Hoof shape and loading in sound and lame horses; how this is influenced by farriery

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Sarah Seery

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Acknowledgements

This thesis is dedicated to Elidir. May you rest in peace, my son.

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Thesis Abstract

Hoof shape and loading in sound and lame horses; how this is influenced by farriery

By Sarah Seery

Hoof abnormalities and lameness events are associated with foot shape and loading patterns. Farriery has an important role in maintaining optimal foot shape and manipulating foot loading, yet there are few published data on long-term changes in these features, or on optimal foot trimming. Previous clinical studies of lame horses have not evaluated foot shape alongside loading and clinical findings. Epidemiological studies have linked equine lameness events with the use of arena surfaces, however arenas have not previously been studied over different seasons, or longitudinally.

This thesis examined the following hypotheses: farriery affects foot shape and loading, both at a single time point and over time; foot shape is influenced by both genetic and environmental factors; lameness results in poor foot balance and decreased loading of affected limbs; arena surfaces are used by a majority of horses and their surface properties change significantly between seasons. In the first study horses free from lameness were recruited. Photographs of forelimb feet enabled acquisition of foot shape measurements pre- and post-trimming by a farrier at a single timepoint. This highlighted a decrease in foot lengths and increase in foot angles post-trimming. A Tekscan™ commercial pressure mat was used to collect objective foot loading data pre-and post-trimming, demonstrating that post-trimming the most common change to loading was increased pressure on the central region of the foot. Collection and analysis of a questionnaire identified that farrier, breed and exercise were the most important factors influencing foot shape.

The second study was longitudinal. Digital photographs and pressure mat readings were obtained for forelimb feet, pre- and post-trimming. This study revealed that the hoof capsule enlarged over time. Lame and sound limbs showed different loading patterns at the end of the study period, with some horses exhibiting greater loading by the lame limb than the sound limb.

The third study recruited horses referred to the Philip Leverhulme Equine Hospital for investigation of lameness localised to the foot. Digital photographs and pressure mat readings were collected at a single time point. Clinical history and magnetic resonance imaging (MRI) findings were compared with foot shape and loading results. Lame feet in this study had different loading patterns from sound feet in the first study. Feet affected by navicular disease were shown to be smaller in size with steeper angles compared with other MRI findings.

The fourth study comprised a questionnaire on the use of arena surfaces by horses in the first study and surface testing of 11 arenas for hardness (Clegg Hammer), resistance to penetration (Longchamps penetrometer) and moisture content. Testing was carried out once in June and once in December to assess differences between seasons. Hardness and moisture content were significantly lower in June compared with December. Base material, wax and indoor surfaces significantly changed arena hardness and moisture content. Surface membrane was the most important factor affecting resistance to penetration.

These studies highlight the significant impact farriery has on foot shape and loading. Changes in these outcomes over time were found to oppose that observed following foot trimming, raising concerns about maintenance of optimal foot shape over time. Loading of lame limbs of horses affected by lameness was not always less than sound limbs. Use of arena surfaces is almost universal and surface properties can be influenced by season as well as arena construction factors.

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Chapter 1

Introduction

1.1 Background

Lameness has been reported to be the most common health problem in the horse, with estimated prevalence of around 30% in the United Kingdom (UK) equine population (Blue Cross, 2018, 2021). This is supported by a study into dressage horses in the United Kingdom which revealed that 33% had suffered a lameness event at some point during their career (Murray *et al.*, 2010). Many factors can influence the risk of a horse being affected by lameness events, including age, breed, conformation, discipline, farriery, work pattern and the properties of surfaces on which that work is done (Kobluk *et al.*, 1990; Murray *et al.*, 2006; Ducro, Bovenhuis and Back, 2009; Murray, *et al.*, 2010b). Farriery involves the application of shoes and maintenance of optimal foot shape and balance. Several conflicting theories of what constitutes the ideal foot shape remain (Caldwell, 2017; Bras and Redden, 2018). A lack of scientific literature into trimming and shoeing techniques means that farriery remains a highly subjective profession, which is not driven by evidence-based findings (Thomason, 2007).

The relationship between foot shape and lameness has been well-documented, though the causality aspect of this association has yet to be elucidated (Wright, 1993; Page and Hagen, 2002; Dyson *et al.*, 2011; Holroyd *et al.*, 2013). Greater research is required to tease out the influence of farriery on foot shape and lameness events so that evidence-based farriery protocols can be developed, which may help to reduce the pain, suffering and economic losses that accompany equine lameness in the future.

1.2 Foot structure

The highly evolved equine digit is composed of a hard, keratinised outer hoof wall that encapsulates the bony structures of the distal phalanx (P3), the distal sesamoid or navicular bone (NB) and the distal portion of the middle phalanx (P2). The hoof also houses many soft tissue structures: a network of nerves and blood vessels, the digital cushion, cartilages of P3, the deep digital flexor tendon (DDFT) as well as suspensory and collateral ligaments of the distal interphalangeal joint (Sack, 1975; Habermehl, 1981; Nickel, Schummer and Seiferle, 1986). The dorsal, medial and lateral surfaces of the hoof capsule are termed hoof wall whilst the ventral (or palmar/plantar) surface is known as the sole (Stashak, 2002).

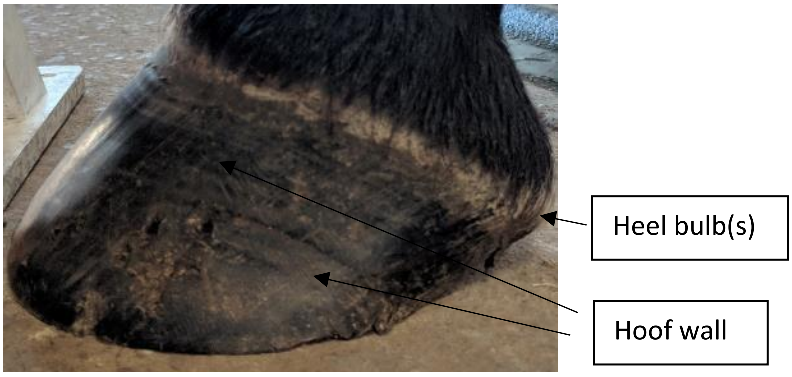

Figure 1.1: Photograph of the lateral view of an equine foot illustrating hoof wall that covers the outer surface of the dorsal, medial and lateral aspects, as well as the location of the heel bulbs

The hoof wall is composed of three distinct layers (Stump, 1967; Reilly *et al.*, 1996). Stratum internum, the innermost layer, is composed of primary and secondary epidermal laminae, which interdigitate with the dermal laminae covering the surface of P3 (Pollitt, 2010). These structures provide a huge surface area for attachment of P3 (suspensory apparatus of the distal phalanx (SADP)) to the hoof wall and consequently this attachment is very strong.

The middle layer, stratum medium, is the primary load-bearing part of the hoof wall structure and extends from the coronary band down to the bearing border of the foot, where it interacts with the ground. It is composed of keratinised cells (corneocytes) that form tubular and inter-tubular horn; these two structures are oriented at 90° to one another, creating a composite material which is strong in all directions (Bertram and Gosline, 1987; Pollitt, 2010). Within the stratum medium there are four areas of density (Reilly, Collins and Cope, 1998). The outermost is that with the highest tubule density; this is the most rigid region whilst the innermost region is the most flexible, due to being the least densely populated with tubules and having the highest water content. The outermost layer of hoof wall is the stratum externum, which is composed of mature corneocytes, and alongside supporting the weight of the horse (Pollitt, 1998), also prevents the movement of water and water-soluble molecules across the hoof surface.

The sole of the hoof is composed of tubular and intertubular horn, which is softer in nature than that of the hoof wall. The sole covers the ventral surface of the hoof capsule between the hoof wall and a structure known as the frog (Stashak, 2002). Wedge-shaped with its base at the heels, the frog merges with the heel bulbs caudally. The frog is composed of tubular horn and fatty secretions from glands in the digital cushion keep it soft and pliable. The junction between sole and hoof wall is known as the white line. It is made up of some stratum medium and stratum internum as well as terminal papillae from the laminar dermis (Pollitt, 1992).

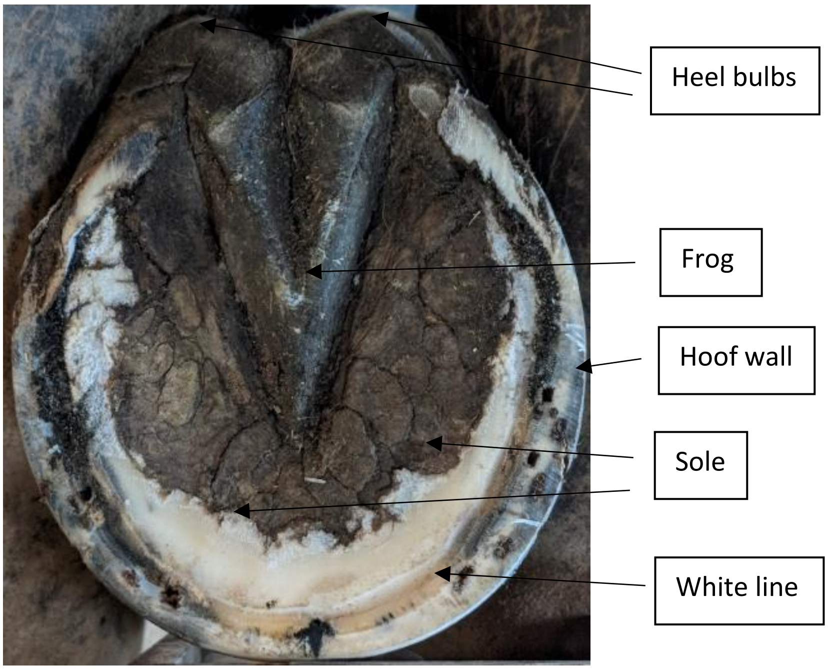

Figure 1.2: Photograph of the solar view of an equine hoof with key anatomical structures labelled

1.3 Foot function

The equine locomotor apparatus represents a highly evolved system to allow horses to move rapidly over rough terrain using long, light limbs and a hard hoof surface encasing the sensitive structures within. Various aspects of this hoof structure play a key role in dissipating the large forces encountered at the foot-ground interface, particularly at high speeds (Thomason, Biewener and Bertram, 1992; Dyhre-Poulsen, Smedegaard and Roed, 1994). One such aspect is lateral expansion of the heels during locomotion, which is thought to occur alongside flattening of the sole and descent of P3 within the foot (Colles, 1989; Thomason, Biewener and Bertram, 1992; Parks, 2003). The mechanism behind expansion of the heels has been somewhat disputed, with a number of studies demonstrating the effect of increased frog pressure on heel expansion (Colles, 1989; Roepstorff, Johnston and Drevemo, 2001). Other studies have measured low pressures in the digital cushion during loading, suggesting that the frog is not under pressure at this time, but that rotation of the middle phalanx results in heel expansion (Dyhre-Poulsen, Smedegaard and Roed, 1994). An anatomical study showed that the firmness of the digital cushion may be an important factor in support of the foot both during stance and when moving (Bowker *et al*., 1998). The findings of a more recent study supported this theory but could not confirm the role of the digital cushion in reducing the displacement of foot components, instead concluding that the primary function of the structure was to facilitate (passively or actively) movement of the caudal portion of the hoof and thus enable it to cope with variable loading environments (Taylor, 2005).

The enormous surface area of attachment between P3 and the hoof wall, through primary and secondary lamellae, promotes resistance to separation between these structures. Since this attachment comprises the main opposing force against the flexor moment of the deep digital flexor tendon (DDFT), it is an important anatomical feature that prevents rotation of P3 within the hoof capsule in a healthy horse (Leach, 1980; Colles, 1989).

The composite structure of tubular horn and intertubular horn provides the stratum medium with the ability to withstand tensile and compressive forces in multiple directions (Pollitt, 1998; Parks, 2003). Indeed this structure is capable of experiencing compressive forces of over ten times that of normal locomotion before it will result in structural failure (Thomason, Biewener and Bertram, 1992). As the main weight-bearing structure of the foot, in combination with the SADP, the stratum medium transfers ground reaction forces to the appendicular skeleton (Kasapi and Gosline, 1998). During this process the density gradient of tubules in the stratum medium allows for smooth energy transfer from the outer hoof wall to P3 (Reilly *et al.*, 1996; Reilly, Collins and Cope, 1998; Pollitt, 2010). It has been reported that over 90% of the vibrations experienced by the hoof wall as it interacts with the ground surface are dampened by the time they reach the lamellar surface of P3 (Dyhre-Poulsen, Smedegaard and Roed, 1994). This likely prevents damage occurring to internal structures of the foot.

1.4 Foot loading

1.4.1 Static foot loading

In the standing horse, the weight of the horse is opposed by ground reaction force (Figure 1.3). This force generally passes through the centre of pressure (COP), hypothesised to be located 9.5mm caudal to the apex of the frog (Duckett, 1990). A number of studies have cited the most likely method of transmission of forces to P3 and the appendicular skeleton is from the hoof wall, through the laminar interface. A study of 30, mixed-breed horses with no lameness issues found that when on a deformable surface, the ventral surface of P3 may be a weight-bearing structure due to pressure on the solar surface of the foot (Hood, Taylor & Wagner, 2001). The authors concluded that on both non-deformable and deformable surfaces, this transmission of forces is likely to play a role in loading of P3.

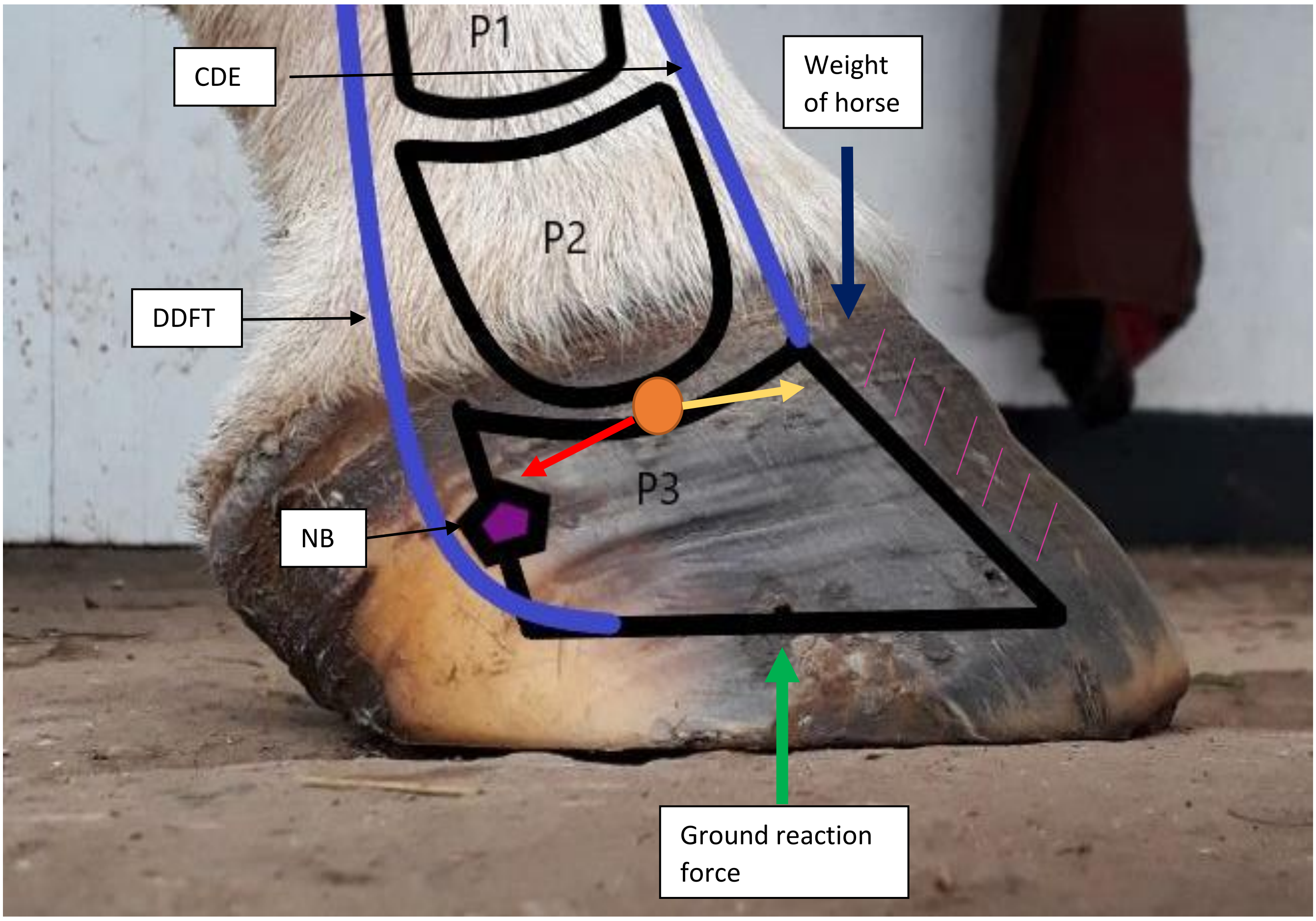

Figure 1.3: Schematic diagram demonstrating forces acting on the equine foot structure at stance. Ground reaction force (large green arrow) opposes the weight of the horse (large blue arrow). The deep digital flexor tendon (DDFT) curves around the navicular bone (NB) to insert ventrally on the distal phalanx (P3). Pink diagonal lines represent the lamellae that form the main opposition to the flexor action of the DDFT, along with the common digital extensor tendon (CDE), which runs down the dorsal aspect of the distal limb and attaches to the extensor process of P3. The red arrow represents the flexor moment, and the yellow arrow the extensor moment as described by Wilson and others (2001)

1.4.2 Dynamic foot loading

In the horse there are five phases of gait: initial contact, impact, stance, breakover and swing (Clayton, 1998) (Figure 1.4). Initial contact with the ground is commonly heel-first, but may also be flat, toe-first or lateral-landing first (Balch, 1993; Merkens and Schamhardt, 1994). Flat landing has been suggested to occur in a well-balanced foot (O'Grady and Poupard, 2003). Trimming and shoeing style as well as breed, conformation, gait, speed and ground surface can influence what part of the hoof touches the ground first (Clayton, 1990; Merkens and Schamhardt, 1994; Van Heel *et al.*, 2005; Clayton *et al.*, 2007; Mokry *et al.*, 2021).

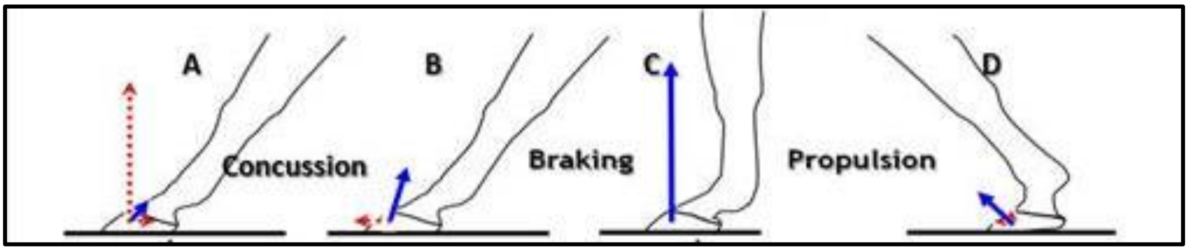

Figure 1.4: Four phases of gait where the foot is in contact with the ground, modified from Thomason et al. (2008). A indicates initial contact, B indicates impact, C indicates stance and D indicates breakover. Swing phase follows D but is not shown in this figure.

The impact phase involves the attenuation of high frequency vibrations from ground reaction force. Studies on have shown that around 90% of these vibrations are dissipated between the foot and the metacarpus, demonstrating the importance of various soft tissue structures within the foot in managing these forces (Lanovaz, Clayton and Watson, 1998; Willemen, Jacobs and Schambardt, 1999; Gustås, Johnston and Drevemo, 2006).

From the end of impact, the stance phase begins. A single study found that ground reaction force is directed slightly medial to the dorsal third of the frog (Barrey, 1990), with its craniocaudal component initially directed caudally as the horse decelerates, and latterly directed cranially as the horse moves forward. Conversely a study on five toed-in Warmblood horses found equivalent loading of the toe and heel regions during midstance (Oosterlinck *et al.*, 2015). At the end of stance, as the breakover phase begins, the ground reaction force moves cranially to the toe region (Balch, 1993; Oosterlinck *et al.*, 2015).

Breakover describes flexion of the distal limb causing it to be lifted off the ground. The duration of breakover can be affected by foot shape and shoe type (Page and Hagen, 2002). It has been hypothesised that feet with a long toe, low heel conformation have a greater 'breakover distance' and are therefore subjected to increased tension in the DDFT and forces on the NB, predisposing these structures to pathological changes over time. Conversely, shoes with a rolled toe or similar modifications can decrease the length of breakover and the forces required to produce the flexor moment and toe-off (Eliashar *et al.*, 2002; Van Heel, Weeren and Back, 2010). Despite reduction of breakover distance being successfully used in the field, researchers have struggled to prove definitively that a reduced breakover distance results in lower tension in the DDFT and surrounding structures (Chateau, Degueurce and Denoix, 2004; Lawson *et al.*, 2007; Hüppler *et al.*, 2016).

The swing phase of the stride is when the leg is in the air, moving forward in protraction,then retracted to contact the ground again. The weight of a shoe, shape of the foot and type of gait can alter the mechanics of the swing phase, with implications for the way the foot lands and all other phases that follow (Bras and Redden, 2018).

1.5 Assessment of foot shape and loading

1.5.1 Foot shape

Optimal foot shape of the horse has long been a topic of controversy. Foot shape ideals asserted in farriery literature of the 20th century and before; that contralateral foot pairs must be symmetrical and that the toe angle should measure 45°, have been largely contested by more recent work on equine podiatry (Redden, 2003; Bras and Redden, 2018). These ideals have been shown not only to be incorrect when applied across a general equine population, but in some cases damaging when a greater focus is placed on external hoof appearance rather than the function of internal structures (Bras and Redden, 2018). Various studies have highlighted the range of foot shapes that exist in healthy horses (Kummer *et al.*, 2006; Dyson *et al.*, 2011; Gordon *et al.*, 2013) exemplifying that what may be considered abnormal can still be healthy, whilst what is considered normal may be unhealthy in particular individual horses (Bras and Redden, 2018). Foot shape can be considered as an aspect of both hoof conformation and foot balance. Whilst the former refers to the static limb and is considered to be relatively permanent (Parks, 2003), foot balance can be altered in the adult horse and pertains to both the static and dynamic interactions of the foot with the ground, as well as structures within the foot (Bras and Redden, 2018).

1.5.2 Foot balance

There are a number of definitions of foot balance: some describe it as foot shape and function both in relation to the underlying surface and the limb above (Parkes and Witte, 2015). Others define ideal foot balance as that which enhances performance without impairing the long-term athletic ability of the horse (Balch, Butler, and Collier, 1997). Foot balance affects the kinetics and the kinematics of gait (Clayton, 1990; Balch *et al.*, 1995; Wilson *et al.*, 1998), with resultant changes in forces experienced by joints and soft tissues of the lower limb (Lochner *at al*., 1980; Gibson and Stashak, 1990).

There are several theories around optimal foot balance, and how it can be achieved and assessed. The natural balance model is based on the view that the way horses' feet naturally become shaped in the wild, is the ideal shape both in terms of soundness and mechanical efficiency (Ovnicek, Erfle and Peters, 1995). Duckett's method centres around particular external reference points (Duckett's dot and Duckett's bridge, Figure 1.5) for assessment of foot balance (Duckett, 1990; Eliashar, 2012). Geometric balance hinges on symmetry of the foot around the longitudinal midline of the sole, whilst dynamic balance aims for the foot to interact with the ground in a prescribed pattern during locomotion (Hood, Taylor and Wagner, 2001). Aside from the specifics of these theories, the primary ways foot balance is assessed across the board are in two planes: dorsopalmar and mediolateral.

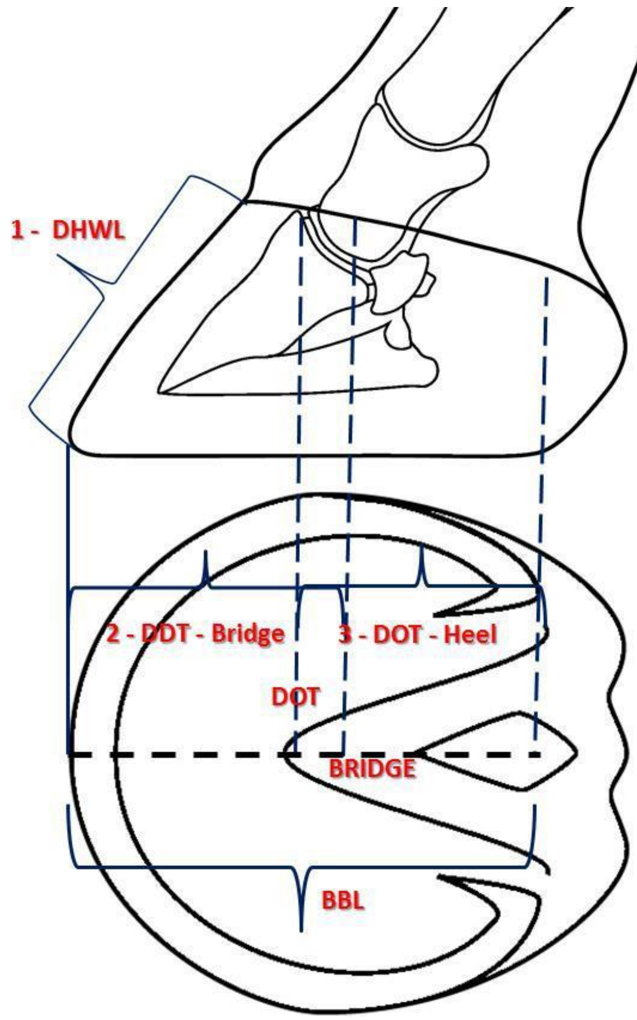

Figure 1.5: Diagram of external reference points "Duckett's Dot" and "Duckett's Bridge". Duckett hypothesised that distances 1-3 (1 = Dorsal hoof wall length, 2 = toe to widest point of the bearing border, 3 = distance from 9.5mm palmar to the frog apex to the widest point of the frog) must be equivalent for static foot balance to be achieved (reproduced from published thesis (Caldwell, 2017))

1.5.2.1 Dorsopalmar Balance

Dorsopalmar balance considers the foot in the sagittal plane. This can be considered in terms of the hoof-pastern axis (HPA). If the angle of the pastern is steeper than the dorsal hoof wall then the HPA is described as 'broken-forward', and if the opposite is true it is described as 'broken-back' (Figure 1.6). The ideal is felt to exist when the foot angles (dorsal hoof wall and heel angle) are both parallel to that of the pastern (Colles, 1983; Stashek and Adams, 1987). Dorsopalmar imbalance has been associated with various musculoskeletal conditions, most notably navicular disease (Wright, 1993; Page and Hagen, 2002) as well as risk of injury in racehorses (Kobluk *et al.*, 1990; Pinchbeck *et al.*, 2004). Broken back HPA often occurs in combination with collapsed heels. These are common hoof abnormalities in Thoroughbreds, however horses may also become prone to such a conformation as a result of long shoeing intervals, or trimming protocols that aim to achieve it (Stashek and Adams, 1987; Pinchbeck *et al*., 2004).

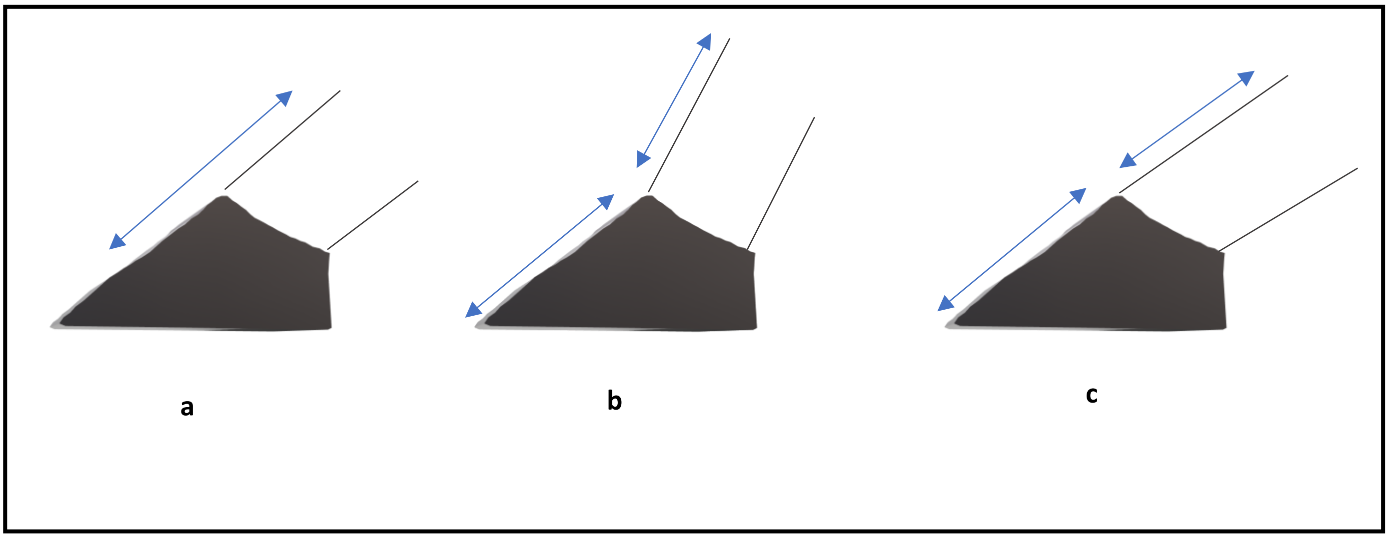

Figure 1.6a-c: Diagrams illustrating equine dorsopalmar balance and imbalance in terms of the hoof-pastern axis (HPA). a: straight hoof-pastern axis, hoof wall angle is parallel to pastern angle; b: broken back hoof-pastern axis, pastern angle is steeper than hoof wall angle; c: broken forward hoof-pastern axis, pastern angle is less steep than hoof wall angle.

1.5.2.2 Mediolateral balance

Mediolateral balance refers to symmetry of the foot when observed from the dorsal or palmar aspect. The foot is considered to have mediolateral imbalance when the medial and lateral sides are of a different length or angle (Figure 1.7) (Balch, White and Butler, 1991; Balch *et al*., 1997). This condition has been shown to cause uneven loading on joints of the distal limb (Wilson *et al*., 1998), which is likely to predispose such joints to degenerative conditions such as osteoarthritis or cause damage to soft tissue structures supporting the joints (Dyson, 2011).

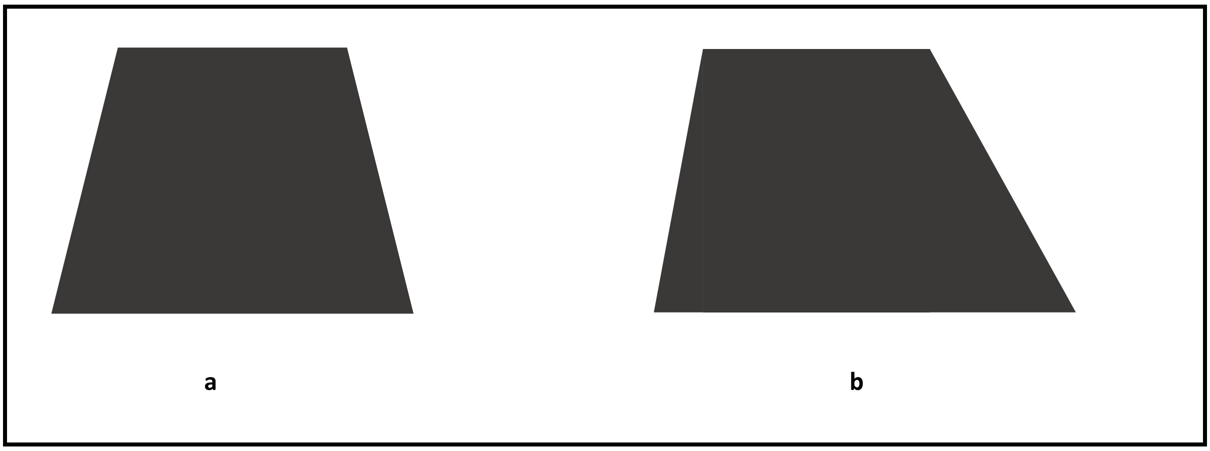

Figure 1.7a-b: Schematic diagram illustrating equine mediolateral foot (im)balance from the dorsal view. a: foot with symmetrical mediolateral balance, length and angle of hoof walls are equal to one another; b: foot with mediolateral imbalance, length and angle of hoof walls are not equal.

1.5.2.3 Uneven foot pairs

Although dorsopalmar or mediolateral imbalance are generally assessed within the foot, observing differences between feet of contralateral limbs is also relevant to preventive foot care. Asymmetric or 'uneven' forelimb foot pairs, defined as those have different shape and size from one another (Van Heel *et al.*, 2006), have been associated with early retirement in both show-jumpers and dressage horses (Fournet-Hanocq and Ricard, 1997; Ducro *et al.,* 2009). A recent study of sound riding school horses in England identified left-right asymmetry in the dorsal hoof wall angle (DHWA); the differences between contralateral limbs increased with greater horse height and mass (Leśniak *et al.*, 2019). A study of sport horses in New Zealand also identified asymmetry in foot pairs, though in most cases these went untreated (Labuschagne *et al.*, 2017). Such differences may reflect how contralateral feet are loaded, resulting in a greater injury risk to one or other limb. Alternatively, these findings may reflect a degree of normal variation within the equine population.

1.6 Farriery

The act of shoeing horses with a nailed metal shoe is thought to have begun around the 5th century, though there is little written evidence to support this. Bronze shoes were being used across Europe by 1000 AD (Caldwell, 2017). Ready-made shoes were available to buy in the 13th century, with hot-shoeing becoming commonplace in the 16th century. A shift in farriery and equine care texts to a more medical persuasion from the 1720s onwards has been documented previously (McKay, 2009). By the end of the 1800s further works on horse feet and shoeing had been produced (Russell, 1897; Dollar, 1898). Since that time, despite huge advances in recent decades in terms of equine biomechanical research and technology to support such studies, the art of farriery remains just that:

an art rather than a science. Care, trimming and shoeing of the equine foot is carried out in much the same way now as it has been for centuries, since, until recently, there has been little scientific research into the actual shoeing or trimming process.

1.6.2 Farriery and foot balance

As well as fitting and placing the shoe, one of the primary roles of a farrier is to balance the horse's foot. Farriers have a unique opportunity to maintain foot balance through regular trimming of horses under their care, and consequently minimise the risk of lameness events (Gill, 2007; Jackman, 2019). Although some objective measurement tools are available, assessment of foot balance remains largely subjective (Van Heel *et al*., 2004; Eliashar, 2007). This can result in significant variability both between individual farriers and between consecutive shoeing cycles of the same farrier (Kummer *et al*., 2009). The lack of scientific evidence around different models of foot trimming and balance inhibit the farriery and veterinary professions from moving forward with evidence-based protocols. As described in section 1.2.1, there are a number of contradictory theories regarding foot balance, with no literature to support the use of one over another or in what situations each theory might be applied correctly. This may lead to inappropriate application of these approaches and consequently poor foot health and lameness.

1.6.2.1 Foot balance changes over the shoeing cycle

Although farriers attempt to balance the foot during trimming, the foot changes shape as it grows during the interval before the next trim. If shod, this interval has been reported anecdotally to be around 4-8 weeks in most horses (Leśniak *et al.*, 2017). During this time, the toe of the hoof will grow, whilst the heel is worn by the shoe, which can result in changes in foot balance. Longer shoeing intervals can predispose horses to foot imbalance, particularly in the dorsopalmar plane. Studies have shown a 3.5° decrease in the hoof wall angle over an 8-week shoeing cycle, resulting in a broken back HPA and increased forces through the DDFT and on the NB (Van Heel *et al*., 2005; Moleman *et al*., 2006). Similarly, a 2.6° change in hoof wall angle was recorded over a 4-6 week shoeing interval in a population of working horses, leading to the recommendation to shoe horses frequently to avoid poor dorsopalmar balance (Leśniak *et al.*, 2017).

1.6.3 Association with lameness

As well as their role in managing foot balance, farriers aim to protect the horse's foot. This often involves application of metal shoes, which alter the way horses interact with the ground surface (Moyer and Anderson, 1975, Riemersma *et al.,* 1996). The weight of a shoe increases the inertia of the distal limb, and shod horses have been shown to experience greater maximal forces than those that are unshod (Roepstorff, Johnston and Drevemo, 1999). These changes can increase the risk of damage to structures within the limb. Time since shoeing, styles of foot trimming and shoe modifications have also been shown to be associated with musculoskeletal injuries (Kane *et al*., 1998; Pinchbeck *et al*., 2004). It has been demonstrated that different shoe types and application of studs to shoes can result in significant alterations in distribution of weight over the foot surface (Hüppler *et al*., 2016). This can have repercussions for other structures in the distal and proximal limb, resulting in uneven wearing or strain, and ultimately increased risk of orthopaedic injury.

As well as the above impacts, conventional metal shoes have been shown to restrict heel expansion during locomotion compared with unshod horses or those shod with a split-toe shoe (Dyhre-Poulsen, Smedegaard and Roed, 1994; Roepstorff, Johnston and Drevemo, 2001; Brunsting *et al*., 2019). Long term restriction of the heels has been linked to the development of contracted heels and consequent lameness events in affected horses.

1.7 Intrinsic factors affecting foot shape

Conformation, particularly of the distal limb, can affect foot shape and is thought to be a significant factor in lameness development in both hind and fore limbs of the horse (Parks, 2003; Ross, 2011). Horses that have abnormal conformation will have increased susceptibility to non-physiological loading and consequently lameness in certain regions or structures (Stashak, 2002; Parks, 2003). Base-narrow or base-wide conformation, for example, will cause a horse to load primarily on the lateral or medial aspect of the foot, respectively (Figure 1.8). This leads to that same side of the limb being subject to greater forces during locomotion (Stashak, 2002). Base-narrow may be accompanied by toe-in or toe-out conformation, whilst base-wide is often accompanied by toe-out conformation (Figure 1.9).

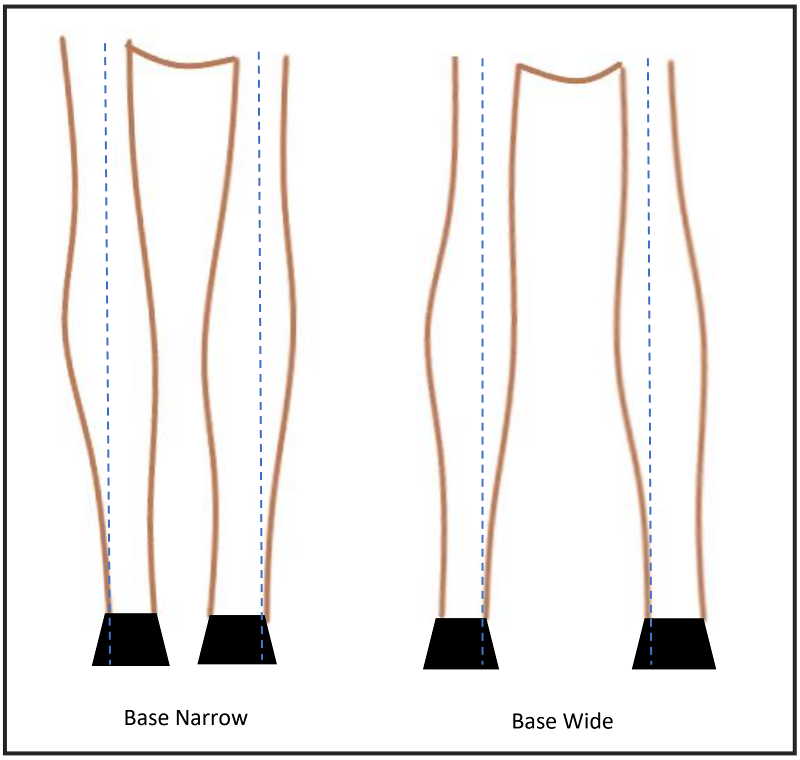

Figure 1.8: Diagram illustrating base narrow and base wide conformation of the equine forelimbs. Blue dotted lines indicate the plumb line of forces down the limb and consequently how lateral and medial aspects of the limb can become overloaded with these conformation types

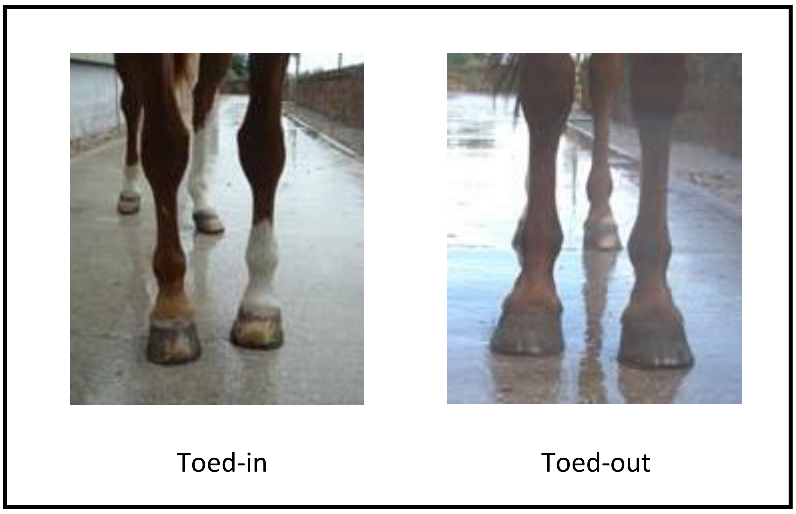

Figure 1.9: Photographs showing examples of toed-in and toed-out conformation in equine forelimbs

Breed is also a factor which may affect foot shape; Thoroughbreds have been reported to have 'flat' feet – prone to long toe, low heel conformation (Morrison, 2013). Conversely native breeds are more likely to have upright, boxy feet. A number of studies have documented high prevalence of asymmetry in forelimb foot pairs in Warmbloods (Ducro *et al.*, 2009; Wilson, McDonald and O'Connell, 2009).

1.8 Extrinsic factors affecting foot shape

1.8.1 Work pattern

Research into competition horses (primarily racehorses) has identified work pattern-related risk factors for injury. Smaller amounts of high intensity work are protective against injury compared to larger volumes of low intensity work. Higher speeds as well as longer distances in racing are risk factors for musculoskeletal injury (Pinchbeck *et al.*, 2004). Although most research to date has focussed on competition horses, the less organised work pattern of leisure horses has the potential to also put them at high risk of injury (Dyson, 2002). Lower amounts of exercise are associated with hoof abnormalities, however the cause and effect aspects of this finding are currently unknown (Holzhauer *et al.*, 2017). A study on young racehorses found that hoof length increased in horses 0-1 and 1-2 years of age, but decreased in horses of 2-3 years of age, which was considered to be an effect of trimming (Anderson and McIlwraith, 2004). In the same study, dorsal hoof wall angle reduced for 0-2 years of age but did not change in 2-3 years of age. Given that racehorses are brought in to work as 1-year olds, this may represent an initial response to training, which later plateaus.

1.8.2 Stable management

Management aspects can be important in equine foot shape and abnormalities. Hoof abnormalities are associated with lower intake of food or a poor diet (Anthauer, Mulling and Budras, 2005; Holzhauer *et al.*, 2017). Stabling and turnout can also be factors in the development of hoof abnormalities; the risk of thrush is shown to be lower when horses are turned out on pasture, rather than being stabled (Holzhauer *et al.*, 2017). This is similar to a finding observed in cattle (Holzhauer *et al.*, 2012).

When horses are stabled, different bedding types also present increased or decreased risks to the occurrence of hoof abnormalities. 'Humid' bedding increases the risk of thrush by almost 3-fold (Holzhauer *et al.*, 2017) whilst shavings have a protective effect over straw. The type of straw used as bedding material has also been reported to be influential in the presence of white line disease, a pathological condition of the foot which leads to separation at the junction between the stratum medium and the stratum internum (Holzhauer *et al.*, 2017).

Foot care is also important. Horses that do not have their feet picked out regularly have three times the risk of developing hoof wall cracks, compared with those that do have their feet picked out (Holzhauer *et al.*, 2017). Dirt has been shown to lead to increased fragility and subsequent infection of horn in cows (Bell *et al.*, 2009). As described previously, regular farriery is important for maintenance of good foot balance (Leśniak *et al.*, 2017).

1.9 Relationship between foot shape and lameness

1.9.1 Lameness

The forelimbs have a greater predisposition to lameness compared with the hindlimbs of the horse (Ross, 2011). One reason for this may be that forelimbs are estimated to support 60% of total bodyweight. Forelimbs also experience higher vertical and mechanical forces than the hindlimbs (Back *et al.*, 1995a; Gustås *et al.*, 2004), which may explain the increased rate of lameness in forelimbs (Barrey, 1990). Additionally, hindlimb lameness can be harder to discern than forelimb lameness (Ross, 2011), which may result in reduced recognition of these events. This is compounded by the fact that some animals may be perceived as more prone to forelimb lameness (e.g. racing Thoroughbreds), and so assumed to have pain in the forelimb when in fact, the hindlimbs are affected (Ross, 2011).

1.9.2 Foot-related lameness

The foot is a common source of lameness in the horse. Ninety-five percent of lameness events in the forelimb are due to lesions at or distal to the carpus (Adams, 1957; Ross, 2011). In draught horses, foot lameness is also the most common location for hindlimb lameness events (Ross, 2011). The equine digit is a highly evolved structure, providing shock absorption, grip and return of venous blood flow to the limb above. Although some lameness events are due to acute trauma, the majority are the consequence of a chronic degenerative process within the musculoskeletal tissues. There are numerous risk factors that contribute to, or prevent against, such acute or chronic overload (Hobbs *et al*., 2014).

Dorsopalmar foot balance has been the focus of much work investigating lameness, due to its association with navicular disease (Wright and Douglas, 1993; Page and Hagen, 2002) as well as other foot pain conditions (Holroyd *et al*., 2013). A ‘broken back’ HPA has been shown to be present in over 70% of horses with forelimb lameness (Wright and Douglas, 1993). However, the current literature does not provide enough evidence to indicate whether this relationship is causative or if poor foot balance occurs as a result of the lameness pathology and potential unloading of painful foot regions.

A study of 95 racehorses demonstrated that low dorsal hoof wall angles were a significant risk factor for catastrophic musculoskeletal injury (Kane *et al.*, 1998). In another racehorse study, the combination of long dorsal hoof wall and collapsed heels was a risk factor for musculoskeletal injury (Pinchbeck *et al.*, 2004); indeed this combination has been associated with suspensory apparatus, collateral ligament and NB problems in racehorses (Kobluk *et al*., 1990; Hood, Taylor and Wagner, 2001; Holroyd *et al*., 2013), as well as distal interphalangeal joint (DIPJ) arthritis in sport horses (Cochran, 1990). Lame horses with a sole angle <13^{o} were more likely to have suffered a lesion of the DDFT or NB than those with a higher sole angle (Holroyd *et al.*, 2013).

1.9.2.1 Magnetic resonance imaging

Previous to the development of magnetic resonance imaging (MRI) of the equine foot, diagnosing lameness that had been localised to the foot was elusive in many cases (Dyson, Murray and Schramme, 2005). Limitations of other imaging modalities such as radiography and ultra-sound mean that MRI is the only method that allows detailed imaging of soft and hard tissues within the hoof capsule (Murray *et al*., 2006; Dyson, Blunden and Murray, 2008; Dakin *et al*., 2009). MRI has been shown to be useful in detection of soft tissue lesions within the equine foot (White and Barrett, 2016). The classification of lesions using MRI corresponds well with those obtained by histological examination (Dyson, Blunden and Murray, 2008). A study comparing horses with and without palmar foot pain found significant differences in MRI findings of various structures within the foot (Murray *et al.*, 2006), confirming its usefulness as a tool in providing diagnoses for horses affected by palmar foot pain. A study has also examined the relationship between both foot features and lesions detected at MRI, finding that lower solar angle was associated with certain pathologies (Holroyd *et al.*, 2013).

1.10 Gait analysis

As discussed previously, lameness is one of the most common health problems in horses, with many lameness issues considered to be a result of chronic overload of specific structures, rather than acute injury (Balch, White and Butler, 1993; Trotter, 2001; Wilson *et al.*, 2001). Hence there is a constant drive to identify lameness or limb asymmetries early, so that treatment and prevention can be implemented before pathology becomes irreversible. Subjective assessment is still the most common approach to both gait asymmetry and clinical lameness evaluation in the horse (May and Wyn-Jones, 1987; Buchner *et al.*, 1996; Weishaupt *et al*., 2004). However, subjective assessment has been shown to be somewhat unreliable even across those with similar levels of training (Keegan *et al.*, 2010), particularly when approaching mild or moderate lameness (Donnell *et al.*, 2015), or lameness in multiple limbs, which makes identification of the primary limb difficult (Ross, 2011). Such lack of repeatability within and between observers causes difficulties in achieving a consistent approach to assessment, treatment, and monitoring for improvements in lameness cases. Hence there has been a desire within the veterinary industry for reliable, objective lameness detection methods (Keegan *et al.*, 2010). In recent decades such technologies have become available; some are only suitable for use in research facilities (e.g. force plates), but others have been validated for use in the field (Keegan *et al.*, 2011).

1.10.1 Kinetic techniques

Kinetics is the study of forces involved in motion. In terms of gait analysis in horses, force plates and pressure mats enable collection of kinetic data. Force plates (also known as force platforms) have been described as the gold standard in lameness detection (Keegan *et al.*, 2012; Donnell *et al.*, 2015). Indeed, their measurement of ground reaction force parameters of individual limbs has led to their use in lameness assessment and quantification of improvements following treatment. Duration of stance and peak vertical force measurements have been shown to be particularly associated with detection of lameness (Weishaupt *et al.*, 2004; Ishihara, Bertone and Rajala-Schultz, 2005; Weishaupt *et al.*, 2006; Ishihara *et al.*, 2009). Force plates excel in displaying highly accurate, absolute measurements of force. However, their high cost and lack of portability prevents usage outside of research facilities (Weishaupt *et al.*, 2004; Keegan, 2007; McCracken *et al.*, 2012; Donnell *et al.*, 2015). Another disadvantage is that if a single force plate is used, it is not possible to collect data over multiple consecutive strikes of the foot.

