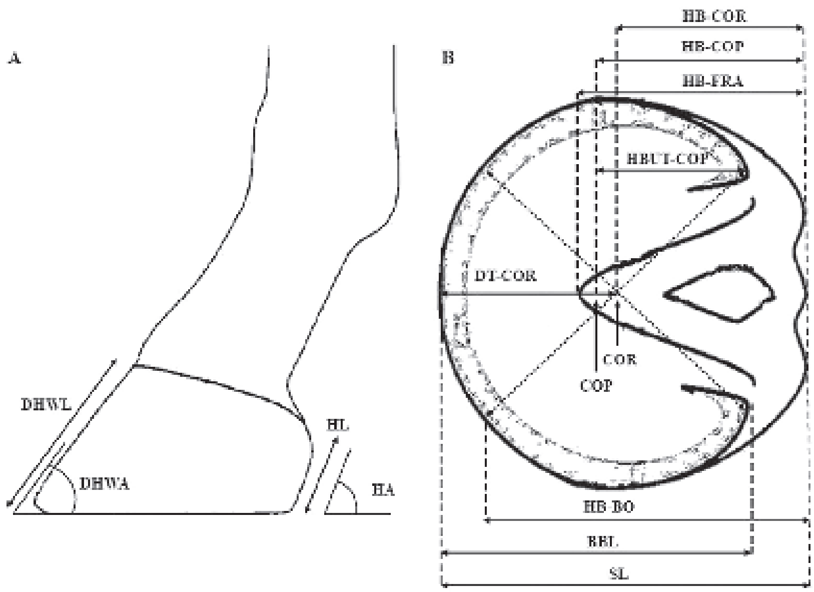

Fig. 1. Schematic view of the external reference points from lateral (A) and solar aspects (B). BBL, length in the sagittal plane between the heel buttresses and dorsal toe; COP, point 9.5 mm palmar to the apex of the frog; COR, point formed by the intersection of the heel buttresses and opposite breakover point (dotted lines); DHWA, angle between the dorsal hoof wall and horizontal ground; DHWL, length in the sagittal plane from the coronary band to the dorsal toe; DT-COR, length in the sagittal plane from the dorsal toe to COR; HA, angle between the heel bulb and horizontal ground; HB-BO, length from the heel bulb to the point of breakover (BO); HB-COP, length from the heel bulb to COP; HB-COR, length from the heel bulb to COR; HB-FRA, length from the heel bulb to the apex of the frog; HBUT – COP, length in the sagittal plane from heel buttresses to a point 9.5 mm palmar to the apex of the frog; HL, length from the coronary hair line to the bearing border of the heel; SL, sagittal length from the heel bulb to the dorsal toe.

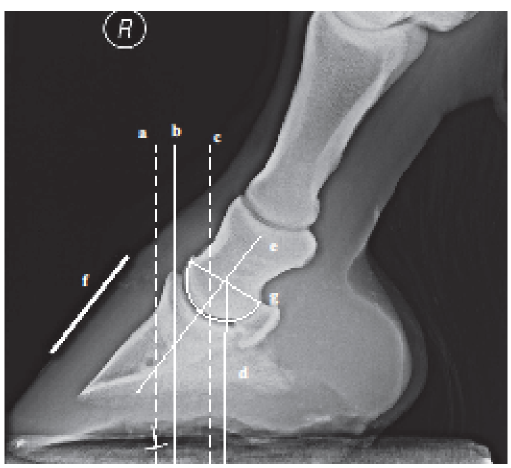

Fig. 2. Lateromedial radiographic projection of the equine digit showing external hoof measure centre of pressure (COP) (dashed line a), vertical line through extensor process of P3 (solid line b), external measure of centre of rotation (COR) (dashed line c) and vertical line through centre of rotation of the distal interphalangeal joint (DIPJ) (solid line d). The centre of rotation of the DIPJ was located as the intersection of a line (e), parallel to the dorsal hoof wall marker (f), midway through the DIPJ at the chord of the arc (g) of the surface of the DIPJ. External hoof measure COP (dashed line a) was located at the entry point of a metallic pin, 9.5 mm palmar to the point of the frog and external hoof measure COR (dashed line c) was calculated from the COP-COR distance and mapped onto the image after correction for magnification.