Pressure mats or pressure plates provide objective quantification of load exerted by horses' limbs. Though deemed less accurate in recording of absolute force than force plates, pressure mats provide high resolution temporal and spatial measurement of pressures exerted by the foot during loading (Van Heel *et al.*, 2004; Oosterlinck *et al.,* 2010a; Oomen *et al.,* 2012; Oosterlinck *et al.*, 2015). Hence, pressure mats can be used to understand specific loading patterns over the foot surface in individual horses, rather than just overall values per foot (Oomen *et al.*, 2012). The portability of pressure mats means their usage is not limited to laboratory settings and gives the opportunity for pressure mats to be used in the field and to study a greater range of horses, in a greater range of situations than force plates. However, pressure mats suffer the same problem as force plates in the fact that, due to their limited size, they are unable to record data from multiple consecutive foot strikes in the horse. Most scientific studies involving pressure mats have been used in sound horses to test the influence of specific breeds, conformation, surface, handling, foot-trimming or shoe design on foot loading (Rogers and Back, 2003; Van Heel *et al.*, 2010; Oomen *et al.*, 2012; Oosterlinck *et al.*, 2013; Van de Water, Oosterlinck and Pille, 2016; Faramarzi, Nguyen and Dong, 2018). However in recent years, pressure mats have also been shown to detect differences in loading between sound and lame limbs in horses suffering from lameness events (Pitti *et al.*, 2018).

Pressure mats can be comprised of different materials, which affects the way in which they record loading over their surface. Tekscan™ pressure mats use resistive ink to measure changes in pressure, whereas RS® scan pressure mats have a polymer-based resistive layer. As a consequence the latter can be used in conjunction with force plates, enabling dynamic calibration (Oosterlinck *et al.*, 2012). Successful calibration of pressure mats has been shown to be problematic in previous studies, impeding their ability to identify lameness in horses (Perino, 2002).

Developments in pressure mat technology have also led to the creation of in-shoe pressure sensors. Early work on the validation of these sensors found that they collected data with less variability than force platforms (Perino, 2007), however it was also identified that further work was required to ensure the accuracy of such systems (Perino *et al.*, 2007). These sensors have been used both to measure pressures between the shoe and the foot, and the shoe and the ground (Hagen *et al.*, 2016, 2017). An advantage of in-shoe sensors over force or pressure plates that are placed or embedded in the ground is that they enable the collection of data over a number of sequential strides.

1.10.2 Kinematic techniques

Kinematics is a branch of biomechanics which measures how body segments move in time, without consideration of the forces that bring about that motion. Kinematic study of equine gait began in the late 1800s when Muybridge set up a series of cameras to examine a horse's motion (Muybridge, 1887). Optical motion capture, following major technological developments, is still used today (Day *et al.*, 2013; Moorman *et al.*, 2013a; Rhodin *et al.*, 2018; Byström *et al.*, 2021). This involves the placement of markers on the skin at specific anatomical landmarks, with cameras positioned at certain angles to capture data in the plane(s) of interest (Wiggers *et al.*, 2015). The advantages of this technique are that it is non-invasive, and it also enables data collection over multiple, consecutive strides. Disadvantages of this technique is that the cameras required are expensive, and also that the skin covering the anatomical landmarks of interest can move during locomotion, creating artefactual results.

Developments in technology have led to the creation of movement sensors that are small enough to be attached to the trunk or distal limbs of horses (and other species) without causing discomfort or creating artefactual measurements (Keegan *et al*., 2012). Consequently, various systems have been manufactured that not only record movement data from horses but also use algorithms to decide which limb(s) and which phase of the stride(s) are affected in horses. These have been validated (Keegan *et al.*, 2011) and are currently used in equine practices and universities to support diagnoses, treatment plans and follow up assessments (Keegan *et al.*, 2011; Maliye *et al*., 2013; Moorman *et al*., 2013a, 2013b). One such system (Equinosis Q) is reported to be currently used across 32 countries and 65 university institutions (Copyright © 2007-2019 Equinosis) indicating the ability of these systems to be used in practical situations.

Several studies have examined the relationship between findings from inertial movement sensors and force plates. Originally, due to force plates being regarded as the 'gold standard' for lameness detection, this was in order to prove the effectiveness of inertial movement sensors in lameness assessment (Keegan *et al.*, 2012; Serra Bragança *et al.*, 2017). In forelimbs, findings from the movement sensors which indicate lameness in a particular limb have been reflected in lower peak vertical force values recorded by the force plate on that limb (McCracken *et al.*, 2012). However, in hindlimbs this association has been less reliable. Further, an induced model of mild lameness found that force plate assessment was less able to detect a lame limb than inertial movement sensors or subjective evaluation, and that therefore it is not to be considered the gold standard for lameness detection (Donnell *et al.*, 2015).

Furthering the use of inertial movement sensors, a hoof-mounted system (Werkman Black) has been developed recently and shown to produce reliable data (Tijssen *et al.*, 2020). Compared with sensors positioned elsewhere on the body, mounting the sensor on the hoof provides detailed temporal and spatial information regarding the distal limb at all phases of gait (Hagen *et al.*, 2021). To date this system has been shown to have value in the measurement of various gait parameters both around and separately from foot trimming and the application of shoes (Tijssen *et al.*, 2020; Hagen *et al.*, 2021). As with optical motion capture and in-shoe pressure sensors, this method facilitates data recording over multiple consecutive foot strikes.

1.11 Synthetic arena surfaces

Synthetic surfaces have become increasingly popular in the last few decades and as a result most horses are exercised regularly on such surfaces. However, little is known about the implications of the use of these surfaces on training, performance and lameness events. Certain properties and construction features of arenas, as well as the way they change in different weather conditions have been associated with lameness in horses (Murray *et al.*, 2010b).

1.11.1 Surface properties

Shear resistance of an arena surface refers to the friction between foot and surface, as well as between particles within the surface, as regards movement in the horizontal plane (Hobbs *et al.*, 2014). Different sports require different amounts of grip in order to prevent horses from slipping or falling (Murray *et al*., 2010a), whilst also preventing them from experiencing excessive forces when turning or landing that may result in injury (Gustås, Johnston and Drevemo, 2006; Claußen *et al*., 2019). A surface needs to provide enough resistance to allow horses to move off for the next stride. Insufficient shear resistance means the toe has to endure greater rotation into the surface during impact (Crevier-Denoix *et al*., 2010), whilst at midstance there is reduced elastic recoil energy storage in the suspensory ligament (SL) and superficial digital flexor tendon (SDFT). Consequently, surrounding muscles work harder, and when fatigued place increased passive strain on SDFT. This increases the risk of injury in these structures (Butcher *et al*., 2007; Crevier-Denoix *et al*., 2010). There have been recent developments in testing of shear resistance, since for many years there was a lack of validated equipment (Lewis *et al*., 2015). Although there are tools to measure this parameter in human sports surfaces, they do not provide a good measure of the horse-surface interaction due to the low mass and drop heights involved (Lewis *et al*., 2015).

Increased hardness of a surface, whether natural or synthetic, has been shown to increase the risk of musculoskeletal injury in the horse (Radin *et al*., 1991; Bailey *et al.*, 1998) due to the accompanying increase in magnitude of high frequency vibrations experienced as the horse makes contact with the ground (Gustås, Johnston and Drevemo, 2006). The majority of these high frequency vibrations are attenuated at the level of the foot (Lanovaz *et al.*, 1998; Willemen, Jacobs and Schamhardt, 1999) but such vibrations have been associated with bone and cartilage damage (Folman *et al.*, 1986; Barstow *et al.*, 2019). Conversely, softer surfaces can increase the energy output of horses, and increase the risk of falls, slips or fatigue of structures within the limb (Butcher *et al*., 2007). Although firmness of a surface may be an inherent property, it is also likely to be influenced by environmental factors, such as heat and moisture. To a certain point, increasing moisture content is associated with firmer surfaces, due to the cohesion between sand particles by water. However, if such a surface becomes saturated, the shear strength of the surface will decrease (Hobbs *et al*., 2014).

In sports surfaces (grass or synthetic areas used for sports) hardness is often tested using a Clegg hammer (Brosnan *et al*., 2009; Hobbs *et al*., 2014). A Clegg hammer consists of a known mass, dropped from a known height and enables quantification of the maximum vertical deceleration on impact. Although this is a useful tool, it is not able to emulate the forces experienced by the equine limb at various gaits and speeds. Several other drop-hammer methods involving larger masses have been used (Ratzlaff *et al.*, 1997; Setterbo *et al.*, 2011) to better characterise the vertical forces experienced by the equine limb. However, these do not consider other forces that are likely to be at play during equine locomotion, for example rotational forces.

In the context of equine arena surfaces, spatial and temporal consistency are of importance, such as how much variation exists across different regions of the surface and how arena properties change over time. Measuring spatial variation in arenas is a relatively recent advance in surface testing (Blundell, 2010; Tranquille *et al.*, 2012; Northrop *et al.*, 2016) and there are currently very few data looking at changes over time, even though it is well known that arenas degrade with age (Hobbs *et al.*, 2014).

Variation in depth across a surface has been shown to be associated with fatigue and increased lameness risk in dressage horses (Dyson, 2002), as well as being reported to increase the likelihood of slipping or loss of balance (Murray *et al.*, 2010b). Moisture content has been reported as the single most influential factor affecting surface properties (Mahaffey, Peterson and Roepstorff, 2013; Hobbs *et al.*, 2014; Northrop *et al.*, 2016). This potentially explains the popularity of wax or polymer-mixed surfaces in the last several years (Hobbs *et al*., 2014). By coating surface materials in a hydrophobic substance, moisture content will not affect the surface to the same extent, which facilitates consistency.

1.11.2 Surface constituents

Sand-based surfaces are reportedly the most popular in the UK, particularly amongst dressage riders (Murray *et al.*, 2010b). Often sand-based surfaces will be mixed with rubber or fibres, which can help reduce compaction (Setterbo *et al.*, 2011) as well as helping with stability and drainage. The way the sand interacts with other materials is affected by the distribution of sand particle sizes (Barrey, Landjerit and Walter, 1991).

Rubber surfaces most commonly comprise particles of 2-5mm in size, or 25-40mm size. In the latter case these are layered over a sand subsurface (Hobbs *et al.*, 2014). Though rubber does not become compacted like other surfaces, inconsistency can still develop and therefore lack of routine maintenance may lead to increased injury risk.

Woodchip surfaces have been shown to be associated with an increased risk of slipping (Murray *et al.*, 2010b), though woodchip below the surface has been reported to provide cushioning (Drevemo and Hjerten, 1991). As with rubber-based surfaces, inconsistencies can develop and so regular maintenance is important in woodchip surfaces (Hobbs *et al*., 2014).

Waxed surfaces have been shown to be a component in the degree of grip – in comparison to other surfaces waxed ones can exhibit greater or lesser shear resistance (Crevier-Denoix *et al*., 2010; Lewis *et al*., 2015). However, it is unknown whether wax is the true factor in this, or simply associated with surface density (Lewis *et al.*, 2015).

1.11.3 Surface maintenance

The way a surface is prepared for use or maintained between uses has an influence on the top layer of the surface, which provides cushioning during impact (Northrop *et al.*, 2013). Maintenance methods include harrowing, rolling, grading, watering and levelling (Hobbs *et al*., 2014). The entire maintenance routine may also involve basic tasks such as removing faeces from the arena and clearing drainage systems. Since arenas are used for many different activities, there is no one perfect type of arena or maintenance procedure for all situations and there is currently limited evidence as to what are their ideal maintenance procedures (Hobbs *et al.*, 2014; Claußen *et al.*, 2019). However, it is known that harrowing reduces surface hardness and shear resistance, thus increasing the deformability of the surface, whilst rolling has the opposite effect (Northrop *et al*., 2013). Hence, different maintenance protocols may be appropriate for different activities. In all circumstances the aim should be to reduce concussion and also return energy to the limb for it to move forward in the next stride (Northrop *et al*., 2013).

It is known that appropriate maintenance reduces variability across surfaces (Hobbs *et al.*, 2014) and consequently the risk to horses using them (Murray *et al.*, 2010a). Infrequent maintenance will only compound the effect of compaction and inconsistency across surfaces that occurs with use, posing an even greater risk of musculoskeletal injury in the horses that use them (Kai *et al*., 1999; Peterson and McIlwraith, 2008; Murray *et al*., 2010a). Given that privately-owned arenas were shown to pose the least risk of orthopaedic injury to dressage horses when compared with other arena locations such as livery yards (Murray et al., 2010b), it may be that the quantity and type of usage an arena is subject to are important factors to consider when developing an optimal maintenance protocol.

1.11.4 Impact of climate and environment

The geographical location of arena surfaces determines the climatic effects surfaces are subject to and therefore affects their functional properties and how they change over time. This is particularly true with respect to moisture content, which is said to be the most important physical property of an equine surface (Hobbs *et al.*, 2014). The degree of moisture content in a surface has been shown to affect peak force (Ratzlaff *et al*., 1997), surface compaction (Brosnan and McNitt, 2009) and peak vertical deceleration (Chateau *et al*., 2010). Hence it is a very important risk factor for injuries to horses training and competing on surfaces. Additionally, whether the surface is indoor or outdoor has a large effect on the susceptibility of the surface to climatic conditions, whilst the size and type of sand particles used to make up the surface will also determine the extent to which water affects the surface's physical properties (Hobbs *et al*., 2014).

1.12 Conclusions

Lameness and hoof abnormalities are common in the equine population. Many factors influence the occurrence of these conditions, farriery, conformation and management to name a few. Despite farriery being one of the most important factors, there is little scientific evidence for how the feet of horses should be trimmed, or which shoes are best to use in particular situations.

Much work has been done to study equine biomechanics in the past. This has been aided by technological developments in recent decades. Consequently there are currently a number of kinetic and kinematic methods available for gait analysis in the horse.

Previous work has identified the increasing popularity of equine synthetic arena surfaces, as well as the risk these surfaces pose to equine lameness.

1.13 Hypotheses

i. *Foot trimming by a farrier at a single time point affects foot shape and loading*
ii. *Foot trimming by a farrier over time affects foot shape and loading*
iii. *Foot shape is influenced by both genetic and environmental factors*
iv. *Lameness results in poor foot balance and decreased loading of the affected limb*
v. *Synthetic arena surfaces are used by a majority of horses*
vi. *The surface properties of synthetic arena surfaces change significantly between seasons*

1.14 Aims

The overall aims of this thesis were to:

- *Assess the effect of foot trimming by a farrier on foot shape and loading at a single time point, as well as longitudinally*
- *Determine the impact of lameness on changes in foot shape and loading over time*
- *Describe phenotypic and environmental factors which influence foot shape in horses and the occurrence of hoof abnormalities*
- *Assess the associations between MRI findings, foot lameness events and foot shape and loading*
- *Describe the usage of arena surfaces by a general population of sound horses*
- *Measure the hardness, resistance to penetration and moisture content of a sample of arenas and determine the impact of surface characteristics on these results*

Chapter 2

Materials and Methods

2.1 Ethical Approval

Ethical approval for this study was obtained from the University of Liverpool Veterinary Research Ethics committee (VREC 538; approval gained 28th April 2017 (Chapters 3, 4 and 6) and VREC209b; approval gained April 2017 and updated February 2019 for the purposes of Chapter 5). Written owner consent was obtained for inclusion of horses into the study.

2.2 Lameness assessment

2.2.1 Subjective assessment

Visual lameness assessment is carried out in most cases using one of three major scales (Singer, 2015). One of the most common is a United Kingdom-based 11 point scale (0-10) which has been used to quantify lameness in several research studies (Arkell *et al.*, 2006; Singer, 2015). Another, recommended by Dyson (2011), runs from 0-8. The American Association of Equine Practitioners advocates a 6-point scale (American Association of Equine Practitioners, 2019), where the score incorporates how the horse moves at both walk and trot. In each scoring system, 0 signifies horses free from lameness and the highest number on the scale refers to a non-weight-bearing lameness. In the studies described in this thesis, the 11-point scale was used as this is the scale that the primary researcher was most familiar with.

Horses were assessed at walk (approx. 1m/s) and trot (approx. 3m/s) in a straight line at the time of recruitment to the study, in order to confirm that they were free from lameness. Where possible a hard, flat surface was used and a minimum of 20 strides were observed in trot. Any horse exhibiting an identifiable lameness was excluded from the study and veterinary examination recommended to the owner or keeper present.

2.2.2 Methodological development: lameness assessment

Subjective lameness assessment was validated over a convenience-based sample of 24 horses with a widely used objective lameness assessment tool which consists of body-mounted sensors. This was the Eickermeyer® Equinosis Q™ with Lameness Locator® software (Keegan *et al.*, 2011; Coleman, 2020). Spearman's correlation coefficient was used to determine the correlation between the results of subjective lameness assessment by the primary researcher and objective lameness assessment using the Eickermeyer® Equinosis Q™. This analysis was carried out in R Studio (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). A moderate, positive correlation was identified ($r=0.47$, $p=0.02$).

2.3 External foot measurements

To assess external foot measurements, digital photographs were taken of dorsal, medial, lateral and solar views with a measurement scale included in the image for calibration later (Figure 2.4). Digital photographs have been shown to be as accurate as radiographs for measurement of various hoof landmarks (White *et al.*, 2008), and have been used extensively in the study of the equine foot (Kane *et al.*, 1998; Dyson *et al.*, 2011; Leśniak *et al.*, 2017, 2019). Photographs were taken by farriers or by the main researcher using a smartphone camera (minimum 8 megapixels). For each horse, the same photographer took the photos throughout the study period. Details of when photographs were taken is provided in each relevant chapter. Photographs were imported into Image J version 1.52a (Schneider, Rasband and Eliceiri, 2012) in order to gain quantitative foot measurements.

2.3.1 Measurements

Quantitative foot measurements were created from importing digital photographs of dorsal, lateral, medial and solar views of horses' feet into Image J. The different measures collected from each view are described in Table 2.1 and Figures 2.1-2.3.

Table 2.1 Description of foot measurements obtained from digital photographs used in this study

View	Measurement name	Description
Dorsal	Lateral hoof wall length	Coronary band to where hoof contacts the floor
	Lateral hoof wall angle	Angle created between the ground and lateral hoof wall length
	Medial hoof wall length	Coronary band to where hoof contacts the floor
	Medial hoof wall angle	Angle created between the ground and medial hoof wall length
Lateral	Dorsal hoof wall length	Dorsal coronary band to dorso-distal toe, where the toe contacts the ground
	Dorsal hoof wall angle	Angle created between the ground and dorsal hoof wall length
	Heel length	Coronary band at the heel to where heel contacts the ground
	Heel Angle	Angle created between the ground and heel length
Medial	Dorsal hoof wall length	Dorsal coronary band to dorso-distal toe, where the toe contacts the ground
	Dorsal hoof wall angle	Angle created between the ground and dorsal hoof wall length
	Heel length	Coronary band at the heel to where heel contacts the ground
	Heel angle	Angle created between the ground and heel length
Solar	Sagittal length	Caudal-most area of heel bulb to dorso-distal toe
	Bearing border length	Heel buttress to dorso-distal toe
	Heel buttress to frog apex	Heel buttress to distal frog apex
	Frog apex to toe	Distal frog apex to dorso-distal toe
	Width	Measured at the widest part of the solar surface
	Heel buttress-centre of rotation	Distance from heel buttresses to centre of rotation
	Heel buttress-centre of pressure	Distance from heel buttresses to centre of pressure (9.5mm caudal to frog apex)
	Centre of rotation to frog apex	Distance from centre of rotation to distal frog apex
	Centre of Rotation to Centre of Pressure	Distance from centre of rotation to centre of pressure (9.5mm caudal to frog apex)
	Lateral solar width	Lateral portion of solar width
	Medial solar width	Medial portion of solar width

a b

Figure 2.1a- b: Photographs of dorsal and lateral aspects of an equine foot illustrating foot measurements taken from the dorsal view (a) and medial or lateral views (b) of horses' feet during the study. Dorsal view (a) showing measurements: yellow line=LHWL, yellow curve=LHWA; green line=MHWL and green curve=MHWA. Lateral view (b) showing measurements: orange arrow=dorsal hoof wall length and orange curve=dorsal hoof wall angle; green arrow=heel length and green curve=heel angle. Medial view measurements were taken in the same way as lateral view

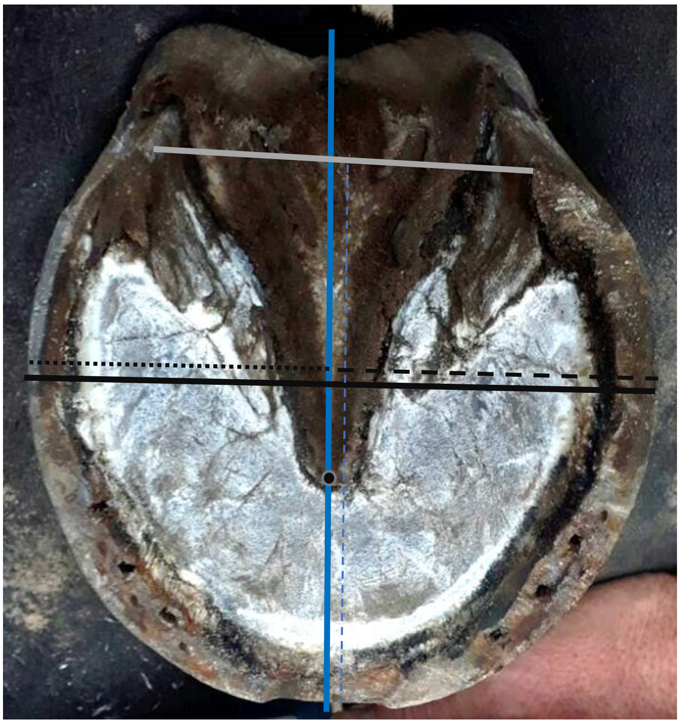

Figure 2.2 Photograph of the solar aspect of an equine foot showing foot measurements and anatomical landmarks from which measurements are taken: heel buttress-heel buttress (grey line), sagittal length (SL) (blue line), width at widest part (black line), medial solar width (black dotted line), lateral solar width (black dashed line), bearing border length (BBL) (blue dashed line), frog apex (black dot)

Figure 2.3: Photograph of the solar aspect of an equine foot showing method of location of centre of rotation (blue dot) at intersection of lines running from heel buttress to contralateral breakover point (grey lines). Blue dashed lines show how breakover point was found, perpendicular to the heel buttress. This method of locating the centre of rotation on the external surface of the foot has been shown to be associated with the true centre of rotation of the distal interphalangeal joint on radiographs (Caldwell *et al.*, 2016)

2.3.2 Methodological development: external foot measurements

A pilot study was carried out to provide training to the farriers involved in data collection. This led to some minor adjustment to the procedure including modification of the measurement ruler to allow it to stand unassisted, as well as minimising the text on the identification labels to horse identifier, date, limb and pre- or post-condition (Figure 2.4). It also highlighted the need for a scale that was easily visible in a range of different lights and of a definite length. Farrier training included demonstrating best placement of the scale (i.e.in the same plane as the structures being measured), positioning of the camera and quality control measures to prevent collection of unusable or highly variable data.

a **b**

Figure 2.4a-b: Photographs demonstrating the methodological development of gathering photographs of horses' feet to enable external foot measurements to be taken. a shows the original scale used to calibrate digital photographs of horses' feet and enable measurement of various aspects of foot shape and b shows the modified scale.. The modified scale did not need to be held in place which removed the need for an additional person in data collection.

2.3.3 Intra- and inter-operator repeatability

Intra-operator repeatability was estimated by repeating foot measurements five times on the same images of a single foot of one horse. All measurements were performed by the main researcher and enabled calculation of the coefficient of variation (CoV) of the foot measurements. Measurements demonstrated high repeatability, and those with CoV <5% were included in the final analysis (Table 2.2).

Table 2.2: The coefficient of variation of external foot measurements measured in this study

View	**Measurement**	**Coefficient of Variation (%)**
Dorsal	Medial Wall Length (cm)	4.5
	Medial Wall Angle (°)	1.21
	Lateral Wall Length (cm)	3.65
	Lateral Wall Angle (°)	0.74
Lateral/Medial	Dorsal Hoof Wall Length (cm)	3.66
	Dorsal Hoof Wall Angle (°)	1.44
	Heel Length (cm)	4.89
	Heel Angle (°)	4.42
Solar	Heel Buttress-Heel Buttress (cm)	0.93
	Sagittal Length (cm)	0.37
	Bearing Border Length (cm)	0.76
	Width (cm)	0.21
	Frog Apex-COR (cm)	5.53
	Toe-COR (cm)	1.92
	Frog Apex-Toe (cm)	0.14
	COR-Heel Buttress (cm)	1.94
	Medial Solar Width (cm)	0.95
	Lateral Solar Width (cm)	0.68

COR=centre of rotation

Inter-operator repeatability was estimated using intraclass correlation coefficients. A second operator was trained to measure the photographs and consequently measured the left forelimb pre-trimming photographs of 10 different horses. Intraclass correlation estimates were calculated using R Studio based on a mean rating (k=2), consistency, one-way random effects mode. The results of the second operator were compared with the primary researcher, with the outcomes shown in Table 2.3.

Table 2.3: Results of intra-class correlation testing of external foot measurements taken by two raters

View	Measurement	ICC (95% CI)	P value
Dorsal	Medial Wall Length (cm)	0.75 (0.30, 0.93)	0.003
	Medial Wall Angle (°)	0.86 (0.56, 0.96)	<0.001
	Lateral Wall Length (cm)	0.83 (0.47, 0.95)	<0.001
	Lateral Wall Angle (°)	0.86 (0.56, 0.96)	<0.001
Lateral	Dorsal Hoof Wall Length (cm)	0.38 (-0.26, 0.80)	0.12
	Dorsal Hoof Wall Angle (°)	0.89 (0.65, 0.97)	<0.001
	Heel Length (cm)	0.20 (-0.44, 0.71)	0.27
	Heel Angle (°)	0.83 (0.47, 0.95)	<0.001
Medial	Dorsal Hoof Wall Length (cm)	0.63 (0.08, 0.89)	0.02
	Dorsal Hoof Wall Angle (°)	0.55 (-0.04, 0.87)	0.03
	Heel Length (cm)	0.74 (0.27, 0.93)	0.003
	Heel Angle (°)	0.41 (-0.22, 0.81)	0.10
Solar	Heel Buttress-Heel Buttress (cm)	0.42 (-0.21, 0.81)	0.09
	Sagittal Length (cm)	0.90 (0.67. 0.97)	<0.001
	Bearing Border Length (cm)	0.86 (0.56, 0.96)	<0.001
	Width (cm)	0.85 (0.54, 0.96)	0.002
	Frog Apex-COR (cm)	0.84 (0.52, 0.96)	<0.001
	Frog Apex-Toe (cm)	0.73 (0.25, 0.92)	0.004
	Toe-COR (cm)	0.86 (0.57, 0.96)	<0.001
	COR-Heel buttress (cm)	0.64 (0.08, 0.89)	0.01

ICC=Intra-class correlation coefficient, 95% CI = 95% confidence intervals, COR=centre of rotation, cm = centimetres

2.4 Hoof abnormalities

In Chapters 3 and 4 horses were also examined for hoof abnormalities. These included assessment of mediolateral and dorsopalmar foot imbalance as described in Chapter 1 as well as forelimb foot asymmetry, flat feet, small feet, and a number of horn and frog abnormalities as illustrated in Figures 2.5 and 2.6.

Figure 2.5a-e: Photographic examples of hoof abnormalities (indicated by blue arrows). a shows solar bruising, b shows widened white lines, c shows sheared heels, d shows contracted heels, e shows crumbling horn

Figure 2.6a-d: Photographic examples of hoof abnormalities (indicated by blue arrows) . a shows underrun heels, b shows missing horn, d shows prominent growth rings, d shows hoof wall cracks

2.5 Foot loading data

Pressure plate data were collected when horses were unshod at stand and walk using a commercial pressure plate (Tekscan™ Medical Sensor 5400N). The timing of this data collection is described in the relevant individual chapters. A rubber mat of thickness 3mm and shore hardness 70°was always placed over the pressure mat during use, following manufacturer's recommendations to prevent damage to the sensels by the horse's feet. The pressure plate was placed on the floor rather than embedded in the walking surface. For consistency, the mat was also placed over the pressure mat during calibration.

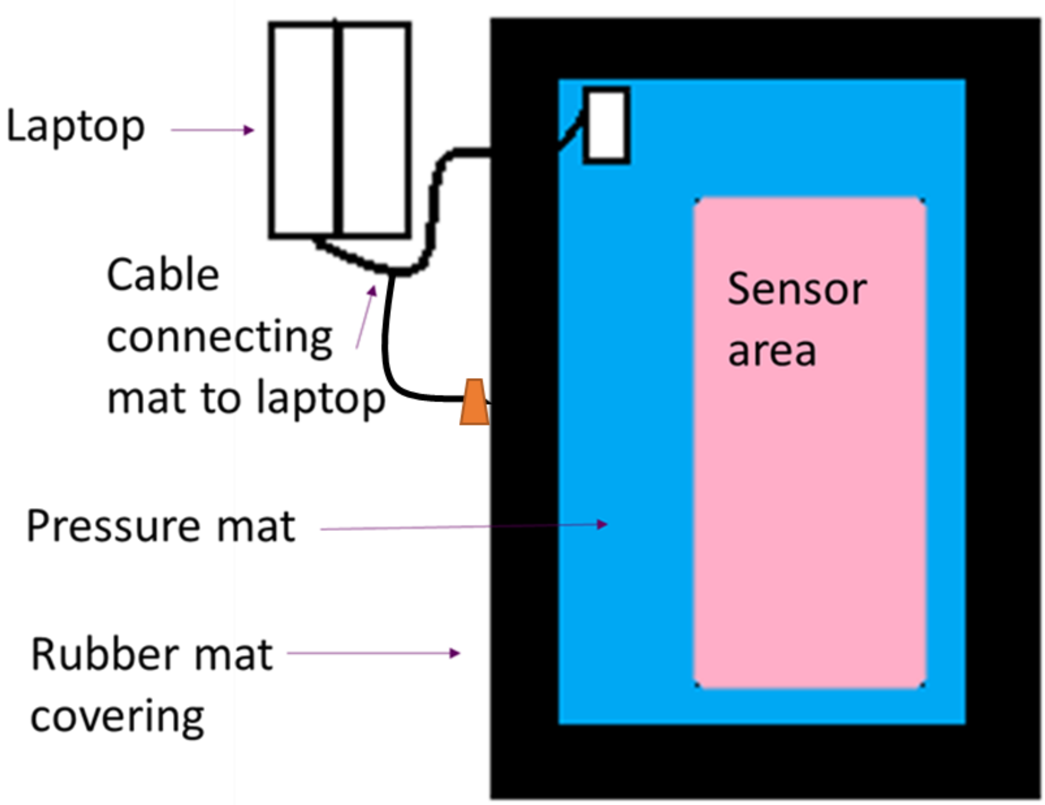

Figure 2.7: Schematic diagram illustrating the experimental set up of the pressure mat used for data collection. Orange trapezium indicates webcam.

2.5.1 Pressure mat data recording

A pilot study was carried out to optimise the use of the pressure mat. This involved recording a convenience sample of two different horses from the Philip Leverhulme Equine Hospital herd walking and standing on the pressure mat, as planned for data collection. This was performed after ethical approval had been granted for the study.

Data from the pressure mat were recorded using a laptop with the Tekscan™ Footmat Research 7.10 software installed. The pressure mat was connected to the laptop via a USB cable (Figure 2.7). Each recording of the pressure mat was calibrated by loading the most recent calibration file into the system. The lowest sensitivity (named 'low-1' by the software) was used for all recordings, and the Tekscan™ software was set to record data at 59.998 frames per second. A webcam (Microsoft™ EasyCam) was also attached to the laptop via a USB cable. This enabled video recording synched with the Tekscan™ 'movies'. The video recorded at 30 frames per second, which was almost exactly half the speed of recording by the pressure mat, enabling synchronisation of the video and pressure mat recordings.

2.5.2 Calibration

Pressure mats require calibration before or during use to correctly quantify the forces that are being exerted by subjects. A pilot study revealed that calibration with a human (performed as per the manufacturer's recommendations) was insufficient to calibrate the mat to the correct sensitivity to collect good quality data from horses, as a large proportion of the senor cells (sensels) recording data in each foot strike were becoming saturated (Figure 2.8). This meant that they could only record forces up to a certain magnitude and hence, the data were limited.

Consequently a different approach was used involving a live horse and a modified method of that described by Oosterlinck and others (2010a) was developed. This involved recording the weight exerted by a single horse standing on one forelimb (the other forelimb was raised by a human assistant) on a weighbridge. Five weights were recorded in this way and an average was calculated. The pressure mat was then calibrated using the average weight recorded whilst the horse stands on the pressure plate in the same way as it did on the weighbridge; with a single forelimb only. This method allowed calibration of the mat at a low enough sensitivity that none or a very small number of the sensels become saturated when used for data collection with horses (Figure 2.8).

The pressure plate was recalibrated after approximately five uses (as described above), as with usage the sensels can change their sensitivity.

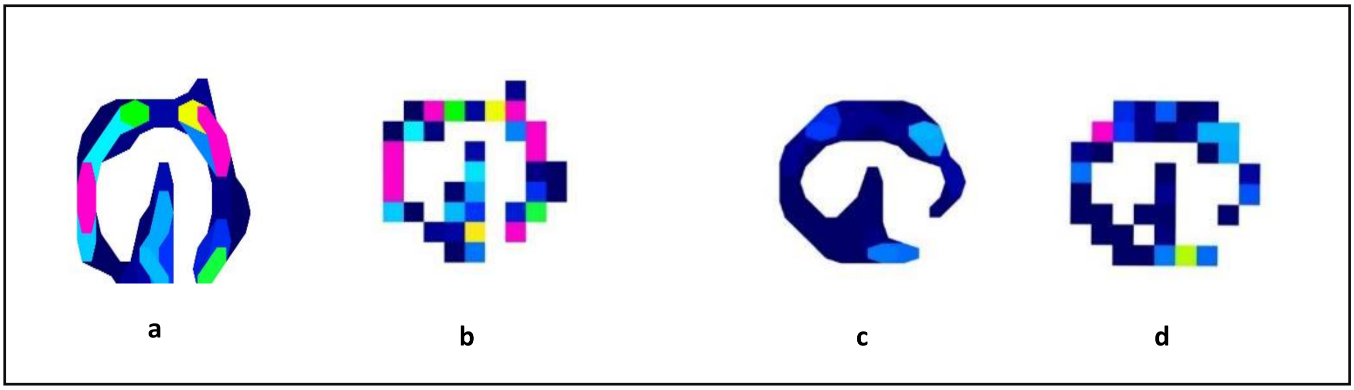

Figure 2.8a-d: Example foot strikes recorded following different calibration methods of the pressure mat. a is an example of a smoothed foot strike image with the original calibration: pink areas indicate where pixels were saturated; b is an example of a detailed foot strike image with the original calibration: pink pixels were saturated; c in an example of a smoothed foot strike image with the adapted Oosterlinck method of calibration, no saturation evident; d is an example of a pixelated foot strike image with the adapted Oosterlinck method of calibration, only a single pixel was saturated.

2.5.3 Data processing and acquisition

2.5.3.1 Tekscan recordings

Dynamic pressure mat data were recorded in the form of Tekscan™ 'movie' files (.fsx format) with a linked video file (.avi format). These files contain all the strikes that the horse created by walking on the pressure mat in each condition. The linked video file enabled identification of individual limbs at the time of valid strikes on the pressure mat. Speed of walking was not measured during data collection, but strikes were considered valid when the horse was moving at a constant speed and direction, and the entire foot landed in the sensor area of the pressure mat (Figure 2.9) (Oomen *et al.*, 2012).

Figure 2.9: Photograph illustrating an example of valid foot strike for dynamic pressure mat data collection. The foot has landed fully within the sensor area (corners demarcated by orange tape) and the horse is walking with its head straight in front and on a loose rein.

Static pressure mat data were also recorded in the form of Tekscan™ movies, and with a video recording to facilitate selection of the best data. Horses were led on to the mat perpendicular to the direction in which they were walked over it for the dynamic recordings. Data were collected when horses were weight bearing evenly on all four limbs, and the two forelimbs were square on the mat, within the sensor area and with the horse's head and neck straight and not moving for the duration of data recording (Figure 2.10). One static recording, lasting for a minimum of 6 seconds was gained from each horse for both pre- and post-trim conditions, though the majority of recordings lasted for 10 seconds or more. This was similar to that described by Nauwelaerts , Malone and Clayton, (2013).

Figure 2.10: Photograph demonstrating a typical static pressure mat stance required for recording. The horse is weight-bearing evenly on all four limb and the forelimbs are within the sensor area (orange tape on corners mark the borders)

2.5.3.2 MATLAB analysis

Custom-written MATLAB® 2018 (The Mathworks, Inc.) code was used for processing and analysis of pressure mat data. Pressure mat data files were exported from the Tekscan™ software in .csv format. These data were processed until each print had been separated (Figure 2.11). Video recordings were then used to identify which limb was responsible for each recorded print. This information was recorded in .txt files, with right and left abbreviated to 'R' and 'L', and fore and hind abbreviated to 'F' and 'H', respectively. Any prints which were not valid were denoted 'N/A'. Where foot strikes were incorrectly separated or amalgamated by the software, this was corrected manually.

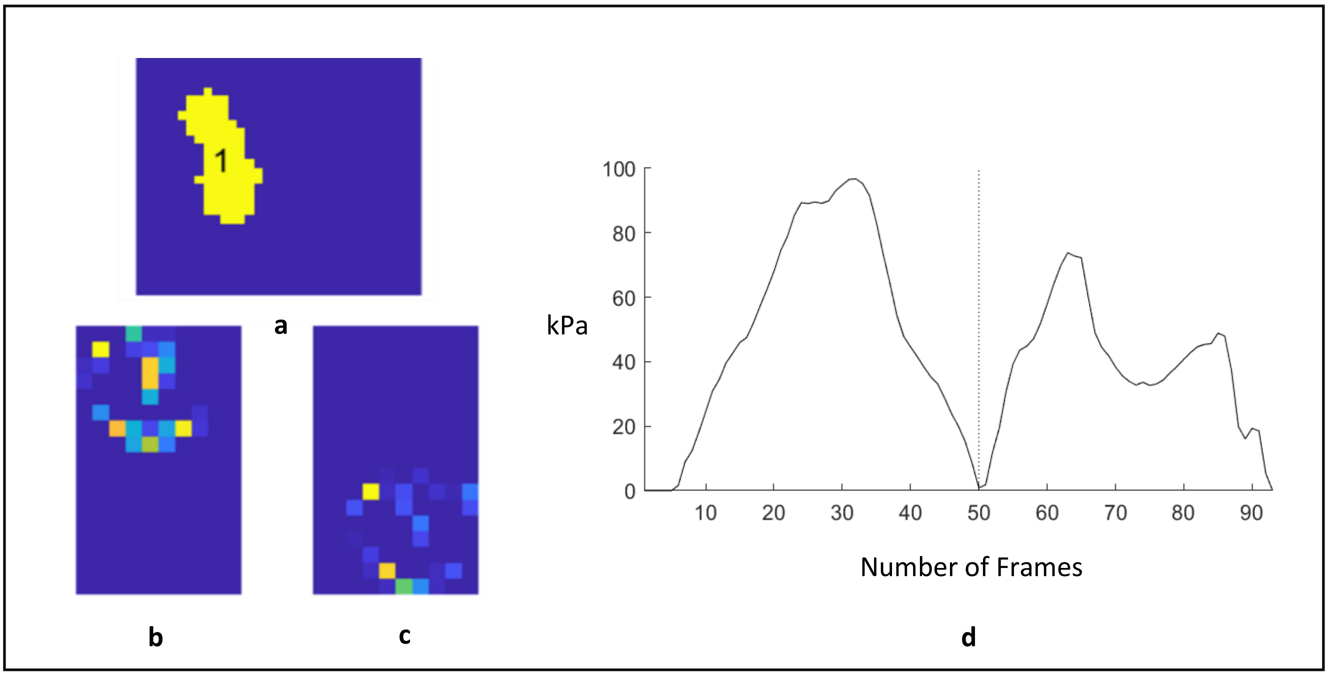

Figure 2.11a-d: Representative images and graph of equine foot strikes recorded on the pressure mat and subsequently separated using custom-written MATLAB code. a is an example of two prints, likely a fore- and hind-limb of the same side; b is the first print; c is the second print (i.e. b is forelimb and c is hindlimb; d is a graph showing mean pressure against number of frames, for a consecutive fore- and hind-foot strike. The dotted line shows where the pressure dips to zero and the two prints are separated. The left side of the dotted line is characteristic of a forelimb strike, and the right side, a hindlimb strike.

Once the prints had been assigned a limb, further processing was performed using MATLAB® to compile all prints from each limb and rotate them as necessary until they all had the same orientation, to allow comparison. Prints of right limbs were 'flipped' to allow topological comparison with left limb prints.

2.5.3.2.1 Quadrant analysis

Custom-written MATLAB® code was used to divide the prints into dorsolateral, dorsomedial, palmarolateral, palmaromedial quadrants, to enable comparison between these different regions of interest (Figure 2.12). This method was an objective approach based on the method used by Oosterlinck and others (2013) to examine medio-lateral and toe-heel differences in sound sport horses.

The division occurred based on the number of pixels in each quadrant. Since some prints had a low number of pixels, which would result in half or quarter pixels being assigned to different quadrants, the prints were expanded by a factor of 100 before then being divided. This enabled even division of the print into quadrants. Maximum and mean values for each quadrant of each recorded foot strike were obtained from this analysis. The code also created images which enabled assessment of the success of the foot-splitting process.

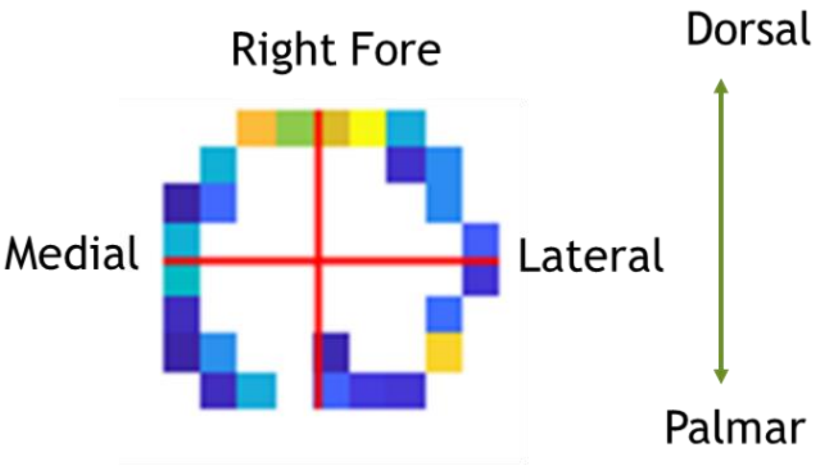

Figure 2.12: Example image of an equine foot strike recorded by the pressure mat and divided into quadrants using custom-written MATLAB code

2.5.3.2.2 Pedobarographic Statistical Parametric Mapping (pSPM)

This analysis allowed comparison of the total pixels activated during each foot strike – e.g. between left and right limbs, pre- and post-trimming or start and end of the study depending on the study aims.

Once the left and right fore prints for each limb were identified and collated for each file, custom-written MATLAB® 2018 (The Mathworks, Inc.) code was used to flip the left prints so that they topographically matched right fore prints. This allowed e.g. medial and lateral aspects to be compared. Prints were then registered to the mean print in each set. At this point the results were visually inspected (Figure 2.13).

Figure 2.13: Image demonstrating an example output of successful foot print registration in MATLAB software. All prints are aligned in the same orientation and within the black dots.

Once registration within each set of prints had occurred and been checked, prints to be compared were registered against one another. The prints were then compared using mean pressure plots to visualise differences in loading between the relevant conditions and a t-test performed to determine the statistical significance of any of these differences (Figure 2.14)

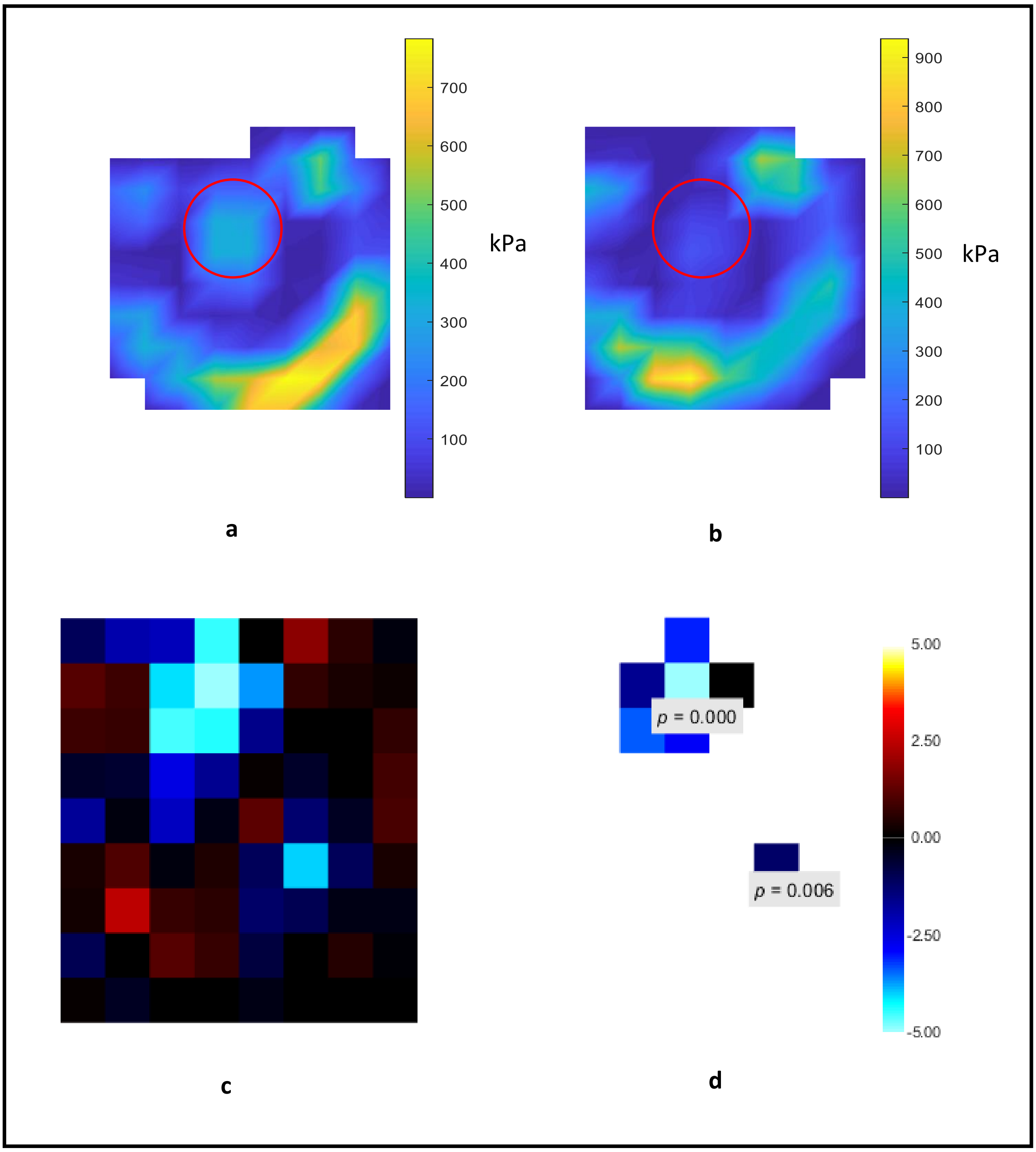

Figure 2.14a-d: An example of pedobarographic statistical parametric mapping (pSPM) output showing the comparison of left and right forelimbs in a single horse, indicating less loading of the right fore base of frog region than the left fore. a shows the mean pressure plot for the left forelimb strikes post-trimming, b shows the mean pressure of the right forelimb strikes post-trimming, c shows the difference between a and b and d shows the areas of significant differences in loading between the left and right forelimbs. In this example plots a and b indicate that the loading over the frog region is greater in the left forelimb than the right (red circles). The cluster of six pixels (p=0.000) and the single pixel (p=0.006) in plot d are significantly different between limbs. Single pixel changes are often indicative of artefactual differences; in this case the single pixel difference is not considered meaningful. Comparison of the six-pixel cluster with plot c indicates that the location is the caudal, central hoof (i.e. base of frog) region. The colour of the pixels in this cluster indicate a negative change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means that there is less pressure in the right fore strikes than left fore.

2.5.4 Methodological development: managing erroneous pressure mat data

When maximum pressure results were obtained, it became clear that some horses were outputting identical maximum pressure values. The horses that shared these results were not necessarily of similar heights and weights, however the same calibration files had been used to calibrate their pressure mat data recordings. Hence the conclusion was reached that these calibration files were determining what the highest maximum pressure that could be recorded was; in effect creating a ceiling maximum pressure, which varied depending on the calibration.

To establish the effect that this ceiling effect was having on the data, pSPM analysis for pre- vs post-trimming results was compared for a) 'raw data' (i.e. that with error), b) 'error removed' data where the maximum values had been replaced with zero and c) 'smoothed data' where the maximum values had been 'smoothed' by taking an average of them and the cells neighbouring them. This was performed for the 10 heaviest horses in the dataset with the aim of observing the greatest possible impact. Of those 10 horses eight showed no difference for both the raw and the smoothed data. For the two that showed differences, these were mild changes in the individual pixels that were affected, but did not alter the region of the foot where the difference was seen, nor did it change the direction of the difference (i.e. higher pressure post-trimming).

When raw data were compared with that where the error values had been removed, again eight horses showed no difference in the results. One horse showed a significant change in a two-pixel cluster of the raw data that was not evident in the error removed result. However, the other merely showed some changes in individual pixels affected, whilst the region of the foot and the direction of change remained the same. The results of these comparisons demonstrate that in every case when the maximum values were smoothed, and almost all when these values were removed completely, the overall conclusions that were made from the data remained unchanged.

Chapter 3

Examination of Factors Influencing Foot Shape and Loading in a Cohort of Sound Horses

3.1 *Introduction*

Optimal foot shape and balance have long been topics of controversy amongst horse owners, farriers and veterinary surgeons alike, not least because of their impact on foot loading and equine lameness (Eliashar, McGuigan and Wilson, 2004). Recent studies have called in to question some long-held ideals regarding foot shape and balance in historical farriery texts (Russell, 1897), such as that the ideal angle of the dorsal hoof wall is 45°, which has now been shown to be 50-55° (O'Grady and Poupard, 2001), though variation has been documented around this figure (Kummer *et al.*, 2006; Gordon *et al.*, 2013). The role of the hoof care professional in maintenance of optimal foot shape is considered key for long term soundness (Clayton, 1990; Balch, Butler and Collier, 1997; Gill, 2007; Jackman, 2019). As well as farriery, many factors have been shown to influence foot shape as well as the occurrence of hoof abnormalities. These include inherent factors such as breed or height, and environmental factors such as stable management and work pattern (Gill, 2007; Holzhauer *et al.*, 2017). A recent study on a cohort of riding school horses demonstrated that greater height and weight are associated with a more upright foot shape, as well as greater asymmetry between forefoot pairs (Leśniak *et al.*, 2019). There is variation in average foot measurements displayed in the literature, where individual studies have focussed on one breed, which may be indicative of breed as well as overall use and management differences (Kane *et al*., 1998; Kummer *et al*., 2006).

Numerous studies have measured foot shape using digital photographs, either at a single time point or longitudinally (Kummer *et al.*, 2006; White *et al.*, 2008, Leśniak *et al.,* 2017, 2019). However, most of the literature describes small study populations of individual breeds of horses (Warmbloods (WB), Thoroughbreds (TB)), which makes it hard to be sure how much these results apply to a general equine population. Few studies have looked at changes in foot shape around trimming (Kummer *et al.*, 2006; Gill, 2007; White *et al.*, 2008; Caldwell *et al.*, 2016; Leśniak *et al.*, 2017). The point at which horses are in their shoeing or trimming cycle when measured may have significant effects on the results of such studies. A previous study of radiographic measurements showed that trimming had an important effect on foot shape and alignment of bones within the foot (Kummer *et al.*, 2006). Another study found that many foot measurements changed significantly between pre- and post-trimming in a 4-6 week shoeing interval, leading the authors to conclude that any greater interval would increase the risk of overloading the palmar aspect of the foot and consequently lameness events (Leśniak *et al.*, 2017).

In recent years measurement of ground reaction forces using force plates and pressure platforms has increased (Van Heel *et al.*, 2004; Oomen *et al.*, 2012; Oosterlinck *et al.*, 2015, Pitti *et al.*, 2018; Faramarzi *et al.*, 2020; Mokry *et al*., 2021). In comparison to force plates, their high spatial resolution provides detailed information on loading across the bearing surface of the hoof. Validation studies using both pressure mats and force plates have demonstrated that the former provide valuable data on foot loading (Oosterlinck *et al.*, 2010a). Previous studies have looked at the impact of foot shape on the stresses experienced by various structures within the foot (Page and Hagen, 2002; McClinchey, Thomason and Jofriet, 2003). Foot measurements such as toe angle and length, heel angle and medial and lateral wall angles and lengths have all been shown to have biomechanical implications for the limbs of the horse (Kobluk *et al*., 1990; Thomason *et al*., 2004). Longer and lower toes have been shown to be associated with a longer breakover phase (Eliashar, McGuigan and Wilson, 2004), as well as a greater risk of musculoskeletal injuries in Thoroughbred racehorses (Kobluk *et al.*, 1990). However, these studies have not assessed the relationship between foot shape and the way the foot is loaded. Similarly, although foot loading has been the topic of a number of scientific studies, using either force plates or pressure plates (Van Heel *et al.*, 2004; Oosterlinck *et al.*, 2010a; Oosterlinck *et al.*, 2010b; Oomen *et al.*, 2012; Oosterlinck *et al.*, 2015), few of these have assessed changes in foot loading following foot-trimming by a farrier or hoof care professional (Hood, Taylor and Wagner, 2001; Van Heel *et al*., 2004; Faramarzi *et al*., 2018). This lack of evidence makes it difficult to conclude the true impact of various foot shapes as well as foot trimming on the way the foot is loaded.

This chapter describes results from an interview questionnaire used to gather information about demographics, stable management, and foot care of horses in order to test the relevance of these factors to foot shape and the occurrence of hoof abnormalities.

Digital photographs were used to collect foot shape measures both before and after trimming at a single time point to assess the effect of trimming on foot shape. Horses were also assessed for hoof abnormalities at the outset of the study. Foot loading data were obtained (through use of a commercial pressure mat) before and after trimming by a farrier, in order to assess the true relationship between foot shape and foot loading, and how this relationship was altered by foot trimming.

3.2 Hypotheses

i. *Foot shape measures are significantly changed following foot trimming by a farrier*
ii. *Foot loading (as measured by a pressure mat) is significantly changed following foot trimming by a farrier*
iii. *Environmental and genetic factors have an impact on foot shape and the occurrence of hoof abnormalities*
iv. *Foot shape is associated with foot loading*

3.3 Aims

The overall aim of this study was to assess the effect of trimming on foot morphology and foot loading in a cross-section of sound horses at a single time point, and to ascertain the relationships between demographics, work pattern and environmental factors and foot shape, loading and occurrence of hoof abnormalities

3.4 Study design

3.4.1 Study population

The equine sample population were recruited by convenience sampling through their farriers, this method of recruitment had not been previously used by the research group behind this study. Initially four farriers were recruited to the study. However, it became evident that this was not going to yield a sufficient number of study subjects, hence recruitment was expanded and in total eleven farriers from North Wales and the North-West of England were recruited to the study. The farriers were provided with postcards that they gave to the owners or keepers of eligible horses (those in work, free from lameness and shod regularly), which in turn were posted back to the investigator by those willing to be involved, in keeping with ethical approval from the University of Liverpool Veterinary Research Ethics committee (General Data Protection Regulation compliant). Owners were contacted by telephone using details provided on the recruitment postcards. Where they were still keen and eligible for inclusion in the study, informed consent was obtained before any data were gathered for the study purposes. Inclusion criteria for involvement in the study were horses that were free of lameness (assessed at trot at the point of first visit by the primary researcher) and in regular work (defined as exercising at least once in every 14-day period).

3.4.2 Data collected

3.4.2.1 Questionnaire

A quantitative interview questionnaire (Appendix 1) was designed with the aim of collecting data on horse demographics, stable management, veterinary and farriery care, including history of lameness or hoof abnormalities. Information was also collected on the intensity of work the horse was currently doing, the type and number of different activities each horse did per week, as well as what surfaces these activities were carried out on (Chapter 6). Where owner-reported activity data included a range of number of sessions per week or time per session, a mean was calculated and used for analysis.) These data were collected to investigate the effect of such environmental factors on foot shape outcomes. Many questions were closed categorical to facilitate analysis of results, however some open questions were included to capture data that did not fit in the categories provided. An interview questionnaire was used to maximise the response rate. The questionnaire was designed using both a review of the relevant literature (Murray *et al.*, 2010; Murray *et al.*, 2010; Ireland *et al.*, 2012; Ireland *et al.*, 2012) as well as input from the supervisory team who had considerable expertise in questionnaire-based research on the equine population in the UK.

The questionnaire was piloted on a convenience-based sample of eight horse owners to ensure that questions were appropriate and answerable, as well as to enable optimisation of the questionnaire layout. This highlighted the need for additional answer boxes for some closed questions to gather responses that did not necessarily fit the answers provided. Since no major issues were identified, the pilot study group was not expanded further.

Data were recorded on paper or digital copies of a word document and transcribed into a Microsoft® Access® 2016 database. Questionnaire data were collected at the time of recruitment or data collection, where possible. In those instances when the owner or keeper of the horse was not present, the data were gathered within 14 days of the recruitment/data collection.

3.4.2.2 Whole body conformation

The conformation of study subjects was assessed at recruitment, using a linear score modified from Mawdsley used in previous studies examining equine foot and lameness problems (Mawdsley *et al.*, 1996; Gordon *et al.*, 2013). This was initially collected as a 7-point score but collapsed to a 3-point score for analysis.

Table 3.1 Description of conformation score

Trait	Scoring
Carpus (front view)	1 – Forward at the knee
	4 – Straight
	7 – Back at the knee
Carpus/ cannon angle	1 – Carpal varus
	4 – Straight
	7 – Carpal valgus
Hoof pastern axis	1 – Broken forward
	4 – Straight
	7 – Broken back
Foot angle	1 – Upright/boxy
	4 – Straight
	7 – Long toe, low heel

A pilot study was conducted to assess the within intra-rater repeatability of the scoring system. A convenience-based sample of seven horses in the Philip Leverhulme Equine Hospital, University of Liverpool teaching herd were scored three consecutive times over a two-day period by the author. The researcher was blinded to previous scores when recording each new score. The scores were assessed for their repeatability using Fleiss' Kappa test in R Studio (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). Only conformational traits that showed at least moderate agreement ($\kappa \geq 0.4$) and $p<0.05$ were included in the final study. These traits are displayed in Table 3.1. Horses were examined for hoof abnormalities by the primary researcher (Chapter 2 Section 2.4). These were recorded in binary format (present/not present).

3.4.2.3 Foot shape and foot loading

Digital photographs were taken of the feet of both left fore (LF) and right fore (RF) limbs before and after trimming by the farrier as described in Chapter 2 Section 2.3, at a single time point, , to obtain quantitative foot measurements. Where possible, static (standing) and dynamic (walking) foot pressure data were also obtained using a Tekscan™ pressure mat (Chapter 2, Section 2.5) before and after trimming at a single time point. As in previous studies (Oosterlinck *et al.*, 2010a; Oomen *et al.*, 2012; Faramarzi, Nguyen and Dong, 2018), for dynamic pressure mat data collection a minimum of 5 valid strikes per forelimb were recorded for pre- and post-conditions, though in most cases, where time and circumstances allowed, at least 10 strikes were recorded per limb. Foot pressure data were analysed as described in Chapter 2, Section 2.5.3.2.

Horses were recruited from July 2017 to June 2019. Foot shape measures for pre- and post-trimming conditions were compared to identify changes that occur following trimming by a farrier.

Questionnaire data were analysed to elucidate their effect on foot shape measures. Five key foot measures (section 3.5.3) were chosen as outcome measures for multivariable analysis. These five were selected based on the fact that they provided a meaningful description of foot shape, and they were not strongly correlated ($r<0.7$) with any other foot measures. Questionnaire data were also analysed to assess their effect on the occurrence of hoof abnormalities in the study population.

Foot quadrant pressures were used to assess changes in foot loading between pre- and post-trimming conditions, as well as between LF and RF. The five key foot shape measures were assessed for their correlation with foot quadrant pressures in both static and dynamic pressure mat data, to understand the relationship between foot shape and foot pressure, pre- and post-trimming. Pedabarographic statistical parametric mapping (pSPM) analysis was used on the dynamic foot pressure data to assess changes within each horse between LF and RF as well as pre-vs-post-trimming.

3.4.3 Data analysis

Data analysis was carried out in R Studio for Windows (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). Data were assessed for normality using the Shapiro-Wilk test. Normally distributed data were presented as mean +/- 95% confidence intervals (CI) whilst non-normally distributed data were presented as median and interquartile range (IQR). Univariable analysis of continuous variables involved the use of the student's t-test in the case of normally distributed data, or the Wilcoxon signed rank test for non-normally distributed data. The Kruskal-Wallis test was used to analyse categorical and continuous data, whilst the Mann-Whitney U test was used to analyse binary and continuous data. Chi-squared test was used to compare categorical variables. Unweighted Cohen's Kappa test was used to assess the agreement between two raters for categorical or binary variables.

Where correlations were sought, Pearson's or Spearman's correlation coefficient were estimated for normally or non-normally distributed data, respectively. Significance was set to $p<0.05$ unless otherwise specified.

3.4.3.1 Questionnaire and foot data

Analysis of the effect of demographic and environmental factors on foot shape was assessed using pre-trim foot shape measures. Variables that were associated with the outcome variables ($p<0.2$) in univariable analyses were considered for multivariable analysis, which was performed using linear mixed models with backwards stepwise selection. In these models horse was included as a random effect, with limb (LF and RF) forced into the model as a fixed effect to allow assessment of left-right differences. All continuous variables were assessed for linearity with the outcome variable before being included in the model and transformed (squared or cubed) as necessary. Correlation matrices were used to assess the relationships between explanatory variables. Where two variables were highly correlated ($r>0.7$) only one of these was included in the multivariable model; that which was likely to be more meaningful. Since five separate models were run, significance for the outputs was adjusted to account for multiple comparisons using the Bonferroni method. Significance for the output of these models was set to $p<0.01$.

Logistic regression was used to analyse the relative importance of variables on both dorsopalmar and mediolateral foot imbalance. As previously, variables were screened for inclusion using univariable analysis, with only those with $p<0.2$ taken forward to the multivariable model. Similarly, correlation matrices were used to determine the relationship between explanatory variables and where two variables were highly correlated ($r>0.7$) only one of these was included in the multivariable model. Backwards stepwise method with re-entry was used to identify the most important factors contributing to the outcomes. Chi-squared goodness of fit method was used to establish the fit of the model.

3.4.3.2 Foot shape and foot loading data

Results of the correlation between foot shape and foot pressure measurements were adjusted for multiple comparisons using the Bonferroni method, with significance set to $p<0.01$ (five foot outcome measures: 0.05/5 = 0.01). Where pairwise comparisons were performed to identify significant differences between individual foot quadrants, results were adjusted for multiple comparisons using the Bonferroni method with significance set to $p<0.008$ (0.05/6 = 0.008). Where pairwise comparisons were performed to identify significant differences between pre- and post-trimming foot shape measures, results were adjusted for multiple comparisons using the Bonferroni method. For solar foot measurements there were 12 different measurements being compared, so the adjusted threshold for significance was $p<0.004$ (0.05/12 = 0.004). There were 12 medial and lateral view measures in total (six of each) for each limb so the adjusted threshold for significance for medial and lateral view measures was $p<0.004$ (0.05/12 = 0.004).

3.5 Results

3.5.1 Questionnaire data

Details of 93 horses were obtained for the questionnaire data. The median age of the sample population was 10.6 years (IQR 8.13-14.8), with a mean height of 154cm (95% CI: 150, 158) and mean bodyweight of 537kg (95% CI: 522, 551). The majority (61/93, 65.6%) of the sample were geldings, with the rest mares.

3.5.1.1 Demographics and activity of the sample population

Table 3.1 shows the demographics of the sample population. Native breeds were the most common, and of those Welsh Section D and Connemara were most frequent. Warmbloods, TBs and Irish Sports Horses (ISH) were also frequently represented.

Table 3.1: Demographics of questionnaire study population (n=93 horses)

Breed	Number of Horses (% of total)
All Native and Native X	35 (37.6)
Welsh	12 (12.9)
Connemara	8 (8.6)
Unspecified	4 (4.3)
Cob	3 (3.2)
Native X	8 (8.6)
WB	17 (18.3)
TB	16 (17.2)
ISH	13 (14.0)
Other Crossbred	7 (7.5)
Arab	3 (3.2)
Other Purebred	2 (2.1)

TB = Thoroughbred; WB = Warmblood; ISH = Irish Sports Horse; Native X = Native crossbreed

The most common discipline was hacking or leisure riding, followed by riding and pony club activities. Eventing, show-jumping, and dressage were also reported frequently. Fifty-two horses were reported to compete, including all eventing, endurance and showing horses, as well as most showjumpers and most dressage horses (Table 3.2). Over half of those involved in riding and pony club activities competed, whilst only a small number of horses used for hacking or leisure did any competitions, and none of the riding school horses competed. Most horses competed at local events, whilst some did compete at a national or international level (Table 3.2).

Table 3.2: Discipline and competition status of the equine study population (n=93 horses)

Discipline and Competition Status	Number of (% total study population)	Number of Horses Competing
Discipline		
Hacking/leisure	26 (28.0)	3
Riding and Pony Club Activities	19 (20.4)	12
Eventing	14 (15.0)	14
Dressage	10 (10.8)	7
Show-jumping	10 (10.8)	9
Riding School	7 (7.5)	0
Showing	4 (4.3)	4
Endurance	3 (3.2)	3
Competition Status	Number of horses	
Yes	52	
Local	20	
Regional	15	
National	12	
International	4	
No	41	

For those horses that competed (52/93, 55.9%), most of them (40/52, 76.9%) did 1-2 competitions per month, but 4 (7.7%) horses did 3 or more per month (Figure 3.1). Five horses had an unknown number of competitions per year due to being relatively new to the owner or having had time off due to illness or injury. The median number of years spent competing at the time of the questionnaire was 3 (IQR: 2-6.8).

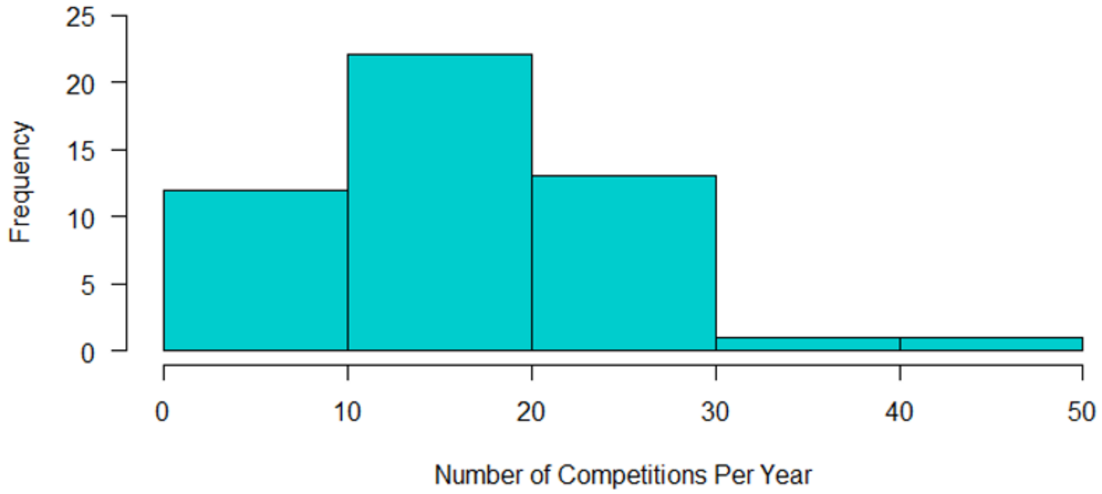

Figure 3.1: Histogram illustrating the frequency with which the study population attended competitions

3.5.1.1.2. Exercise and activity patterns

Most horses (57/93, 61.3%,) were described as being in 'medium' level work, with 21/93 in hard work and 13/93 in light work (Appendix 1 includes definitions of work intensity). Ten horses were described to be in a different exercise intensity from usual, due to a previous lameness event (4/10), due to a change in ownership (2/10) or miscellaneous reasons (4/10). Previous lameness events were associated with a reduction of work intensity, whilst both cases of change in ownership resulted in an increase in work intensity.

Flatwork and trail riding were the most popular activities undertaken with 76.3% (71/93) and 75.2% (70/93) of horses doing at least one session per week, respectively. Other commonly reported activities were jumping 53.8% (50/93) and lunging 33.3% (31/93). Sixteen horses (17.2%) were reported to be regularly exercised on a horse walker. Five horses participated in other activities, including interval training on gallops (2/93, 2.2%), endurance competitions (2/93, 2.2%) and pole work (1/93, 1.1%).

Table 3.3 shows that flatwork was the most frequently reported activity with lunging and jumping the least frequent activities. Time per session varied significantly between activity types (Table 3.3).

Most horses who had a warm-up period did so before flatwork or jumping (Table 3.3), on average this lasted for around 10 minutes for both flatwork and jumping.

Table 3.3: Average number and duration of of different exercise sessions carried out per week from the study population (n=93 horses)

Exercise Type	Median Sessions Per Week (IQR)	Median Minutes Per Session (IQR)	Number of Horses Doing Warm-Up (%)	Median Warm-Up in Minutes (IQR)
Lungeing [ab]	1.0 (1.0-2.0)**	20.0 (20.0-25.0)	2.0 (6.5)	8.8 (8.1-9.4)
Horsewalker	1.5 (1.0-7.0)	26.0 (20.0-60.0)	0.0 -	-
Flatwork[b]	2.5 (2.0-3.3)*	35.0 (30.0-43.8)**	46.0 (64.8)	10.0 (7.5-10.0)
Jumping[ab]	1.0 (1.0-1.4)**	30.0 (25.0-40.0)**	38.0 (76.0)	10.0 (7.5-10.0)
Trail-riding[a]	2.0 (1.0-3.0)*	52.5 (30.0-60.0)**	0.0 -	-
Other	2.0 (1.0-4.5)	25.0 (12.5-120.0)	0.0 -	-

*IQR= interquartile range; [a]Significantly different from flatwork, [b] Significantly different from hacking, [c] Significantly different from lungeing, [d] Significantly different from hacking. *(p<0.01) **(p<0.001)*

3.5.1.2 Stable management

Most horses were kept on livery yards (38/93, 40.9%), with privately-owned yards being the next most common premise type (26/93, 28.0%). Twelve horses (12.9%) came from a rehabilitation/retraining yard. Over half of horses (52/93, 55.9%) were kept at pasture during the day, and stabled at night, whilst 19.4% (18/93) were stabled during the day and out at night. Fifteen horses were turned out at pasture for 24 hours per day, and eight horses were stabled 24 hours per day at the time of the questionnaire. Horses were turned out for a median of 8 hours per day (IQR: 4.75-16). Horses were recruited over a 15-month period so season may have affected these findings.

Of the 78 horses that spent some time stabled, the stable was fully cleaned out daily for 88.5% (69/78) of horses, whilst for nine horses (11.5%) a deep litter bedding management system was run, with a full clean out once a week or once a month.

3.5.1.3 Diet and nutrition

Around a third of the study population were fed at least one supplement regularly (29/93, 31.2%); 13 horses were fed >2 supplements, with two horses fed five supplements at once. Feed balancers were the most used supplements, accounting for a quarter of all the supplements fed (14/56). Joint (9/56, 16.1%), gastric and vitamin and mineral supplements (both 5/56, 10.7%) were also popular. Ten horses were reported to be on supplements following recommendations from a nutritionist, with five and three following veterinary or farriery advice, respectively. Others were due to recommendations by a friend, following research by the owner or for other reasons.

Most owners described their horse as a ‘normal’ bodyweight (64/93, 68.8%), with almost one-third of horses described as overweight (26/93, 28.0%), and three described as ‘thin’. One owner described using a weigh tape regularly for weight management purposes.

3.5.1.4 Foot care and farriery

Most owners (70/93, 75.3%) reported cleaning out their horses’ feet at least once daily. In contrast 16.1% (15/93) described almost never cleaning them out.

Ten horses were reported to need an increase in shoeing frequency during the summer. In all other horses the owners reported no change in shoeing frequency over the year. The median trimming frequency was 6 weeks (Figure 3). This ranged from 4 to 8 weeks across the study population, though most horses (63/93, 67.7%) were shod every 5-6 weeks.

Ten horses (10.7%) were shod remedially; most of these were reported by the owners to be due to foot conformational defects (7/10), with some to help alleviate previous lameness conditions (3/10). The median time that horses had been under the care of their current farrier was 1.3 years (IQR: 0.5-3.0).

3.5.1.5 Previous lameness events

A history of previous lameness events was reported in 40.8% (38/93) of horses recruited to the study. All lameness issues were resolved prior to recruitment to the study; most were reported to have occurred 13-24 months prior to the time of the questionnaire (Table 3.4) though some variation existed around this. Almost all horses with a lameness event (30/37, 81.1%) received veterinary treatment and of these only three did not receive a diagnosis. Unfortunately, almost half of owners were not able to recall the diagnosis that the lameness received (Table 3.4). Of those that did, osteoarthritis was reported to be the most common condition followed by tendon or ligament injuries.

Table 3.4: Timing and diagnosis of previous lameness events in the study population (n=93 horses)

Previous lameness	**Number (%) of Horses Affected**
No history of previous lameness	56 (60.2)
Total horses with a previous lameness	37 (39.8)
Lameness Diagnosis (of those that were veterinary treated; n=30)	**Number (%*) of Horses**
Owner Unsure of Diagnosis	14 (46.7)
Osteoarthritis	6 (20.0)
No Diagnosis	3 (10.0)
Tendon/ligament injury	3 (10.0)
Wound/abscess	2 (6.7)
Bruised bone	2 (6.7)
Timing of Most Recent Lameness Event	**Number (%) of Horses Affected**
< 6 months	8 (8.6)
6-12 months	9 (9.7)
13-24 months	12 (12.9)
>24 months	8 (8.6)

** Percentage of horses that were veterinary treated for the previous lameness event*

3.5.1.6 Hoof abnormalities

A total of 49 hoof abnormalities (Chapter 2, Section 2.4) were reported by owners/keepers. Eight horses had more than one hoof abnormality, which meant that 44.1% of the study population (41/93) had at least one hoof abnormality. Foot imbalance was the most reported type of abnormality; dorsopalmar imbalance was more common than mediolateral imbalance (Table 3.5). In terms of horn abnormalities, hoof wall cracks and thrush were frequently reported. The majority of abnormalities were being, or had been, actively managed (43/49, 87.8%). Of those 76.7% (33/43) had ongoing treatment at the time of the questionnaire. Treatment methods included trimming or shoeing management (29/43, 67.4%) as well as topical application of medication (4/43, 9.3%), feed supplements (1/43, 2.3%) and 'other' (9/43, 20.9%) which included excision of affected areas (2/43, 4.7%), application of a poultice (1/43, 2.3%), prevention of solar bruising (1/43, 2.3%) and unknown treatment (5/43, 11.6%).

Table 3.5: Owner-reported and veterinary-observed hoof abnormalities in the study population (n=93 horses). Cohen's Kappa measurement of agreement between veterinary observed and owner-reported abnormalities.

Owner-Reported Current Hoof Abnormality	**Number of Horses Reported (% study population)**	**Veterinary-Observed Hoof Abnormality Reported by Owners**	**Number of Horses Observed (% study population)**	**Cohen's Kappa (k)**
Long toe, low heel	13 (14.0)	Long Toe, Low Heel	41 (44.1)	0.04
Asymmetrical feet	1 (1.1)	Asymmetrical feet	22 (23.7)	0.04
Mediolateral imbalance	6 (6.5)	Mediolateral Imbalance	14 (15.1)	0.27
Sheared heels	3 (3.2)	Sheared heels	6 (6.5)	0.35
Hoof wall cracks	5 (5.4)	Hoof wall cracks	13 (14.0)	0.26
Crumbling Horn/Poor Hoof Wall Quality	4 (4.3)	Crumbling Horn/Poor Hoof Wall Quality	9 (9.7)	0.31
Thrush	3 (3.2)	Thrush	7 (7.5)	0.39
Owner-Reported Historical Hoof Abnormality	**Number of Horses Reported (% study population)**	**Veterinary Observed Hoof Abnormality Not Reported by Owners**	**Number of Horses Observed (% study population)**	
Thrush	2 (2.2)	Widened White Lines	2 (2.2)	-
Seedy Toe	3 (3.2)	Prominent Growth	13 (14.0)	-
Laminitis	2 (2.2)	Convex Soles	2 (2.2)	-
Thin/low soles	2 (2.2)	Contracted Heels	2 (2.2)	-
Abscess	1 (1.1)	Underrun Heels*	3 (3.2)	-

k = 0.01-0.20; 'slight agreement', k = 0.21-0.40; 'fair agreement'

Prior to performing objective foot measurements, a subjective assessment of the foot was first undertaken to provide the prevalence of horses with hoof abnormalities (Table 3.5). A large number of hoof abnormalities were observed; almost half the study population were found to have long toe, low heel conformation, and almost a quarter to have asymmetrical front feet (Table 3.5). Mediolateral imbalance, hoof wall cracks and prominent growth rings were each observed in approximately 15% of the study population (Table 5). There were considerable differences between the results of owner-reported and veterinary-observed hoof abnormalities. Mediolateral imbalance and sheared heels were identified by the veterinary observer to be over two-times as prevalent compared with the owner-reported number; kappa analysis revealed 'fair' agreement. Long toe, low heel conformation and asymmetrical feet were 3- and 20-fold the owner-reported prevalence, respectively: 'slight' agreement. A similar pattern was seen in the horn abnormalities, with fair agreement found between owners and veterinary observations, where the same abnormalities were reported (which was not the case for a number of horn abnormalities).

3.5.2 Foot shape measurements

3.5.2.1 *Dorsal foot measurements*

Table 3.6 shows foot measurements as viewed from the dorsal aspect, before and after trimming, in LF and RF feet. Lateral hoof wall length (LHWL) and medial hoof wall length (MHWL) significantly decreased post-trimming, whilst medial hoof wall angle (MHWA) significantly increased post-trimming. Interestingly, lateral hoof wall angle (LHWA) did not change in either fore foot. When foot measures were compared between LF and RF (both pre- and post-trim) there were no significant differences between any measurement.

Table 3.6: Dorsal view foot measurements of the left and right fore foot, pre- and post-trimming by a farrier at a single time point (n=76 horses)

Limb	Foot measurement	Pre-trim Mean (95% CI)	Post-trim Mean (95% CI)	Pre-Post Difference (cm) Mean (95% CI)	P value
Left Fore	LHWL (cm)	7.40 (7.16, 7.63)	6.94 (6.73, 7.15)	-0.48 (-0.31, -0.63)	**<0.001**
	LHWA (°)	73.74 (72.74, 74.73)	74.21 (73.23, 75.18)	0.47 (0.37, 1.19)	0.30
	MHWL (cm)	7.49 (7.24, 7.75)	6.98 (6.77, 7.20)	-0.52 (-0.70, -0.34)	**<0.001**
	MHWA (°)	71.01 (69.65, 72.36)	72.68 (71.38, 73.99)	1.72 (0.89, 2.58)	**<0.001**
Right Fore	LHWL (cm)	7.23 (7.01, 7.46)	6.80 (6.59, 7.02)	-0.43 (-0.54, -0.26)	**<0.001**
	LHWA (°)	73.53 (72.28, 74.78)	73.91 (72.56, 75.27)	0.38 (0.29, 1.21)	0.23
	MHWL (cm)	7.53 (7.31, 7.75)	7.15 (6.94, 7.34)	-0.36 (-0.52, -0.20)	**<0.001**
	MHWA (°)	71.97 (71.00, 72.95)	73.25 (72.15, 74.36)	1.68 (0.53, 2.84)	**0.005**

LHWA = lateral hoof wall angle; LHWL = lateral hoof wall length; MHWA = medial hoof wall angle; MHWL = medial hoof wall length; 96% CI = 95% confidence intervals

3.5.2.2 Lateral and medial view foot measurements

Table 3.7 shows foot measurements as viewed from the lateral and medial aspects, before and after trimming, in LF and RF feet. In both LF and RF, when viewed from the lateral aspect, DHWL and HL significantly decreased whereas DHWA increased after trimming (Table 3.7). Other parameters did not significantly change after trimming when viewed from the lateral side. For the medial side there was a significant reduction in DHWL in both fore feet but only in the LF was there a change in DHWA (increase) and HL (decrease). In the right fore hoof angle (HA) significantly decreased post-trim. From the medial view, there was also a significant increase in the difference between DHWA and HA in LF.

Table 3.7: Lateral and medial view foot measurements of the left and right fore foot, pre- and post-trimming by a farrier at a single time point (n=76 horses)

Limb	**Lateral Foot Measurement**	**Pre-trim Mean (95% CI)**	**Post-trim Mean (95% CI)**	**Pre-Post Difference Mean (95% CI)**	**P value**
Left Fore	DHWL (cm)	10.05 (9.81, 10.29)	9.37 (9.14, 9.61)	-0.68 (-0.83, -0.53)	**<0.001**
	DHWA (°)	49.11 (48.24, 49.98)	50.38 (49.55, 51.22)	1.27 (0.68, 1.91)	**<0.001**
	HL (cm)	5.37 (5.16, 5.57)	4.94 (4.74, 5.14)	-0.42 (-0.59, -0.26)	**<0.001**
	HA (°)†	46.13 (44.46, 47.81)	46.50 (44.68, 48.31)	0.37 (1.32, 2.04)	0.67
	DHWA-HA (°) ‡	2.98 (1.52, 4.44)	3.89 (2.29, 5.48)	0.91 (0.07, 2.77)	0.07
	DHWL:HL ‡	1.91 (1.84, 1.97)	1.95 (1.86, 2.03)	0.04 (0.03, 0.11)	0.33
Right Fore	DHWL (cm)	10.08 (9.12, 10.35)	9.51 (9.23, 9.72)	-0.58 (-0.75, -0.42)	**<0.001**
	DHWA (°)†	49.79 (49.05, 50.52)	51.24 (50.57, 51.92)	1.45 (1.01, 1.94)	**<0.001**
	HL (cm)	5.22 (5.01, 5.43)	4.80 (4.63, 4.97)	-0.43 (-0.61, 0.25)	**<0.001**
	HA (°)†	45.61 (43.71, 47.51)	46.89 (45.04, 48.74)	1.28 (0.11, 2.60)	0.07
	DHWA-HA (°)‡	4.18 (2.50, 5.85)	4.35 (2.65, 6.05)	0.18 (1.05, 1.50)	0.73
	DHWL:HL	1.95 (1.85, 2.05)	2.02 (1.95, 2.09)	0.06 (-0.01, 0.15)	0.10
Limb	**Medial Foot Measurement**	**Pre-trim Mean (95% CI)**	**Post-trim Mean (95% CI)**	**Pre-Post Difference Mean (95% CI)**	**P value**
Left Fore	DHWL (cm)	10.26 (9.97, 10.54)	9.38 (9.15, 6.61)	-0.87 (-1.05, -0.69)	**<0.001**
	DHWA (°)	48.96 (48.16, 49.76)	50.55 (49.78, 51.32)	1.59 (1.08, 2.21)	**<0.001**
	HL (cm)	5.16 (4.93, 5.38)	4.80 (4.61, 4.99)	-0.36 (-0.52, -0.20)	**<0.001**
	HA (°)	43.63 (41.76, 45.50)	43.47 (41.50, 45.45)	-0.16 (-1.73, 1.42)	0.84
	DHWA-HA (°)	5.33 (3.73, 6.93)	7.07 (5.27, 8.87)	1.74 (0.41, 3.36)	0.02
	DHWL:HL	2.04 (1.96, 2.13)	2.01 (1.92, 2.10)	-0.04 (-0.11, 0.04)	0.33
Right Fore	DHWL (cm)	10.04 (9.79, 10.28)	9.35 (9.13, 9.57)	-0.69 (-0.83, -0.54)	**<0.001**
	DHWA (°)	49.22 (48.48, 49.96)	49.61 (48.17, 51.05)	0.39 (-1.00, 1.77)	0.58
	HL (cm)	5.37 (5.14, 5.60)	5.10 (4.73, 5.47)	-0.27 (-0.61, 0.07)	0.12
	HA (°)	43.96 (42.27, 45.65)	42.00 (39.89, 44.11)	-1.96 (-3.47, 0.45)	0.02
	DHWA-HA (°)	5.26 (3.79, 6.73)	7.61 (5.94, 9.27)	2.34 (0.98, 3.71)	**<0.001**
	DHWL:HL*	1.92 (1.84, 2.00)	1.93 (1.84, 2.02)	0.01 (-0.06, 0.08)	0.74

DHWA= dorsal hoof wall angle; DHWL= dorsal hoof wall length; HA = heel angle; HL = heel length; DHWA-HA = difference between dorsal hoof wall angle and heel angle; DHWLHL = ratio of dorsal hoof wall length and heel length, LF = left fore, RF = right fore; 96% CI = 95% confidence interval. After adjustment for multiple comparisons using the Bonferroni method p<0.004 for pre-post trim differences.
†Lateral>medial (P<0.05); ‡Medial>lateral (P<0.05), **Pre-trim LF>pre-trim RF (P<0.05)*

When lateral and medial views were compared for each foot, there were significantly greater values on the lateral versus medial view for hoof angle (LF and RF foot) and DHWA (right foot only). Conversely DHWA-HA (LF and RF foot) and DHWL:HL (left foot only) were higher in the medial side versus the lateral side. Comparing left and right pre- and post-trim, in the LF DHWL:HL was significantly greater than the right fore at pre-trim only.

3.5.2.3 Solar foot parameters

Table 8 shows pre-and post-trim foot measures in the LF and RF feet when viewed from the solar aspect. Following trimming, in both fore feet, there were significant reductions in heel buttress width, sagittal length and distance from frog apex to toe. In the LF width also decreased after trimming. Conversely there was an increase in the distance between Centre of Rotation and frog apex (COR-FRA) and the distance between Centre of Rotation and Centre of Pressure (COR-COP) in both fore feet. This is likely to represent a narrowing and flattening of the feet after trimming. There were no significant differences when each parameter was evaluated between LF and RF, both pre- and post-trimming.

Table 3.8: Solar view external foot measurements of the left and right fore foot, pre- and post-trimming by a farrier at a single time point (n=76 horses)

Limb	**Foot Measurement (cm)**	**Pre-trim Mean (95% CI)**	**Post-trim Mean (95% CI)**	**Pre-Post Difference Mean (95% CI)**	**P Value**
Left Fore	Heel Buttress	8.04 (7.75, 8.33)	7.5 (7.24, 7.77)	-0.60 (-0.72, -0.33)	**<0.001**
	Sagittal Length	16.3 (16, 16.6)	15.8 (15.5, 16.1)	-0.51 (-0.67, 0.14)	**<0.001**
	Frog Apex-Toe	4.88 (4.74, 5.03)	4.59 (4.48, 4.70)	-0.34 (-0.44, -0.16)	**<0.001**
	Width	14.4 (14.1, 14.8)	13.9 (13.6, 14.2)	-0.68 (-0.69, -0.27)	**<0.001**
	BBL	13.4 (13.1, 13.6)	13.2 (13.0, 13.5)	-0.20 (-0.38, -0.06)	0.17
	COR-Frog Apex	2.55 (2.4, 2.7)	2.8 (2.67, 2.92)	0.25 (0.11, 0.40)	**<0.001**
	COR-COP	1.6 (1.45, 1.75)	1.85 (1.74, 1.97)	0.25 (0.11, 0.42)	**<0.001**
	COR-Toe	7.38 (7.23, 7.53)	7.32 (7.18, 7.45)	-0.06 (-0.19, 0.08)	0.38
	Hbutt-COR	6.01 (5.88, 6.14)	5.93 (5.80, 6.05)	-0.08 (-0.22, 0.03)	0.13
	Hbutt-COP	7.62 (7.4, 7.83)	7.78 (7.59, 7.97)	0.16 (-0.05, 0.38)	0.13
	Lateral solar width	7.31 (7.15, 7.47)	7.02 (6.87, 7.18)	-0.29 (-0.40, 0.14)	**<0.001**
	Medial solar width	7.05 (6.88, 7.23)	6.81 (6.65, 6.97)	-0.24 (-0.36, -0.12)	**<0.001**
Right Fore	Heel Buttress	7.99 (7.66, 8.32)	7.6 (7.28, 7.92)	-0.30 (-0.61, -0.14)	**<0.001**
	Sagittal Length	16.2 (15.9, 16.5)	16.0 (15.6, 16.3)	-0.20 (-0.55, 0.09)	0.15
	Frog Apex-Toe	4.97 (4.83, 5.11)	4.69 (4.56, 4.81)	-0.28 (-0.41, 0.15)	**<0.001**
	Width	14.4 (14.0, 14.8)	14.1 (13.7, 14.4)	-0.30 (-0.62, -0.09)	0.01
	BBL	13.4 (13.1, 13.6)	13.4 (13.1, 13.7)	0.00 (-0.18, 0.30)	0.62
	COR-Frog Apex	2.46 (2.34, 2.59)	2.78 (2.65, 2.90)	0.32 (0.21, 0.42)	**<0.001**
	COR-COP	1.51 (1.39, 1.64)	1.83 (1.70, 1.95)	0.32 (0.21, 0.42)	**<0.001**
	COR-Toe	7.35 (7.21, 7.49)	7.40 (7.25, 7.54)	0.05 (-0.09, 0.19)	0.46
	Hbutt-COR	6.02 (5.89, 6.16)	6.01 (5.88, 6.14)	-0.01 (-0.13, 0.12)	0.94
	Hbutt-COP	7.54 (7.34, 7.73)	7.84 (7.64, 8.04)	0.30 (0.12, 0.50)	**<0.001**
	Lateral solar width	7.27 (7.08, 7.46)	7.11 (6.90, 7.32)	-0.17 (-0.28, -0.03)	0.02
	Medial solar width	7.02 (6.83, 7.22)	6.91 (6.69, 7.12)	-0.11 (-0.22, 0.04)	0.18

BBL = bearing border length; COP = centre of pressure; COR = centre of rotation; HButt = heel buttress; 96% CI = 95% confidence interval. After adjustment for multiple comparisons using the Bonferroni method p<0.004

3.5.2.4 Foot balance measures

Bearing border length (BBL) was used with other foot measures to create foot balance measures based on Duckett's theory of hoof proportionality (Duckett 1990). Table 3.9 shows how DHWL/BBL decreased and Hbutt-COP/BBL increased following trimming in both fore feet, although COR-Toe/BBL in both fore feet did not change.

Table 3.9: Foot balance measures based on Duckett's theory of hoof proportionality (Duckett, 1990), left and right fore foot, pre- and post- trimming by a farrier at a single time point (n=76 horses)

Limb	**Foot balance Measure**	**Pre-trim Mean (95% CI)**	**Post-trim Mean (95% CI)**	**Pre-Post Difference Mean (95% CI)**	**P value**
Left Fore	Lateral DHWL/BBL	0.75 (0.73, 0.77)	0.71 (0.69, 0.73)	-0.04 (-0.06, -0.03)	**<0.001**
	Medial DHWL/BBL	0.77 (0.75, 0.79)	0.71 (0.69, 0.73)	-0.06 (-0.08, -0.04)	**<0.001**
	Hbutt-COP/BBL	0.57 (0.56, 0.58)	0.59 (0.58, 0.59)	0.02 (0.01, 0.03)	**<0.001**
	COR-Toe/BBL	0.55 (0.55, 0.56)	0.55 (0.55, 0.56)	0.00 (-0.01, 0.00)	0.61
Right fore	Lateral DHWL/BBL	0.76 (0.74, 0.78)	0.71 (0.69, 0.73)	-0.05 (-0.07, -0.03)	**<0.001**
	Medial DHWL/BBL	0.75 (0.74, 0.77)	0.70 (0.69, 0.72)	-0.05 (-0.07, -0.03)	**<0.001**
	Hbutt-COP/BBL	0.56 (0.56, 0.57)	0.58 (0.58, 0.59)	0.02 (0.01, 0.03)	**<0.001**
	COR-Toe/BBL	0.55 (0.55, 0.55)	0.55 (0.55, 0.55)	0.00 (-0.01, 0.00)	0.57

BBL = bearing border length; COP = centre of pressure; COR = centre of rotation; DHWL = dorsal hoof wall length; HButt = heel buttress; LF = left fore; RF = right fore; 96% CI = 95% confidence interval

3.5.3 Factors influencing foot shape measurements

Following univariable analysis of questionnaire variables that may influence foot measures (Appendix 2, Table 1), five foot measures were chosen to model using multivariable methods: Bearing Border Length (BBL), hoof width (Width), Frog Apex to Toe distance (FrA-Toe), lateral hoof wall angle (LHWA) and the difference between dorsal hoof wall and heel angles (DHWA-HA). Multivariable modelling revealed that individual horse factors have an important bearing on these foot measurements. Breed was a significant factor in BBL (Table 3.10) and LHWA (Table 3.11). With BBL, TB and Native X horses had a significantly shorter BBL compared to WBs, whilst all other breeds had a longer BBL than WBs. When looking at LHWA (Table 3.12), in the majority of breed categories this measure was lower than that of WB, though Arabs and Native breeds showed the opposite of this. Height was a significant factor (p<0.001) in BBL, Width and FrA-Toe distance with increases in horse height related to increases in these foot measurements.

The type of work a horse did was also shown to be important (Table 3.11). FRA-toe was significantly associated with horse discipline; horses that undertook show-jumping, riding or pony club activities and endurance had a shorter FRA-toe distance compared with the reference category (hacking/leisure). Conversely dressage, showing and eventing were positively correlated with FRA-toe length. As well as the described discipline of the horse, the time spent regularly doing specific activities was also important; hoof width was negatively associated with total time spent jumping per week (Table 3.13), whilst DHWA-HA was greater when the average time spent hacking was increased (Table 3.14). Individual farrier was a significant factor in DHWA-HA, with marked differences evident between farriers. The same trend was observed for hoof width, though this was not significant following adjustment for multiple comparisons.

Table 3.10: Multivariable linear regression model of factors associated with bearing border length (BBL) (n=76 horses)

Variable		**Regression coefficient**	**Standard error**	**P value**
Intercept		4.81	2.16	-
Breed	WB	(Ref)	-	**0.002**
	TB	-0.42	0.31	
	Native	0.38	0.34	
	ISH	0.75	0.32	
	Arab	0.24	0.52	
	Native X	-0.25	0.39	
	Other X	0.35	0.34	
Height (per cm increase)		0.05	0.01	**<0.001**
Limb	LF	Ref	-	0.85
	RF	-0.02	0.13	
Within horse Variance (standard deviation)			0.27 (0.52)	

ISH = Irish Sports Horse; TB = Thoroughbred; WB = Warmblood; RF = Right Forelimb, LF = Left Forelimb; Ref= reference category

Table 3.11: Multivariable linear regression model of factors associated with lateral hoof wall angle (LHWA) (n=76 horses)

Variable		**Regression coefficient**	**Standard error**	**P value**
Intercept		74.7	1.02	-
Breed	WB	(Ref)	-	**<0.001**
	TB	-1.95	1.36	
	Native	1.28	1.25	
	ISH	-2.63	1.38	
	Arab	6.61	2.19	
	Native X	-2.11	1.55	
	Other X	-2.74	1.50	
Limb	LF	Ref	-	-
	RF	-0.21	0.69	0.76
Within horse Variance (standard deviation)			1.88 (1.37)	

ISH = Irish Sports Horse; TB = Thoroughbred; WB = Warmblood; RF = Right Forelimb; LF = Left Forelimb; Ref= reference category

Table 3.12: Multivariable linear regression model of factors associated with Frog apex to toe (FRA-Toe) (n=76 horses)

Variable		**Regression coefficient**	**Standard error**	**P value**
Intercept		1.40	0.98	-
Height (per cm increase)		0.02	0.006	**<0.001**
Discipline	Trail/Leisure	Ref	-	**<0.001**
	SJ	-0.24	0.19	
	Eventing	0.08	0.18	
	Endurance	-0.52	0.28	
	Showing	0.15	0.28	
	RC/PC	-0.41	0.14	
	Dressage	0.20	0.21	
Limb	LF	Ref	-	-
	RF	0.08	0.07	0.22
Within horse Variance (standard deviation)			0.13 (0.36)	

SJ = Show-jumping; RC = Riding Club; PC = Pony Club; RF = Right Forelimb; LF = Left Forelimb; Ref= reference category

Table 3.13: Multivariable linear regression model of factors associated with hoof width (n=76 horses)

Variable		**Regression coefficient**	**Standard error**	**P value**
Intercept		5.35	2.5	-
Height (per cm increase)		0.07	0.02	**<0.001**
Farrier ID	1	Ref	-	0.05
	2	-0.36	0.67	
	3	-0.94	0.57	
	4	-1.64	0.51	
	5	1.58	0.74	
	6	-0.35	0.78	
	7	-2.62	0.55	
	8	-1.77	0.57	
	9	-2.41	-0.76	
	10	-2.42	1.12	
	11	0.02	1.16	
Limb	LF	Ref	-	-
	RF	0.05	0.12	0.67
Total time (minutes) spent jumping per week (per minute increase)		-0.02	0.008	**0.005**
Within horse Variance (standard deviation)			0.77	

RF = Right Forelimb; LF = Left Forelimb; Ref= reference category

Table 3.14: Multivariable linear regression model of factors associated with lateral view Dorsal Hoof Wall Angle and Heel Angle difference (DHWA-HA) (n=76 horses)

Variable		**Regression coefficient**	**Standard error**	**P value**
Intercept		3.30	2.30	-
Farrier ID	1	Ref	-	**<0.001**
	2	0.11	2.90	
	3	-0.59	2.74	
	4	-7.49	2.59	
	5	5.53	3.60	
	6	-10.21	3.70	
	7	-1.15	2.62	
	8	-5.81	2.72	
	9	3.81	3.66	
	10	-1.12	5.42	
	11	0.50	5.46	
Limb	LF	Ref	-	-
	RF	1.25	0.80	0.12
Mean time (minutes) spent hacking per week (per minute increase)		0.06	0.02	**0.006**
Within horse Variance (standard deviation)			12.2 (3.5)	

RF = Right Forelimb; LF = Left Forelimb; Ref= reference category

3.5.3.1 Risk factors for hoof abnormalities

Following univariable screening (Appendix 2, Table 2), logistic regression analysis identifed the risk factors associated with mediolateral (ML) and dorsopalmar (DP) foot imbalance (Table 3.15). In both types of imbalance, farriers being enrolled in or having completed a course in higher education was associated with improved foot balance. The odds of ML imbalance being present in horses in the sample population increased almost 20-fold when the farrier had never undertaken further education, compared with those that had. For DP imbalance the same effect is seen, though the odds were 3-fold.