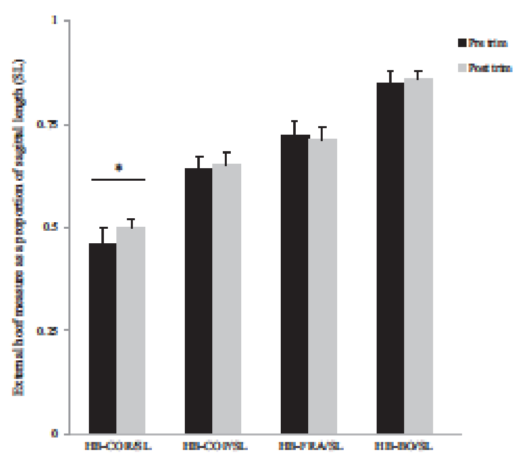

Fig. 3. Bar chart of external hoof measures (HB–COR, HB–COP, FRA and BO) as a proportion of sagittal length (SL) before (pre) and after (post) trimming using the standardised trimming protocol as described. SL, sagittal length from the heel bulb to the dorsal toe; HB–COR, length from the heel bulb to a point formed by the intersection of the heel buttresses and opposite breakover point; HB–COP, length from the heel bulb to a point 9.5 mm palmar to the apex of the frog; HB–FRA, length from the heel bulb to the apex of the frog; HB–BO, length from the heel bulb to the point of breakover. Bar chart represents means ± s.d., $n = 49$ limbs. $^{*}P < 0.05$.

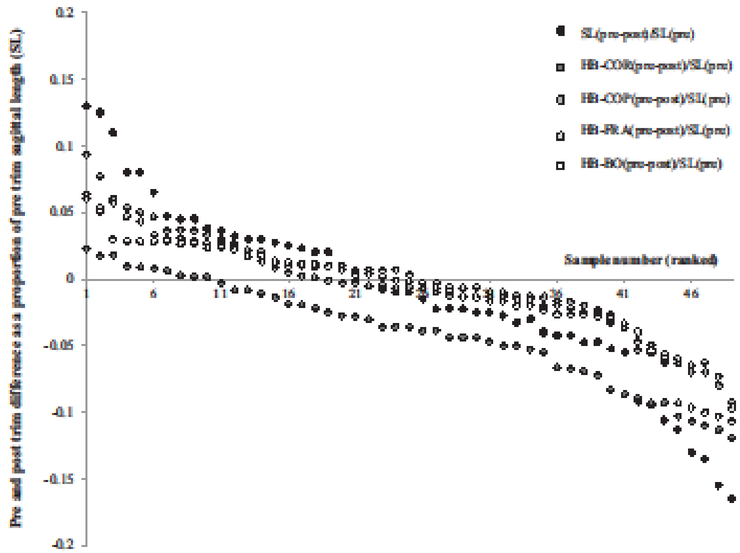

Fig. 4. Ranked plot of 49 cadaver feet showing the difference of hoof measures (SL, HB-COR, HB-COP, HB-FRA and HB-BO) before (pre) and after (post) trimming using the standardised trimming protocol described in Materials and Methods as a proportion of pre trim sagittal length. SL, sagittal length from the heel bulb to the dorsal toe; HB-COR, length from the heel bulb to a point formed by the intersection of the heel buttresses and opposite breakover point; HB-COP, length from the heel bulb to a point 9.5 mm palmar to the apex of the frog; HB-FRA, length from the heel bulb to the apex of the frog; HB-BO, length from the heel bulb to the point of breakover.

Table 1
Summary of equivalence of means between three hoof balance indicators as a proportion of the bearing border length (BBL) before and after trimming in the cadaver and prospective cohort studies. Data are presented as means ± s.d. with equivalence intervals based on accepted tolerance of ±2.8%. Upper and lower *P*-values are shown for each comparison with significance set at $P < 0.05$.

Group	Trim number	Comparison	Hoof balance indicator post-trim as a proportion of BBL	Equivalence interval	Upper and lower *P*
Cadaver	–	DHWL/BBL; DT-COR/BBL	0.62 ± 0.03; 0.59 ± 0.02	±0.017	<0.001; 0.005
		DHWL/BBL; HBUT-COP/BBL	0.62 ± 0.03; 0.58 ± 0.03	±0.016	<0.001; <0.001
		DT-COR/BBL; HBUT-COP/BBL	0.59 ± 0.03; 0.58 ± 0.03	±0.016	<0.001; 0.266
Unshod group	1	DHWL/BBL; DT-COR/BBL	0.58 ± 0.07; 0.57 ± 0.04	±0.017	0.020; 0.319
		DHWL/BBL; HBUT-COP/BBL	0.58 ± 0.07; 0.58 ± 0.05	±0.017	0.263; 0.044
		DT-COR/BBL; HBUT-COP/BBL	0.57 ± 0.04; 0.58 ± 0.05	±0.017	0.440; 0.001
	2	DHWL/BBL; DT-COR/BBL	0.53 ± 0.03; 0.54 ± 0.03	±0.017	0.240; 0.002
		DHWL/BBL; HBUT-COP/BBL	0.53 ± 0.03; 0.56 ± 0.05	±0.017	0.001; 0.400
		DT-COR/BBL; HBUT-COP/BBL	0.54 ± 0.03; 0.56 ± 0.05	±0.017	0.414; 0.001
	3	DHWL/BBL; DT-COR/BBL	0.54 ± 0.02; 0.53 ± 0.05	±0.017	0.001; 0.171
		DHWL/BBL; HBUT-COP/BBL	0.54 ± 0.02; 0.53 ± 0.05	±0.017	0.015; 0.055
		DT-COR/BBL; HBUT-COP/BBL	0.53 ± 0.05; 0.53 ± 0.05	±0.017	0.184; 0.024
Shod group	1	DHWL/BBL; DT -COR/BBL	0.58 ± 0.03; 0.57 ± 0.04	±0.017	0.023; 0.333
		DHWL/BBL; HBUT-COP/BBL	0.58 ± 0.03; 0.57 ± 0.04	±0.017	0.023; 0.333
		DT-COR/BBL; HBUT-COP/BBL	0.57 ± 0.04; 0.57 ± 0.04	±0.017	0.141; 0.149
	2	DHWL/BBL; DT-COR/BBL	0.57 ± 0.03; 0.56 ± 0.06	±0.017	0.075; 0.415
		DHWL/BBL; HBUT-COP/BBL	0.57 ± 0.03; 0.57 ± 0.04	±0.017	0.110; 0.116
		DT-COR/BBL; HBUT-COP/BBL	0.56 ± 0.06; 0.57 ± 0.04	±0.017	0.420; 0.097
	3	DHWL/BBL; DT-COR/BBL	0.57 ± 0.02; 0.59 ± 0.03	±0.017	0.276; 0.001
		DHWL/BBL; HBUT-COP/BBL	0.57 ± 0.02; 0.55 ± 0.05	±0.017	0.009; 0.394
		DT-COR/BBL; HBUT-COP/BBL	0.59 ± 0.03; 0.55 ± 0.05	±0.017	<0.001; 0.050

BBL, length in the sagittal plane between the heel buttresses and dorsal toe; DT-COR, length in the sagittal plane from the dorsal toe (DT) to COR; DHWL, length in the sagittal plane from the coronary band to the dorsal toe; HBUT-COP, length in the sagittal plane from heel buttresses to a point 9.5 mm palmar to the apex of the frog.

($n = 49$) showing that intra-horse external hoof proportions followed a similar pattern.