Table 3.15: Multivariable logistic regression of factors associated with mediolateral and dorsopalmar foot imbalance (n=76 horses)

Mediolateral imbalance						
Variable		Affected	Unaffected	Odds Ratio (95% CI)	Standard Error	P value
Farrier Further Education	Completed/Enrolled	2	49	Ref	-	-
	Not undertaken	11	14	18.9 (3.4, 185.1)	0.8	**<0.001**
Dorsopalmar imbalance						
Variable		Affected	Unaffected	Odds Ratio (95% CI)	Standard Error	P Value
Farrier Further Education	Completed/Enrolled	19	32	Ref	-	-
	Not undertaken	16	9	3.0 (1.0, 9.2)	0.5	**0.03**

Ref= reference category; 95% CI = 95% confidence intervals

3.5.4 Pressure mat data

3.5.4.1 Static measurements

3.5.4.1.1 Quadrant analysis: pre- and post- trim differences between quadrants

Static foot pressures were recorded before and after trimming. In both LF and RF feet the dorsolateral quadrant appeared to experience the highest mean pressure and the palmaromedial quadrant the lowest even after trimming (Figures 3.2a-d). Apart from the comparison between the dorsomedial and palmaromedial quadrants in the LF following trimming, the mean pressure dorsal quadrants were consistently greater than the palmar quadrants pre- and post-trimming, though these differences were not always significant between medial quadrants.

Maximum recorded pressures in foot quadrants demonstrated a similar pattern to those of the mean pressures (Figures 3.3a-d). Significant differences were only seen between the dorsolateral quadrant and either palmarolateral or palmaromedial quadrants in maximum pressure data. Results of pairwise comparisons between static foot quadrants of both mean and maximum foot quadrant data is displayed in Appendix 2, Tables 3 and 4, respectively.

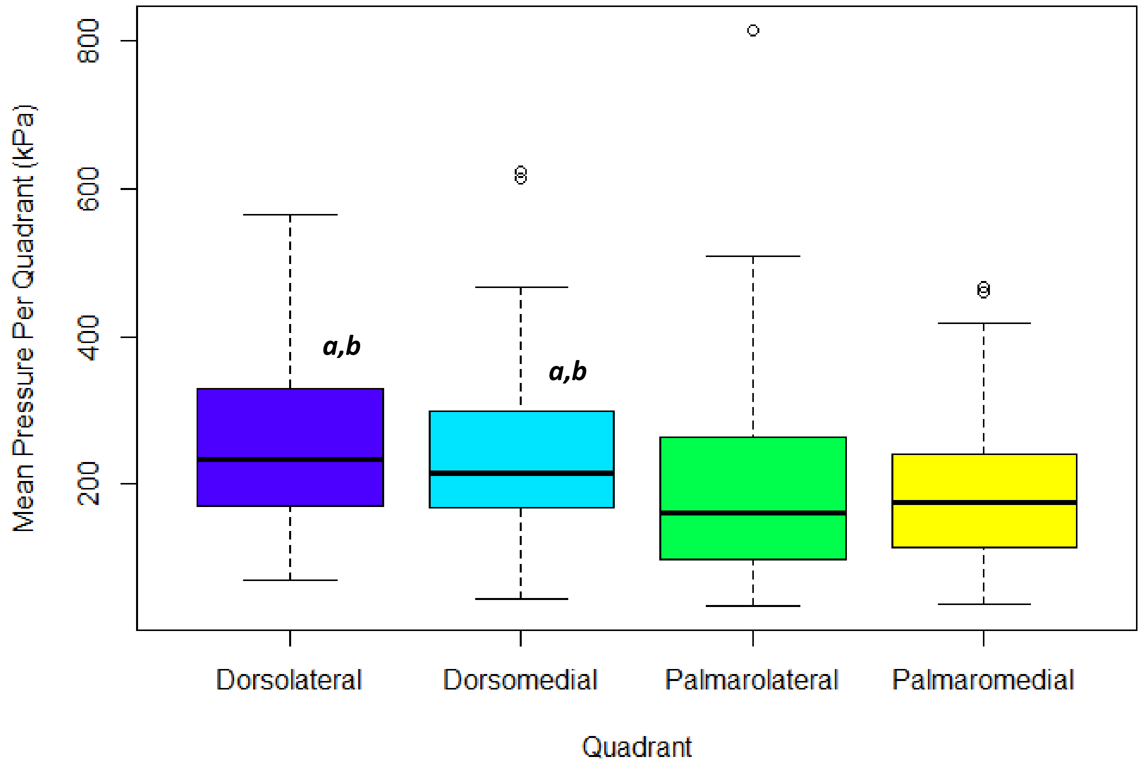

Figure 3.2a: Boxplot showing differences between mean pressure (kilopascals (kPa)) recorded in LF pre-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.05), b indicates difference from palmaromedial quadrant (p<0.08)

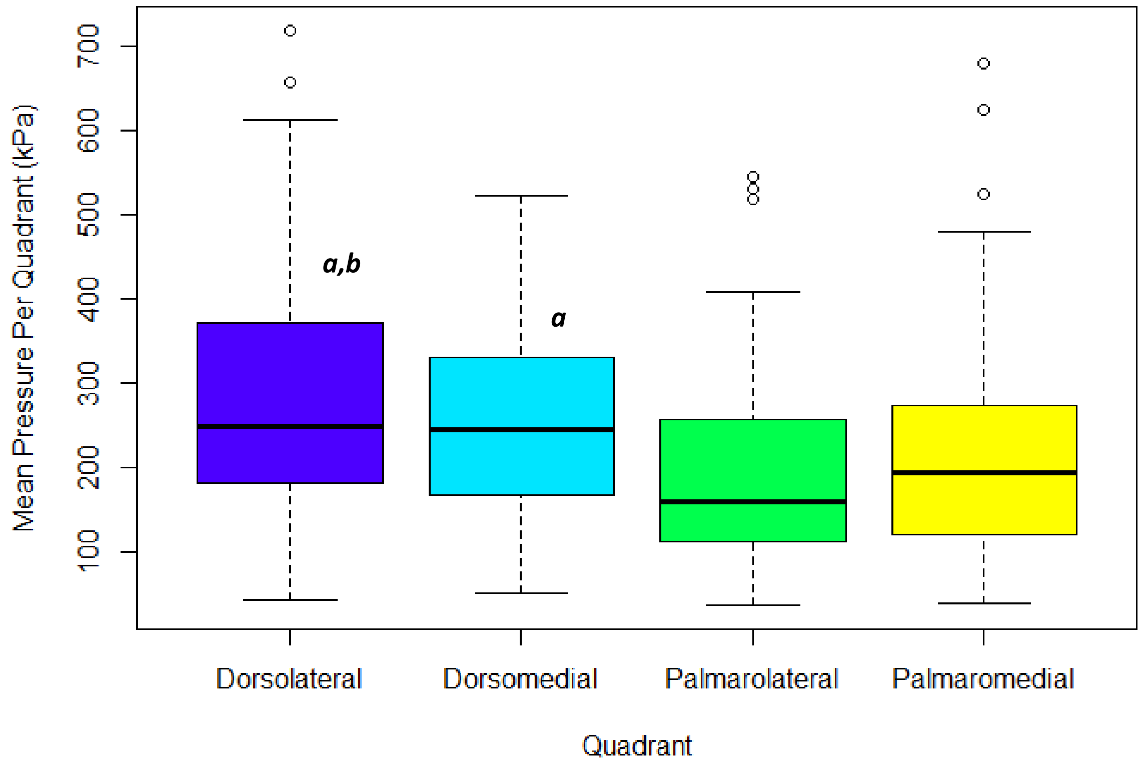

Figure 3.2b: Boxplot showing differences between mean pressure (kilopascals (kPa)) recorded in right fore pre-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.05), b indicates difference from palmaromedial quadrant (p<0.08)

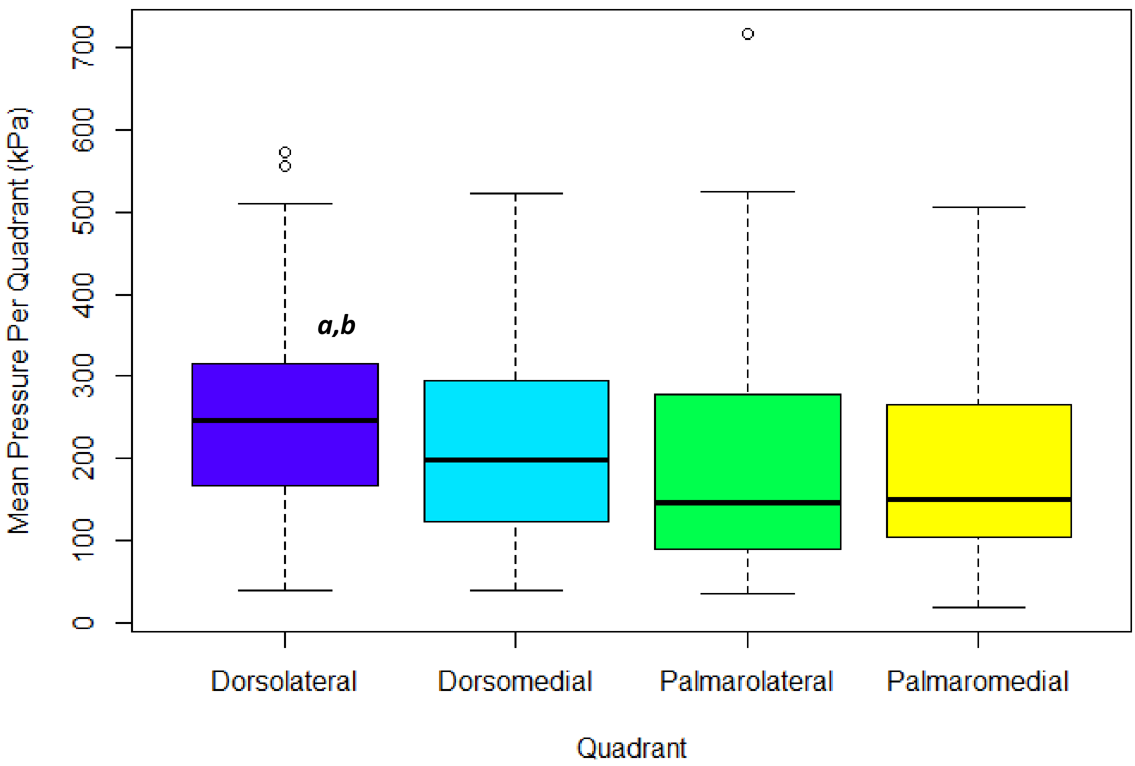

Figure 3.2c: Boxplot showing differences between mean pressure (kilopascals (kPa)) recorded in left fore post-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.05), b indicates difference from palmaromedial quadrant (p<0.08)

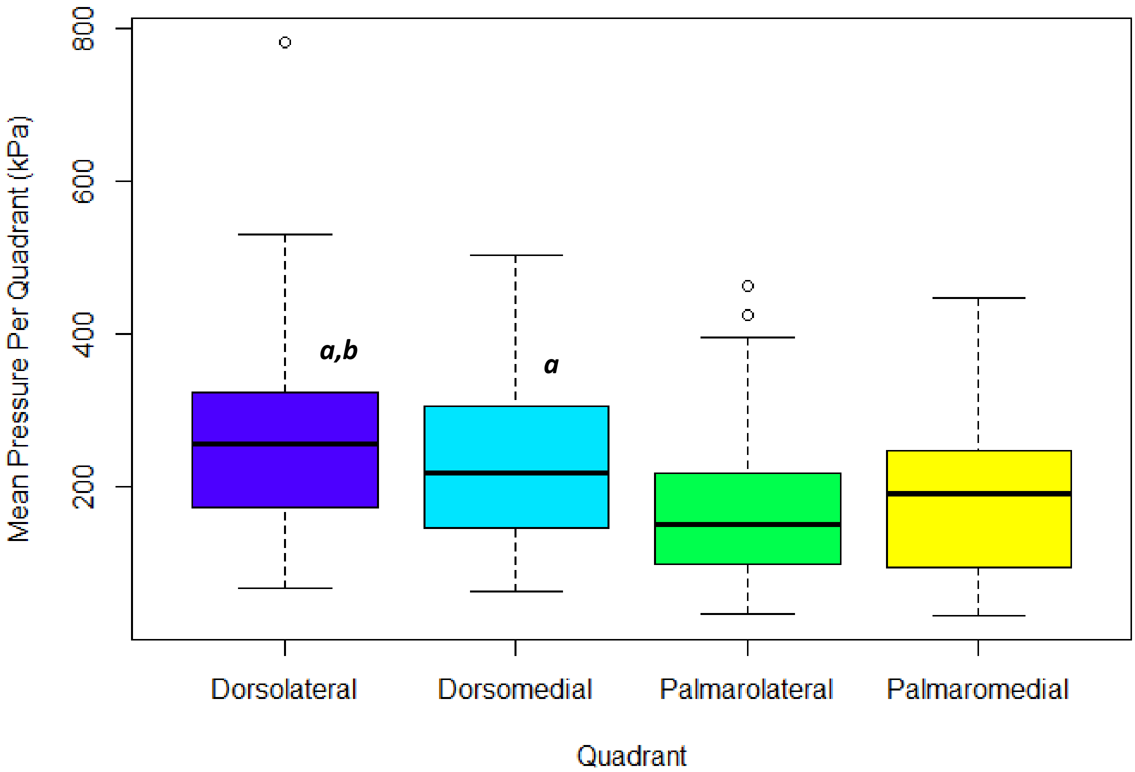

Figure 3.2d: Boxplot showing differences between mean pressure (kilopascals (kPa)) recorded in RF post-trim quadrants (n=69 horses), a indicates significant difference from palmarolateral quadrant (p<0.05), b indicates difference from palmaromedial quadrant (p<0.08)

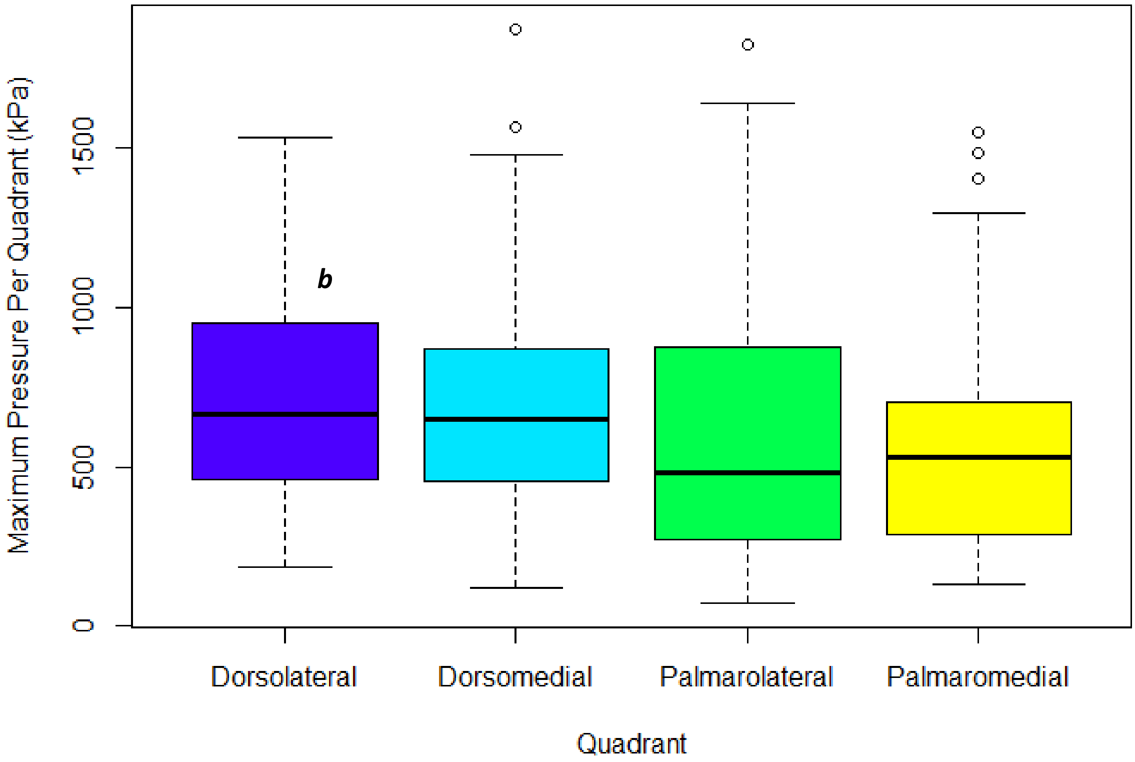

Figure 3.3a: Boxplot showing differences between maximum pressure (kilopascals (kPa)) recorded in LF pre-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.08), b indicates difference from palmaromedial quadrant (p<0.08)

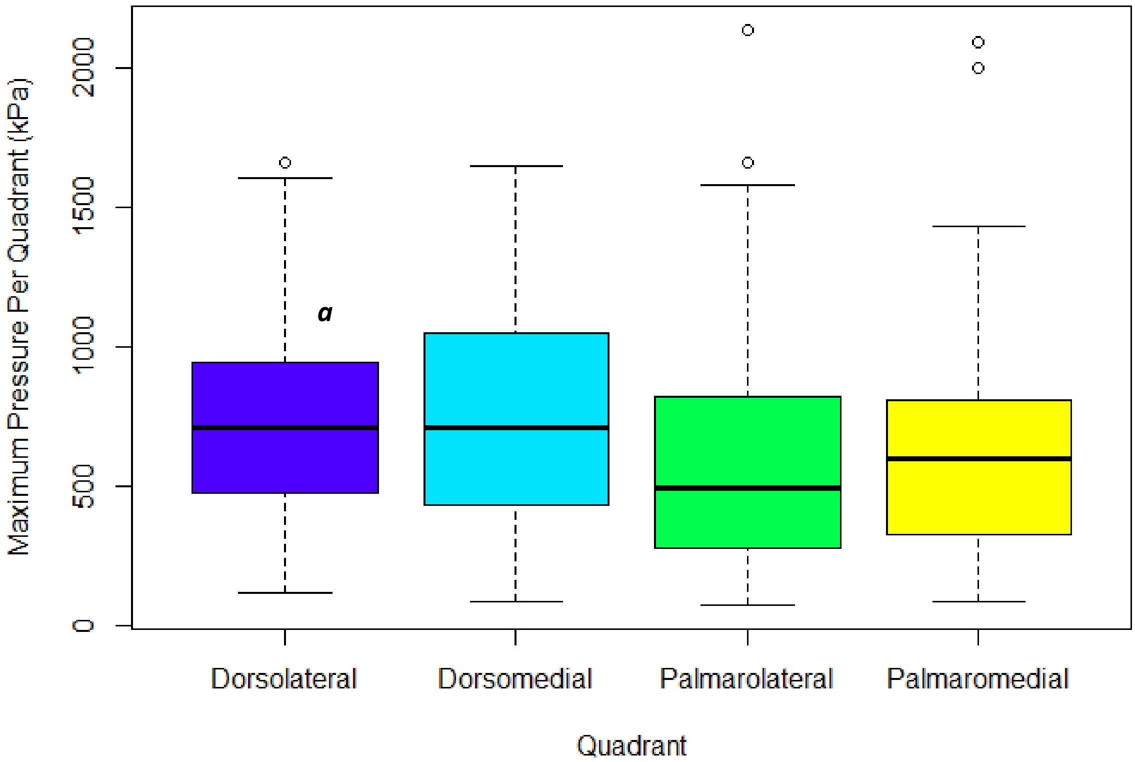

Figure 3.3b: Boxplot showing differences between maximum pressure (kilopascals (kPa)) recorded in RF pre-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.08), b indicates difference from palmaromedial quadrant (p<0.08)

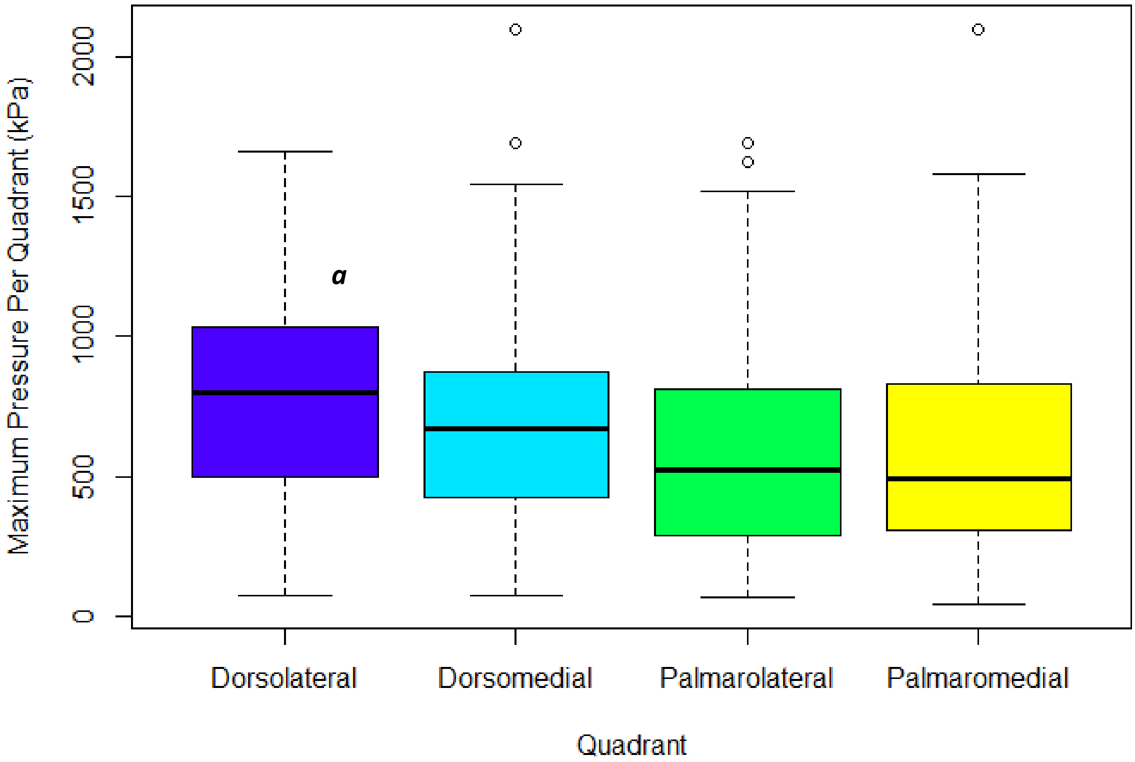

Figure 3.3c: Boxplot showing differences between maximum pressure (kilopascals (kPa)) recorded in left fore post-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.01), b indicates difference from palmaromedial quadrant (p<0.01)

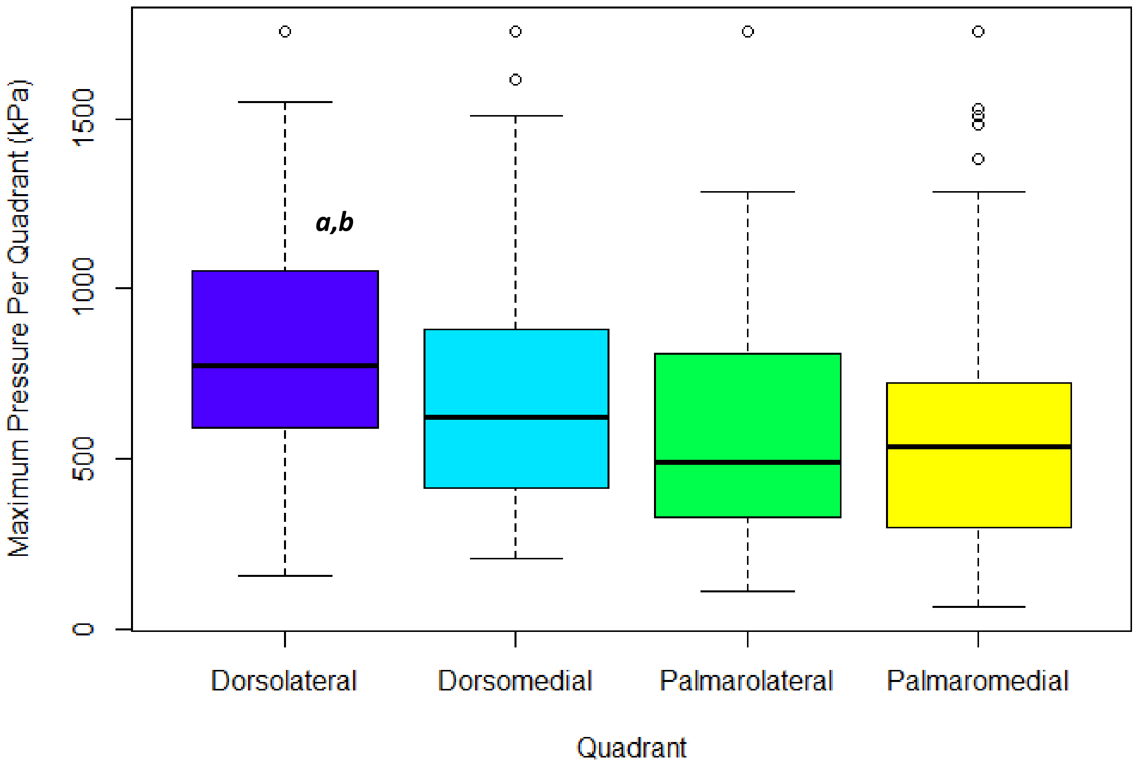

Figure 3.3d: Boxplot showing differences between maximum pressure (kilopascals (kPa)) recorded in right fore post-trim quadrants (n=69 horses). a indicates significant difference from palmarolateral quadrant (p<0.08), b indicates difference from palmaromedial quadrant (p<0.08)

3.5.4.1.2 Quadrant analysis: pre- and post-trim differences within each quadrant

Pre- and post-trim mean and maximum pressures were compared for each quadrant. There were no significant differences after trimming for each quadrant in both LF and RF feet (Table 3.16). Figures 3.4a-d show that in all quadrants (other than palmarolateral) the RF mean pressures were greater than LF although these differences were not statistically significant.

Table 3.16: Mean pressure (kilopascals) for each foot quadrant pre- and post-trim in left and right fore foot (static), with result of statistical analysis on the change post-trimming (n=69 horses)

Limb	Quadrant	Pre-Trim Mean kPa (95% CI)	Post-Trim Mean kPa (95% CI)	Pre-post trim difference Mean kPa (95% CI)	P Value
Left Fore	Dorsolateral	256.9 (230.2, 283.6)	245.3 (216.5, 274.2)	-11.6 (-42.4, 24.1)	0.43
	Dorsomedial	238.3 (211, 265.6)	219.7 (193.5, 245.9)	-18.6 (-49.4, 14.3)	0.25
	Palmarolateral	195.2 (162.5, 227.8)	195.4 (161.5, 229.3)	0.2 (-43.9, 35.5)	0.94
	Palmaromedial	186.8 (163.7,209.8)	193.3 (163.0, 223.6)	6.5 (-28.3, 41.6)	0.97
Right Fore	Dorsolateral	278.2 (245.6, 310.8)	266.5 (235.2, 297.9)	-11.7 (-52.5, 32.3)	0.68
	Dorsomedial	254.5 (227.4, 281.5)	228.7 (203.1, 254.4)	-25.8 (-57.3, 6.4)	0.07
	Palmarolateral	192.4 (163.2, 221.6)	171.8 (146.9, 196.7)	20.6 (-12.6, 58.4)	0.22
	Palmaromedial	211.3 (180.1, 242.5)	191.3 (164.8, 217.8)	20 (-12.8, 58.4)	0.44

kPa=kilopascals; 95% CI = 95% confidence intervals

As with previous mean pressure results, RF quadrants showed greater maximum contact pressure than LF quadrants. However, neither pre-post trim differences nor LF-RF differences for maximum pressures recorded per quadrant were statistically significant (Table 3.17and Figure 3.5a-d).

Table 3.17: Maximum pressure (kilopascals) for each foot quadrant pre- and post-trim in left and right fore foot (static) with results of statistical analysis of changes post-trimming (n=69 horses)

Limb	Quadrant	Pre-Trim Mean kPa (95% CI)	Post-Trim Mean kPa (95% CI)	Pre-post trim difference Mean kPa (95% CI)	P Value
Left Fore	Dorsolateral	743.2 (659.4, 827.1)	777.2 (679.9, 874.5)	34 (-71.5, 148.6)	0.34
	Dorsomedial	686.3 (608.4, 764.2)	712.6 (617.1, 808.1)	26.3 (-75.0, 131.5)	0.57
	Palmarolateral	609.5 (507.5, 711.5)	589.7 (498.1, 681.3)	-19.8 (-123.8, 119.9)	0.52
	Palmaromedial	574.4 (490.3, 658.6)	604.5 (502.5, 706.4)	30.1 (-92.9, 142.1)	0.69
Right Fore	Dorsolateral	754.9 (668.9, 840.9)	829.5 (736.7, 922.2)	74.6 (-45.7, 202.3)	0.18
	Dorsomedial	757.8 (668.1, 847.5)	709.2 (618.8, 799.7)	-48.6 (-154.0, 66.0)	0.21
	Palmarolateral	629.6 (513.9, 725.3)	578.6 (492.8, 664.4)	-51 (-178.5, 82.8)	0.48
	Palmaromedial	636.3 (539.5, 733.0)	572.6 (477.4, 667.7)	-63.7 (-192.5, 53.0)	0.18

kPa=kilopascals; 95% CI = 95% confidence intervals

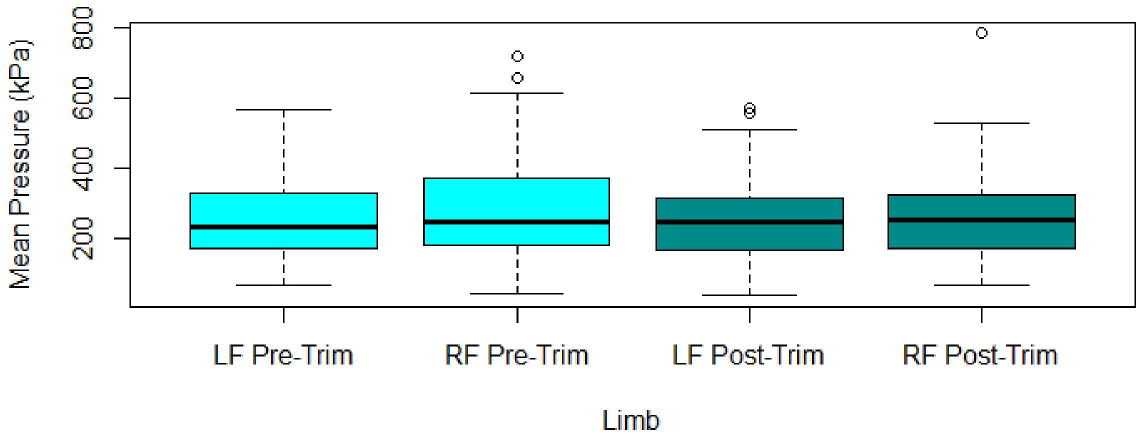

Figure 3.4a: Boxplot showing left fore (LF) and right fore (RF) limb pre- and post-trim mean pressures (kilopascals (kPa)), dorsolateral quadrant (n=69 horses)

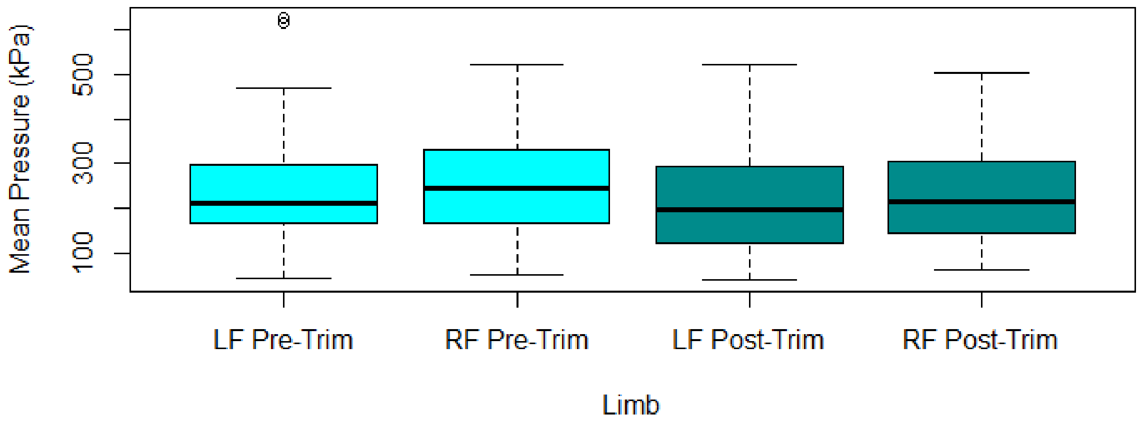

Figure 3.4b: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean pressures (kilopascals (kPa)), dorsomedial quadrant (n=69 horses)

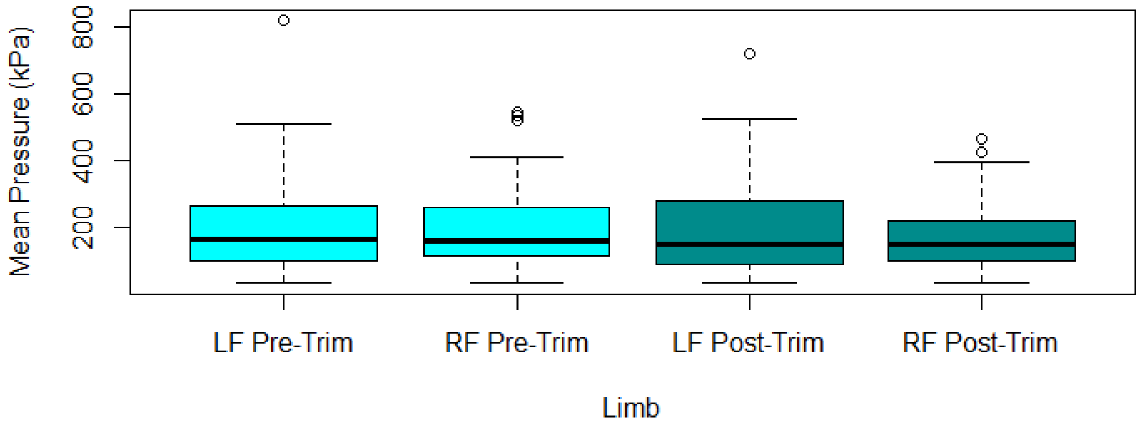

Figure 3.4c: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean pressures (kilopascals (kPa)), palmarolateral quadrant (n=69 horses)

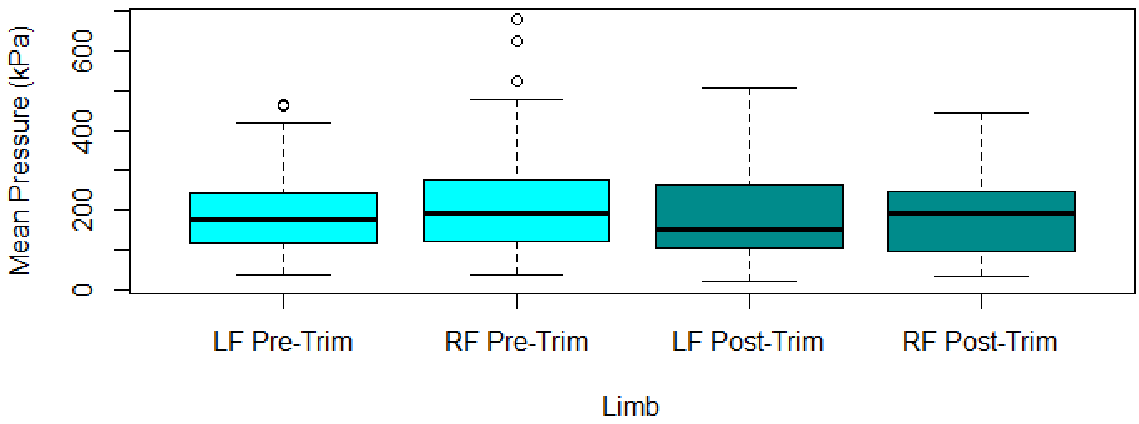

Figure 3.4d: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean pressures (kilopascals (kPa)), palmaromedial quadrant (n=69 horses)

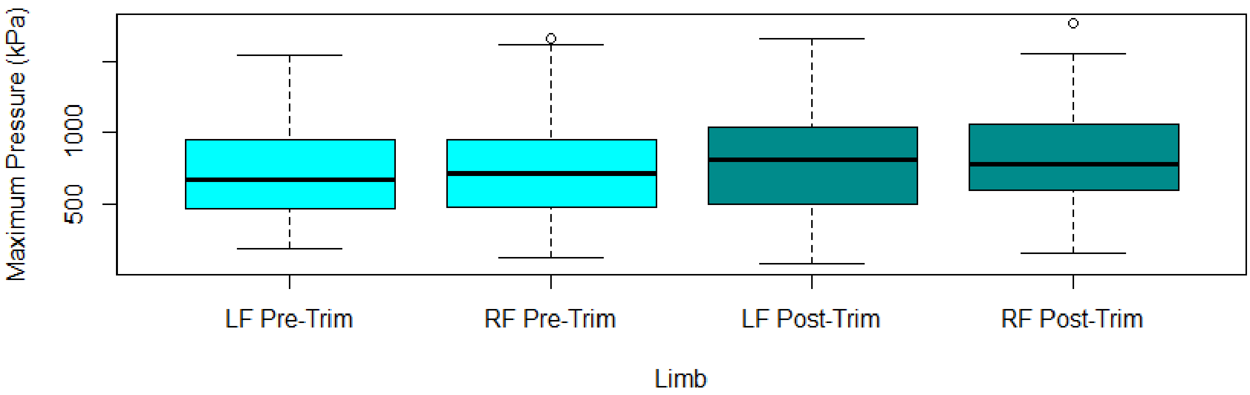

Figure 3.5a: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum pressures (kilopascals (kPa)), dorsolateral quadrant (n=69 horses)

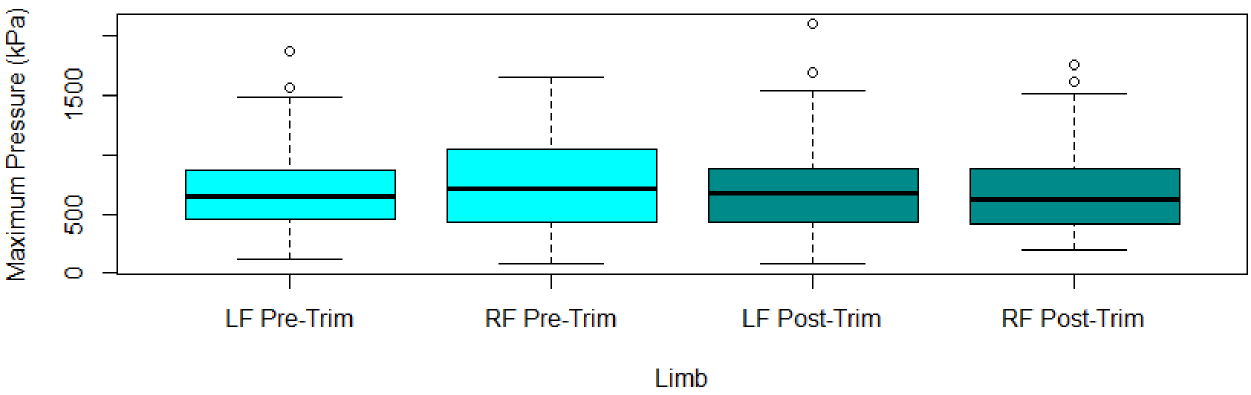

Figure 3.5b: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum pressures (kilopascals (kPa)), dorsomedial quadrant (n=69 horses)

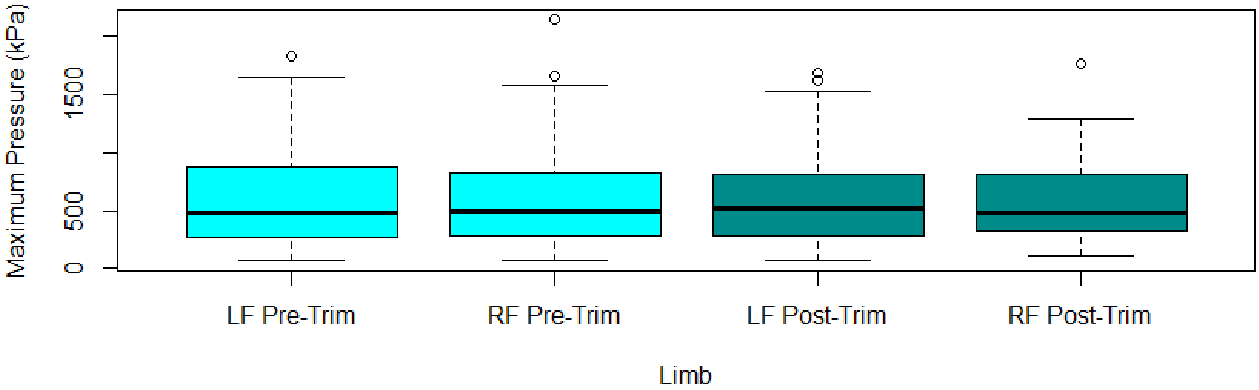

Figure 3.5c: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum pressures (kilopascals (kPa)), palmarolateral quadrant (n=69 horses)

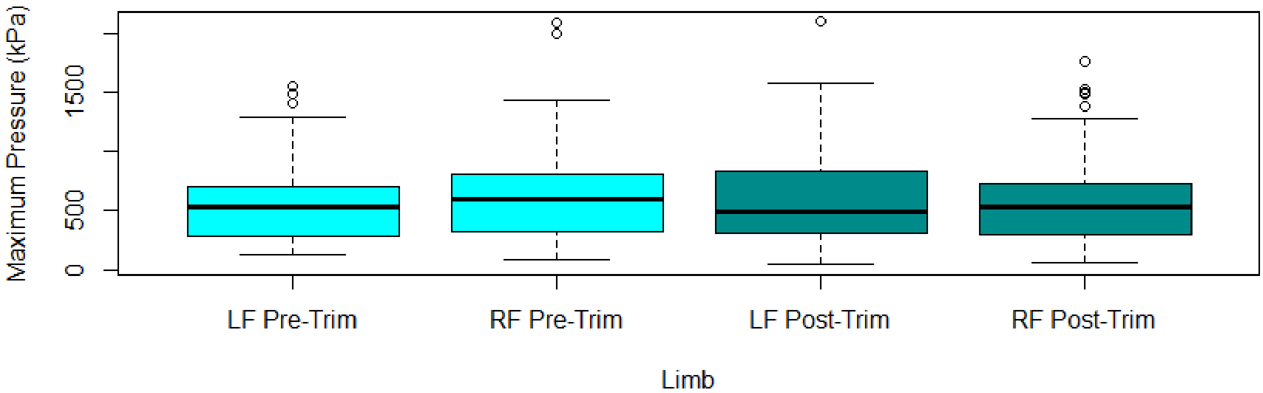

Figure3.5d: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum pressures (kilopascals (kPa)), palmaromedial quadrant (n=69 horses)

3.5.4.2 Dynamic measurements

Dynamic measurements were obtained for the LF and RF feet of 61 horses at walk (approximately 1m/s), pre- and post-trimming at a single time point.

3.5.4.2.1 Quadrant analysis: pre- and post-trim differences between quadrants

Dorsal quadrants showed consistently higher mean pressures than palmar quadrants before and after trimming (Figures 3.6a-d) in both fore feet. Mean pressures were significantly higher in dorsolateral quadrants compared to other quadrants in both fore feet irrespective of trimming (Appendix 2, Table 5). In both fore feet, the mean pressure of the dorsomedial quadrant was higher than the palmaromedial (pre- and post-trim) but only in the RF was the mean pressure in the dorsomedial quadrant significantly higher than the palmarolateral quadrant before and after trimming. Interestingly, compared to static mean pressures, there was a significant difference between palmarolateral and palmaromedial quadrants with increased mean pressure experienced in the palmaromedial quadrant in both feet pre-trim. After trimming, the difference between palmaromedial and palmarolateral quadrants in the RF was no longer present (Appendix 2, Table 5).

The results for maximum pressure showed a similar pattern compared to mean pressures in each foot pre- and post-trimming, though there were no significant differences between pre- and post-trimming in these results (Figures 3.7a-d and Appendix 2 Table 6).