Mean dorsal hoof wall/heel wall ratio before trimming was 2.4 ± 0.6:1, increasing to 2.8 ± 0.7:1 after trimming ($P < 0.001$). Mean dorsal hoof wall and heel angle difference, however, did not significantly change between trimming (−13 ± 11° before trimming; −14 ± 6° after trimming, $P = 0.65$).

Using the three proportional measurements based on Duckett's theory, HBUT-COP/BBL increased whereas DHWL/BBL and DT-COR/BBL decreased after trimming (all $P < 0.05$). For hoof balance to be achieved, all three proportional measurements need to show equivalence using the pre-determined equivalence intervals of ± 2.8%. Table 1 shows that in the cadaver group, these three hoof balance proportions were not equivalent following trimming.

Of the 22 cadaver limbs radiographed, there was no significant difference between the external reference point COR and the centre of rotation of the DIPJ. The location of COP to the extensor process of the distal phalanx, however ranged from to −4.4 to −10.9 mm (mean −7.4 ± 6.8 mm, $P < 0.001$).

Prospective cohort study

In both cohorts after three trimming cycles, dorsal hoof wall and lateral heel angle parallelism was absent, with mean differences of −10.8 ± 1.8° (unshod) and −15.7 ± 0.8° (shod). DHWL:LHL ratio in the unshod group increased from 2.6:1 to 2.8:1 ($P < 0.01$) after three trimming cycles with no significant difference in the shod group. Heel migration in the shod group after three trimming cycles was −7.1 ± 1.6 mm ($P < 0.05$) compared to 2.3 ± 4.9 mm in the shod group. BBL difference after three trimming cycles in the unshod group was −4.9 ± 6.9 mm compared to −2.9 ± 5.3 mm in the shod group. When assessing the COP-COR distance the shod group showed significant increase in COP-COR over the study period (8.6 ± 6.5 mm) ($P < 0.05$) whereas in the unshod group this value did not significantly change (5.9 ± 10.5 mm); this appeared to be primarily due to an increase in HB-COP in shod horses.

Table 1 shows that equivalence between the three hoof balance measures (DHWL, HBUT-COP and DT-COR) as a proportion of BBL (Duckett's theory) was absent in both the unshod or shod groups