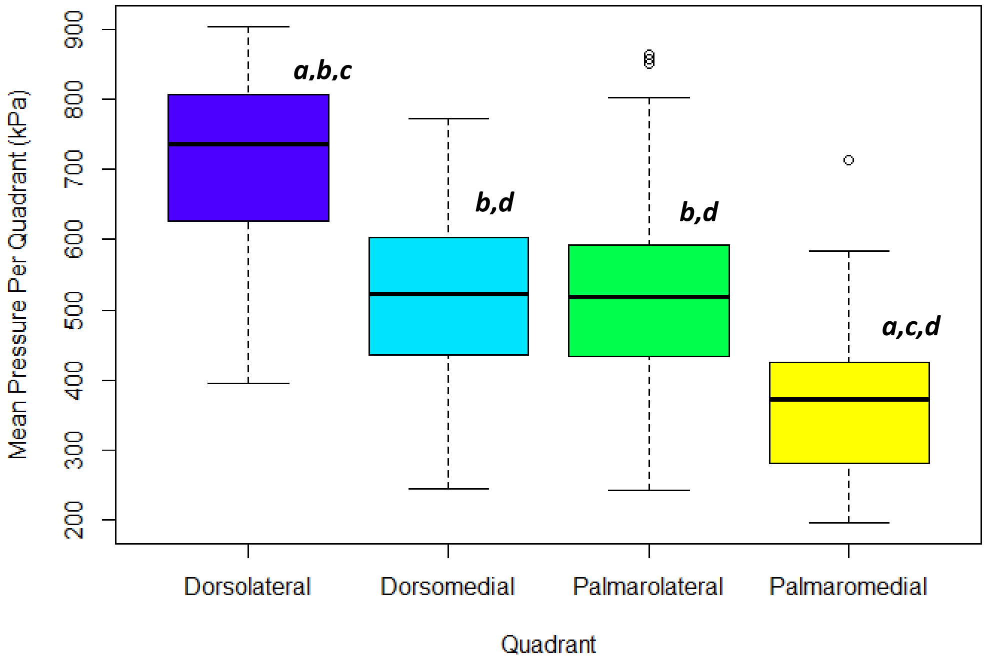

Figure 3.6a: Boxplot showing differences between mean pressure (dynamic) recorded in left fore pre-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

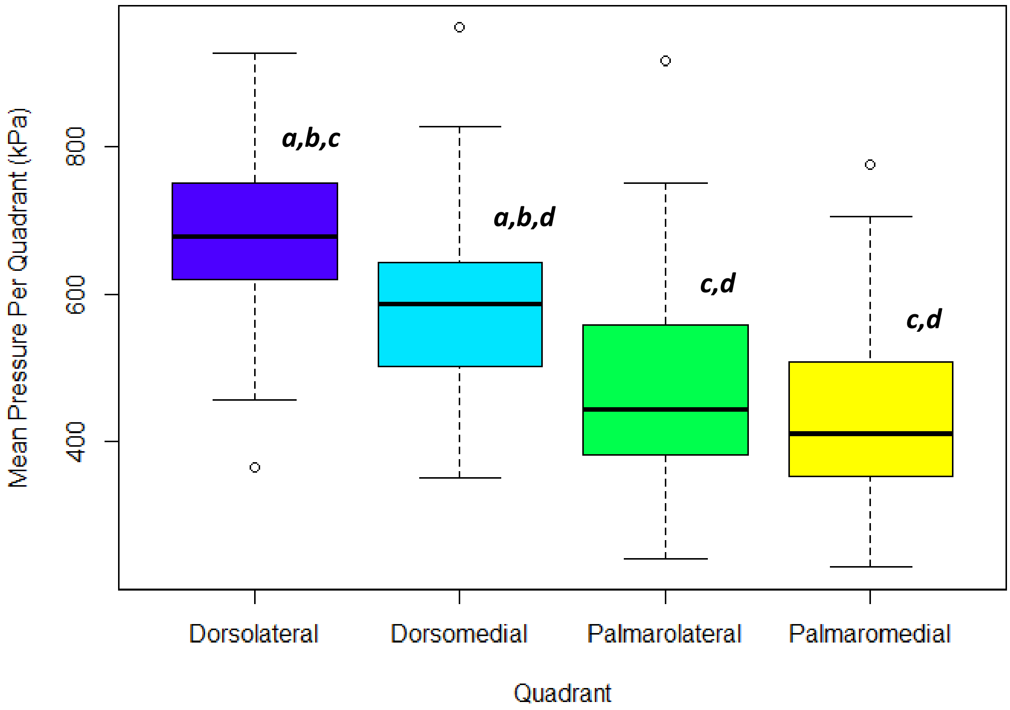

Figure 3.6b: Boxplot showing differences between mean pressure (dynamic) recorded in right fore pre-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

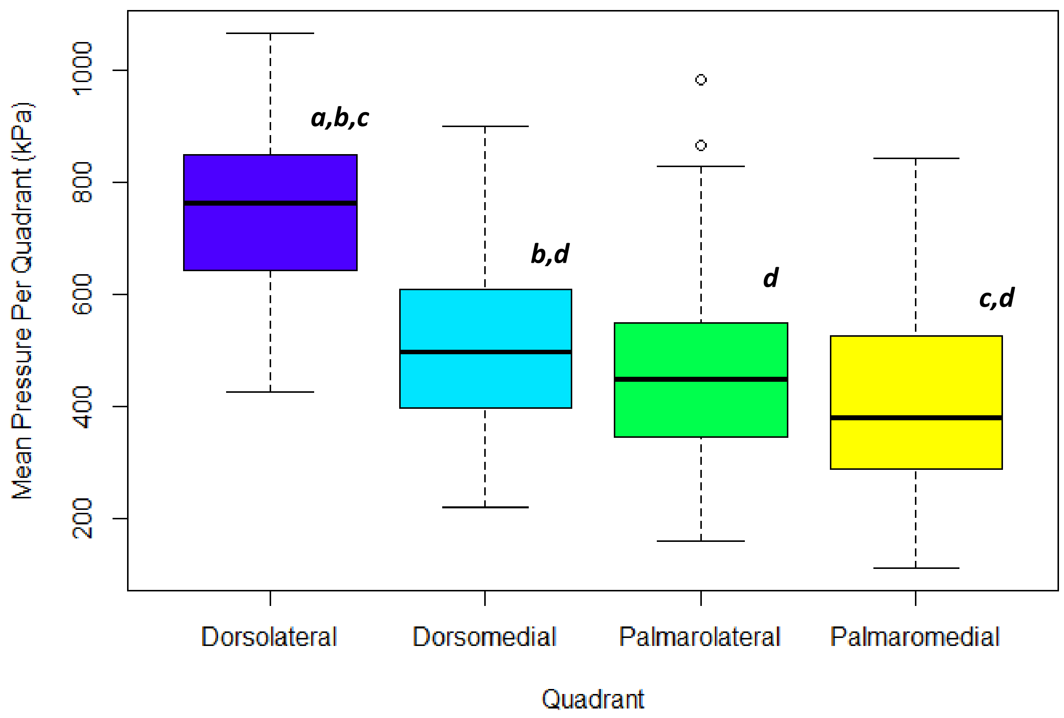

Figure 3.6c: Boxplot showing differences between mean pressure (dynamic) recorded in left fore post-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

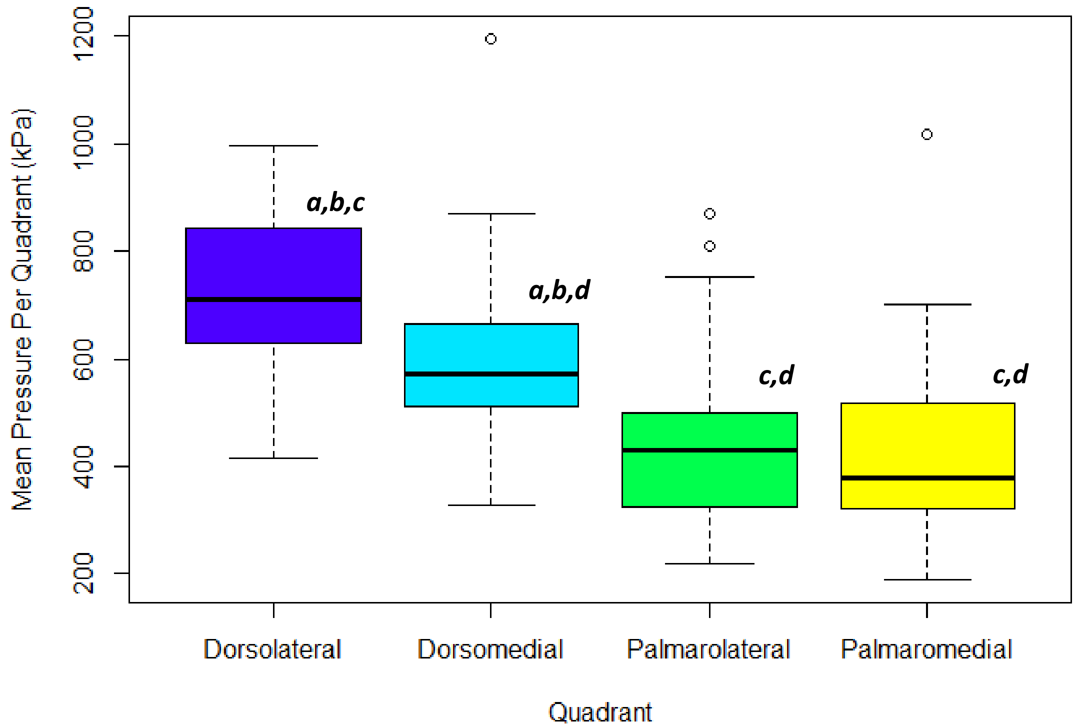

Figure 3.6d: Boxplot showing differences between mean pressure (dynamic) recorded in right fore post-trim quadrants (n=61 horses) a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

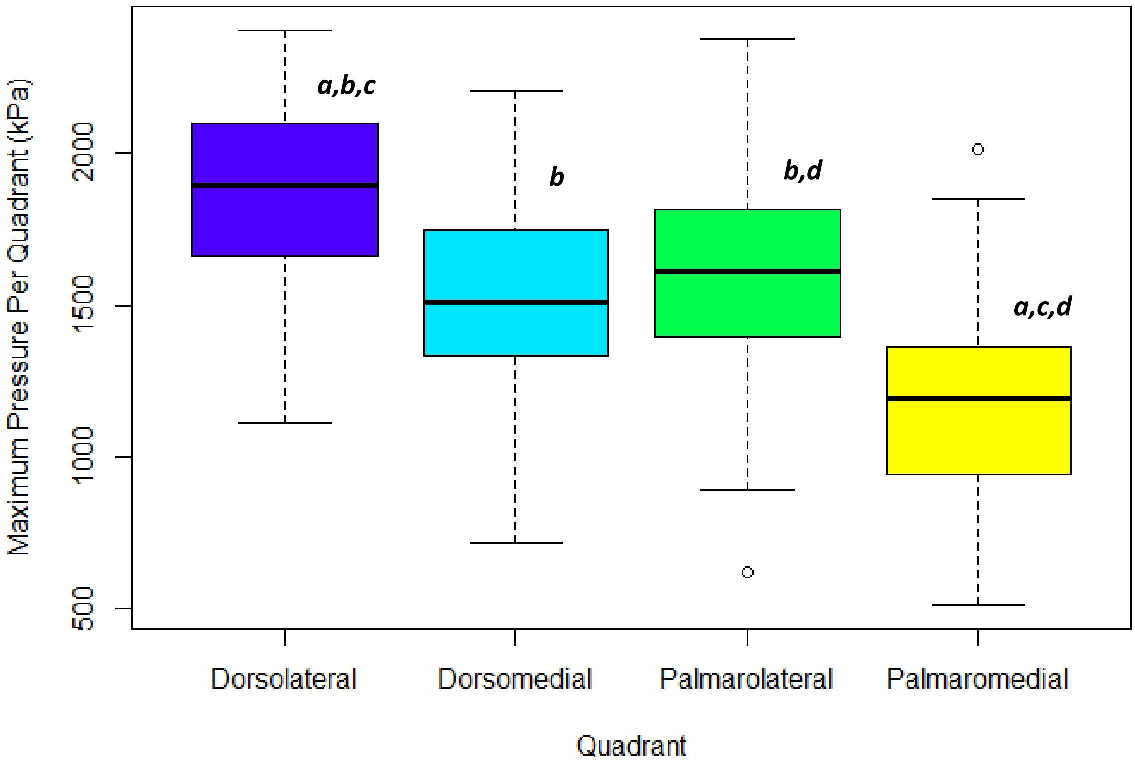

Figure 3.7a: Boxplot showing differences between maximum pressure (dynamic) recorded in left fore pre-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

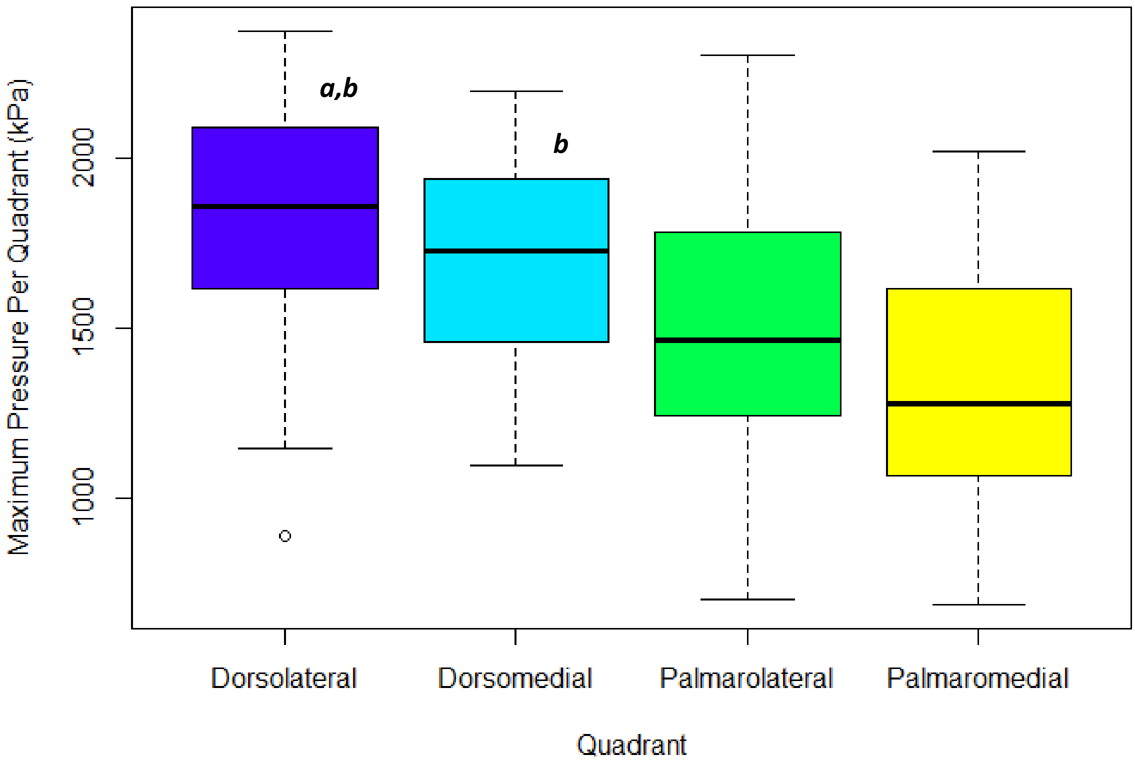

Figure 3.7b: Boxplot showing differences between maximum pressure (dynamic) recorded in right fore pre-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

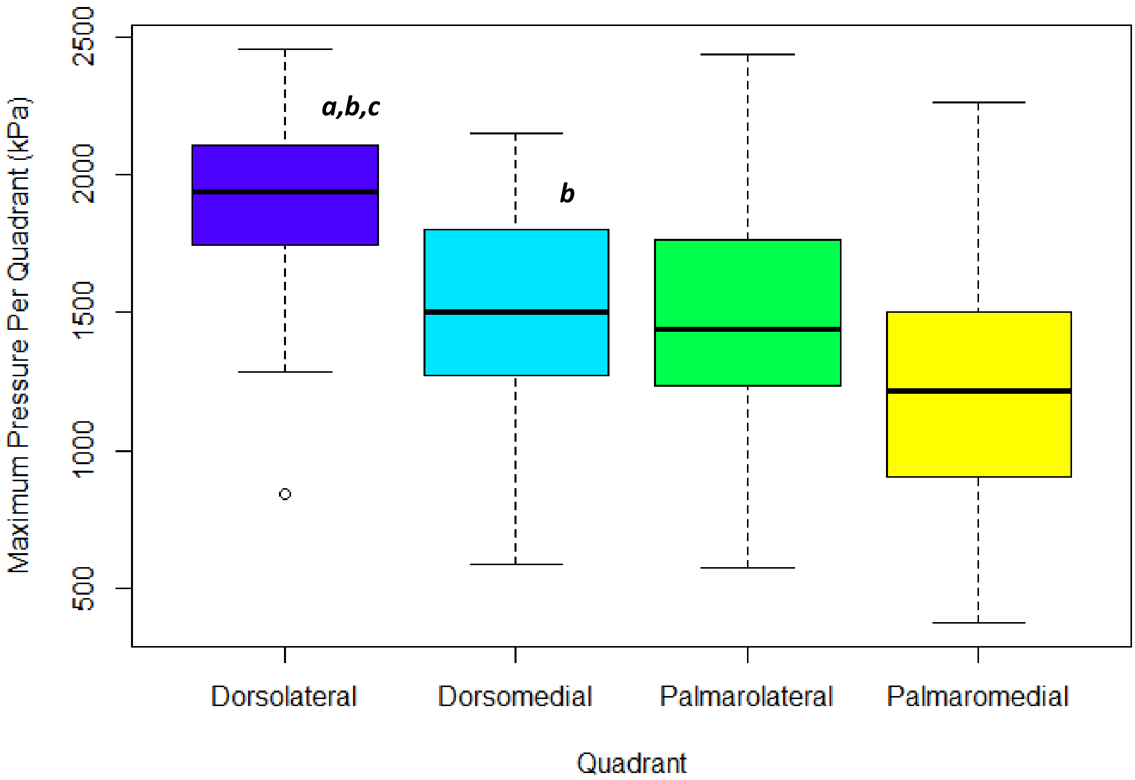

Figure 3.7c: Boxplot showing differences between maximum pressure (dynamic) recorded in left fore post-trim quadrants (n=61 horses), a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

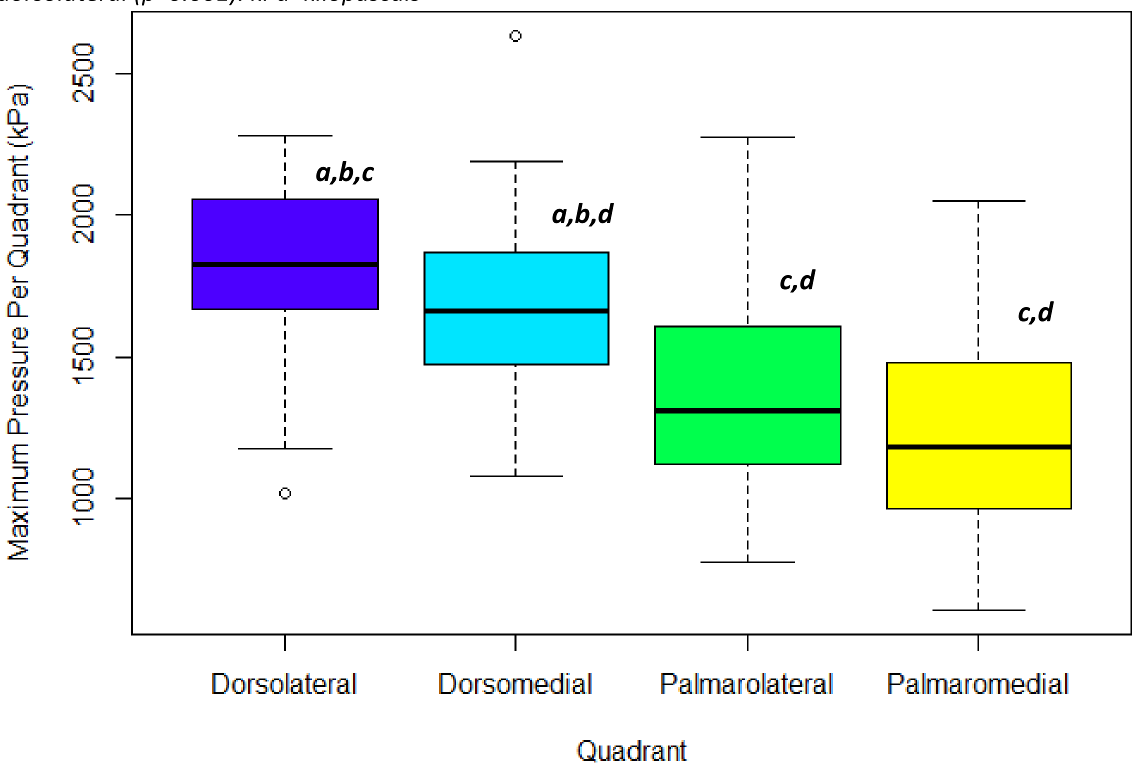

Figure 3.7d: Boxplot showing differences between maximum pressure (dynamic) recorded in right fore post-trim quadrants (n=61 horses). a significant difference from palmarolateral (p<0.001), b significant difference from palmaromedial (p<0.001), c significant difference from dorsomedial (p<0.001), d significant difference from dorsolateral (p<0.001). kPa=kilopascals

3.5.4.2.2 *Quadrant analysis: pre-post trim differences within each quadrant*

Mean pressure differences between pre- and post-trimming for each quadrant in LF and RF foot at walk were calculated (Figures 3.8a-d). Maximum pressures are shown in Figures 3.9a-d. Following trimming, the mean and maximum pressures experienced by the palmarolateral quadrant were significantly reduced in both LF and RF (Tables 3.18 and 3.19). In all other quadrants there was no significant change in mean or maximum pressure after trimming.

Table 3.18: Mean pressure (kilopascals) for each foot quadrant pre- and post-trim in left and right fore feet (dynamic) and result of statistical testing of difference between pre- and post-trim values (n=61 horses)

Limb	Quadrant	Pre-Trim Mean kPa (95% CI)	Post-trim Mean kPa (95% CI)	P Value
Left Fore	Dorsolateral	711.9 (677.8, 746.1)	744.4 (706.9, 781.9)	0.06
	Dorsomedial	524.9 (494.4, 555.3)†	510.2 (471.3, 549.0)†	0.45
	Palmarolateral	524.8 (486.8, 562.7)†	467.2 (425.6, 508.9)	**0.001**
	Palmaromedial	368.2 (339.7, 396.8)†	398.3 (359.6, 436.9)	0.40
Right Fore	Dorsolateral	680.5 (646.4, 714.7)	720.6 (681.8, 759.4)	0.07
	Dorsomedial	586.8 (553.7, 619.8)†	583.6 (545.4, 621.7)†	0.40
	Palmarolateral	473.0 (437.1, 509.0)†	434.4 (400.1, 468.7)	**<0.001**
	Palmaromedial	429.2 (396.8, 461.7)†	414.1 (373.2, 455.0)	0.09

kPa=kilopascals; 95% CI = 95% confidence intervals
† indicates left fore and right fore are significantly different (p<0.05)

Table 3.19: Maximum pressure (kilopascals) for each foot quadrant pre- and post-trim in left and right fore feet (dynamic) and result of statistical testing of difference between pre- and post-trim values (n=61 horses)

Limb	Quadrant	Pre-Trim Mean kPa (95% CI)	Post-Trim Mean kPa (95% CI)	P Value
Left Fore	Dorsolateral	1863.9 (1783.6, 1944.2)	1911.5 (1829.9, 1993.1)	0.13
	Dorsomedial	1526.7 (1443.7, 1609.6)†	1530.3 (1441.7, 1618.9)†	0.61
	Palmarolateral	1618.3 (1523.7, 1712.9)	1476.8 (1375.0, 1578.6)	0.04
	Palmaromedial	1174.2 (1081.6, 1266.8)	1238.9 (1123.2, 1354.5)	0.66
Right Fore	Dorsolateral	1834.6 (1747.8, 1921.3)	1837 (1761.2, 1912.8)	0.99
	Dorsomedial	1695.0 (1615.1, 1774.9)†	1663.9 (1585.6, 1742.3)†	0.08
	Palmarolateral	1507.4 (1403.8, 1610.9)	1399.8 (1294.1, 1505.7)	0.15
	Palmaromedial	1313.2 (1216.0, 1410.4)	1248.9 (1152.9, 1344.8)	0.11

kPa=kilopascals; 95% CI = 95% confidence intervals
† indicates left fore and right fore are significantly different (p<0.05)

Comparing the same quadrants in the left to the right foot before and after trimming showed the data from the dorsomedial quadrant in the right fore to be consistently higher than the same quadrant in the LF (mean and maximum pressure) both before and after trimming (Table 3.18 and 3.19). In the LF, pre-trim mean pressure in the palmarolateral quadrant was significantly higher than the RF whereas the mean pressure in the palmaromedial quadrant was greater in the right than the LF (pre-trim only).

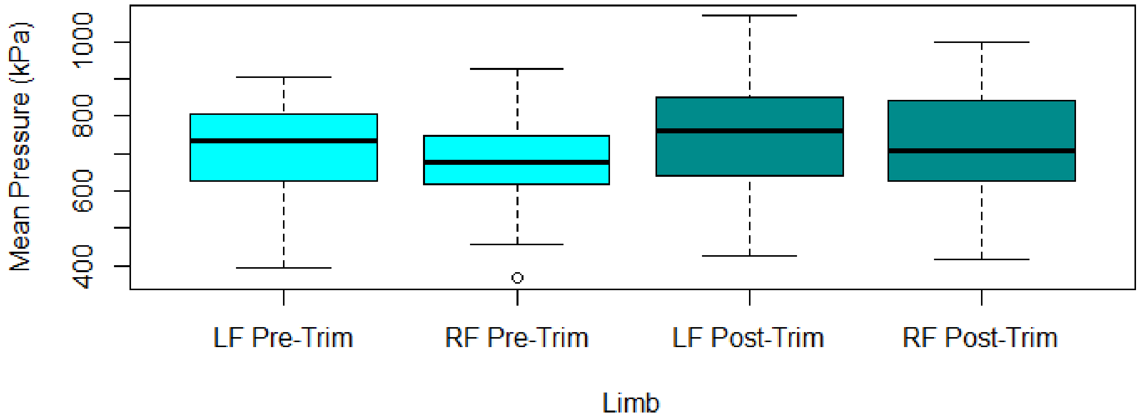

Figure 3.8a: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean dynamic pressures (kilopascals (kPa)), dorsolateral quadrant (n=61 horses)

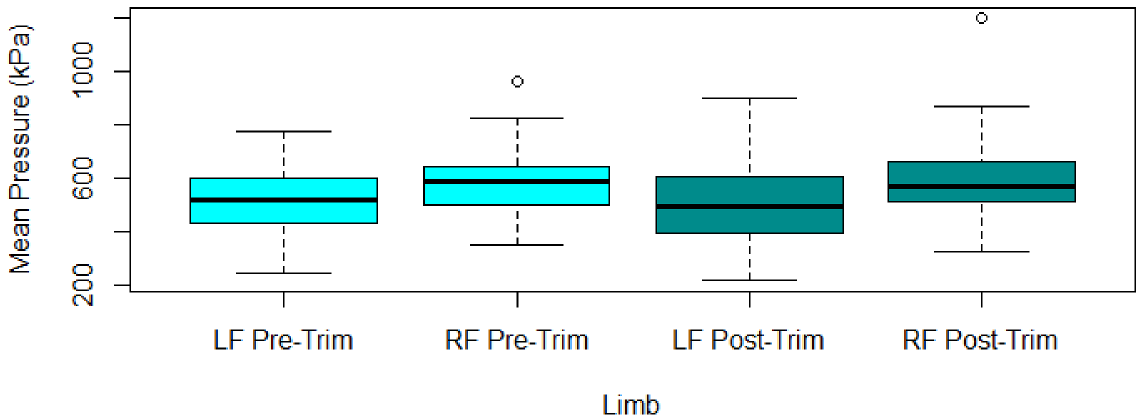

Figure 3.8b: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean dynamic pressures (kilopascals (kPa)), dorsomedial quadrant (n=61 horses)

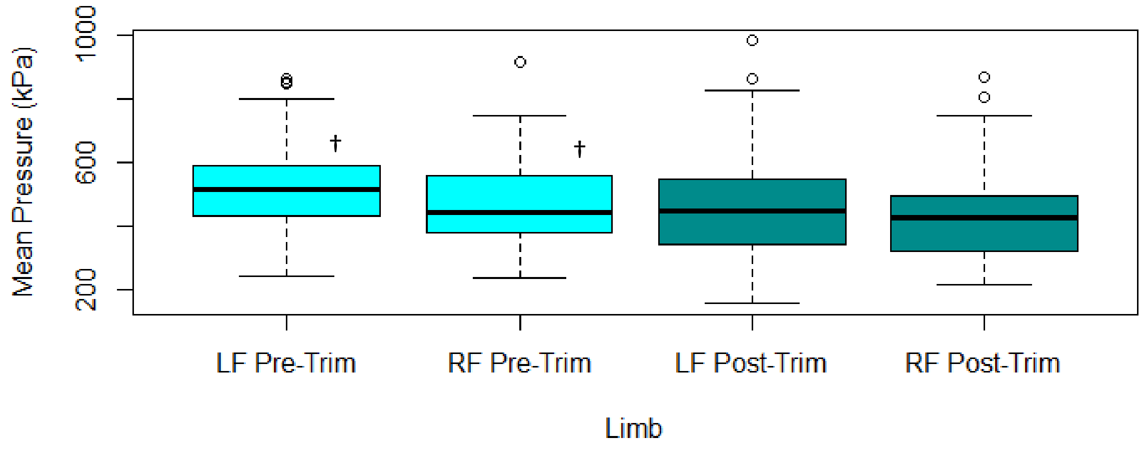

Figure 3.8c: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean dynamic pressures (kilopascals (kPa)), palmarolateral quadrant (n=61 horses). †significant reduction post-trimming (p<0.01)

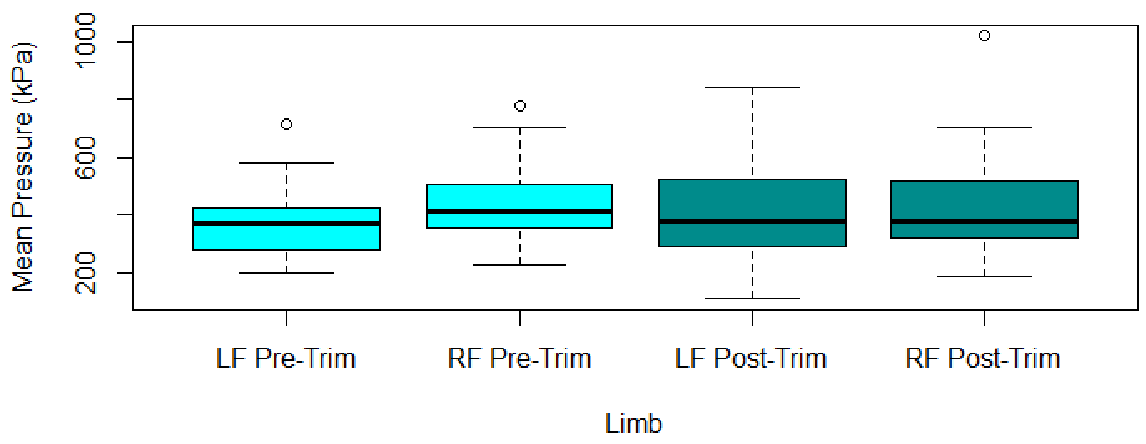

Figure 3.8d: : Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim mean dynamic pressures (kilopascals (kPa)), palmaromedial quadrant (n=61 horses)

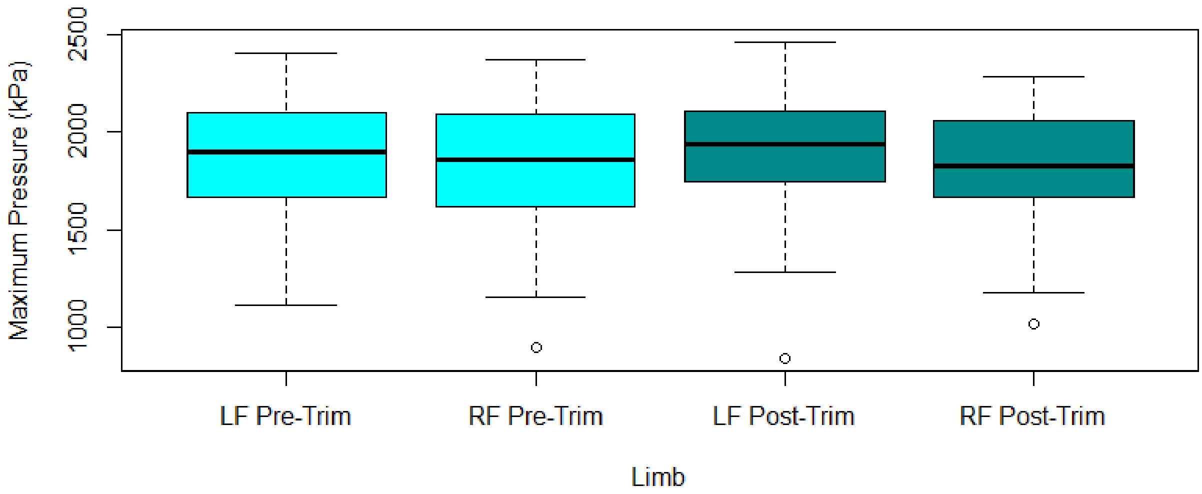

Figure 3.9a: : Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum dynamic pressures (kilopascals (kPa)), dorsolateral quadrant (n=61 horses)

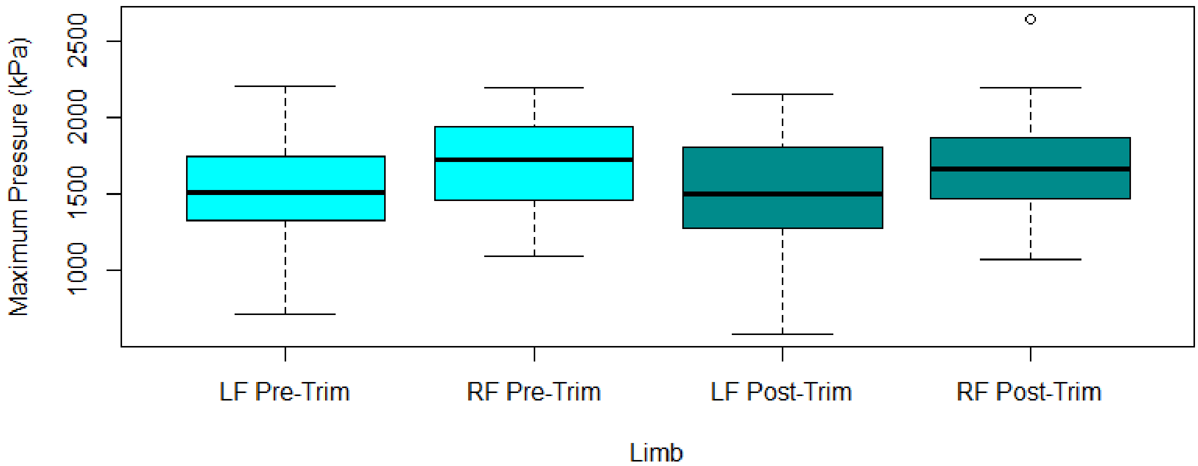

Figure 3.94b: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum dynamic pressures (kilopascals (kPa)), dorsomedial quadrant (n=61 horses)

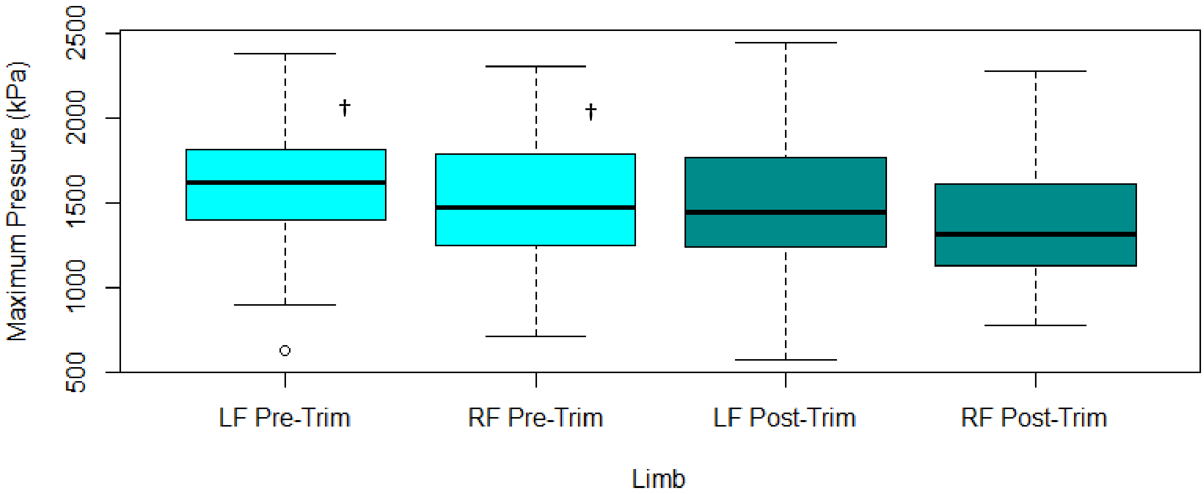

Figure 3.9c: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum dynamic pressures (kilopascals (kPa)), palmarolateral quadrant (n=61 horses)
†significant reduction post-trimming (p<0.01)

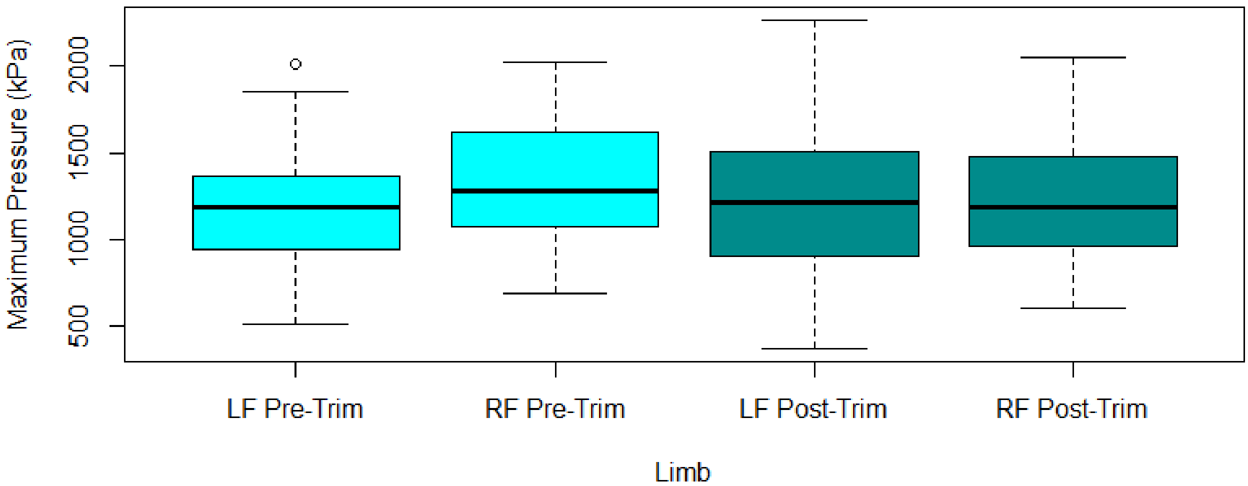

Figure 3.9d: Boxplot showing left fore (LF) and right fore (RF) limb, pre- and post-trim maximum dynamic pressures (kilopascals (kPa)), palmaromedial quadrant (n=61 horses)

3.5.4.2.3 Estimate of pressure mat data variability

In order to estimate the variability of the pressure mat data, coefficient of variation was calculated for foot quadrant pressures. The results are displayed in Table 3.20: coefficient of variation was >25% in all cases, and highest for mean dynamic pressure.

Table 3.20: Coefficient of variation for static and dynamic pressure mat data

	Static		Dynamic	
Limb and Condition	**Mean CoV (%)**	**Maximum CoV (%)**	**Mean CoV (%)**	**Maximum CoV (%)**
Left fore pre-trim	33.1	27.6	43.0	36.2
Right fore pre-trim	30.6	26.1	41.2	35.7
Left fore post-trim	35.2	26.8	47.3	39.4
Right fore post-trim	32.9	25.4	45.6	38.5

CoV = coefficient of variation

3.5.4.3 Comparison of foot measurement data and static foot pressure data

Correlation between foot measurements and mean and maximum pressure values in each quadrant in both LF and RF feet pre- and post-trimming was evaluated. Five key foot measures, FrA-Toe, BBL, width, DHWA-HA and LHWA (as used for multivariable modelling in the previous section of this chapter) were selected. Results are presented in Appendix 2, Tables 7 and 8.

Foot measures and mean or maximum pressure values in any quadrant were correlation coefficients <0.4 throughout. Pre-trim foot width was negatively correlated with dorsolateral static mean pressure in the LF before trimming, but this effect was lost following trimming. In the RF, there were positive correlations between FrA-Toe length and mean pressure in the dorsolateral quadrant pre-trim, and also between DHWA-HA and palmarolateral mean pressure. Interestingly following trimming in the RF the correlation between DHWA-HA and palmarolateral mean pressure became reversed whereas after trimming there was no longer an association with dorsolateral quadrant and FrA-Toe length. When assessing association of static maximum pressure and each foot quadrant there were no significant correlations apart from between hoof width and dorsomedial maximum pressure following trimming in the RF only (Appendix 2, Table 8).

3.5.4.4 Comparison of foot measurement data and dynamic foot pressure data

3.5.4.4.1 Quadrant analysis pre- and post-trim

Dynamic mean pressure showed positive correlation between DHWA-HA and dorsomedial and palmaromedial quadrants pre-trim in the RF (Appendix 2, Table 9). Following trimming the association only remained significant between this foot measure and the palmaromedial quadrant. When evaluating maximum pressures (dynamic) the only correlations between quadrants and foot measures (FrA-toe, hoof width and DHWA-HA), were observed in the RF, mainly pre-trimming

(Appendix 2, Table 10). After trimming the associations remained between DHWA-HA and dorsomedial quadrant in the RF and became significant between the same foot measure and the palmaromedial quadrant, similar to mean pressure data.

3.5.4.5 Pedobarographic Statistical Parametric Mapping (pSPM)

As well as evaluating the different quadrants of the foot, pedobarographic statistical parametric mapping (pSPM) analysis was performed which allowed topological comparison of foot strikes recorded during dynamic pressure mat trials. This method allowed identification of particular areas of difference between LF and RF limbs as well as pre- and post-trimming conditions. Findings from this analysis are summarised in Table 3.21 and 3.22. Results were not available from pre-trimming pressure mat recordings for three horses, and post-trimming pressure mat recordings for five horses. The results are presented from the remaining horses (pre-trim n=58, post-trim n=56).

3.5.4.5.1 Left fore compared to right fore, pre- and post-trimming

Table 3.21 shows that there was a variety of differences identified between limbs in the pre-trim condition. Notably the RF more commonly had higher areas of pressure than the LF. Following trimming the frog region was the most common area for a significant difference to be detected, accounting for 7 of the 15 significant areas of change. Examples of the most commonly seen differences are depicted in Figures 3.10-3.12, examples of the other differences are included in Appendix 2 (Figures 1-6).

Table 3.21: Results of pedobarographic Statistical Parametric Mapping of differences between left and right forelimbs in both pre- (n=58 horses) and post-trimming (n=56 horses) conditions

Trim status	**Description**	**Number of horses (%)**
Pre-trim difference	Higher pressure lateral heel right fore	2 (3.4)
	Higher pressure lateral toe right fore	1 (1.7)
	Higher pressure frog right fore	1 (1.7)
	Lower pressure medial hoof wall right fore	1 (1.7)
	Lower pressure medial midsole-toe right fore	1 (1.7)
	Lower pressure frog region right fore	2 (3.4)
	No significant or meaningful difference	50 (86.2)
Post-trim difference	Higher pressure frog right fore	3 (5.4)
	Higher pressure medial heel right fore	1 (1.8)
	Lower pressure base of frog right fore	3 (5.4)
	Lower pressure medial hoof wall right fore	1 (1.8)
	Lower pressure lateral heel right fore	1 (1.8)
	Lower pressure medial midsole-toe right fore	1 (1.8)
	No significant or meaningful difference	46 (82.1)

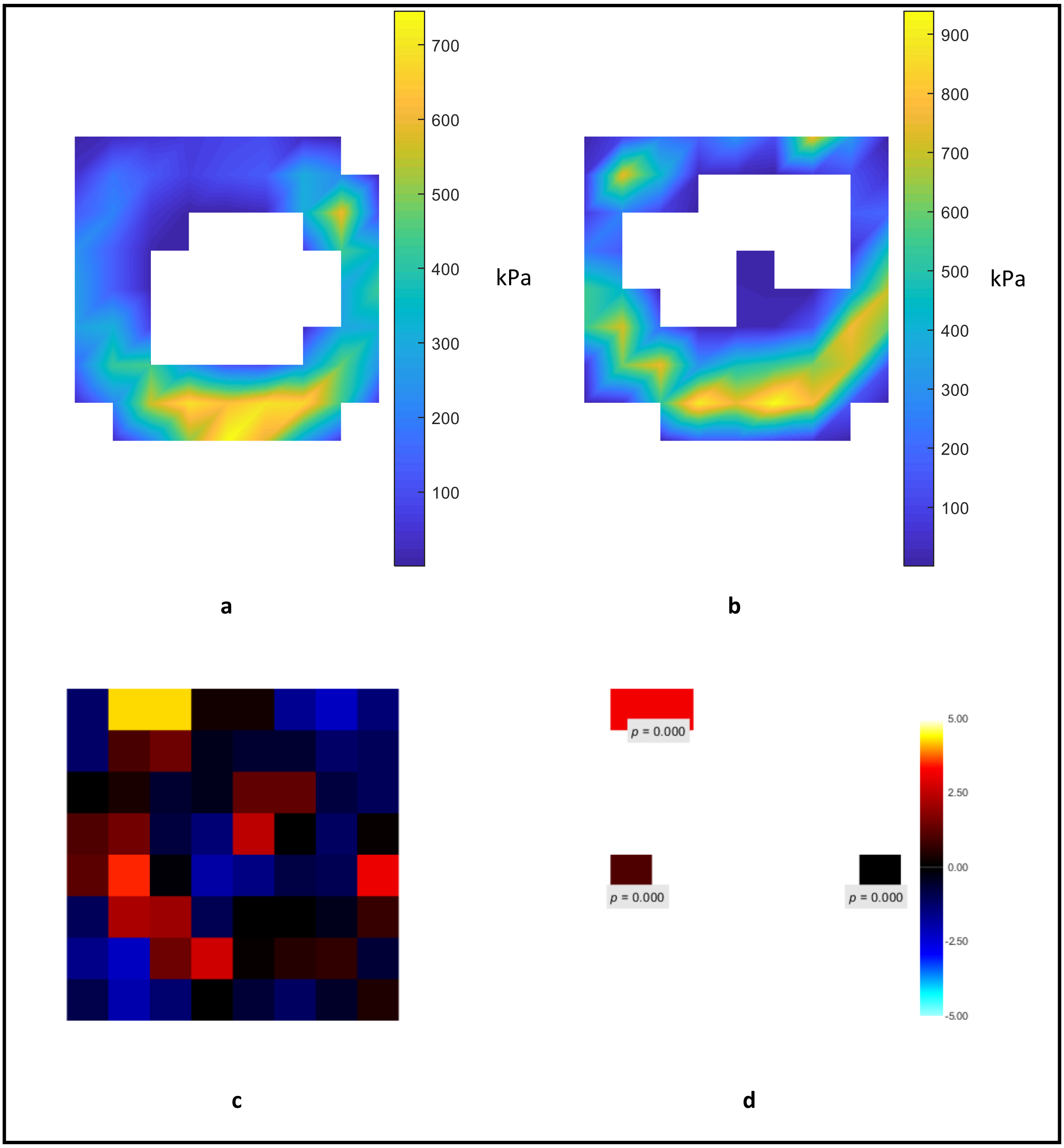

Figure 3.10: An example of higher pressure in the lateral heel of the right fore compared with the left fore. Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs pre-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore pre-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate increased loading of the right fore lateral heel region compared with the left fore. A cluster of two pixels that are significantly different (p<0.001) between left and right is demonstrated in plot d; comparison with c indicates the location is the lateral heel region. The colour of the pixels indicate a positive change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means higher pressure was exerted in this region on the right fore than the left fore. The two other single pixel changes were not considered meaningful due to their location as well as the small area they affected. kPa=kilopascals

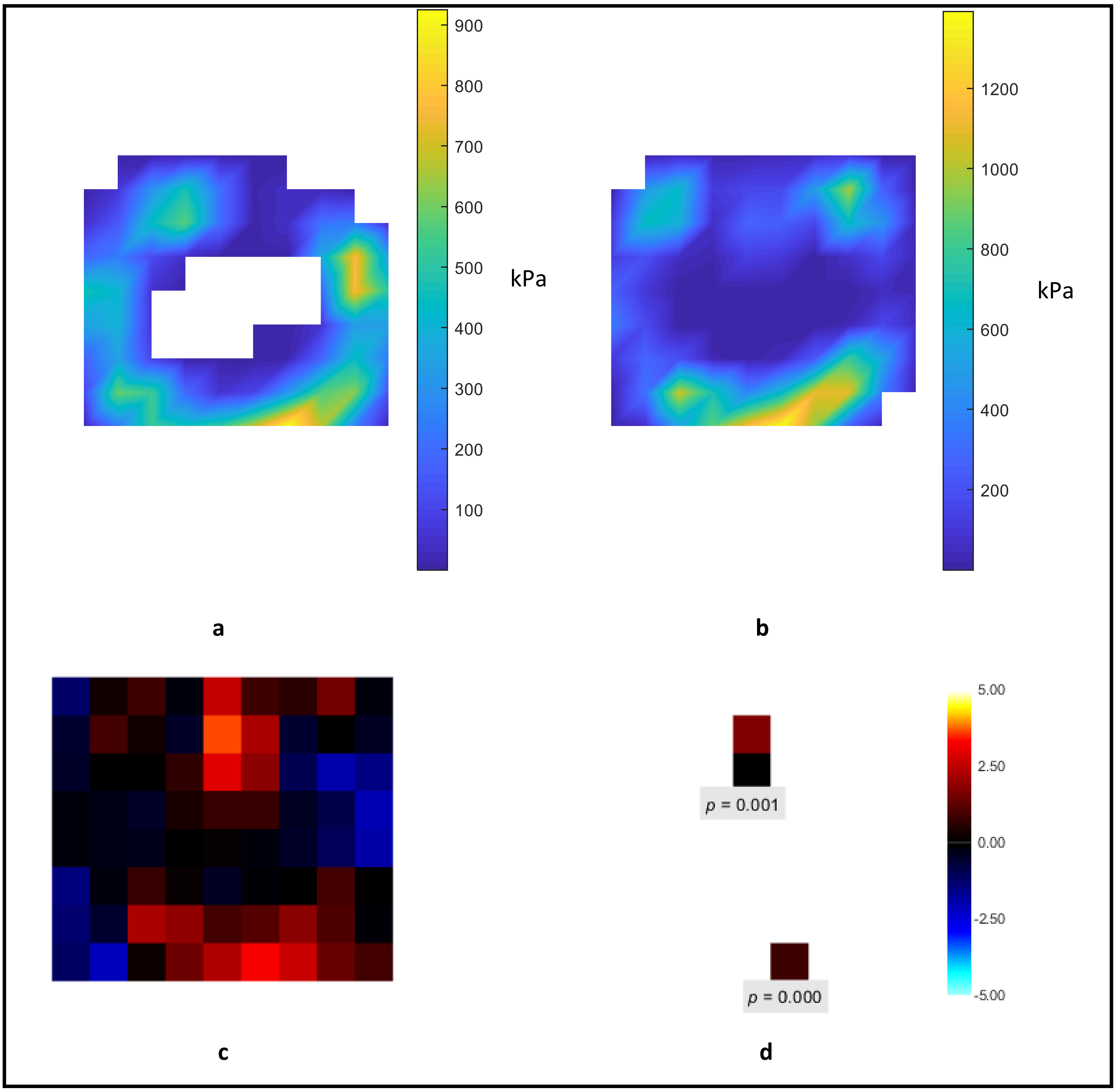

Figure 3.11: An example of higher pressure in the frog of the right fore, compared with the left fore. Plots a-d indicating mean pressure and significant differences in loading between left and right forelimbs pre-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore pre-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate Increased loading of the distal frog region in the right fore compared with the left fore. A cluster of two pixels that are significantly different (p=0.001) between left and right is shown in plot d. The colour of the pixels indicate a positive change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means higher pressure was exerted in this region on the right fore than the left fore. The single pixel change at the toe region was not considered meaningful due to the small area it affected. kPa=kilopascals

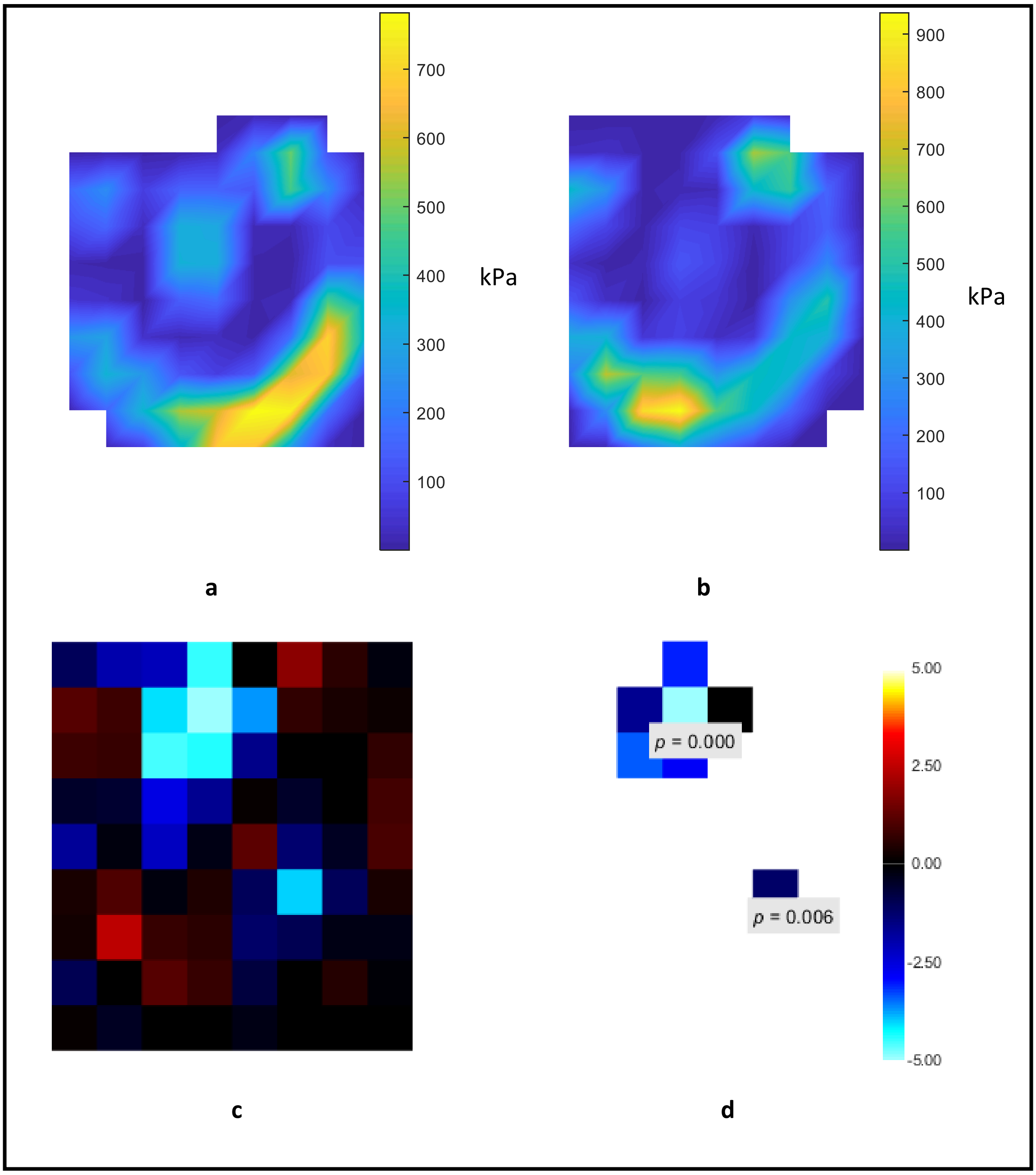

Figure 3.12: An example of lower pressure in the frog region of the right fore, compared with the left fore. Plots a-d indicating mean pressure and significant differences in loading between left and right forelimbs post-trimming. a is a plot of the mean pressure distribution of left fore post-trim strikes, b is a plot of the mean pressure distribution of right fore post-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate decreased loading of the caudal frog region in the right fore compared with the left fore. A cluster of six pixels that are significantly different ($p<0.001$) between left and right is shown in plot d. The colour of the pixels indicate a negative change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means lower pressure was exerted in this region on the right fore than the left fore. The single pixel difference ($p=0.006$) also in plot d was not considered a meaningful change due to the small area it covered and the location of the change. kPa=kilopascals

3.5.4.5.2 *Pre- vs post-trimming loading patterns*

Table 3.22 demonstrates that after trimming, the most significant change in how the foot was loaded was an increase in pressure over the palmar region of the foot. An example of this change is presented in Figure 3.13. Smaller numbers of horses also showed increased pressure on the bridge of the foot post-trimming (Figure 3.14).

Table 3.22: Significant differences in loading between pre- and post-trim conditions in left fore and rightfore limbs (n=56)

Trim status	**Type of change**	**Number of horses (%)**	
		Left fore	**Right fore**
Post-trim	Increased pressure palmar region of foot	11 (19.6)	10 (17.9)
	Increased pressure frog/bridge of foot post-trimming	3 (5.4)	2 (3.6)
	No significant or meaningful difference	42 (75.0)	44 (78.5)

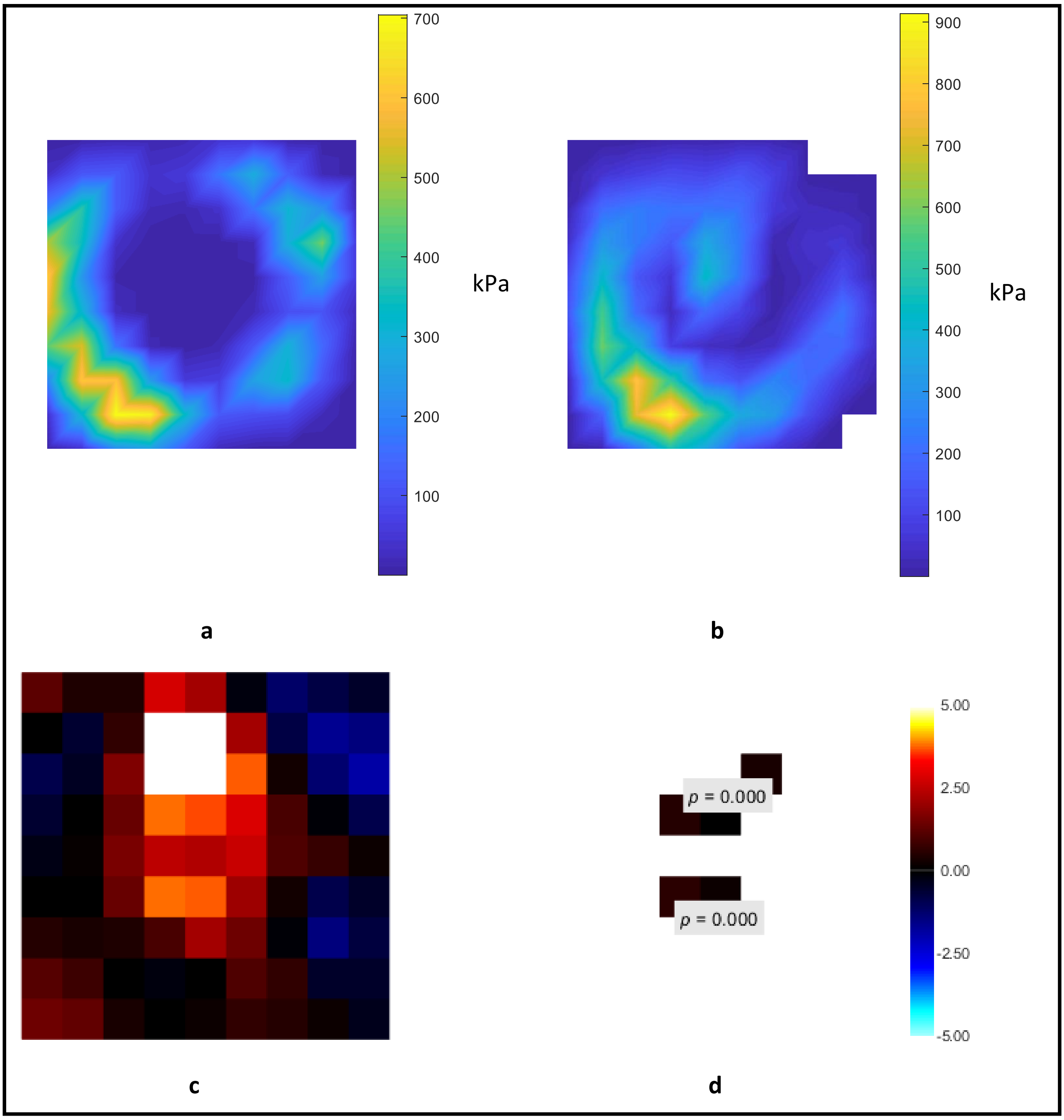

Figure 3.13: an example of increased loading of the frog region post-trimming compared with pre-trimming. Plots a-d indicate mean pressure and significant differences in loading between left forelimbs pre- and post-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of left fore post-trim strikes. c is a plot of the difference between pre- and post-trim and d plots the areas of significant differences in loading between pre- and post-trimming. In this horse a and b indicate increased loading of the caudal frog region and bridge of foot region post-trimming compared with pre-trimming. A cluster of three pixels and another cluster of two pixels that are significantly different (p<0.001) between pre- and post-trimming is shown in plot d. The colour of the pixels indicates a positive change; since the pSPM method involves mapping pre-trim strikes on to post-trim strikes this means more pressure was exerted in this region post-trimming than pre-trimming. kPa=kilopascals

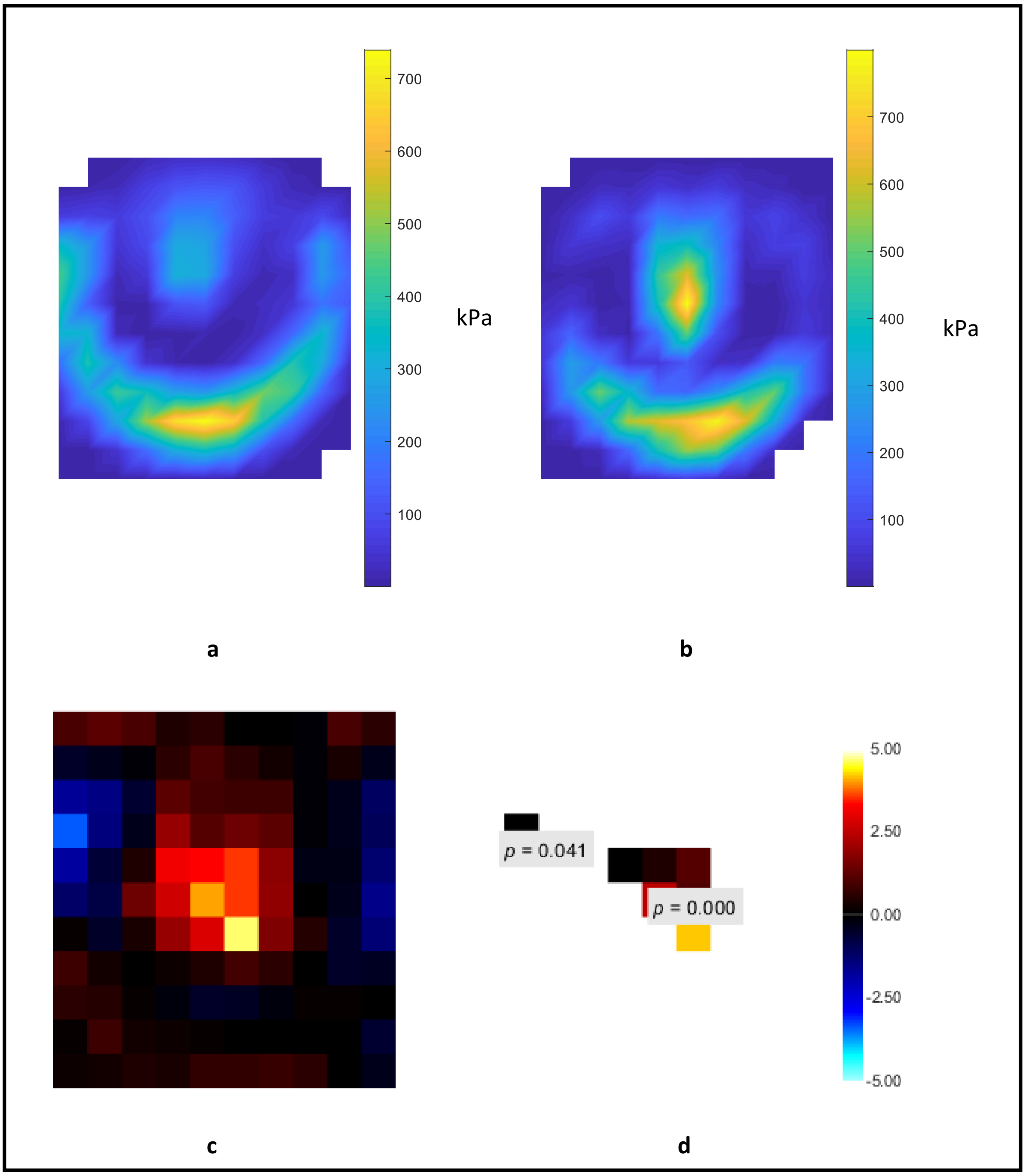

Figure 3.14: an example of increased loading of the frog apex/bridge region of the foot post-trimming compared with pre-trimming. Plots a-d indicate mean pressure and significant differences in loading between right forelimbs pre- and post-trimming. a is a plot of the mean pressure distribution of right fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore post-trim strikes. c is a plot of the difference between pre- and post-trim and d plots the areas of significant differences in loading between pre- and post-trimming. In this horse a and b indicate increased loading of the frog apex/bridge of foot region post-trimming compared with pre-trimming. A cluster of six pixels that are significantly different (p<0.001) between pre- and post-trimming is shown in plot d. The colour of the pixels indicates a positive change; since the pSPM method involves mapping pre-trim strikes on to post-trim strikes this means more pressure was exerted in this region post-trimming than pre-trimming. The single pixel (p=0.04) was not considered meaningful due to the small area it covered and the location of the change. kPa=kilopascals

3.6 Discussion

This chapter examined the demographics and stable management of a mixed breed, mixed discipline population of sound horses in the North-West of England and North Wales. Foot shape measures and foot loading data were obtained before and after trimming at a single time point. From these data, the relative influence of various horse and environmental factors on foot shape and foot balance were analysed, as well as the relationship between foot shape, foot loading and foot trimming.

3.6.1 Questionnaire findings

The demographics of the study population in this chapter were similar to those identified in a recent survey of 14,000 horses in the United Kingdom (UK) (Blue Cross, 2018); with near identical proportions of native breeds, WBs and TB-type horses reported. The greater number of geldings compared with mares reflected the findings of surveys carried out both in the UK and United States of America (USA) (Wylie *et al.*, 2013; Caston and Burzette, 2018). The average age of horses in this study population (10.6 years of age) was comparable with the findings from low level event horses (Caston and Burzette, 2018) but was a little lower than that recorded across a more general equine sample population in the UK in 2013 (13 years) (Wylie *et al.,* 2013). This may be because the current study population only included animals in work, potentially excluding the older parts of the UK equine population.

In terms of stable management, a large proportion of horses in this study (75.0%) spent time both stabled and at pasture. Eight horses (8.6%) were stabled 24 hours per day; over double the proportion found in a previous study (Wylie *et al*., 2013). However, all of these horses were kept at two yards which suggests this was a yard management policy exclusive to these premises. Some horses (16.1%) were not stabled at all; these horses were all recruited to the study between the months of May and October, thus season may have been a factor in this. Despite these differences, the average time spent stabled was within the range previously described (Wylie *et al*., 2013). Livery yards were the most common places for horse to be kept, followed by private yards, as reported in National Equine Health Survey (NEHS) (Blue Cross, 2018). Another UK equine survey identified that a large proportion of horses were kept at the owner's home (Wylie *et al.,* 2013).

Though the proportion of horses used primarily for trail or leisure riding was lower than in other surveys of UK equines, it was still the most common use for horses in the study population, in keeping with other studies of the past decade (Wylie *et al*., 2013; National Animal Health Monitoring System, 2016, 2017a; Smyth and Dagley, 2016; Blue Cross, 2018) A greater proportion of horses were used for dressage, show-jumping, eventing and riding or pony club activities in this study compared with others (Ireland *et al.*, 2013; National Animal Health Monitoring System, 2016; Blue Cross, 2018). This may have been due to the requirement to be both sound and in work at the time of study recruitment, as well as horses being recruited through their farrier rather than through their veterinary practices (Wylie *et al*., 2013) or through stratified sampling of equine premises (National Animal Health Monitoring System, 2016). The study population contained no horses used for racing or breeding, which may reflect the low number of these enterprises in North-West England and North Wales.

The median number of sessions and duration of trail riding and jumping per week were similar to that reported by another study of UK horses (Wylie *et al*., 2013). As detailed in the literature, most horses were exercised on a number of different surfaces (Wylie *et al*., 2013; Caston and Burzette, 2018).

Reflecting the results of a survey of 14,000 horse owners in the UK (Blue Cross, 2018), around two-thirds of the horses in the current study were described a 'normal' bodyweight by their owner. The remaining third of horses were mostly described as overweight, with only 3.2% labelled 'thin'. This may be due to this population of horse owners having a more accurate awareness of their horse's weight, or that they avoid describing their horses as thin. Just over 30% of horses were fed supplements; around half that reported in previous studies of the UK equine population (Wylie *et al*., 2013) though similarly, the reasons given for feeding supplements were wide-ranging.

Almost half of horses recruited (40.9%) had suffered a previous lameness event. This is greater than that found in a 2018 survey of UK horses (Blue Cross, 2018), which reported a lameness prevalence of 29%. However, the latter asked respondents to detail current issues at the time of the survey, rather than historical lameness as in this study. For around two-thirds of horses with a lameness problem, veterinary advice had been sought, which is similar but slightly higher rate than that reported in a survey carried out in the USA (National Animal Health Monitoring System, 2017b). The prevalence of various veterinary diagnoses was similar to that recorded in a previous study (Caston and Burzette, 2018). However, details were not recorded of how these diagnoses were made, hence the results may not be accurate.

Hoof abnormalities are considered a major cause of lameness, poor welfare and reduction in the lifetime of a horse (Lloyd and Kaneene, 1997; Floyd and Mansmann, 2007; Collins *et al.*, 2010). Most hoof abnormalities are multifactorial in origin (Bergsten, 2003; Hunt and Wharton, 2010) and related to management. The current study identified a large difference between owner-reported and veterinary-observed hoof abnormalities within the study population, as previously reported (Floyd and Mansmann, 2007; Ireland *et al.*, 2012; Thirkell and Hyland, 2017). The exact reason for this is unknown. It may be through a lack of owner awareness or understanding of various hoof abnormalities. Poor client-farrier communication may also be a factor; previous work identified that 41% of horse owners struggled to find a farrier that they trusted, and 23% had criticisms of their farrier (Thirkell and Hyland, 2017).

A cross-sectional study carried out by farriers across the Netherlands (Holzhauer *et al.*, 2017) found that 85% of clinically normal, regularly trimmed horses had at least one hoof abnormality. Similarly, a study of UK horse owners reported 89% of horses had suffered a hoof problem in the past 5 years (Thirkell and Hyland, 2017). These are almost double that identified on veterinary examination in the current study. Comparison between studies is made difficult through recording of different abnormalities and their severity, the timescale and horse demographics over which the studies took place, and the frequency of trimming the study populations were subject to.

Breed, turnout and bedding material have been identified as significant factors in the occurrence of various hoof abnormalities. Cleaning out feet less than once per week was associated with an increased risk of perforating hoof wall cracks and widening of the white line, compared with picking feet out daily (Holzhauer *et al.*, 2017). In the current study nearly 80% of horses were reported to have their feet picked out at least once daily, though 16% reportedly never had their feet picked out. Asymmetrical foot pairs were identified in 23.7% of the current study population, higher than that detected (18%) in sport horses in New Zealand (Dijkstra *et al.*, 2018).

The current study population corroborated previous findings that foot trimming occurs on average every 6 weeks (Ireland *et al.*, 2013; National Animal Health Monitoring System, 2017b; Dijkstra *et al.*, 2018). Dijkstra and others found that only 5% of horses had remedial farriery (Dijkstra *et al.*, 2018). In the current study corrective foot trimming or shoeing was described in 10.7% of the study population, similar to that estimated by a recent survey of horses in the USA (National Animal Health Monitoring System, 2017b).

3.6.2 Foot shape and the effect of trimming

Dorsal hoof wall length (DHWL) and heel length (HL) measurements recorded in the present study resembled those reported in a recent study on sport horses (Dijkstra *et al.*, 2018), but were greater than those seen in racing Thoroughbreds (Labuschagne *et al*., 2017). The current study recorded a more acute dorsal hoof wall angle (DHWA) than previously recorded in racing Thoroughbreds, sport horses and WBs, whilst having a steeper heel angle (HA) than racehorses and mildly more acute HA than sport horses in New Zealand (Moleman *et al.*, 2006; Labuschagne *et al.*, 2017; Dijkstra *et al.*, 2018). Results from the current study population fell within the prescribed DHWL:HL ratio of <3:1

(Turner, 1992). This is in contrast to a study of racing Thoroughbreds in New Zealand (Labuschagne *et al.*, 2017). Differences in foot angulation between the medial and lateral sides were demonstrated by the difference between DHWA and HA being less than 5° on the lateral view measurements, yet greater than 5° on the medial view measurements. Average differences between DHWA and HA in racing Thoroughbreds was 14° (Labuschagne *et al.*, 2017). This supports the dogma that racing TBs have a steeper DHWA but a more acute HA than other breeds as represented by the mixed-breed population in this study.

Solar measurements of hoof width and length in the present study were very similar to those reported for Thoroughbred racehorses (Labuschagne *et al.*, 2017) and sport horses (Dijkstra *et al.*, 2018). In the latter case a greater average foot length was observed, which may be due to the greater average height of horses within that study (165cm as opposed to 155cm in the current study), or breed differences.

Changes in foot measurements observed following trimming by a farrier were: decreased length at the toe, increased size of the palmar area of the foot and decreased hoof width. When hoof width was divided into lateral and medial portions, the lateral portion was shown to be larger than the medial portion. Trimming resulted in a significant reduction of lateral width only. Trimming also resulted in a steeper medial hoof wall angle. Both medial and lateral hoof wall lengths decreased post-trimming in the current study, in contrast to the findings of Lesniak and others (2017), whose population of mixed breed, working horses had increased medial and lateral hoof wall lengths following trimming, accompanied by no significant changes in medial and lateral hoof wall angles. Interestingly, their recorded values for medial and lateral hoof wall lengths were also much smaller (3.57-4.09cm) than those recorded in this study (6.80-7.53cm), which may represent large differences in study horse demographics, trimming protocol or measurement method.

Reduction of the DHWL at trimming has been reported as 1.0cm for an 8-week shoeing interval (Kummer *et al.*, 2006; Moleman *et al.*, 2006). The current study's median trimming interval of 6 weeks would infer an average expected change in DHWL of 0.75cm over the shoeing interval, which is slightly greater than what was actually recorded. Reduction of DHWL was accompanied by an increase in steepness of the DHWA in the lateral view of the LF and RF, reflecting the findings of Lesniak and others (2017). The recognised ideal range of the DHWA is 50-55°, though the literature shows it can range from 45-60° (Eliashar, McGuigan and Wilson, 2004; Kummer *et al.*, 2006; Cruz *et al.*, 2007; Dyson *et al.*, 2011). The average DHWA recorded pre-trimming in this study was just below 50°, but post-trimming it was within the recommended limits. DHWA results from this study are aligned with that in the literature (Thomason, Biewener and Bertram, 1992; Dyson *et al.*, 2011;

Leśniak *et al.*, 2019). HL reduced significantly following trimming, though this was to a lesser extent than DHWL and not related to a change in HA.

This study presented a novel assessment of foot shape by including results from the medial view, which have not previously been published. Findings from the LF medial view broadly reflected those of the LF lateral view. However, in the RF medial view DHWL and HA significantly decreased post-trimming. Furthermore, significant changes observed in the LF medial view were not observed in the RF. These differences between the lateral and medial views were also observed in the DHWA-HA difference which increased post-trimming in the medial view measures to be greater than 5°, outside the suggested ideal for a balanced foot. These findings indicate that future research should not assume that lateral and medial views are equivalent, nor LF and RF limbs. Further evidence is required to elucidate the causes of mediolateral and left-right differences. In this study all farriers were right-handed.

Foot balance measures were used to estimate the effect of trimming on geometric proportionality (as proposed by Duckett (1990)) of the feet in the study population. Similar to a previous study which assessed foot balance measures (Caldwell *et al.*, 2016), geometric proportionality of the foot was not achieved, even after foot trimming.

Linear regression was used to elucidate the relative effect of horse and environmental factors on various foot shape parameters. Genetics, discipline and farriery have been shown to be associated with foot measures in previous studies (Kobluk *et al.*, 1990; Gill, 2007; Dijkstra *et al.*, 2018; Leśniak *et al.*, 2019). TB and Native-crossbred animals had a significantly shorter BBL compared with the reference breed (WB), whilst all other breeds had a longer BBL. Most breeds had a more acute LHWA compared to WB, though in Arabs and Native breeds it was steeper. This may indicate that Arab and Native horses have more upright foot conformation and are less predisposed to lateral hoof wall flares than other breeds in the study population. Height was a significant factor in BBL, width and FrA-Toe. Increased horse height was related to increases in these parameters, likely due to isometric scaling. This contrasts with a recent study that found no significant relationship between horse height and foot dimensions, citing body mass as the more influential factor of the two (Leśniak *et al.*, 2019). In the current study, height and mass were strongly correlated ($r>0.7$). Height was chosen for inclusion in multivariable models since weight was estimated using a weigh tape and therefore was likely to be a less accurate recording than height, which was measured using a measuring stick.

Work pattern has been shown to have an effect on foot dimensions (Kane *et al.*, 1996; Peel, Peel and Davies, 2006), though most published literature refers to racehorses. This study found that FrA-Toe length was shorter than the reference (trail/leisure) for horses used primarily for show-jumping, riding or pony club activities and endurance riding. This may indicate that horses primarily used for leisure riding are trimmed less frequently and develop a longer toe. Horses primarily used for dressage, eventing and showing had a greater FrA-Toe length than the reference, which may be explained by the influence of horse height on FrA-Toe length. Hoof width was smaller in horses that spent a greater total time jumping per week, which may be due to adaptation of the foot to workload, or the demographic of jumping horses. A greater DHWA-HA difference was associated with horses that spent a greater average time per week trail riding. Ass with FrA-Toe length, this may reflect that horses used primarily for leisure activities have less frequent farriery care.

Trimming and shoeing have long been recognised as important factors in foot shape (Van Heel *et al*., 2004). However, a number of studies have identified differences in trimming styles as well as opinions on foot balance both within and between individual farriers (Kummer *et al*., 2009; Thirkell and Hyland, 2017), which can affect the way that horses are trimmed. These findings were reflected in the current study where individual farrier was found to be a significant factor in DHWA-HA difference. Similarly, whether a farrier had enrolled in or completed a course of higher education had an important effect on the risk of horses experiencing foot imbalance. This was a more significant factor than years since qualifying or trimming protocol of the farrier. This may indicate that continuing professional development (CPD) is a crucial part of a farrier developing good practice in the shoeing and trimming of horses' feet. Alternatively, it may be that those farriers that decide to undertake higher education are more conscientious in their work regardless of the effect of the training. Continuing professional development for qualified farriers only became a requirement in 2015, hence many practising farriers have never had an obligation to undertake training during their career. Changes that have occurred in the scientific literature regarding optimal foot shape and foot balance, as well as the impact of these factors on performance and long-term soundness of the horse may mean that many farriers are still working towards long-outdated ideals, to the detriment of equine health and welfare.

3.6.3 Foot loading and relationship with foot shape

Few studies have addressed both foot loading and foot shape simultaneously, allowing assessment of the relatedness of these measures. In this study custom-written MATLAB® code was used to divide foot prints into quadrants for analysis, in order to avoid the potential biases that can occur when manually dividing prints into regions (Pataky and Goulermas, 2008; Oomen *et al.*, 2012).

This study found that in static trials dorsal foot quadrants were subject to significantly greater pressures than palmar quadrants, with the dorsolateral quadrant recording the largest pressures. This was true both for pre- and post-trim conditions. The same pattern was seen in the results of the dynamic trials. Previous studies also found the dorsal foot region subject to greater pressure than the heels (Van Heel *et al.*, 2005; Oomen *et al.*, 2012). Others have found the lateral aspect of the foot to be subject to greater loading than the medial side in Irish Draught horses and WBs (Eliashar *et al.*, 2002; Van Heel *et al.*, 2004; Oosterlinck *et al.*, 2013). Similarly, studies investigating the location of the centre of pressure have identified the dorsolateral quadrant of the foot as the most common site (Caudron *et al*., 1998; Van Heel *et al*., 2005) though others have found its location to be medial (Colahan, Leach and Muir, 1991).

The results of dynamic trials showed that almost all quadrants had significantly different pressure recordings from one another. There were also differences between the same quadrants in contralateral limbs except for the dorsolateral quadrant. The palmarolateral quadrant was the only quadrant to exert significantly different pressure post-trimming compared with pre-trimming. Pressure was decreased post-trimming in both forefeet.

The pSPM method provides a pixel-level view of foot pressure distribution, avoiding potential bias due to anatomical, rather than functional division of prints (Pataky *et al.*, 2008). It is an approach which equine biomechanics research has been aspiring to for a number of years (Oomen *et al.*, 2012; Oosterlinck *et al*., 2013), following its adoption in human biomechanical studies (Pataky and Goulermas, 2008). In this study, pSPM demonstrated that most contralateral limb differences before trimming were greater pressure in areas of the RF, compared with the LF. Post-trimming the LF-RF differences almost exclusively affected the frog region or the heels and, conversely to pre-trimming, there were a greater number of horses with higher pressure in regions of the LF than the RF. In the case of the heels both medial and lateral sides were affected, with neither one appearing to be particularly more common in LF or RF. The differences between pre- and post-trimming may indicate how trimming addresses asymmetrical loading across contralateral limbs. However, findings here indicate that trimming does not always lead to symmetrical loading either across limbs or individual feet. The short time between foot trimming and data collection may also be a factor in this, as horses had little time to adapt to their trimmed feet before trial data was collected.

The greatest number of differences seen between pre- and post-trimming were greater pressure being exerted on the palmar or frog regions of the foot, post-trimming. This was the same in both limbs and may correspond to the findings of previous studies where trimming resulted in an increased bearing surface of the foot allowing for faster complete support for the limb following impact, and reduction of high frequency vibrations at impact (Balch *et al.*, 1988; Benoit *et al.*, 1993; Van Heel *et al.*, 2004).

Although much work has been done to determine optimal foot shape and loading, a small minority of studies have simultaneously studied foot shape and foot pressure around foot-trimming events. Two studies examined the changes in foot conformation and foot loading (at trot) of sound WB horses over an 8-week shoeing cycle (Van Heel *et al*., 2005) or standing (Moleman *et al.*, 2006). Both studies identified a reduction in DHWA over the course of the shoeing cycle, this was related to changes in foot pressure, with centre of pressure moving in a palmar direction. It is difficult to compare the centre of pressure results with true pressure results as in this study.Unfortunately in this study the direct comparison of foot shape with both static and dynamic foot pressure resulted in very disparate, weak correlations, precluding the possibility of drawing definitive conclusions.

3.6.4 Limitations

This study had several limitations. Convenience sampling was used to recruit farriers and horses to the study, which may have biased the results (Tyrer and Heyman, 2016)as those farriers that took part may have been more likely to be interested in foot balance and evidence-based farriery. Similarly, horse owners that agreed to participate may have been more engaged in their horse's health and foot care, than the general population of horse owners. Horses were required to be sound at the trot and in work at the time of recruitment, which automatically ruled out certain groups within the UK equine population.

Though horses were screened for lameness at the time of recruitment, it was not possible to rule out the impact of past lameness events on current foot shape and loading behaviour. Data on owner-reported veterinary diagnosis of lameness issues are likely to be highly variable, as demonstrated by the large proportion of owners that did not know or could not remember what the diagnosis was. Severity, prognosis and communication between vet and owner are likely to impact the accurate description of these diagnoses by owners in the current study. These diagnoses may also have been presumptive rather than the result of diagnostic imaging. Given the uncertainty, this data should not be subject to over-interpretation.

The mixed-breed population recruited made the results likely to be more representative of a general equine population than previous studies of foot shape and loading, which have largely focussed on populations of a single breed (Eliashar *et al.*, 2002; Van Heel *et al.*, 2005; Moleman *et al.*, 2006; Oosterlinck *et al.*, 2013). However, all breeds were owner-reported which made it difficult to ascertain the accuracy of some breed types.

The approach to splitting foot strikes into quadrants was systematic, with the aim of avoiding bias. However, splitting a foot at any point is arbitrary, since it is a single continuous structure rather than separate pieces.

The considerable variation in pressure mat results may have affected the results found in this study, as true or conclusive findings may have been masked. The coefficient of variation for pressure data was high (>5%) (Beauchet *et al.*, 2009; McClymont *et al.*, 2016). This variability may be due to pressure mat data having been collected outside of (tightly controlled) laboratory conditions. This allowed many factors to potentially influence the data collected, including ground surface, weather conditions, speed of walking and other activities ongoing at the premises at the time of data collection. Previous studies of human subjects have identified a substantial degree of intra-subject variation in walking data (McClymont *et al.*, 2016). Therefore, the relatively low number of foot strikes recorded per horse in this study may also have impacted the variability of the results gained.

3.6.5 Conclusions

This study found that in a mixed population of horses, foot shape parameters were within those described as optimal, with changes around foot trimming consistent with findings of previous studies. Genetic factors such as breed and height, as well as environmental influences including work pattern and farriery had the greatest influence on foot shape measurements and foot balance. Although all horses recruited to the study were free from lameness, hoof abnormalities were common, and in many instances, owners failed to report them during the questionnaire aspect of this study. Foot pressure data demonstrated how dorsal regions of the foot were subjected to the highest pressures, both during stance and walk. Although foot shape and foot pressure measures were weakly correlated, the pSPM method allowed visualisation of how pressure distribution over the foot differed both between limbs and trimming conditions. Changes seen in foot measurements post-trimming such as increased area over the palmar surface of the foot were also evident in increased loading of these areas.

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Chapter 4

Longitudinal Study into Changes in Foot Shape and Loading

4.1 Introduction

Equine foot shape has a proven association with lameness events, particularly those brought about by pathology within the foot such as navicular disease and deep digital flexor tendon (DDFT) lesions (Kane *et al.*, 1998; Holroyd *et al.*, 2013). As such maintenance of optimal foot shape by farriery is considered crucial for ensuring the long-term soundness of horses (O'Grady and Poupard, 2001). Despite this, there is little information on how the equine foot changes shape over time, and whether these changes are associated with lameness. More data are required in this area so that appropriate measures can be implemented to prevent equine lameness events.

The previous chapter investigated the changes in foot shape at a single trimming event, adding to the findings of other studies around foot shape and foot-trimming; namely that trimming has a significant effect on foot shape and function (Van Heel *et al.*, 2005; Kummer *et al.*, 2006, 2009). However, there is a small number of studies assessing foot shape change in the horse longitudinally, let alone those that assess the impact of foot-trimming by a farrier or other hoof care professionals.

Kummer and others evaluated at changes in radiographic hoof measurements over two consecutive shoeing cycles of eight to ten weeks long, however they found little change between these two trimming events (Kummer *et al.*, 2006). Another study also examined the changes that occurred in foot shape over a single eight-week shoeing interval, this time using measurements from digital photographs (Van Heel *et al*., 2005). These authors found that toe length significantly increased over the shoeing interval, whilst toe angle decreased. Caldwell (2017) found that shod horses suffered increasingly poor dorsopalmar foot balance over three consecutive shoeing cycles. A study examining changes in foot shape in riding school horses advised against long shoeing intervals due to the significant changes that were identified over a four to six week interval (Leśniak *et al.*, 2017). These findings are valuable for farriers, veterinarians and horse owners alike to understand the importance of regular and appropriate farriery. However, the short timespan over which such studies were conducted limits the information they can provide regarding the long-term changes in foot shape. Studies evaluating foot shape over a longer period of time, such as six to nine months are more relevant to determine the effects of trimming on foot shape.

Another important question related to foot shape change is how these changes affect foot loading (i.e. linking shape to form). Similar to longitudinal studies of foot shape, there is a paucity of studies evaluating foot loading and those that exist only follow horses up to a maximum of 70 days (Van Heel *et al.*, 2005; Caldwell, 2017). As described in previous chapters, pressure mats are increasingly being used for biomechanical analysis of the horse (Van Heel *et al*., 2005; Oomen *et al*., 2012; Oosterlinck *et al.*, 2015; Faramarzi *et al*., 2018; Mokry *et al.*, 2021). Their ability to provide detailed objective data on foot loading is exceptionally valuable in identifying exactly which areas of the foot are subject to higher pressures in different conditions (Thomason *et al.*, 2004; Oosterlinck *et al*., 2010). Although the literature has explored how foot shape alters limb biomechanics in the horse (Eliashar *et al.*, 2002; Eliashar, McGuigan and Wilson, 2004; Moleman *et al.*, 2006; Eliashar, 2007; Eliashar, 2012; Panagiotopoulou *et al.*, 2016) as well as the risk of lameness (Kobluk *et al.*, 1990; Boden *et al.*, 2007), direct links between foot shape and loading have not been fully established. Van Heel and colleagues (2005) found that changes in hoof unrollment pattern over an eight-week shoeing interval were not directly related to changes in toe length or angle, suggesting that the horse is able to influence foot loading to some extent. In Chapter 3 of this thesis, weak correlations were identified between foot shape and loading of different foot quadrants, suggesting that the effects of foot shape on loading may be more complex than has been previously postulated (Clayton, 1990; Riemersma *et al.*, 1996; Eliashar, McGuigan and Wilson, 2004).

This chapter used a commercial pressure mat as well as digital photography to collect foot loading and foot shape data respectively. Foot shape data explored both changes over consecutive foot-trimming intervals, as well as comparison between the start and end of a 12 month period, when foot loading data was also collected. These data enabled assessment of how the feet changed shape over time, as well as how those shape changes related to loading of the foot in horses that remained sound and those that developed lameness.

4.2 Hypotheses

i. *External foot parameters will show consistent changes over a minimum of six consecutive shoeing cycles*
ii. *Changes in external foot parameters over time will be reflected in changes in foot loading at the end when compared with the start of the study period*
iii. *Changes in external foot parameters and foot loading will be different in horses that were lame at the end of the study compared with horses that were sound throughout the study period*

4.3 Aims

- *Assess trends in key foot parameters over a minimum of six consecutive shoeing cycles in a group of sound horses*
- *Determine whether there is a change in static and dynamic foot loading related to external foot measurements after a minimum of 12 months in horses that remained sound throughout the study period and in horses that became lame*

4.4 Study design

4.4.1 Data collection and study population

Horses recruited for the cross-sectional study (Chapter 3, Section 3.4.1) were simultaneously recruited to this longitudinal study where possible and subsequently analysed in two main groups (Figure 4.1).

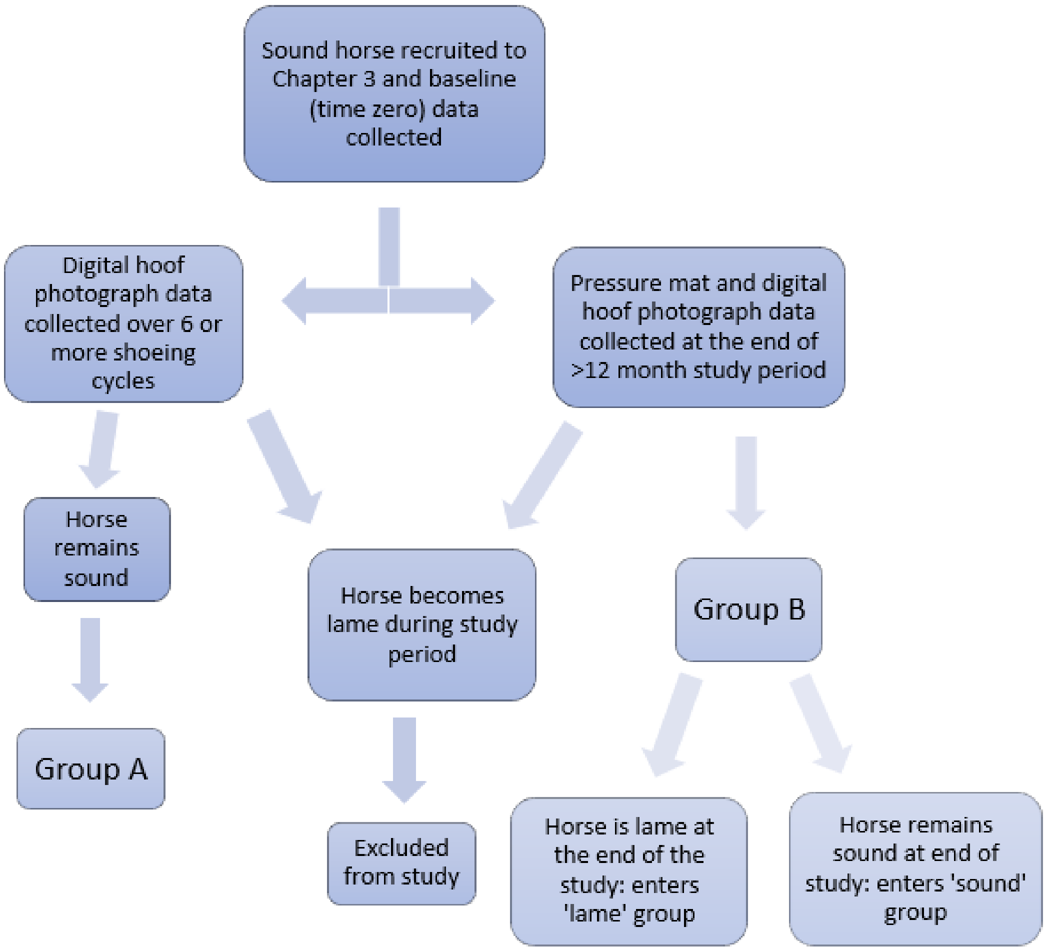


Figure 4.1: Flowchart illustrating inclusion and exclusion criteria for Groups A and B in this chapter

4.4.1.1 Group A

Horses in Group A had digital photographs compromising dorsal, lateral, medial and solar views of each fore foot, obtained before and after each trim for six consecutive shoeing cycles (i.e. five consecutive shoeing intervals). Seven foot measures were chosen based on results from Chapter 3. These measures were: lateral hoof wall angle (LHWA), dorsal hoof wall angle-heel angle difference (DHWA-HA), solar hoof width (Width), bearing border length (BBL), dorsal hoof wall length (DHWL) and centre of rotation to toe distance (COR-Toe). Photographs were taken by the same farrier attending the same horse at each cycle. Differences in foot measures of each individual horse over the six shoeing cycles were assessed between each trimming event; i.e. the difference seen between post-trim measurements of one session and pre-trim measurements of the next shoeing session. Horses were retained in this group if they remained sound during this period. Horses that became lame during this period were removed from this group.

4.4.1.2 Group B

Horses in Group B had digital photographs of each foot and pressure mat data collected pre- and post-trimming at the start of data collection and then repeated at a minimum of 12 months later. As in previous studies (Oomen *et al.*, 2012; Faramarzi, Nguyen and Dong, 2018), for pressure mat data collection a minimum of 5 valid strikes per forelimb were recorded for pre- and post-conditions, though in most cases, where time and circumstances allowed, at least 10 strikes were recorded per limb. Horses that remained sound throughout the study period or were lame at the end of the study period remained in this group for analysis. Horses that became lame and subsequently recovered during the study period were excluded. Horses were assessed for lameness at the start and end of the study. Descriptions of lameness of affected horses in this study were taken from a combination of findings from assessment at the time of data collection as well as owner or keeper history and veterinary clinical records. Where a specific diagnosis was listed, this had been confirmed by diagnostic imaging on veterinary clinical records.

Data were examined for changes over the study period, both pre-trim and post-trim conditions. Contralateral limbs were compared in the sound group, whilst in the lame group, left fore (LF) lame and right fore (RF) lame limbs were compared. Results between sound and lame horses were also compared. Static and dynamic foot quadrant pressure data was obtained as described in Chapter 2. To assess the topological changes in dynamic foot loading over this period of time, and between contralateral limbs in each horse at the end of the study, pedabarographic Statistical Parametric Mapping (pSPM) analysis was used as described in Chapter 2, Section 2.5.3.2.

4.4.1.3 Follow up questionnaire

The follow up to the questionnaire carried out in Chapter 3 (Chapter 3, Section 3.4.2.1) was designed to collect information regarding any changes in exercise or management of the horses in the study, as well as any new lameness or foot-related problems. The follow up questionnaire was collected over the telephone or by email every three months and transcribed into Microsoft® Excel® 2016. Its content was identical to the initial questionnaire (Appendix 1), with the exception of any questions for which the answers would remain unchanged for example horse breed, date of birth.

4.4.2 Data analysis

Data analysis was carried out in R Studio for Windows (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). For both group A and B, normally distributed data were presented as mean +/- 95% confidence intervals (95% CI). Non-normally distributed data were presented as median and interquartile range (IQR). Data were assessed for normality using the Shapiro-Wilk test. The student's t-test was used to analyse differences between two groups of normally distributed data, and the Wilcoxon signed rank test for differences between two groups of non-normally distributed data. These tests were paired where appropriate. Significance was set to $p<0.05$ unless otherwise specified.

Where correlations were sought, Pearson's or Spearman's correlation coefficient were estimated as appropriate. Results of the correlation between foot shape and foot pressure measurements were adjusted for multiple comparisons using the Bonferroni method, with significance set to $p<0.007$ (six foot outcome measures: 0.05/6 = 0.008).

4.5 Results

4.5.1 Group A: changes in foot measures over six consecutive shoeing cycles

Demographic data for Group A are detailed in Table 4.1. Data over six consecutive shoeing cycles (five intervals) were available for 13 horses; differences between the post-trim foot measurement of one trimming event and the pre-trim value of the next event are summarised in Table 4.2. The median shoeing cycle length across all 13 horses was 42 days (IQR: 38-57). The overall range of shoeing cycle length was 28-89 days.

Table 4.1: Horse demographics Group A and B

Descriptor	**Group A Number of Horses (%)**	**Group B Sound Number of Horses (%)**	**Group B Lame Number of Horses (%)**
Gender			
Mare	4 (30.8)	10 (38.5)	1 (20.0)
Gelding	9 (69.2)	16 (61.5)	4 (80.0)
Breed			
Warmblood	-	4 (15.4)	-
Thoroughbred	-	2 (7.7)	-
Native	7 (53.8)	8 (30.8)	3 (60.0)
Irish Sports Horse	2 (15.4)	2 (7.7)	2 (40.0
Arab	-	2 (7.7)	-
Native X	2 (15.4)	3 (11.5)	-
Other X	2 (15.4)	3 (11.5)	-
Andalusian	-	1 (3.9)	-
Yard Type			
Privately-Owned	6 (46.2)	15 (57.7)	1 (20.0)
Livery	6 (46.2)	8 (30.8)	4 (80.0)
Riding Stables	1 (7.7)	1 (3.9)	-
Rehabilitation	-	1 (3.9)	-
Discipline			
Hacking/leisure	5 (38.5)	10 (38.5)	-
Show-Jumping	1 (7.7)	2 (7.7)	-
Eventing	3 (23.1)	2 (7.7)	2 (40.0)
Endurance	1 (7.7)	3 (11.5)	-
Showing	2 (15.4)	1 (3.9)	-
Riding/Pony Club	1 (7.7)	5 (19.2)	3 (60.0
Dressage	0	2 (7.7)	-
Farrier ID			
2	2 (15.4)	2 (7.7)	1 (20.0
3	-	7 (26.9)	-
4	5 (38.5)	2 (7.7)	3 (60.0)
6	-	1 (3.9)	1 (20.0)
7	-	1 (3.9)	-
8	6 (46.2)	9 (34.6)	-
9	-	3 (11.5)	-
	Group A mean (95% CI)	**Group B Sound mean (95% CI)**	**Group B Lame mean (95% CI)**
Age (years)	12.5 (9.2, 15.9)	12.1 (9.9, 14.2)	11.4 (7.3, 15.6)
Height (cm)	152.2 (146.7, 157.8)	154.5 (150.4, 158.7)	155.2 (143.7, 166.7)
Weight (kg)	531.0 (497.0, 565.0)	533.7 (510.2, 557.1)	522.4 (478.8, 566.0)

Native X = native crossbreed; Other X = other/unknown crossbreed; 95% CI = 95% confidence intervals

Results demonstrate that DHWL measurements increase over each cycle (Table 4.2), suggesting foot capsule enlargement over time. Combined with the findings from LHWA, which decreases almost every cycle, it appears the foot becomes more splayed over time whilst increasing in size.

In the LF, DHWA-HA decreased each cycle (Table 4.2), though the magnitude of this change was quite variable. RF DHWA-HA showed greater changes per interval than the LF, and these fluctuated between positive and negative values. Hoof width increased mildly over each cycle. BBL did not show a consistent pattern, with some increases and some decreases, similar to the results for COR-Toe (Table 4.2).

Table 4.2: Foot parameter differences over each interval between the post-trim value of the previous shoeing cycle and the pre-trim value of the following shoeing cycle of sound horses (n=13 horses)

Limb	**Shoeing Interval**	**Dorsal View**	**Lateral View**		**Solar View**		
		LHWA (°) Median (IQR)	**DHWL (cm) Median (IQR)**	**DHWA-HA (°) Median (IQR)**	**Width (cm) Median (IQR)**	**BBL (cm) Median (IQR)**	**COR-Toe (cm) Median (IQR)**
Left Fore	1	0.91 (-4.99; 3.32)	0.93 (0.71; 2.55)	-1.91 (-6.32; 2.27)	0.30 (-0.30; 1.23)	0.22 (-1.33; 1.40)	0.15 (-0.39; 0.64)
	2	-0.16 (-0.73; 2.15)	0.45 (-0.02; 0.89)	-0.50 (-3.59; 1.97)	0.47 (0.15; 0.73)	0.19 (-0.20; 0.80)	-0.05 (-0.35; 0.83)
	3	-2.57 (-4.50; 1.81)	0.64 (0.05; 1.51)	-1.51 (-2.99; 1.45)	0.16 (-0.00; 0.33)	-0.10 (-0.45; 0.52)	0.14 (-0.19; 0.46)
	4	-1.11(-2.26; 2.79)	1.07 (0.50; 1.38)	-1.22 (-5.76; 4.53)	0.58 (0.07; 0.83)	0.32 (-0.24; 0.57)	0.24 (-0.15; 0.33)
	5	-0.09 (-3.61; 0.81)	0.98 (0.17; 1.46)	-3.46 (-4.68; 0.46)	0.43 (0.22; 0.67)	0.17 (-0.32; 0.86)	0.00 (-0.34; 0.43)
Right Fore	1	-1.94 (-3.88; 2.30)	0.48 (-0.25; 1.72)	2.75 (-0.54; 7.13)	0.56 (-0.03; 1.42)	-0.04 (-0.78; 0.55)	-0.01 (-0.37; 0.25)
	2	-0.44 (-0.82; 2.92)	1.13 (0.17; 1.77)	-3.43 (-4.84; -0.44)	0.21 (-0.08; 0.79)	-0.02 (-0.37; 0.21)	0.03 (-0.31; 0.16
	3	-1.48 (-3.42; 2.88)	0.83 (0.31; 1.40)	0.78 (-4.64; 5.28)	0.15 (-0.30; 0.41)	-0.39 (-1.00; 0.29)	-0.42 (-0.59; 0.01)
	4	-1.61 (-3.92; -0.45)	0.60 (0.14; 1.28)	2.81 (1.55; 5.17)	0.47 (0.17; 1.41)	0.53 (-0.46; 1.09)	0.04 (-0.31; 0.42)
	5	-1.74 (-4.13; 1.69)	0.42 (-0.02; 0.77)	-0.89 (-4.95; 4.68)	0.37 (0.11; 0.74)	-0.30 (-0.58; 0.84)	-0.07 (-0.21; 0.34)

Lateral hoof wall angle (LHWA), Dorsal Hoof Wall Angle-Heel Angle difference (DHWA-HA), solar hoof width (Width), Bearing Border Length (BBL), (Dorsal Hoof Wall Length) DHWL) and Centre of Rotation to Toe distance (COR-Toe), IQR = interquartile range.

4.5.2 Group B: changes in foot shape and loading over a minimum 12-month period

4.5.2.1. Changes in foot shape over a minimum 12-month period

Foot measurement data were collected from 31 sound horses at the start and 26 sound and 5 lame horses at the end of a period of at least 12 months. Details of horses that were lame at the end of the study period are included in Table 4.3.