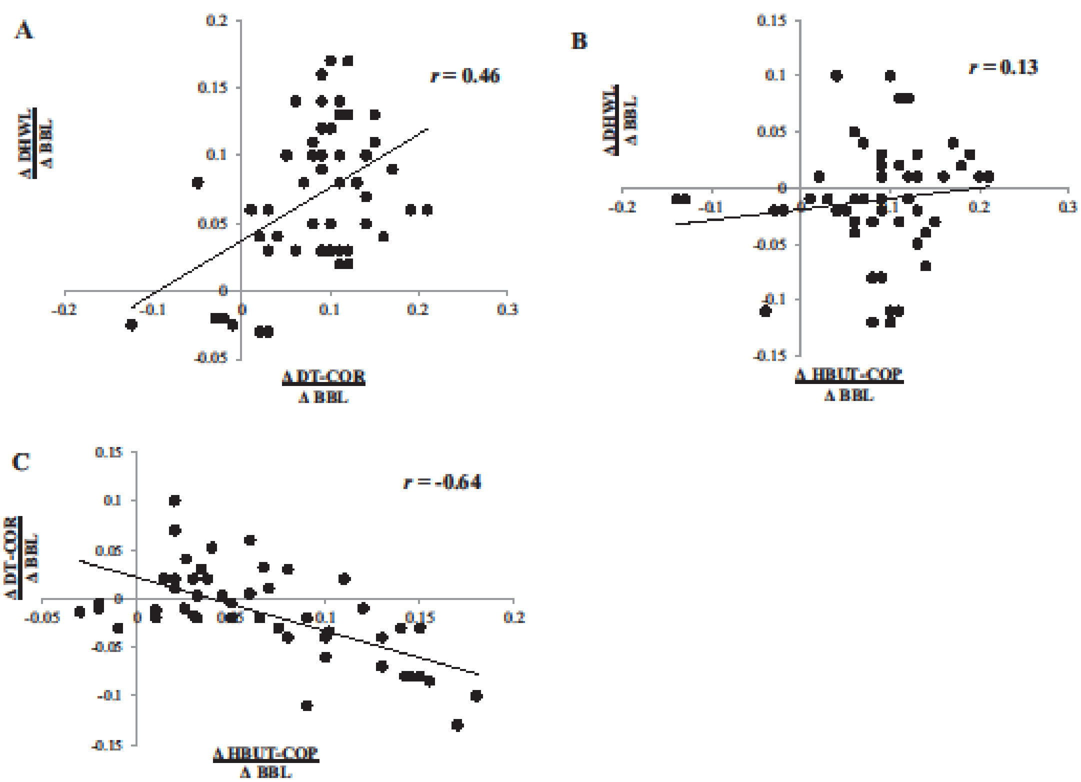

Fig. 5. Scatter diagrams representing the relationship between the differences before (pre) and after (post) trimming using the standardised trimming protocol of three hoof measures (DHWL, DT-COR and HBUT-COP) as a proportion of the pre and post trimming difference of BBL for each fore foot in the cadaver (A–C, $n = 49$, black circles), unshod in vivo (D–F, $n = 40$, dark grey circles) and shod in vivo groups (G–I, $n = 12$, light grey circles). For the cadaver group the differences were measured before and after one trim whereas for the in vivo groups the differences were between pre trim 1 and post trim 3. DHWL, length in the sagittal plane from the coronary band to the dorsal toe; DT-COR, length in the sagittal plane from the dorsal toe to COR (identified as the intersection of the heel buttresses with the opposite breakover point); HBUT-COP, length in the sagittal plane from heel buttresses to a point 9.5 mm palmar to the apex of the frog; BBL, length in the sagittal plane between the heel buttresses and dorsal toe.