Table 4.3: Details of horses in Group B that went lame during the study period, which limb they became lame on, the region or anatomical location of the limb affected and the time they remained in the study for (n=5 horses)

Horse ID	**Study Period (days)**	**Lame Limb**	**Lameness Location**
Lame001	406	Right Fore	Suspensory ligament
Lame002	374	Right Fore	Foot
Lame003	540	Left Fore	Foot (DDFT)
Lame004	479	Left Fore	Foot (DDFT)
Lame005*	495	Right Fore	Foot (DDFT)

*DDFT = Deep Digital Flexor Tendon *dynamic pressure mat data was not collected from this horse either at the start or end of the study*

The median study period of horses that had no lameness events was 394 days (IQR: 373-462). Results from pre-trim and post-trim data at the start and end of the study period are shown in Table 3 where comparisons are made of each foot to itself at the start and end of the study period. DHWL was significantly larger at the end of the study for LF post-trim and RF in both pre- and post-trim conditions. Hoof width and BBL were also larger at the start of the study LF pre-trimming but not RF. No significant differences were identified when LF and RF were compared into each other in this group.

The median study time for the horses that exhibited lameness during the study period was 479 days (IQR: 406-495). Results from pre- and post-trim data at the start and end of the study period are shown in Table 4.4. DHWL increased over the study period, whilst hoof width, BBL and COR-Toe decreased over the study period. LHWA was steeper at the end of the study compared with the start. However, none of these changes were statistically significant.

Post-trim DHWA-HA in the LF was roughly double that of RF lame feet (p=0.008) at the end of the study. LHWA was significantly steeper in the pre-trim LF lame feet than RF (p=0.008). The same trend was seen in post-trimming results (p=0.04).

When sound and lame datasets were compared, LHWA pre-trim was significantly greater in the lame feet ($p=0.02$). Similarly, LF DHWA-HA was significantly larger in the lame feet compared with sound feet at the end of the study pre-trimming ($p=0.01$) and post-trimming ($p=0.02$).

Table 4.4: External foot shape measurements in sound horses over the study period (n=26 horses)

Limb	Foot Measure	Pre-Trim			Post-Trim		
		Start Mean (95% CI)	**End Mean (95% CI)**	**P Value**	**Start Mean (95% CI)**	**End Mean (95% CI)**	**P Value**
Left Fore	LHWA (°)	74.36 (72.65, 76.07)	73.93 (72.02, 75.83)	0.68	75.29 (73.74, 76.83)	75.05 (72.53, 77.57)	0.93
	DHWL (cm)	10.53 (9.98, 11.09)	10.46 (10.05, 10.86)	0.78	9.62 (9.14, 10.10)	10.14 (9.82, 10.46)	**0.03**
	DHWA-HA (°)	3.44 (0.53, 6.35	1.04 (-2.43, 4.51)	0.19	3.75 (0.79, 6.71)	2.08 (-0.17, 4.32)	0.14
	Width (cm)	14.15 (13.75, 14.55)	13.73 (13.24, 14.24)	**0.01**	13.53 (13.13, 13.94)	13.66 (13.09, 14.24)	0.48
	BBL (cm)	13.36 (13.02, 13.70)	12.97 (12.60, 13.35)	**0.02**	13.07 (12.72, 13.43)	12.74 (11.91, 13.58)	0.45
	COR-Toe (cm)	7.38 (7.17, 7.60)	7.28 (7.07, 7.50)	0.43	7.23 (7.04, 7.42)	7.57 (6.92, 8.22)	0.28
Right Fore	LHWA (°)	74.89 (71.08, 78.69)	73.39 (62.55, 84.22)	0.82	73.88 (71.61, 76.16)	73.11 (70.88, 75.35)	0.36
	DHWL (cm)	10.21 (9.70, 10.71)	10.86 (10.43, 11.29)	**0.004**	9.72 (9.27, 10.16)	10.36 (9.93, 10.79)	**0.007**
	DHWA-HA (°)	4.15 (1.42, 6.89)	3.11 (-0.27, 5.95)	0.22	4.64 (1.99, 7.29)	5.08 (2.11, 8.04)	0.74
	Width (cm)	13.92 (13.40, 14.44)	14.18 (13.55, 14.82)	0.29	13.76 (13.27, 14.26)	13.76 (13.27, 14.26)	0.45
	BBL (cm)	13.31 (12.90, 13.71)	13.30 (12.79, 13.82)	1.00	13.35 (12.83, 13.86)	13.23 (12.83, 13.63)	0.64
	COR-Toe (cm)	7.29 (7.07, 7.52)	7.42 (7.12, 7.72)	0.31	7.05 (6.41, 7.69)	7.14 (6.58, 7.71)	0.44

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; FrA = frog apex; 95% CI = 95% confidence intervals

Table 4.5: Foot parameter changes in lame limbs at the end of the study period (left fore: n=2 horses, right fore: n=3 horses)

Limb	Foot Measure	Pre-Trim			Post-Trim		
		Start Median (IQR)	**End Median (IQR)**	**P Value**	**Start Median (IQR)**	**End Median (IQR)**	**P Value**
Left Fore Lame	LHWA (°)	77.66 (75.25-80.27)	82.48 (81.84, 83.12)	0.5	78.23 (76.59-79.88)	84.31 (81.18-87.43)	0.5
	DHWL (cm)	8.76 (7.80-9.71)	11.25 (10.96, 11.53)	0.5	9.37 (8.81-9.92)	9.92 (9.78, 10.06)	1
	DHWA-HA (°)	7.16 (4.41-9.92)	5.76 (5.56, 5.95)	1	8.57 (8.41-8.74)	4.90 (4.85, 4.96)	0.5
	Width (cm)	14.09 (13.88-14.30)	12.87 (12.75, 13.10)	0.5	13.73 (13.50-13.95)	13.09 (12.90-13.28)	0.5
	BBL (cm)	12.96 (12.94-12.98)	12.42 (12.24-12.59)	0.5	13.09 (12.76-13.41)	13.03 (12.78-13.28)	1
	COR-Toe (cm)	6.95 (6.86-7.03)	6.89 (6.83-6.96)	0.5	7.05 (6.87-7.24)	6.53 (6.33-6.72)	1
Right Fore Lame	LHWA (°)	71.55 (71.34-73.76)	72.47 (71.90, 74.84)	0.25	71.53 (69.56-74.44)	75.54 (74.84-78.56)	0.25
	DHWL (cm)	10.58 (10.41-11.71)	13.44 (11.49, 13.71)	0.75	9.20 (8.46-10.81)	12.71 (11.07, 12.92)	0.25
	DHWA-HA (°)	-0.14 (-0.62- -0.10)	1.34 (-4.54, 3.95)	1	3.48 (-1.04 – 6.03)	2.43 (1.13, 3.53)	1
	Width (cm)	14.58 (14.31-14.69)	13.59 (12.61-14.23)	0.5	13.14 (13.02-13.99)	12.58 (12.13-13.67)	0.5
	BBL (cm)	14.05 (13.81-14.10)	13.24 (12.59-13.29)	0.25	13.09 (12.69-13.76)	12.44 (12.02-13.23)	0.25
	COR-Toe (cm)	7.41 (7.14-7.46)	7.11 (6.85-7.25)	0.25	7.00 (6.82-7.54)	7.08 (6.68-7.34)	0.5

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; IQR = interquartile range

4.5.2.2 Changes in static foot pressure over a 12-month period

The difference between start and end static mean pressure mat quadrant data for both sound and lame limbs is displayed in Table 4.6. No consistent pattern of increase or decrease in pressure per foot quadrant was identified in either sound limbs or lame limbs. This finding was the same for maximum pressure results (Table 4.7). Statistical analysis of the difference between sound and lame limbs revealed no significant findings. Similarly, no significant difference was found between contralateral limbs in the lame or sound groups. This was the same for maximum pressure data.

Table 4.6: Displaying the difference between start and end static mean quadrant pressures (kilopascals) recorded across the four foot quadrants, pre- and post-trimming in sound (n=26 horses) and lame horses (left fore n=2 horses, right fore n=3 horses)

Limb	Quadrant	Sound horses median kPa (IQR)		Lame horses median kPa (IQR)	
		Pre-trim	Post-trim	Pre-trim	Post-trim
Left Fore	Dorsolateral	34.61 (-72.16 – 124.91)	-34.11 (-101.70 – 118.47)	-7.05 (-105.13 – 91.02)	67.96 (42.35 – 93.58)
	Dorsomedial	18.80 (-47.45 – 86.10)	-35.73 (-104.97 – 111.27)	162.66 (130.89 – 194.43)	96.56 (56.92 – 136.20)
	Palmarolateral	-31.01 (-116.97 – 51.40)	5.56 (-84.46 – 156.64)	26.16 (-81.97 – 134.29)	-10.69 (-72.33 – 50.95)
	Palmaromedial	-30.56 (-101.37 – 49.10)	-4.32 (-133.27 – 77.08)	110.91 (32.30 – 189.52)	63.08 (4.19 – 121.97)
Right Fore	Dorsolateral	19.50 (-44.96 – 114.77)	47.79 (-42.72 – 128.28)	47.84 (15.21 – 139.31)	40.41 (38.26 – 42.56)
	Dorsomedial	24.18 (-74.88 – 87.38)	-38.77 (-83.74 – 78.59)	130.41 (-41.98 – 132.70)	-111.65 (-202.41 – -20.88)
	Palmarolateral	9.55 (-90.70 – 100.36)	20.72 (-22.35 – 75.20)	-142.60 (-150.60 – -142.71)	-42.48 (-73.20 – -11.76)
	Palmaromedial	33.28 (-32.28 – 85.55)	53.97 (-36.18 – 132.30)	91.12 (55.54 – 139.83)	-52.49 (-72.84 – -32.15)

kPa= kilopascals; IQR = interquartile range

Table 4.7: Displaying the difference between start and end static quadrant maximum pressures (kilopascals) recorded across the four foot quadrants, pre- and post-trimming in sound (n=26 horses) and lame horses (left fore n = 2 horses, right fore n=3 horses)

Limb	**Quadrant**	**Sound Foot median kPa (IQR)**		**Lame Foot median kPa (IQR)**	
		Pre-trim	**Post-trim**	**Pre-trim**	**Post-trim**
Left Fore	Dorsolateral	24.4 (-180.7 – 290.5)	-45.9 (-282.5 – 453.0)	378.6 (-4.4 – 761.6)	555.8 (404.8 – 706.9)
	Dorsomedial	190.7 (-222.1 – 402.7)	-61.1 (-411.6 – 597.6)	507.0 (442.0 – 572.0)	118.5 (-33.0 – 270.0)
	Palmarolateral	2.7 (311.5 – 352.2)	126.6 (-143.8 – 352.5)	423.4 (27.0 – 819.7)	533.5 (271.9 – 795.1)
	Palmaromedial	-49.6 (-399.9 – 110.2)	-73.6 (-435.3 – 230.0	432.9 (153.3 – 712.6)	-41.1 (-263.1 – 180.9)
Right Fore	Dorsolateral	-12.5 (-287.9 – 216.9)	256.5 (-95.9 – 689.6)	299.4 (178.9 – 355.4)	188.1 (105.56 – 270.6)
	Dorsomedial	49.9 (-366.1 – 505.3)	-44.5 (-321.2 – 213.6)	278.1 (-40.4 – 533.6)	-602.00(-905.3 – -298.7)
	Palmarolateral	195.1 (-145.4 – 316.0)	11.9 (-107.6 – 350.3)	-461.5 (-501.9 – -449.3)	-508.0 (-702.5 – -313.4)
	Palmaromedial	32.5 (-183.0 – 272.7)	180.0 (-123.4 – 424.2)	385.97 (38.75 – 431.18)	-154.8 (-171.7 – -120.9)

kPa= kilopascals; IQR = interquartile range

4.5.2.3 Changes in dynamic foot pressure over a 12-month period

Dynamic foot pressure data were collected from 22 sound horses at the start and 18 sound and 4 lame horses (Table 4.3) at the end of a period of at least 12 months. Pressure in foot quadrants was higher at the start of the study than the end for sound limbs in all conditions and quadrants except LF post-trim dorsomedial quadrant (Table 4.8). In the lame limbs, the start pressure was also greater than the end pressure for both LF and RF pre-trimming. However post-trimming LF dorsolateral, dorsomedial and palmaromedial and RF dorsolateral, palmarolateral and palmaromedial quadrants exerted higher pressures at the end of the study than the start.

Maximum quadrant pressures largely reflected mean quadrant pressures (Table 4.9). One exception is RF pre-trim where the end data was higher pressure than the start in every quadrant other than palmaromedial. Another was LF post-trim data where every quadrant was higher pressure at the end than the start. Statistical analysis of the difference between sound and lame limbs (i.e. sound LF and lame LF; sound RF and lame RF) revealed no significant findings. Similarly, no significant difference was found between contralateral limbs in the lame or sound groups. This was the same for maximum pressure data.

Table 4.8: Displaying the difference between start and end dynamic mean quadrant pressures (kilopascals) recorded across the four foot quadrants, pre- and post-trimming in sound (pre-trim n=18 horses, post-trim n=16 horses) and lame horses (left fore n=2 horses, right fore n=2 horses)

Limb	Quadrant	Sound median kPa (IQR)		Lame median kPa (IQR)	
		Pre-trim	**Post-trim**	**Pre-trim**	**Post-trim**
Left Fore	Dorsolateral	184.82 (46.63 – 286.67)	94.85 (-8.72 – 207.80)	107.43 (51.12 – 163.74)	-40.08 (-193.06 – 112.90)
	Dorsomedial	46.38 (2.05 – 175.14)	120.62 (-34.77 – 185.47)	30.34 (11.73 – 48.94)	-42.47 (-155.15 – 70.22)
	Palmarolateral	101.47 (-24.09 – 248.87)	-9.38 (-81.55 – 170.47)	50.65 (-123.61 – 224.90)	27.41 (-86.65 – 141.46)
	Palmaromedial	65.87 (-6.71 – 167.48)	149.86 (63.78 – 226.21)	111.96 (93.88 – 130.03)	-120.98 (-191.05 –
Right Fore	Dorsolateral	95.68 (12.82 – 177.78)	140.27 (-61.82 – 308.41)	22.75 (22.42 – 23.09)	-59.54 (-91.36 – -27.27)
	Dorsomedial	167.22 (62.66 – 261.68)	142.09 (77.75 – 307.19)	71.11 (36.27 – 105.94)	219.80 (211.40 – 228.10)
	Palmarolateral	55.03 (2.12 – 120.28)	56.92 (15.35 – 135.68)	44.32 (40.17 – 48.48)	-28.66 (-45.39 – -11.92)
	Palmaromedial	47.82 (-29.13 – 161.20)	91.19 (-5.12 – 185.00)	25.06 (-73.42 – 123.55)	-99.76 (-177.58 - -21.95)

kPa = kilopascals; IQR = interquartile range

Table 4.9: Displaying the difference between start and end dynamic quadrant maximum pressures (kilopascals) recorded across the four foot quadrants, pre- and post-trimming in in sound (pre-trim n = 18 horses, post-trim n=16 horses) and lame horses (left fore n=2 horses, right fore n=2 horses)

Limb	Quadrant	Sound median kPa (IQR)		Lame median kPa (IQR)	
		Pre-trim	**Post-trim**	**Pre-trim**	**Post-trim**
Left Fore	Dorsolateral	272.9 (-129.7 – 773.7)	160.2 (-121.2 – 653.3)	14.5 (-136.4 – 165.4)	-375.4 (-743.7 – -7.1)
	Dorsomedial	113.4 (-94.6 – 544.7)	309.0 (120.6 – 534.7)	83.7 (37.1 – 130.3	-183.8 (-418.6 – 51.0)
	Palmarolateral	44.8 (-208.4 – 536.4)	140.6 (-68.3 – 488.2)	281.2 (-136.9 – 699.4)	-368.1 (-867.6 – 131.5)
	Palmaromedial	2217.6 (-43.5 – 593.5)	505.0 (190.7 – 689.6)	537.6 (470.0 – 605.2)	-124.8 (-277.1 –161.9)
Right Fore	Dorsolateral	145.7 (-31.9 – 697.6)	207.4 (40.0 – 571.6)	-225.1 (-357.8 – -92.4)	-743.20 (-804.4– - 682.0)
	Dorsomedial	380.2 (-60.5 – 583.0)	489.1 (-9.2 – 718.7)	-275.6 (-460.7 – -90.5)	350.80 (333.9 – 367.8)
	Palmarolateral	232.1 (69.9 – 557.8)	162.0 (-42.7 – 446.0)	-246.2 (-374.6 – - 117.8)	-515.2 (-601.1 – -429.3)
	Palmaromedial	297.7 (-37.6 – 433.6)	387.3 (215.8 – 588.1)	223.7 (-97.4 – 544.9)	-426.8 (-832.8 – -20.7)

kPa = kilopascals; IQR = interquartile range

4.5.2.4 Estimation of variability of foot pressure data

In order to estimate the variability of foot pressure data collected as part of this study, coefficient of variation was calculated for all foot strikes in both forelimbs, pre- and post-trimming, static and dynamic data collection. Results of mean and maximum pressures are displayed for sound horses in Table 4.10 and lame horses in Table 4.11. Results are very similar for both lame and sound groups.

Table 4.10: Coefficient of variation of static and dynamic foot quadrant pressures in sound horses

	Static (n=26 horses)		**Dynamic (n=22 horses)**	
Limb and Condition	**Mean CoV (%)**	**Maximum CoV (%)**	**Mean CoV (%)**	**Maximum CoV (%)**
Left Fore pre-trim	54.4	66.7	50.0	46.3
Right Fore pre-trim	52.2	55.3	47.7	44.6
Left Fore post-trim	56.6	58.9	49.1	46.0
Right Fore post-trim	57.5	67.4	49.4	47.0

CoV= Coefficient of Variation

Table 4.11: Coefficient of variation of static and dynamic foot quadrant pressures in lame horses

	Static (n=5 horses)		**Dynamic (n=4 horses)**	
Limb and Condition	**Mean CoV (%)**	**Maximum CoV (%)**	**Mean CoV (%)**	**Maximum CoV (%)**
Left Fore pre-trim	52.1	75.9	51.7	46.6
Right Fore pre-trim	68.0	68.8	45.4	48.7
Left Fore post-trim	49.2	49.5	45.5	46.2
Right Fore post-trim	46.4	50.0	47.0	53.3

CoV= Coefficient of Variation

4.5.2.5 Correlation between foot shape and loading at the end of the study period

Correlations between foot shape and foot quadrant pressures were calculated (Appendix 3, Table 1 and 5). For static foot quadrant pressures and foot measures in sound horses, LHWA and palmarolateral quadrant LF pre-trim were negatively correlated for mean pressures ($r= -0.54$, $p=0.006$) and maximum pressures ($r=-0.61$, $p=0.002$). When foot measures were compared with maximum quadrant pressures COR-FrA was positively correlated with the palmarolateral quadrant ($r=0.59$, $p=0.004$). No significant correlations were identified between lame limb mean or maximum foot quadrant pressures and foot shape measures (Appendix 3, Tables 2 and 6).

When dynamic foot pressures were compared with foot shape measures from sound horses at the end of the study, BBL was positively correlated with the mean pressure in the dorsomedial quadrant LF post-trim ($r=0.76$, $p=0.003$) (Appendix 3, Table 2), as well as with maximum pressure ($r=0.74$, $p=0.004$) (Appendix 3, Table 7). When maximum pressures were compared with foot measures DHWL was also positively correlated with pressure in the dorsomedial quadrant (r=0.68, p=0.006) (Appendix 3, Table 7). In lame limbs no significant correlations were identified between mean or maximum quadrant pressures and foot shape measures (Appendix 3, Table 3 and Table 7).

4.5.2.6 *Pedobarographic Statistical Parametric Mapping (pSPM)*

PSPM analysis was used to assess topological differences in foot pressure between the start and the end of the study, as well as between LF and RF limbs at the end of the study. The findings are shown below in Tables 4.12 and 4.13. The most common changes seen are illustrated in Figures 4.2-4.4. Other changes are illustrated in Appendix 3, Figures 1-9.

Most horses showed no significant difference between the start and end of the study (Table 4.12). Of those that did show a difference, the most common finding in horses that remained sound throughout was lower pressure exerted over the frog region at the end of the study (Figure 4.2). This was true of LF and RF, pre-trim changes over time and LF post-trim changes over time. The most common change over time for RF post-trim was increased frog pressure at the end of the study (Figure 4.3).

Significant asymmetry in loading between contralateral limbs of sound horses was uncommon at the end of the study period: only a single horse demonstrated higher pressure in the LF lateral heel region, post-trim than RF (Table 4.13).

Of the four horses that were lame at the end of the study two demonstrated increased pressure over the frog region at the end of the study, post-trim (Table 4.12). These increases were seen in the lame limbs in both cases. Conversely, a horse that was suffering from a DDFT injury in the LF at the end of the study was found to have lower pressure at the lateral toe at end of the study in the RF pre-trimming, compared with the start. Asymmetry between contralateral limbs at the end of the study was detected in a single lame horse which had suffered a LF lameness; pre-trimming the RF lateral heel was subject to greater pressure than the LF lateral heel (Table 4.13, Figure 4.4).

Table 4.12 Results of pedabarographic statistical parametric mapping analysis determining changes that occurred in foot loading of sound and lame horses over the study period (pre-trim: n=18 sound horses, n=4 lame horses, post-trim: n=16 sound horses, n=4 lame horses)

Limb	Condition	Type of Change	Number of Sound Horses (%)	Number of Lame Horses (%)
Left Fore	Pre-Trim	Decreased pressure frog region at end*	4 (22.2)	0 (0.0)
		Increased pressure frog region at end	1 (5.6)	0 (0.0)
		Decreased pressure toe region at end*	1 (5.6)	0 (0.0)
		Increased pressure medial wall at end*	1 (5.6)	0 (0.0)
		Single pixel change/no significant change	12 (66.7)	4 (100.0)
Right Fore	Pre-Trim	Decreased pressure frog region at end**	3 (16.7)	0 (0.0)
		Decreased pressure lateral toe region at end**	1 (5.6)	1 (25.0)
		Decreased pressure medial toe region at end	1 (5.6)	0 (0.0)
		Decreased pressure medial heel region at end	1 (5.6)	0 (0.0)
		Increased pressure lateral heel region at end	1 (5.6)	0 (0.0)
		Single pixel change/no significant change	11 (61.1)	3 (75.0)
Left Fore	Post-Trim	Decreased pressure frog region at end**	5 (31.3)	0 (0.0)
		Increased pressure frog region at end	1 (6.3)	1 (25.0)
		Decreased pressure medial toe region at end**	1 (6.3)	0 (0.0)
		Decreased pressure medial hoof wall at end	1 (6.3)	0 (0.0)
		Increased pressure medial hoof wall at end**	1 (6.3)	0 (0.0)
		Single pixel change/no significant change	8 (50.0)	3 (75.0)
Right Fore	Post-trim	Decreased pressure frog region at end	1 (6.3)	0 (0.0)
		Increased pressure frog region at end	2 (12.6)	1 (25.0)
		Decreased pressure mid/dorsal sole at end	1 (6.3)	0 (0.0)
		Single pixel change/no significant change	12 (75.0)	3 (75.0)

One horse had a change in three areas (see Figure 2); Two horses had a change in more than one area*

Table 4.13: Results of pedabarographic statistical parametric mapping analysis determining differences in foot loading between left fore and right fore limbs at the end of the study period (pre-trim: n=22 horses, post-trim: n=20 horses)

Condition	**Type of Change**	**Number of Sound Horses (%)**	**Number of Lame Horses (%)**
Pre-trim	Higher pressure right fore lateral heel region	0 (0.0)	1 (25.0)
	Single pixel change/no significant change	18 (100.0)	3 (75.0)
Post-trim	Lower pressure right fore lateral heel region	1 (6.3)	0 (0.0)
	Single pixel change/no significant change	15 (93.7)	4 (100.0)

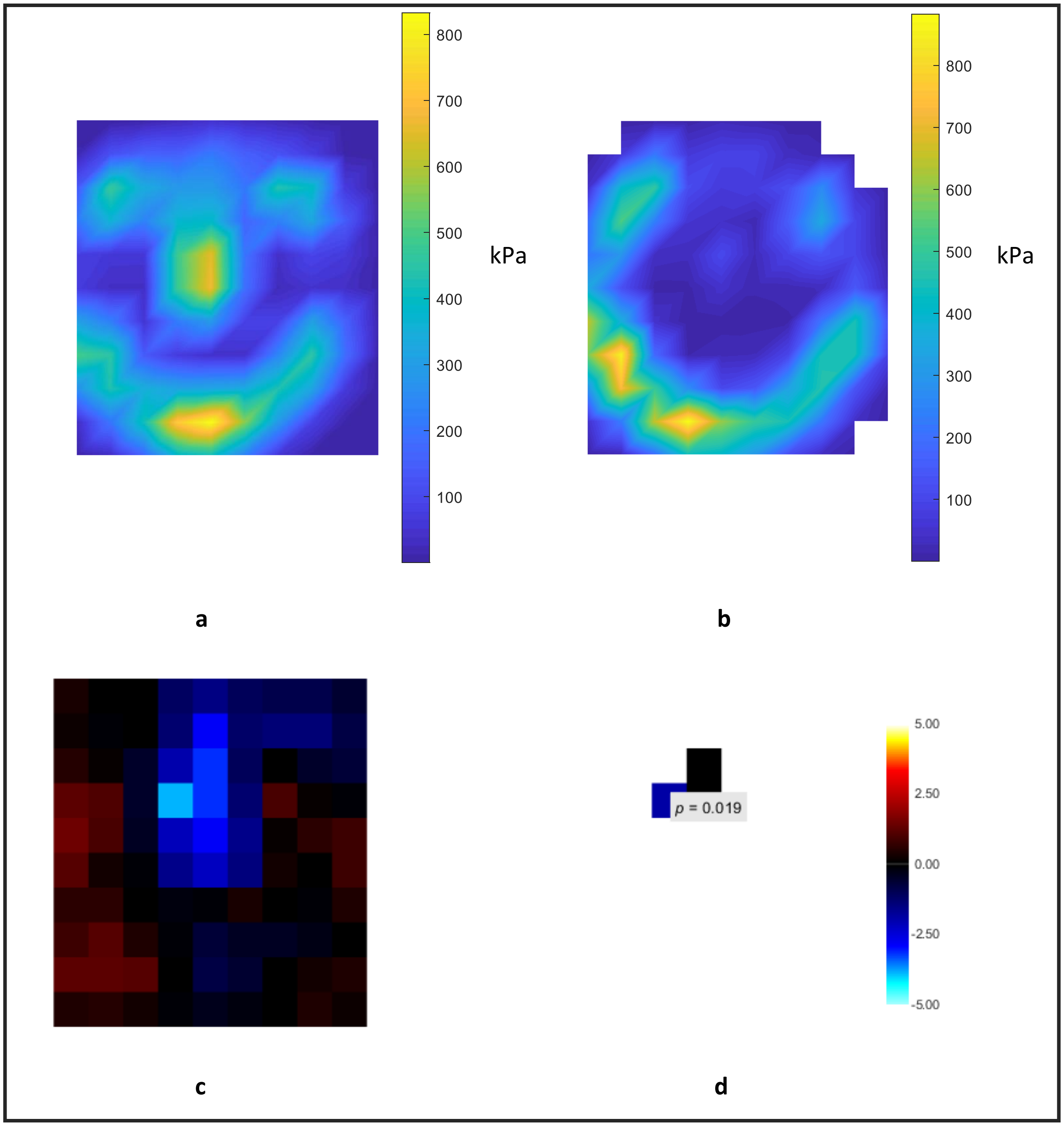


Figure 4.2: An example of decreased pressure over the frog area at the end of the study. Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of left fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of left fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse a and b indicate decreased loading of the frog region at the end of the study compared with the start. A cluster of three pixels that are significantly different between the start and end of the study is demonstrated in plot d; comparison with c indicates the location is the frog region. The colour of the pixels indicate a negative change; since the pSPM method involves mapping start strikes onto end strikes this means lower pressure was exerted in this region at the end than the start.

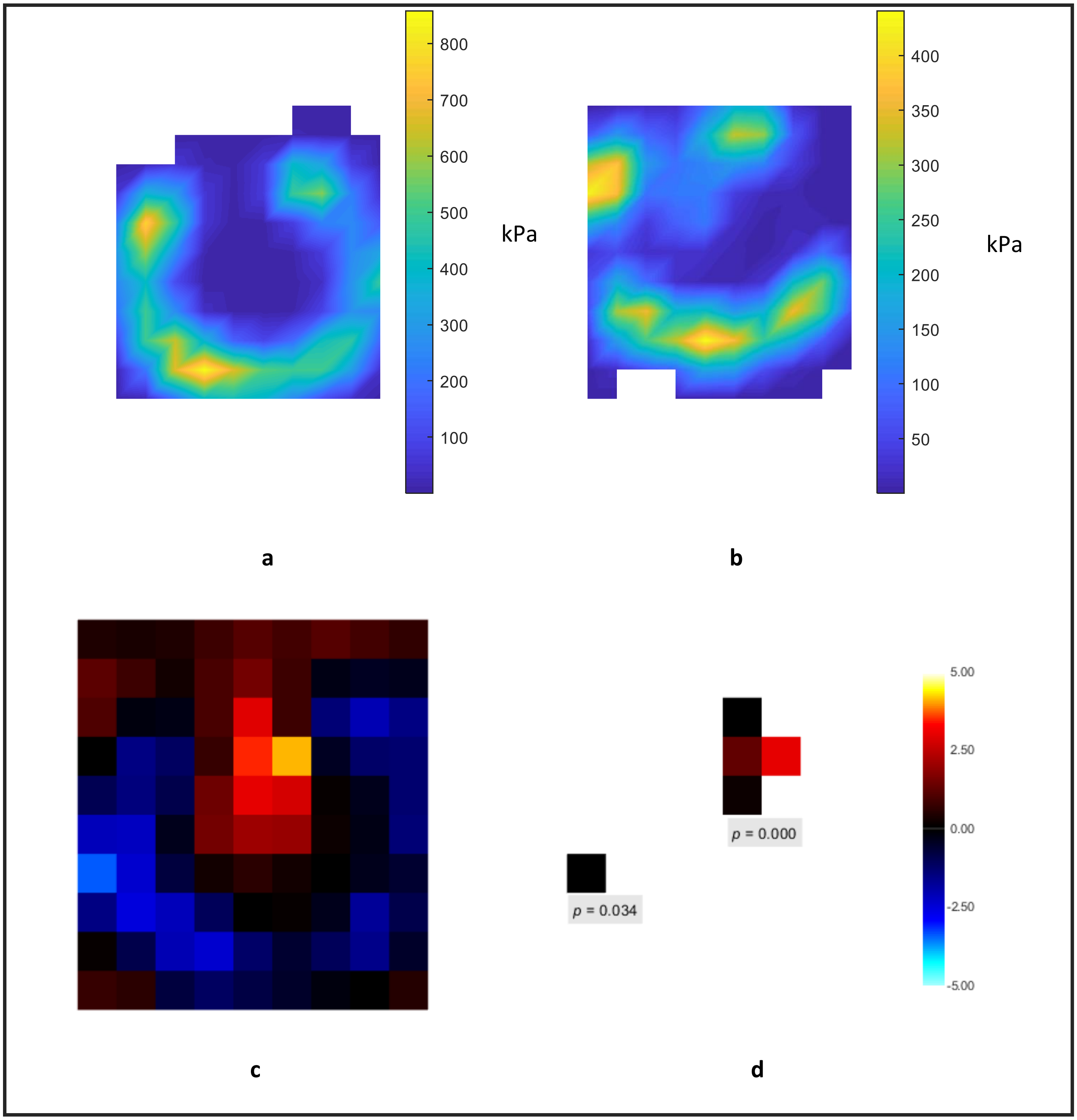


Figure 4.3: An example of increased pressure over the frog region at the end of the study. Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of left fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of left fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse a and b indicate increased loading of the frog region at the end of the study compared with the start. A cluster of pixels that are significantly different at the end than the start ($p<0.0001$) is demonstrated in d; comparison with c indicates the location is the frog region. The colour of the pixels in this cluster indicate a positive change; since the pSPM method involves mapping start strikes onto end strikes this means that there is greater pressure in this region at the end of the study period than the start.

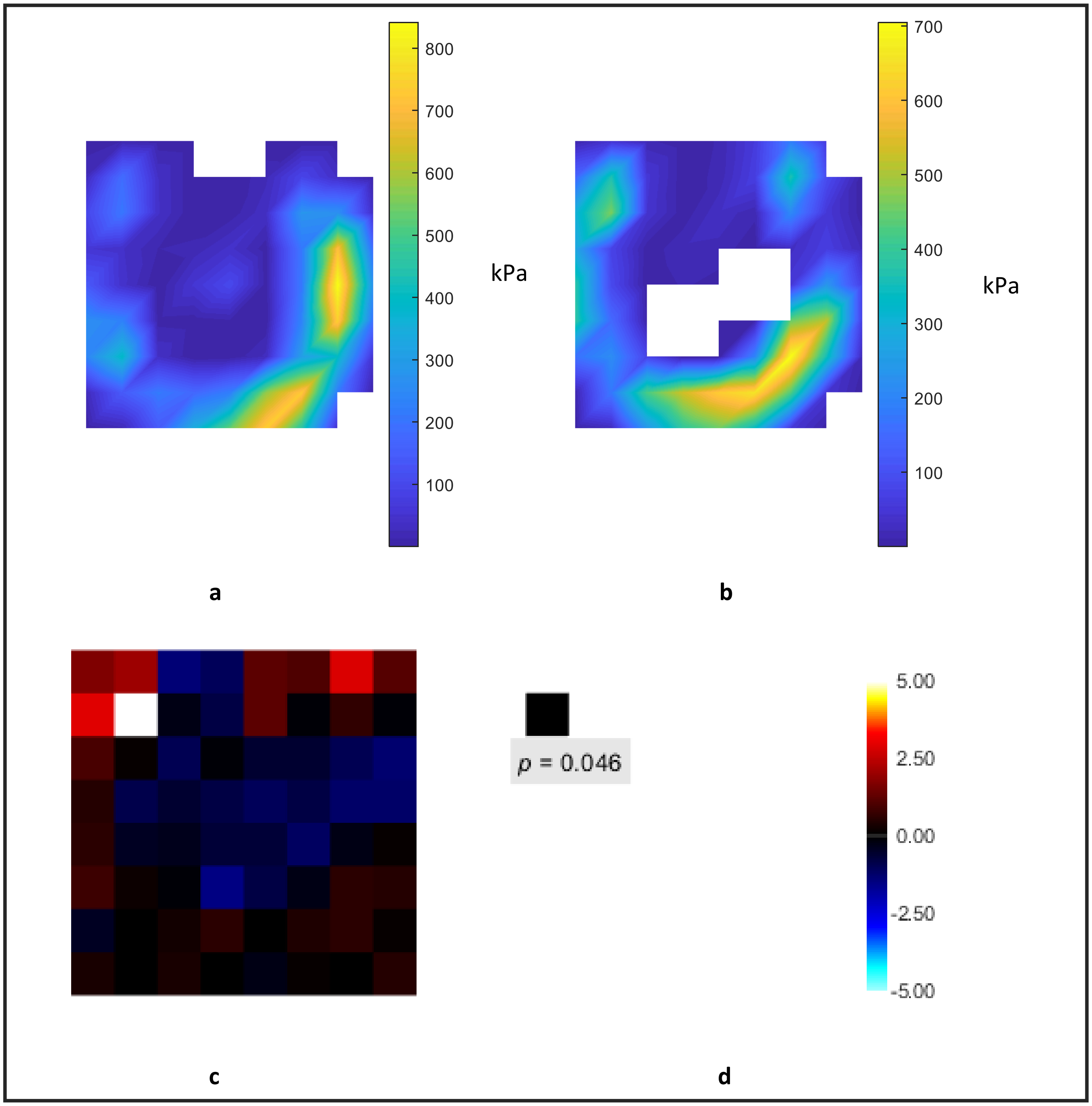


Figure 4.4: An example higher pressure over the lateral heel region of the right fore, compared with the left fore. Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs at the end of the study period in a horse which suffered a left fore lameness. a is a plot of the mean pressure distribution of left fore pre-trim strikes at the end of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse plots a and b indicate greater loading of the right fore lateral heel region compared with the left fore. A single pixel demonstrates a significant difference (p=0.046) in d; comparison with c indicates this affected the lateral heel region of the foot. The colour of the pixels indicate a positive change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means the right fore lateral heel experienced significantly higher loading than the left fore at the end of the study.

4.6 Discussion

This chapter aimed to add to the understanding of how equine foot shape changes over time, including the influence of farriery and foot-trimming on those changes, as well as the differences observed between horses that were lame at the end of the study and horses that remained sound throughout. An additional aim was to understand how any changes identified in foot shape are reflected in changes in foot loading, as per the hypotheses at the start of this chapter. These aims were achieved both by examining changes over consecutive shoeing cycles in a cohort of sound horses, as well as changes at the start and end of a minimum 12-month period in horses that remained sound as well as those that developed a lameness.

4.6.1 Changes in foot shape over six consecutive shoeing cycles

There is a paucity of studies exploring changes in foot shape over multiple shoeing cycles; most that examine foot shape, particularly in relation to farriery, have done so over one or two shoeing cycles (Van Heel *et al.*, 2005; Kummer *et al.*, 2006; Leśniak *et al.*, 2017) whilst another (Caldwell, 2017) studied changes over three consecutive trimming cycles. The current study found that DHWL increased over every trimming interval, which supports the results of Van Heel and others (Van Heel *et al*., 2005), who found that toe length significantly increased over an eight-week shoeing interval. Similarly, their report of a decrease in toe angle over the shoeing interval may reflect the decrease in LHWA seen in this study, as the foot splays with increasing capsule size.

In the current study DHWA-HA decreased at each shoeing cycle in the LF, indicating that toe and heel angles become closer to being parallel, considered to represent ideal foot conformation, over time (Parks, 2003). In the RF, however, the results were more mixed with DHWA-HA decreasing in only two of the five intervals. Regardless, in the RF no net increase was seen in DHWA-HA. These findings oppose that of Caldwell (2017) who found that dorsopalmar foot balance deteriorated over three consecutive trimming cycles. A study of working horses at a single trimming event also concluded that dorsopalmar foot balance deteriorated over the trimming interval (Leśniak *et al.*, 2017).

Although hoof width increased over each shoeing interval, indicating a larger solar surface to the foot, this was not accompanied by any other dimensional increases. BBL and COR-Toe showed fluctuating changes over the five intervals and COR-FrA decreased at every interval, indicating no elongation of the mid-sole region of the foot over this study period. This corroborates the findings of Caldwell; that feet fitted with metal shoes are restricted in their propensity for palmar heel migration (Caldwell, 2017).

4.6.2 Changes in foot shape over a 12-month study period: sound and lame horses

Some changes observed in sound horses over a study period of at least 12 months (Group B) were similar to those seen over consecutive shoeing cycles. These included a significant increase in DHWL, which was evident in post-trim LF and pre- and post-trim RF measures. As described in Section 4.6.1, this finding has been reported previously in shorter studies (Van Heel *et al*., 2005; Kummer *et al*., 2006). The current study is the longest over which horses' foot shape has been measured, and therefore there are no direct comparisons to be made in the literature.

In LF sound horses pre-trimming BBL and Width were shown to decrease significantly over the study period, indicating that foot capsule enlargement does not necessarily occur alongside increase in the bearing surface of the foot. This change was not seen in the RF which implies some laterality, however no significant differences were identified between contralateral sound limbs.

In the five horses that were lame at the end of the study, no significant differences were identified in foot shape between the start and the end of the study. Interestingly, although the changes were not significant, overall, the DHWA-HA had decreased at the end of the study compared with the start for both limbs except the RF pre-trim condition. This opposes the findings of a previous study in sound, shod horses, where increases in DHWA-HA over consecutive trimming cycles were identified (Caldwell, 2017). LHWA increased in steepness, whilst BBL, hoof width and COR-Toe decreased in size indicating that horses that were lame at the end had more upright, boxy feet at the end of the study, as described by (Back *et al*., 1995a; Wiggers *et al.*, 2015). However, the low numbers in each group (LF lame: two horses, RF lame: three horses) and lack of significant differences between start and end foot measurements in these horses preclude making any meaningful conclusions from these data.

When RF lame and LF lame feet were compared a number of significant differences were identified. LF DHWA-HA post-trimming was over double that of RF. This indicates poorer dorsopalmar foot balance in LF lame feet as the dorsal and heel hoof walls deviate further from the ideal of parallelism than in the RF lame limbs. LF LHWA was also significantly steeper than RF both pre- and post-trimming. This steeper hoof wall angle may explain the larger difference between toe and heel angles in the LF, compared with the RF.

When lame and sound limbs were compared, LF lame DHWA-HA was significantly larger than LF sound DHWA-HA at the end of the study, in both pre- and post-trim conditions. This again indicates that dorsopalmar balance is worse in lame LF feet than sound LF feet. LHWA was significantly steeper in lame

LF feet than sound LF feet; again indicating that unloading of lame LF feet results in a more upright conformation, as reported previously (Back, *et al.*, 1995b; Wiggers *et al.*, 2015). No differences were observed between RF sound and RF lame limbs. The low numbers of lame horses may have resulted in the observation or lack of observation of differences between lame and sound feet.

4.6.3 Changes in foot pressure over a 12-month study period: sound and lame horses

Changes in static foot quadrant pressures over the study period did not reveal any particular trend in loading for either sound or lame limbs. Sound and lame limbs were also not shown to be significantly different in the way they are loaded in the numbers studied.

Changes in dynamic foot quadrant pressures showed that loading at the start was greater than at the end of the study in sound limbs, for LF and RF, all quadrants, pre- and post-trimming. The only exception to this was the LF post-trim dorsomedial quadrant. These findings may be due to the increases in foot capsule size over the study period, providing a greater surface area for loading and therefore lower pressure exerted on the solar surface of the foot. Another possibility is that regular shoeing with the same farrier results in more optimal loading of the foot and therefore lower average values per quadrant. Alternatively, it is known that pressure mat sensors age with use; although in this study the pressure mat was recalibrated regularly to mitigate this, it may still have resulted in lower pressures being recorded at the end of the study.

Lame LF and RF limbs had different findings from their sound counterparts; although pre-trimming start pressures were also greater than end pressures, post-trimming the opposite was generally true. This essentially means that relative to when that limb was sound at the start of the study, the foot is subject to increased loading in most regions when it is lame at the end of the study. This disputes previous findings that lame limbs demonstrate decreased loading compared with sound limbs (Buchner, et al., 2001; Rhodin *et al.*, 2013; Pitti *et al.*, 2018). However, it supports the findings of McGuigan and Wilson (2001) that lame limbs can sometimes end up increasing the loading of specific areas even as the horse attempts to unload that region of the foot.

PSPM analysis identified a number of differences in loading over the study period. The most common change in sound horses was a decrease in loading at the toe or frog region, though some individual subjects saw increases in loading at the toe over this time. This is interesting as it is the opposite finding to that of the pre- and post-trim differences observed at the outset of the study (Chapter 3), where post-trimming changes saw increases in pressure in the frog and heel regions of the feet. Given that those pre-post changes were accompanied by decreases in DHWL, whilst these start-end differences are accompanied by increases in DHWL, this may indicate that increases in foot capsule size and or length at the toe result in unloading of the frog region.

Asymmetry between contralateral forelimbs at the end of the current study was only observed in two horses; one sound and one lame horse. In the sound group this constituted 6.3% of the study population in the post-trim condition, and none in the pre-trim condition; much lower than the 15.5% and 26.8% of horses that recorded a significant asymmetry for pre- and post-trim conditions, respectively, at the outset of the study (Chapter 3). This may suggest that regular farriery with the same hoof care professional over many months leads to greater symmetry in loading of contralateral limbs. Alternatively, it may be that the horses that remained in the study were less asymmetrical in their loading patterns throughout the study either as a direct result of regular, consistent foot care or due to other influencing factors such as constant ownership, work pattern and stable management. As previously described, due to a lack of longitudinal studies on foot loading, there is little literature to compare these findings with, to reach firm conclusions about how foot loading changes over time.

The most common change seen between start and end loading in horses that became lame during the study period was increased pressure over the frog region at the end of the study. This is the opposite to that observed in sound horses and was only seen in the post-trim condition. Another horse which was lame on the LF showed decreased loading of the lateral toe region at the end of the study in the RF, pre-trimming, compared with the end of the study.

One lame horse demonstrated increased pressure in the RF heel region compared with LF in the pre-trim condition at the end of the study. This horse was suffering from a LF DDFT injury, so this finding supports that of previous studies that have found reduced loading in lame limbs compared with their sound counterpart (Buchner *et al*., 2001; Rhodin *et al.*, 2013; Pitti *et al.*, 2018).

4.6.4 Relationship between foot shape changes and foot pressure changes, end of study

The current study demonstrated few significant correlations between foot measures and foot quadrant pressures. A recent study (Faramarzi *et al.*, 2020) examined the correlation characteristics between 55 foot measures and kinetic measures. Like this study and the findings of Chapter 3, only a small proportion of pairwise comparisons demonstrated a significant correlation, supporting the possibility that the links between foot shape and foot loading are not as close as has been previously thought.

Comparison of static quadrant pressures and foot measures in sound horses revealed LHWA and the loading of the palmarolateral quadrant of the LF, pre-trim were negatively correlated. Faramarzi and others (2020) also identified a significant relationship between the lateral hoof wall and loading of the palmar area of the foot: they found lateral hoof wall length to be negatively correlated with palmar contact area.

Dynamic pressure results for the LF post-trim dorsomedial quadrant (mean and maximum pressures) were positively correlated with BBL. This may indicate that increases in hoof capsule size which was observed over the study period influences loading in the dorsomedial quadrant of the foot. Longer toes have been shown previously to increase the duration of breakover (Eliashar *et al.*, 2002; Page and Hagen, 2002; Duberstein *et al.*, 2013) in the horse's stride, which may be the cause of increased loading of a dorsal foot quadrant.

4.6.5 Limitations

This study suffered several limitations. Retention of privately owned horses for the required study period(s) was challenging. It was not possible to control the timing and number of horses to which lameness events occurred which resulted in some attrition from the study population as well as low numbers of lame horses to provide comparison at the end of the study. These low numbers may have affected the results of data analysis performed on this group.

The impracticalities of farriers collecting the required data over a long period of time without a financial incentive or reward for their time also led to data not being collected in a consistent way, with missing data as a consequence. Hence the cohort of horses in both Group A and B study may demonstrate certain biases around those horses that were under long-term ownership, regular farriery and that their farriers and owners were able and motivated to donate their time to enable data collection. Horses owned by the same person for many years are both more likely to remain with the same hoof care professional, and to have a more consistent work and stabling routine compared with, for example, horses that are competing internationally.

Owners that were able to give up their time to facilitate and participate in data collection for a study such as this may be more likely to be leisure riders and/or to have an interest or awareness of foot shape and lameness conditions in horses, which may have implications for the way they manage their horses. Farriers that were willing to contribute to data collection in this study were likely to be more motivated and engaged on the topics of foot shape and lameness than the average in the UK. Their participation in a veterinary study may also indicate their confidence and willingness to engage with veterinarians in the course of their work.

Prevailing weather conditions in the North-West of England and North Wales were a barrier against collecting pressure mat data at or around 365 days after the outset data had been collected. Manufacturer's instructions are to avoid water damage, hence where very wet weather coincided with the planned date and time for shoeing or trimming, this prevented data collection, leading to the postponement of the end of the study period for those individual horses and adding to the variation in the length of the study. Similarly, high winds could cause the covering rubber mat to move, creating a safety concern and precluding data collection.

The study design was observational, with the intention of enabling assessment of how the feet of 'normal' horses change over time without outside interventions. However, this will have led to uncontrolled factors for each horse. As described above, factors which may have led to horses staying in the study for the duration may have also had an impact on foot shape and loading, or risk of lameness in these horses. In terms of discipline: two out of the five horses that were lame at the end of the study period in Group B were national level event horses at the time of recruitment to the study. Their work pattern and discipline is likely to be very different from horse primarily used for hacking or leisure riding and may have had a greater impact on their risk of lameness than other factors. Additionally, of the lame group, not all five horses suffered the same lameness issue. Foot, in particular DDFT injuries were over-represented in this study, but differences within such a small sample precludes making any conclusions around the relationship between foot shape, foot loading and specific injuries in the horse.

With regard to farriery and foot care, a number of factors were uncontrolled in Group B of this study, including length of shoeing cycles, the number of shoeing cycles that occurred over the study period as well as factors associated with the individual farrier they received foot care from. It has been well-documented that foot shape changes significantly over the shoeing cycle (Moleman *et al.*, 2006; Leśniak *et al.*, 2017). In the current study the shoeing interval was known and reported for Group A, but due to lapses in data collection as described above it was not available for many horses in Group B, precluding assessment of the impact of this factor.

Individual farrier has been shown to have a significant impact on the shape of a horse's foot in a previous study (Kummer *et al.*, 2009; Thirkell and Hyland, 2017) as well as Chapter 3 of this thesis. Since recruitment of both horses and farriers to this study was through convenience sampling, there was not an equal number of horses shod by each farrier in the study. In Group B, six different farriers attended the 26 sound horses that remained in the study for static foot pressure and foot shape data. There was a range from two to nine horses in the study per farrier. The five horses that became lame during the study were under the care of three farriers with one farrier shoeing three of the five lame horses. Hence it is reasonable to imagine that some degree of bias related to individual farrier: shoeing cycle length, trimming protocol may have occurred in this study.

As in the previous chapter, variation in quadrant pressure data may have affected the findings in this study. Coefficient of variation was high (>5%) (Beauchet *et al.*, 2009; McClymont *et al.*, 2016) for mean and maximum static and dynamic data in both lame and sound horses. Collection of pressure mat data outside of laboratory conditions may have contributed to this variability, as well as the fact that a relatively low number of strikes were collected per subject, limb and condition. The resulting variability may have prevented the identification of some findings within the results.

4.6.6 Conclusions

From this study we can conclude that the hoof capsule increases in size over time in sound horses. Additionally, that over consecutive shoeing cycles under the care of the same hoof care professional, progress can be made towards the ideal of parallelism between toe and heel angle, and therefore improved dorsopalmar foot balance. However, this is the first study to document this finding, and over a 12-month period it was shown to apply differently to contralateral forelimbs and thus may contribute or be related to forelimb asymmetry. Such asymmetry was more pronounced in foot measures from lame limbs, and displayed that the feet of LF and RF lame limbs behave differently from one another.