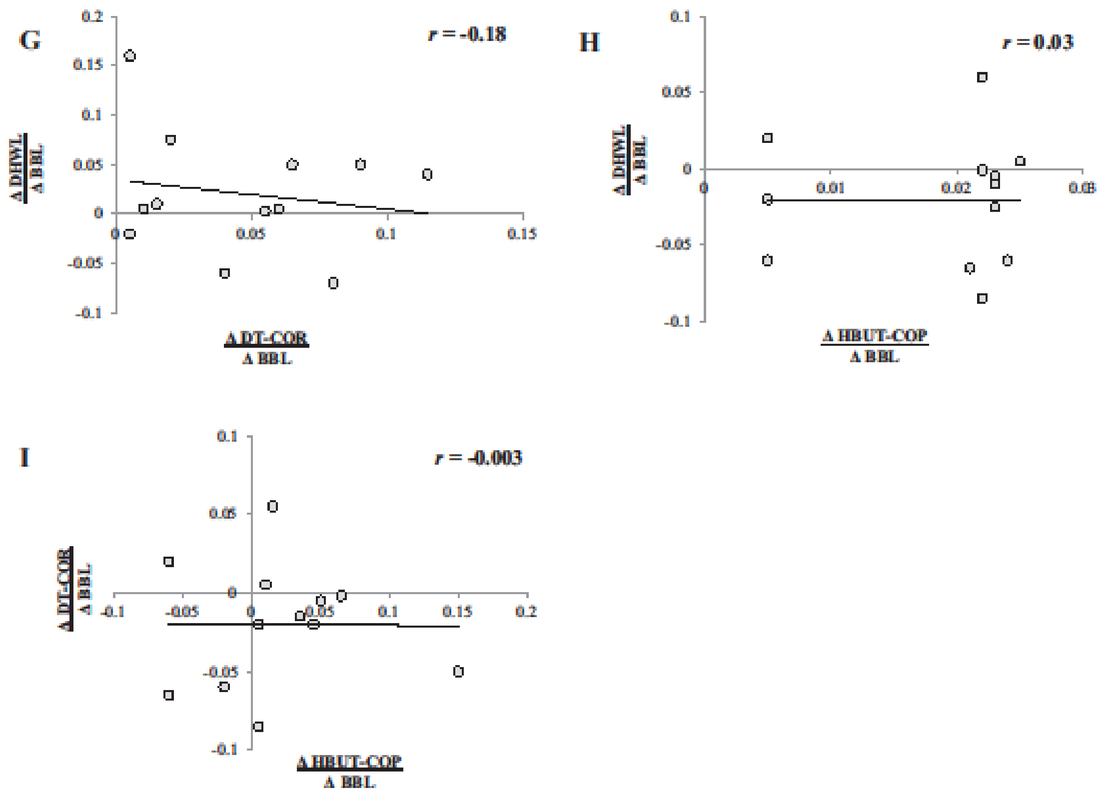

Fig. 5. (*continued*)

time. There is also a potential confounding effect of non-randomising the live cohort groups where horses were pre-selected for being shod or unshod. Ideally a cross-over cohort study would have removed this effect and would entail repeating the study on the same horses the following season. Since we were primarily interested in geometric proportions based on Duckett's theory, the premise we followed was that balance should be achievable regardless of breed.

A fundamental component of hoof trimming is to control BBL. This is achieved by reducing the hoof wall length and rasping the outer dorsal hoof wall, colloquially known as 'backing up the toe'. By manipulating the base of support it is believed that heels will migrate in a palmar direction. In the shod feet, increases in the COP-COR distance, primarily due to reduction in hoof wall height and increases in HBUT-COP following trimming, leads to stretching of the frog and therefore solar flattening, whereas in unshod feet BBL increased with no significant change in COP-COR and the heels migrated in a negative (palmar) direction. These findings help to explain what is experienced in practice and the COP-COR distance appears to be a critical influence on heel migration and hence dorsopalmar proportions.

The reorientation of the hoof capsule will alter the dynamic effects of loading, probably through decreasing both flexor and extensor moment arms and shifting COP dorsally. Since the horse is capable of compensating for changes in hoof morphology over time through postural adaptation (Moleman et al., 2006), by engaging the frog and solar margin in weight-sharing the contact area is increased and the resultant contact pressure (per cm^2) is reduced.

The present study does not support Duckett's theory of equivalence for hoof balance. Using three key hoof balance indicators, as a proportion of bearing border length, equivalence of means was not shown in any group. Despite there being little individual difference in the mean values in each sample group, the lack of equivalence was evident in both the cadaver group and both prospective cohort groups. The absence of correlation in any of the study groups between each proportional hoof balance indicator after trimming (as shown in Fig. 5) may explain the absence of equivalence of means tested for in this study. In this respect, the commonly used theory of geometric proportions for hoof balance does not hold true.

Our findings also add weight to other studies questioning the commonly accepted measures of ideal hoof balance of parallelism and the 3:1 ratio of the dorsal hoof wall to the heel (Eliashar et al., 2004; Dyson et al., 2011). Using criteria of dorsal hoof wall/heel parallelism and 3:1 ratio of hoof wall to heel, our study showed that 74–91% of horses would fall outside of these ideals, even after three trimming cycles. The findings that commonly prescribed ideals of correct hoof measures were absent questions the current concepts of a standardised model of hoof balance that is applicable to all horses.

Conclusions

This study has investigated commonly accepted hoof balance indicators and measures of hoof balance and shown that there is little evidence to support a number of widely held beliefs in the veterinary and farriery fields. It shows how theories of hoof balance, such as Duckett's theory of geometric proportions, can be assessed and evaluated using cohorts of horses over a number of trimming cycles and identify the influence of shoeing on these hoof measures. It therefore supports the notion of trimming on an individual basis rather than trimming all feet to one ideal hoof model.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of this paper.

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