Changes in loading of foot quadrants over time indicated that overall loading was less at the end of the study compared with the start in sound horses, whilst the opposite was true of lame horses. Foot shape and loading were not shown to be directly associated with one another.

Within individual horses, the most common changes over the study period in sound horses was a decrease in loading of the frog region of the foot at the end of the study. In lame horses the opposite was true. Statistical differences in loading of contralateral limbs was more common in the lame group than the sound group.

The results of this study further those of Chapter 3 by observing not just how foot shape and foot loading change at a single trimming event, but over multiple shoeing cycles and a period of over 12 months. The findings confirm the lack of a direct relationship between foot shape measures and foot loading, indicating that, as suspected, the horse itself can influence foot loading. Further work is required to understand the relationship between foot shape, foot loading and risk of lameness in horses.

UNIVERSITY OF LIVERPOOL

Chapter 5

Study of Foot Shape and Loading in a Cohort of Horses with Lameness Localised to the Foot

5. 1 Introduction

Lameness is one of the most common health issues affecting the equine population, with all horses vulnerable regardless of global location, demographic or usage. Lameness due to foot pathology is particularly common, with an estimated 95% of lameness events in the forelimb due to lesions of or distal to the carpus (Adams, 1957; Ross, 2011). Alongside age, breed and discipline (Parkes *et al.*, 2013), foot shape has been implicated as a factor in the development of foot pain (O'Grady and Poupard, 2001; Page and Hagen, 2002; Eliashar, McGuigan and Wilson, 2004; Eliashar, 2007). Previous studies have attempted to unpick the relationship between particular types of foot shape and foot lameness events (Holroyd *et al*., 2013; Nicolai *et al.*, 2017), which is complicated by the conflicting or equivocal findings regarding foot shape of lame limbs. Some horses affected by foot pain have been shown to be more likely to have long toe, low heel conformation (Wright, 1993; Page and Hagen, 2002; Dyson *et al.*, 2011) or a low solar angle (Holroyd *et al.*, 2013). In contrast, other studies have shown horses with foot pathology have a more upright foot conformation (Dyson *et al.*, 2011).

A recent study that aimed to determine trends in foot shape in a population of 121 horses that were referred for investigation of foot lameness found no significant difference in lameness prevalence between horses with splayed and upright forelimb feet (Nicolai *et al.*, 2017). There is some evidence to support the idea that the upright foot develops as a consequence of unloading due to pain (Back *et al.*, 1995; Wiggers *et al.*, 2015). However, biomechanically there is evidence to show that long toe, low heel conformation poses a risk of injury to structures including and related to the deep digital flexor tendon (DDFT) and navicular bone (NB) (Wright, 1993; Eliashar, McGuigan and Wilson, 2004; Moleman *et al.*, 2005).

Similar to the debate around foot shape, there have been conflicting findings regarding foot loading and lameness events. Some studies have unsurprisingly found the lame limb to be unloaded in comparison to healthy limbs (Buchner *et al.,* 2001, Rhodin *et al*., 2013). Conversely, McGuigan and Wilson (2001) found that horses with navicular disease (ND) had much higher forces in the DDFT in the early stance phase compared with healthy horses. When perineural anaesthesia was used at the level of the medial and lateral palmar digital nerves, this increased loading was abolished, indicating that horses with ND may overload the NB even as they are attempting to do the opposite (McGuigan and Wilson, 2001). Such findings indicate the value of scientific studies into foot loading of horses with foot lameness issues, in order to truly understand how the various pathologies affect loading *in vivo*.

Pressure mats have become increasingly used in the study of equine locomotion in recent years, due to their ability to collect foot loading data at a high spatial resolution which allows visualisation of pressure distribution across the foot surface. Their portability has facilitated usage outside of laboratory settings, in comparison to force plates which previously have been considered the gold standard in objective lameness detection (Donnell *et al.*, 2015).

Most research conducted on horses using pressure mats to date has studied sound horses in order to understand the effect of different conformational features, breeds, shoeing techniques, foot-trimming and ground surfaces on locomotion (Van Heel *et al.*, 2005; Oosterlinck *et al.*, 2011; Oomen *et al.*, 2012; Oosterlinck *et al.*, 2013; Mokry *et al*., 2021). A recent study used a pressure mat to understand loading in lame horses during standing (Pitti *et al.*, 2018). This study found that some values measured provided a suitable means of detecting lameness in affected limbs (Pitti *et al.*, 2018), which may support increased use of pressure mats in objective lameness assessment in the future.

At present, magnetic resonance imaging (MRI) is considered the gold standard modality for imaging many aspects of equine distal limb pathology (Dyson, Murray and Schramme, 2003; Murray *et al.*, 2006; Smith, 2015). With appropriate usage and interpretation, MRI can provide accurate diagnoses which allow improved treatment and prognostic outcomes (Sherlock, Mair and Blunden, 2008; Smith, 2015). The most common lesions observed within the foot structures are those affecting the DDFT, ND, injury to the distal interphalangeal joint (DIPJ) and its collateral ligaments (Dyson, Blunden and Murray, 2008; Sherlock, Mair and Blunden, 2008; Holroyd *et al.*, 2013; Parkes, Newton and Dyson, 2013; Parkes and Witte, 2015). Several studies have reported high- and low-field MRI to be significantly associated with histopathological findings when it comes to the most common distal limb lesions in the horse, which gives greater confidence to the use of MRI for diagnosis of lameness localised to the foot (Dyson, Blunden and Murray, 2008; Sherlock, Mair and Blunden, 2008; Sherlock *et al.*, 2015; KottMeier *et al.*, 2020).

This study aimed to identify prevalent foot shapes and foot loading patterns in horses with pathology located in the foot in lame horses. Data on foot loading, foot shape and MRI findings were collected from a population of horses referred for lameness investigation at a single referral hospital in the North-West of England

5.2 Hypotheses

i. *Foot shape and loading in lame limbs are different to sound limbs*
ii. *Foot shape and loading are associated with MRI findings*

5.3 Aims

- *To assess the association between foot measurements, lameness and MRI findings*
- *To assess the association between foot loading in relation to lameness and MRI findings*

5.4 Study design

5.4.1 Study population

Horses were recruited on the basis of being referred to the Philip Leverhulme Equine Hospital, between February 2019 and October 2019 inclusive, for investigation of a lameness that had been localised to one or both front feet. The inclusion criteria were that the lameness in each subject was significantly improved following anaesthesia of the lateral and medial palmar digital nerves, anaesthesia of the distal interphalangeal joint or anaesthesia of the navicular bursa (and therefore the lameness was considered to primarily affect the foot). Additionally that each subject underwent MRI evaluation of both front feet at Philip Leverhulme Equine Hospital.

Horses undergoing MRI examination were sedated with detomidine (0.005-0.01 mg/kg i.v. (intravenous) and butorphanol (0.01- 0.02 mg/kg i.v.). Both forefeet were examined with a 0.27T low-field open MR system (Hallmarq, Guildford, Surrey, UK) using the following protocol: T1 weighted spoiled gradient echo, T2* weighted gradient echo, T2 weighted fast spin echo and short tau inversion recovery (STIR) sequences in frontal, sagittal and transverse planes (Table 5.1).

Table 5.1: Description of parameters used in pulse sequences using low-field (0.27T) magnetic resonance imaging system; that used for imaging the feet of study subjects

Pulse sequence	**Orientation**	**TE**	**TR**	**FOV**	**Slide width**	**Gap**	**Scan time**
T1-weighted 3D	Sagittal/frontal/transverse	7	23	190	3	0	2mins 6 sec
T2*-weighted 3D	Sagittal/frontal/transverse	13	34	190	3	0	2min 23 sec
STIR FSE	Sagittal/frontal	27	2910	190	5	1	3 min 18 sec
T2-weighted FSE	Sagittal/frontal/transverse	84	2000	190	5	1	3 min 46 sec

FOV=field of view; FSE=fast spin echo; MRI=magnetic resonance imaging; STIR=short tau inversion recovery; TE=echo time; TR=repetition time; 3D=three dimensional

5.4.2 Data collected

Digital photographs were taken of both forefeet, as described in Chapter 2, Section 2.3, to obtain objective foot measurements. Static and dynamic pressure mat data were collected as described in Chapter 2, Section 2.5 using a commercial pressure mat (Tekscan™ Medical Sensor 5400N). Although in previous studies a minimum of five strikes per forelimb have been collected (Oomen *et al.*, 2012; Faramarzi, Nguyen and Dong, 2018), in order to prevent poor welfare in horses affected with lameness conditions by walking them for a prolonged period, a minimum of 3 strikes per forelimb were collected during walk in this study, and a single trial of static data. For both photographic and pressure mat data, these were collected with shoes removed. Clinical records from the referring veterinarian in combination with results of diagnostic anaesthesia either by the referring veterinarian or Philip Leverhulme Equine Hospital clinician, or a combination of the two, were used to identify which limb was the lame (in unilateral cases) or more clinically affected (in bilateral cases).

Clinical records were examined using password-protected hospital management software (Tristan Veterinary Practice Management Scheme, Version 1.8.3.1110, Aberdeen, UK, AB11 6DY) which provided demographic data, lameness history and shoeing practices. MRI findings were summarised from clinical and imaging reports. Only the most significant finding (i.e. the pathology described to be the cause of lameness by the attending clinician) for each horse was reported in this study.

All foot measurements were reported for the entire study population. External foot measurements from lame limbs of study subjects in this Chapter were compared with pre-trimming results from the same limbs of sound study subjects in Chapter 3, Section 3.5.2. This is because the sound or sounder limb in lame horses may not be a true control due to the likelihood it will be overloaded in an attempt to compensate for the lame or lame limb. When examining the results of foot measurements, stratified by MRI finding, the five key foot measures used in Chapter 3 were assessed: lateral hoof wall angle (LHWA), lateral view dorsal hoof wall angle-heel angle difference (DHWA-HA), bearing border length (BBL), hoof width (Width), frog apex to toe distance (FrA-Toe).

Similar to external foot measurements, static and dynamic foot quadrant pressure data from lame limbs were compared against results from the same limbs in sound study subjects from Chapter 3. Quadrant pressures were also stratified by MRI findings. To assess topological differences in foot loading between contralateral limbs, pedabarographic Statistical Parametric Mapping (pSPM) analysis was used to identify areas that were loaded in a significantly different way between LF and RF in each individual horse.

5.4.3 Data analysis

Data analysis was carried out in R Studio for Windows (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). Data were assessed for normality using the Shapiro-Wilk test. Normally distributed data were presented as mean and 95% confidence intervals whilst non-normally distributed datasets were presented as median and interquartile range.

Statistical analysis of the difference between two groups (e.g. bilateral and unilateral lameness, lame animals from this study and sound animals from the cohort in Chapter 3) was carried out using the Student's t-test for normally distributed data, and the Wilcoxon rank sum test for non-normally distributed data. Significance was set at $p<0.05$ unless otherwise stated.

Where large numbers of pairwise comparisons were performed in the case of foot measures, adjustment for multiple comparisons was carried out using the Bonferroni method: in these cases the threshold for a significant result was changed to $p<0.004$ (0.05/12 comparisons = 0.004).

5.5 Results

5.5.1 Demographics of study population

Complete data sets were available for 28 horses presented to the Philip Leverhulme Equine Hospital within the study period. The study population had a mean height of 156.2cm (95% CI: 152.8, 159.7), weight of 561.6kg (95% CI: 539.7, 583.6) and age of 11.4 years (95% CI: 10.0, 12.7). Just over half (15/28, 53.6%) of the population were mares, with the rest geldings. Native breeds were the most common breed type in the study population, with Warmbloods (WB) and Thoroughbreds/Thoroughbred-crosses (TB/TB X) also well-represented (Table 5.2).

Table 5.2: Breed demographic of study population (n=28 horses)

Breed	Number of Horses	% of total
All Native and Native X	13	46.4
Cob	4	14.3
Irish Draught	2	7.1
Connemara	3	10.7
Welsh	1	3.6
Dartmoor	1	3.6
Native X	2	7.1
Warmblood	6	21.4
TB or TB X	5	17.9
Friesian	1	3.6
Haflinger	1	3.6
Arab X	1	3.6
Irish Sports Horse	1	3.6

Native X = native crossbreed;TB = Thoroughbred; TB X = Thoroughbred crossbreed; Arab X = arab crossbreed.

Median time between the reported onset of the lameness and the date of hospitalisation was 83 days (IQR: 34.5-152.5). Most horses received diagnostic anaesthesia from their referring veterinary surgeon (21/28, 75.0%), whilst nine horses (9/28, 32.1%) had diagnostic anaesthesia as part of their lameness investigation at the Philip Leverhulme Equine Hospital. Two horses received diagnostic anaesthesia of the palmar digital nerves at Liverpool University to further localise the lameness to the foot, as the referring vet had used an abaxial sesamoid nerve block.

For three horses, the usual shoeing frequency was not recorded and one horse was not usually shod. Of the remaining 24 horses, the median shoeing frequency was 6 weeks (IQR: 5.5-6.25). Where recorded (n=22), there was a mean interval of 27.8 days (95% CI: 19.69, 35.86; range 1 - 70 days) between the most recent shoeing or trimming event and the date of hospitalisation. Table 5.3 provides a breakdown of the location of lameness issues that the study population presented with. Where horses had a bilateral lameness, the lame limb is detailed. Where horses had a bilateral lameness, the limb with the more clinically significant lameness will be referred to as the lame limb, and the limb with the less clinically significant lameness will be referred to as the non-lame limb.

Table 5.3: Classification of forelimb lameness referred for lameness investigation (n=28 horses)

Unilateral	Number of Horses	Bilateral	Number of Horses	Total
Left Fore lame	4	Left Fore lame*	5	9
Right fore lame	7	Right Fore lame*	12	19
Total	11	Total	17	28

**For bilateral lameness, the limb listed as lame is that which had the more clinically significant lameness*

5.5.2 Foot shape measurements

5.5.2.1 Comparison of lame and non-lame feet

Foot measurements were taken from digital photographs of unshod horses. In the unilateral group it was more common for lame limb dorsal, lateral and medial view measurements to be larger than non-lame limb measurements (Table 5.4). For solar measurements, the opposite was true: non-lame limbs were more likely to have larger measurements than lame limbs (Table 5.6). Measurements from all views of the bilateral group were more commonly larger in the limb which was more clinically affected than the less clinically affected limb (Tables 5.5 and 5.7). No significant differences were found between lame and non-lame limbs in the unilateral lameness group (Tables 5.4 and 5.6), nor in the bilateral lameness group (Tables 5.5 and 5.7). Similarly, foot measurements from lame limbs in the unilateral group were not significantly different from the more clinically affected limbs in the bilateral group.

Table 5.4: Foot measurement results from dorsal, lateral and medial view lame and non-lame feet of unilaterally lame horses (n=11 horses)

Foot measurement	Lame Mean (95% CI)	Non-Lame Mean (95% CI)	Difference Mean (95% CI)	P value
LHWL (cm)	7.0 (6.2, 7.6)	7.4 (6.7, 8.1)	-0.4 (-1.4, 0.4)	0.25
LHWA (°)	75.7 (71.9, 79.4)	73.9 (69.6, 78.1)	1.8 (-3.5, 7.1)	0.49
MHWL (cm)	7.5 (6.8, 8.2)	7.7 (7.0, 8.4)	-0.2 (-1.1, 0.8)	0.71
MHWA (°)	70.8 (67.3, 74.2)	71.5 (69.3, 73.8)	-0.8 (-4.6, 3.1)	0.68
Lateral DHWL (cm)	10.2 (9.4, 11.0)	10.1 (9.3, 11.0)	0.1 (-1.0, 1.2)	0.92
Lateral DHWA (°)	50.3 (48.5, 52.1)	49.2 (46.2, 52.2)	1.1 (-2.2, 4.4)	0.49
Lateral HL (cm)	5.7 (5.4, 6.1)	5.4 (4.8, 6.0)	0.3 (-0.4, 1.0)	0.35
Lateral HA (°)	41.9 (38.1, 45.7)	45.2 (38.8, 51.5)	-3.3 (-10.3, 3.7)	0.34
Lateral DHWA-HA (°)	8.4 (4.9, 12.0)	4.0 (-1.0, 9.0)	4.4 (-1.4, 10.2)	0.13
Lateral DHWL:HL	1.8 (1.6, 1.9)	1.9 (1.7, 2.1)	-0.1 (-0.3, 0.1)	0.33
Medial DHWL (cm)	10.5 (9.8, 11.3)	9.9 (9.0, 10.8)	0.7 (-0.4, 1.7)	0.23
Medial DHWA (°)	50.1 (47.3, 52.9)	49.8 (46.5, 53.1)	0.3 (-3.7, 4.4)	0.87
Medial HL (cm)	5.7 (5.4, 6.1)	5.7 (5.1, 6.2)	0.1 (-0.5, 0.7)	0.77
Medial HA (°)	42.0 (36.2, 47.9)	39.4 (33.3, 45.5)	2.6 (-5.3, 10.5)	0.50
Medial DHWA-HA (°)	8.1 (3.6, 12.5)	10.3 (5.7, 15.1)	-2.3 (-8.4, 3.8)	0.44
Medial DHWL:HL	1.8 (1.7, 1.9)	1.8 (1.6, 1.9)	0.1 (-0.1, 0.3)	0.36

LHWL = lateral hoof wall length; LHWA = lateral hoof wall angle; MHWL = medial hoof wall length; MHWA = medial hoof wall angle; DHWL = dorsal hoof wall length; DHWA = dorsal hoof wall angle; HL = heel length; HA = heel angle; DHWA-HA = dorsal hoof wall angle – heel angle difference; DHWL:HL = dorsal hoof wall length:heel length; 95% CI=95% confidence intervals

Table 5.5: Foot measurement results from the dorsal, lateral and medial view of more and less clinically affected limbs of bilaterally lame horses (n=17 horses)

Foot measurement	**Lame* Mean (95% CI)**	**Non-Lame Mean (95% CI)**	**Difference Mean (95% CI)**	**P value**
LHWL (cm)	7.2 (6.6, 7.7)	7.5 (6.9, 8.1)	-0.3 (-1.1, 0.5)	0.41
LHWA (°)	76.6 (73.8, 79.4)	73.1 (70.5, 75.8)	3.5 (-0.2, 7.1)	0.06
MHWL (cm)	7.8 (7.3, 8.3)	7.7 (7.3, 8.1)	0.1 (-0.5, 0.7)	0.78
MHWA (°)	70.1 (67.6, 72.5)	72.8 (70.3, 75.2)	-2.7 (-6.0, 0.7)	0.11
Lateral DHWL (cm)	10.7 (10.4, 10.9)	10.5 (10.1, 10.8)	0.2 (-0.2, 0.7)	0.25
Lateral DHWA (°)	51.0 (49.5, 52.4)	50.1 (48.4, 51.9)	0.9 (-1.4, 3.1)	0.44
Lateral HL (cm)	5.6 (5.1, 6.2)	5.7 (5.3, 6.1)	-0.0 (-0.7, 0.6)	0.86
Lateral HA (°)	43.3 (39.0, 47.6)	42.7 (38.4, 46.9)	0.7 (-5.2, 6.6)	0.82
Lateral DHWA-HA (°)	7.7 (3.6, 11.7)	7.5 (4.2, 10.7)	0.2 (-4.8, 5.2)	0.94
Lateral DHWL:HL	2.0 (1.7, 2.2)	1.9 (1.7, 2.0)	0.1 (-0.2, 0.4)	0.37
Medial DHWL (cm)	10.6 (10.2, 10.9)	10.5 (10.2, 10.9)	0.0 (-0.5, 0.5)	0.92
Medial DHWA (°)	49.9 (48.0, 51.8)	49.3 (47.7, 50.8)	0.6 (-1.7, 3.0)	0.59
Medial HL (cm)	5.8 (5.4, 6.1)	5.6 (5.1, 6.1)	0.1 (-0.5, 0.7)	0.69
Medial HA (°)	40.4 (35.8, 44.9)	38.9 (35.0, 42.8)	1.5 (-4.3, 7.3)	0.61
Medial DHWA-HA (°)	9.6 (6.1, 13.0)	10.4 (6.5, 14.3)	-0.8 (-5.9, 5.2)	0.74
Medial DHWL:HL	1.9 (1.8, 2.0)	1.9 (1.8, 2.1)	-0.1 (-0.2, 0.1)	0.50

*LHWL = lateral hoof wall length; LHWA = lateral hoof wall angle; MHWL = medial hoof wall length; MHWA = medial hoof wall angle; DHWL = dorsal hoof wall length; DHWA = dorsal hoof wall angle; HL = heel length; HA = heel angle; DHWA-HA = dorsal hoof wall angle – heel angle difference; DHWL:HL = dorsal hoof wall length:heel length; 95% CI=95% confidence intervals. * the limb listed as lame is that which had the more clinically significant lameness*

Table 5.6: Solar view foot measures of lame and non-lame feet of unilaterally lame horses (n=11 horses)

Foot Measurement (cm)	**Lame Mean (95% CI)**	**Non-lame Mean (95% CI)**	**Difference Mean (95% CI)**	**P Value**
Heel Buttress	8.2 (7.1, 9.4)	8.1 (7.2, 9.1)	0.1 (-1.3, 1.5)	0.86
Sagittal Length	16.0 (15.0, 17.0)	16.3 (15.2, 17.4)	-0.3 (-1.7, 1.1)	0.65
Frog Apex-Toe	4.6 (4.1, 5.0)	4.7 (4.3, 5.2)	-0.2 (-0.8, 0.4)	0.50
Width	14.4 (13.4, 15.4)	14.6 (13.6, 15.5)	-0.2 (-1.5, 1.1)	0.78
BBL	13.2 (12.5, 13.8)	13.4 (12.6, 14.2)	-0.2 (-1.2, 0.8)	0.63
COR-Frog Apex	2.9 (2.4, 3.4)	2.8 (2.3, 3.2)	0.1 (-0.5, 0.7)	0.74
COR-COP	1.9 (1.5, 2.4)	1.8 (1.4, 2.3)	0.1 (-0.5, 0.7)	0.74
COR-Toe	7.4 (6.9, 7.8)	7.4 (6.9, 7.8)	-0.0 (-0.6, 0.6)	0.91
Hbutt-COR	5.9 (4.5, 6.3)	6.1 (5.6, 6.5)	-0.2 (-0.7, 0.4)	0.50
Hbutt-COP	7.8 (7.2, 8.4)	7.9 (7.2, 8.6)	-0.1 (-0.9, 0.8)	0.84
Lateral solar width	7.4 (6.8, 8.0)	7.4 (6.9, 7.9)	0.0 (-0.7, 0.7)	1.00
Medial solar width	7.0 (6.5, 7.5)	7.1 (6.7, 7.6)	-0.2 (-0.8, 0.5)	0.63

Width = solar width; BBL = bearing border length; COR = centre of rotation; COP = centre of pressure; 95% CI=95% confidence intervals

Table 5.7: Solar view foot measures of more and less clinically affected limbs of bilaterally lame horses (n=17 horses)

Foot Measurement (cm)	**Lame* Mean (95% CI)**	**Non-lame Mean (95% CI)**	**Difference Mean (95% CI)**	**P Value**
Heel Buttress	8.0 (7.4, 8.7)	7.6 (7.0, 8.1)	0.5 (-0.3, 1.3)	0.23
Sagittal Length	16.1 (15.2, 17.0)	15.6 (15.0, 16.3)	0.5 (-0.6, 1.6)	0.33
Frog Apex-Toe	4.8 (4.5, 4.1)	4.7 (4.5, 4.9)	0.1 (-0.3, 0.4)	0.75
Width	14.1 (13.4, 14.9)	13.9 (13.2, 14.5)	0.3 (-0.7, 1.3)	0.55
BBL	13.3 (12.7, 13.9)	13.2 (12.7, 13.7)	0.1 (-0.7, 0.8)	0.86
COR-Frog Apex	2.7 (2.4, 3.0)	2.7 (2.4, 2.9)	0.1 (-0.3, 0.4)	0.72
COR-COP	1.8 (1.5, 2.0)	1.7 (1.5, 1.9)	0.1 (-0.3, 0.4)	0.72
COR-Toe	7.4 (7.1, 7.7)	7.3 (7.0, 7.6)	0.1 (-0.4, 0.5)	0.75
Hbutt-COR	5.9 (5.6, 6.1)	5.9 (5.7, 6.2)	-0.1 (-0.4, 0.3)	0.61
Hbutt-COP	7.6 (7.2, 8.1)	7.6 (7.2, 8.1)	-0.0 (-0.6, 0.6)	0.93
Lateral solar width	7.2 (6.8, 7.6)	7.1 (6.7, 7.4)	0.1 (-0.4, 0.6)	0.68
Medial solar width	7.0 (6.6, 7.4)	6.8 (6.5, 7.1)	0.2 (-0.3, 0.7)	0.49

*Width = solar width; BBL = bearing border length; COR = centre of rotation; COP = centre of pressure; 95% CI=95% confidence intervals. * the limb listed as lame is that which had the more clinically significant lameness*

5.5.2.2 Comparison of lame and sound limbs

Lame RF and LF limbs from the current study were compared with results from sound horses in Chapter 3, section 3.5.2.

5.5.2.2.1 Dorsal, lateral and medial view measurements

Dorsal view measurements of the RF revealed that LHWL was larger in the sound cohort than the lame group, whilst for MHWL the opposite was true, although these differences were not significant. The LHWA was found to be steeper in the lame group than the sound group, yet MHWA was more acute in the lame group than the sound group; this difference was significant for LHWA but not for MHWA between sound and lame cohorts. For both medial and lateral views of the RF, DHWL, DHWA, HL and DHWA-HA were larger in the lame cohort than the sound cohort. Conversely HA and DHWL:HL was smaller in the lame cohort. These changes were statistically significant for lateral HL, HA and DHWL:HL and medial DHWA (Table 5.8). There were no significant differences between lame and sound cohorts of LF limbs (Table 5.9).

Table 5.8: Dorsal, lateral and medial view measurements for right fore lame limbs in the current study population (n=19 horses) and right fore sound limbs in Chapter 3 (n=76 horses)

Foot measurement	Right Fore Lame Mean (95% CI)	Right Fore Sound Mean (95% CI)	Difference Mean (95% CI)	P value
LHWL (cm)	6.9 (6.4, 7.4)	7.2 (7.0, 7.5)	-0.3 (-0.9, 0.3)	0.28
LHWA (°)	77.8 (75.3, 80.4)	73.5 (72.3, 74.8)	4.3 (1.6, 7.1)	**0.003**
MHWL (cm)	7.7 (7.3, 8.2)	7.5 (7.3, 7.8)	0.2 (-0.3, 0.7)	0.41
MHWA (°)	69.2 (67.0, 71.5)	72.0 (71.0, 73.0)	-2.7 (-5.1, -0.4)	0.03
Lateral DHWL (cm)	10.6 (10.1, 11.0)	10.1 (9.1, 10.4)	0.5 (-0.0, 1.0)	0.07
Lateral DHWA (°)	51.4 (50.3, 52.4)	49.8 (49.1, 50.5)	1.6 (0.3, 2.8)	0.02
Lateral HL (cm)	6.0 (5.7, 6.3)	5.2 (5.0, 5.4)	0.8 (0.4, 1.2)	**0.0003**
Lateral HA (°)	40.4 (37.7, 43.2)	45.6 (43.7, 47.5)	-5.2 (-8.5, -1.9)	**0.003**
Lateral DHWA-HA (°)	11.0 (8.5, 13.4)	4.2 (2.5, 5.9)	6.8 (-0.3, -0.0)	0.02
Lateral DHWL:HL	1.8 (1.7, 1.9)	2.0 (1.9, 2.1)	-0.2 (3.9, 9.8)	**<0.001**
Medial DHWL (cm)	10.4 (10.0, 10.5)	10.0 (9.8, 10.3)	0.3 (-0.1, 0.8)	0.17
Medial DHWA (°)	51.1 (49.5, 52.7)	49.2 (48.5, 50.0)	1.9 (0.1, 3.6)	0.04
Medial HL (cm)	5.7 (5.4, 5.9)	5.4 (5.1, 5.6)	0.3 (-0.1, 0.6)	0.09
Medial HA (°)	42.5 (38.9, 46.1)	44.0 (42.3, 45.7)	-1.4 (-0.5, 2.5)	0.46
Medial DHWA-HA (°)	8.6 (5.5, 11.7)	5.3 (3.8, 6.7)	3.3 (-0.1, 6.7)	0.06
Medial DHWL:HL	1.8 (1.8, 1.9)	1.9 (1.8, 2.0)	-0.1 (-0.2, 0.0)	0.12

LHWL = lateral hoof wall length; LHWA = lateral hoof wall angle; MHWL = medial hoof wall length; MHWA = medial hoof wall angle; DHWL = dorsal hoof wall length; DHWA = dorsal hoof wall angle; HL = heel length; HA = heel angle; DHWA-HA = dorsal hoof wall angle – heel angle difference; DHWL:HL = dorsal hoof wall length:heel length. 95% CI=95% confidence intervals. After adjustment for multiple comparisons using the Bonferroni method p<0.004 considered significant.

Table 5.9: Results of dorsal, lateral and medial view measurements for left fore lame limbs in the current study population (n=9 horses) and left fore sound limbs in Chapter 3 (n=76 horses)

Foot measurement	Left Fore Lame Mean (95% CI)	Left Fore Sound Mean (95% CI)	Difference Mean (95% CI)	P value
LHWL (cm)	7.4 (6.7, 8.0)	7.4 (7.2, 7.6)	-0.1 (-0.8, 0.7)	0.90
LHWA (°)	72.8 (69.4, 76.2)	73.7 (72.7, 74.7)	-0.9 (-4.4, 2.6)	0.57
MHWL (cm)	7.5 (6.7, 8.4)	7.5 (7.2, 7.8)	0.1 (-0.8, 0.9)	0.91
MHWA (°)	72.7 (69.1, 76.3)	71.0 (69.7, 72.4)	1.7 (-2.0, 5.4)	0.34
Lateral DHWL (cm)	10.3 (9.8, 10.9)	10.1 (9.8, 10.3)	0.3 (-0.3, 0.9)	0.30
Lateral DHWA (°)	49.3 (46.7, 51.9)	49.1 (48.2, 50.0)	0.2 (-2.5, 2.9)	0.86
Lateral HL (cm)	5.0 (4.28, 5.8)	5.4 (5.2, 5.6)	-0.4 (-1.2, 0.5)	0.35
Lateral HA (°)	47.7 (41.3, 54.0)	46.1 (44.5, 47.8)	0.6 (-4.9, 7.8)	0.60
Lateral DHWA-HA	1.7 (-2.9, 6.2)	3.0 (1.5, 4.4)	-1.3 (-6.0, 3.3)	0.54
Lateral DHWL:HL	2.2 (1.7, 2.6)	1.9 (1.8, 2.0)	1.3 (-0.2, 0.7)	0.22
Medial DHWL (cm)	11.0 (10.3, 11.6)	10.3 (10.0, 10.5)	0.7 (0.0, 1.4)	0.05
Medial DHWA (°)	47.7 (44.7, 50.7)	49.0 (48.2, 49.8)	-1.3 (-4.4, 1.8)	0.37
Medial HL (cm)	5.9 (5.3, 6.5)	5.2 (4.9, 5.4)	0.7 (0.1, 1.4)	0.02
Medial HA (°)	37.8 (29.6, 46.0)	43.6 (41.8, 45.5)	-5.8 (-14.1, 2.4)	0.15
Medial DHWA-HA (°)	9.9 (4.3, 15.5)	5.3 (3.7, 6.9)	4.6 (-1.2, 10.3)	0.11
Medial DHWL:HL	1.9 (1.7, 2.0)	2.0 (2.0, 2.1)	0.2 -(-0.4, 0.0)	0.06

LHWL = lateral hoof wall length; LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA = dorsal hoof wall angle; HL = heel length; HA = heel angle; DHWA-HA = dorsal hoof wall angle – heel angle difference; DHWL:HL = dorsal hoof wall length:heel length. 95% CI=95% confidence intervals. After adjustment for multiple comparisons using the Bonferroni method p<0.004 considered significant.

5.5.2.2.2 Solar view measurements

When measurements from the solar view were compared between lame and sound horses, no significant differences were identified in either RF or LF limbs. Most measurements were larger in the sound limb than the lame limb in the RF. Exceptions to this were COR-FrA, COR-COP, Hbutt-COP and medial solar width measures (Table 5.10). In the LF the same pattern was seen for COR-FrA, COR-COP and Hbutt-COP (Table 5.11). In the LF Hbutt-Hbutt, SL, COR-Toe and lateral solar width were also smaller in the sound limb than the lame limb (Table 5.11).

Table 5.10: Solar view measurements for right fore lame limbs in the current study population (n=19 horses) and RF sound limbs in Chapter 3 (n=76 horses)

Foot measurement (cm)	Right Fore Lame Mean (95% CI)	Right Fore Sound Mean (95% CI)	Difference Mean (95% CI)	P value
Heel Buttress	8.0 (7.3, 8.6)	8.0 (7.7, 8.3)	-0.0 (-0.8, 0.7)	0.92
Sagittal Length	16.0 (15.2, 16.7)	16.2 (15.9, 16.5)	-0.2 (-1.0, 0.6)	0.55
Frog Apex-Toe	4.8 (4.5, 5.0)	5.0 (4.8, 5.1)	-0.2 (-0.5, 0.1)	0.18
Width	14.3 (13.6, 14.9)	14.4 (14.0, 14.8)	-0.1 (-0.9, 0.6)	0.71
BBL	13.2 (12.8, 13.7)	13.4 (13.1, 13.6)	-0.2 (-0.6, 0.4)	0.62
COR-Frog Apex	2.7 (2.4, 3.0)	2.5 (2.3, 2.6)	0.2 (-0.1, 0.6)	0.16
COR-COP	1.7 (1.4, 2.0)	1.5 (1.4, 1.6)	0.2 (-0.1, 0.6)	0.16
COR-Toe	7.3 (7.1, 7.6)	7.4 (7.2, 7.5)	-0.0 (-0.3, 0.3)	0.99
Hbutt-COR	5.9 (5.7, 6.2)	6.0 (5.9, 6.2)	-0.1 (-0.4, 0.2)	0.48
Hbutt-COP	7.7 (7.3, 8.1)	7.5 (7.3, 7.7)	0.1 (-0.3, 0.6)	0.56
Lateral solar width	7.2 (7.8, 7.6)	7.3 (7.1, 7.5)	-0.0 (-0.5, 0.4)	0.83
Medial solar width	7.0 (6.7, 7.4)	7.0 (6.8, 7.2)	0.0 (-0.4, 0.4)	0.98

Width = solar width; BBL = bearing border length; COR = centre of rotation; COP = centre of pressure. 95% CI=95% confidence intervals. After adjustment for multiple comparisons using the Bonferroni method p<0.004 considered significant.

Table 5.11: Solar view measurements for left fore lame limbs in the current study population (n=9 horses) and left fore sound limbs in Chapter 3 (n=76 horses)

Foot measurement (cm)	Left Fore Lame Mean (95% CI)	Left Fore Sound Mean (95% CI)	Difference Mean (95% CI)	P value
Heel Buttress	8.5 (7.3, 9.7)	8.0 (7.8, 8.3)	0.4 (-0.8, 1.7)	0.46
Sagittal Length	16.3 (14.9, 17.7)	16.3 (16.0, 16.6)	0.0 (-1.4, 1.5)	0.94
Frog Apex-Toe	4.5 (4.1, 5.0)	4.9 (4.7, 5.0)	-0.4 (-0.9, 0.1)	0.14
Width	14.2 (13.0, 15.4)	14.4 (14.1, 14.8)	-0.2 (-1.5, 1.0)	0.65
BBL	13.3 (12.2, 14.4)	13.4 (13.1, 13.6)	-0.1 (-1.2, 1.0)	0.81
COR-Frog Apex	3.0 (2.6, 3.4)	2.6 (2.4, 2.7)	0.4 (0.0, 0.8)	0.04
COR-COP	2.0 (1.6, 2.4)	1.6 (1.5, 1.8)	0.4 (0.0, 0.8)	0.04
COR-Toe	7.4 (6.8, 8.0)	7.4 (7.2, 7.5)	0.1 (-0.6, 0.7)	0.86
Hbutt-COR	5.7 (5.3, 6.1)	6.0 (5.9, 6.1)	-0.3 (-0.7, 0.1)	0.16
Hbutt-COP	7.8 (7.0, 8.5)	7.6 (7.4, 7.8)	0.1 (-0.6, 0.9)	0.69
Lateral Solar Width	7.3 (6.7, 8.0)	7.3 (7.15, 7.5)	0.0 (-0.6, 0.7)	0.91
Medial Solar Width	6.9 (7.2, 7.5)	7.1 (6.9, 7.2)	-0.2 (-0.9, 0.5)	0.51

Width = solar width; BBL = bearing border length; COR = centre of rotation; COP = centre of pressure. 95% CI=95% confidence intervals. After adjustment for multiple comparisons using the Bonferroni method p<0.004 considered significant.

5.5.3 Foot loading results

5.5.3.1 Quadrant analysis static pressure mat data

No significant difference was identified between lame and non-lame or lame and non-lame limbs of study subjects with uni- or bilateral forelimb lameness, respectively (Table 5.12 and 5.13). One exception to this was in the dorsolateral quadrant of the bilateral group, where greater maximum pressure was recorded in the non-lame limb than the lame limb (5.13). No significant difference was observed between the loading of lame limbs in unilateral and bilateral lameness groups.

Table 5.12: Static quadrant pressure data from lame and non-lame feet of unilaterally lame horses (n=11 horses)

Pressure (kPa)	Foot Quadrant	Non-lame Mean (95% CI)	Lame Mean (95% CI)	P Value
Mean	Dorsolateral	212.7 (134.9, 290.6)	239.7 (173.7, 306.2)	0.56
	Dorsomedial	262.1 (195.4, 328.8)	250.1 (174.5, 325.8)	0.79
	Palmarolateral	214.6 (109.4, 319.9)	208.9 (126.1, 291.7)	0.93
	Palmaromedial	170.0 (86.0, 254.1)	216.1 (148.7, 283.5)	0.35
Maximum	Dorsolateral	733.0 (500.9, 965.0)	597.0 (445.2, 748.8)	0.29
	Dorsomedial	910.3 (556.0, 1264.7)	684.8 (580.8, 788.7)	0.20
	Palmarolateral	672.3 (327.6, 1017.0)	565.0 (334.4, 795.7)	0.57
	Palmaromedial	539.6 (325.8, 753.5)	735.7 (488.2, 983.3)	0.20

95% CI = 95% confidence intervals; kPa=kilopascals

Table 5.13 Static quadrant pressure data from lame and non-lame feet of bilaterally lame horses (n=17 horses)

Pressure (kPa)	Foot Quadrant	Non-lame Mean (95% CI)	Lame* Mean (95% CI)	P Value
Mean	Dorsolateral	337.1 (277.5, 396.7)	249.8 (190.0, 309.5)	0.04
	Dorsomedial	251.1 (184.7, 317.6)	275.3 (192.4, 358.2)	0.87
	Palmarolateral	216.8 (162.1, 271.6)	196.0 (140.1, 251.9)	0.58
	Palmaromedial	190.8 (109.3, 272.2)	175.6 (102.3, 249.0)	0.95
Maximum	Dorsolateral	845.7 (735.6, 955.8)	658.0 (500.1, 815.9)	0.05
	Dorsomedial	610.1 (461.0, 759.3)	828.3 (579.7, 1076.9)	0.12
	Palmarolateral	636.0 (472.6, 799.4)	754.1 (530.4, 977.7)	0.37
	Palmaromedial	533.7 (287.1, 780.4)	559.7 (305.6, 813.9)	0.76

*95% CI = 95% confidence intervals; kPa=kilopascals * the limb listed as lame is that which had the more clinically significant lameness*

Results of pressure mat data for each quadrant from the lame limbs of study subjects in the current study were compared with quadrant results from sound horses in Chapter 3 section 3.5.4.1 of this thesis. No significant differences were identified between lame and sound cohorts of LF and RF limbs. For both RF and LF dorsolateral and palmaromedial quadrants exerted greater pressure in the sound cohort than the lame cohort and the opposite was true of the palmarolateral quadrant. In the LF, the dorsomedial quadrant was lower in the sound limb than the lame limb, whilst in the RF the dorsomedial quadrant was higher in the sound limb than the lame limb (Figures 5.1a-d and 5.2a-d). The pattern was similar for maximum quadrant pressures (Figures 5.3a-d and 5.4a-d).

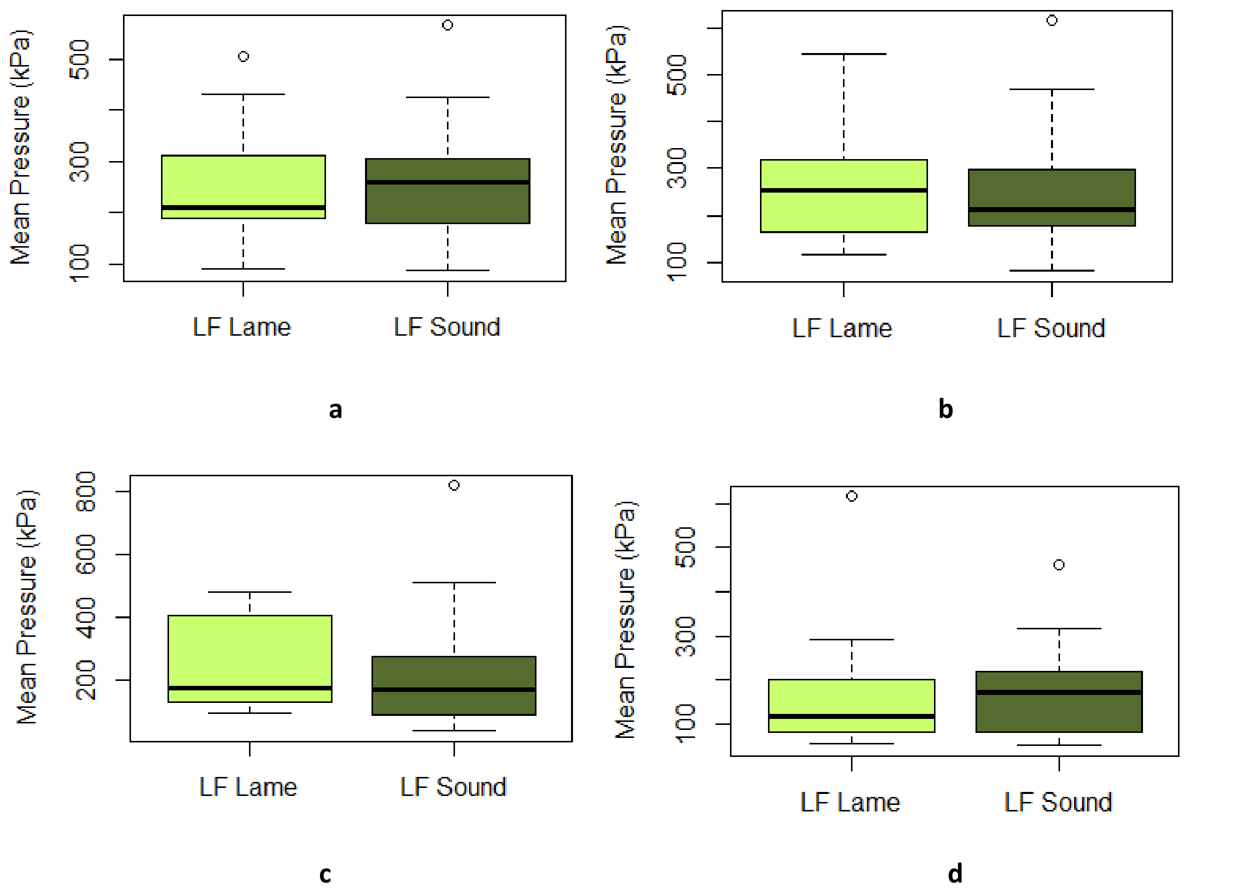


Figure 5.1a-d: Boxplots showing mean static pressures (kilopascals (kPa)) for different foot quadrants of left fore (LF) lame limbs in the current study (n=9 horses) and left fore sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant; d palmaromedial quadrant.

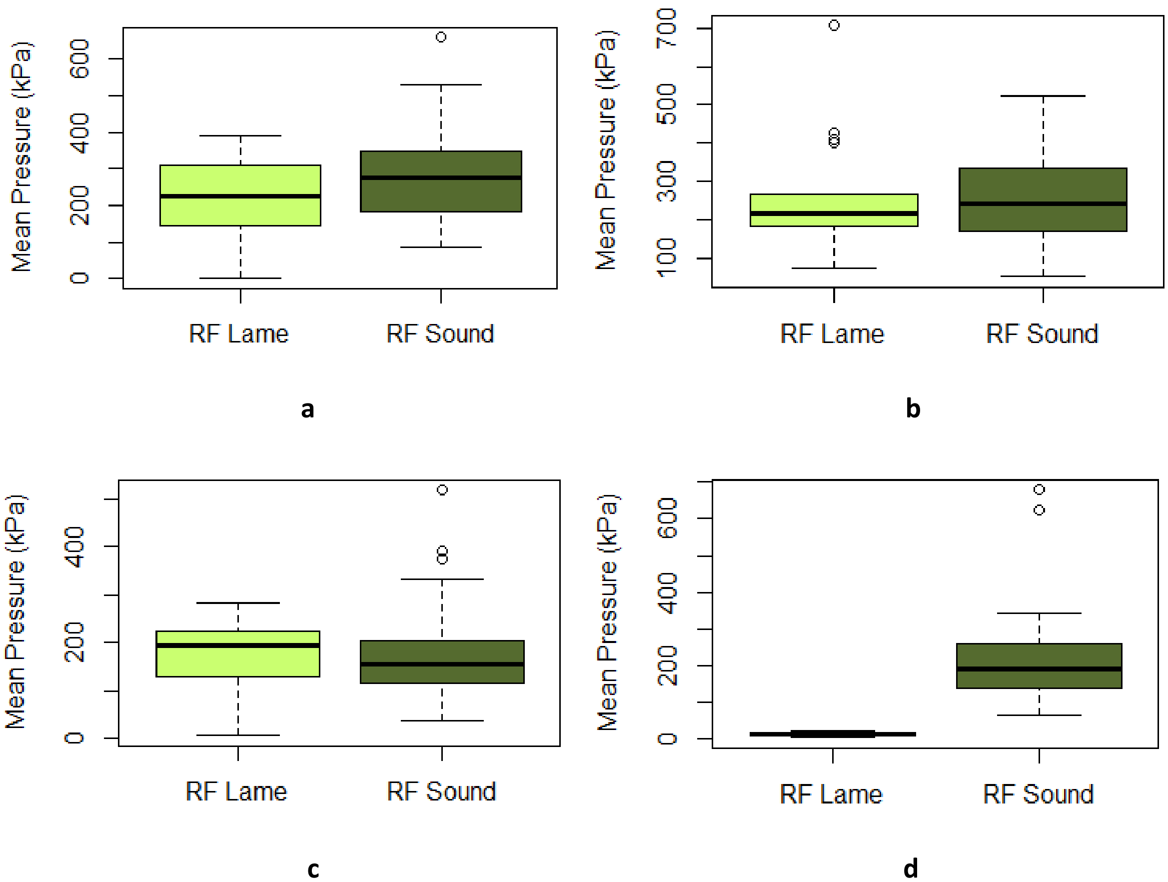
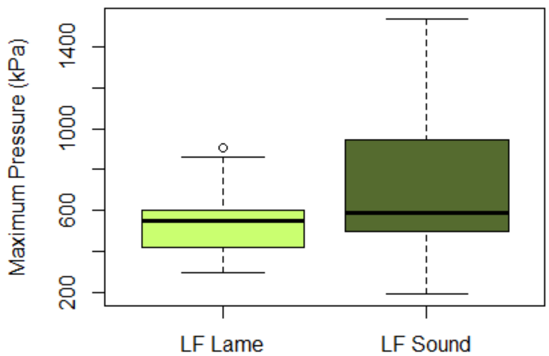


Figure 5.2a-d: Boxplots showing mean static pressures (kilopascals (kPa)) for different foot quadrants of right fore (RF) lame limbs in the current study (n=19 horses) and right fore sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant; d palmaromedial quadrant.



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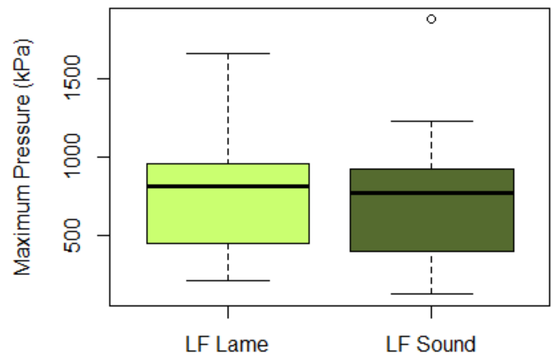

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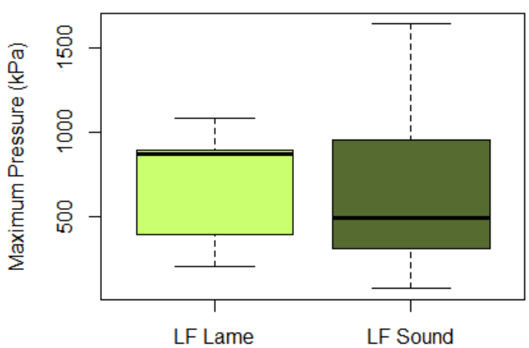

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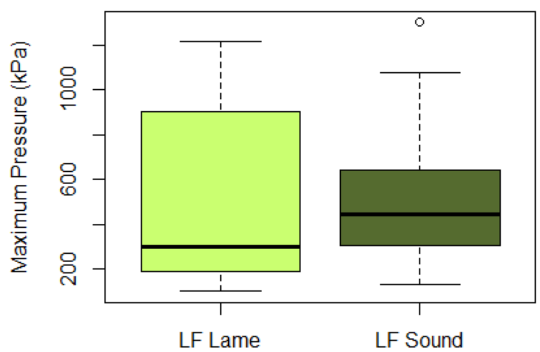

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Figure 5.3a-d: Boxplots showing maximum static pressures (kilopascals (kPa)) for different foot quadrants of LF lame limbs in the current study (n=9 horses) and LF sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant, d palmaromedial quadrant

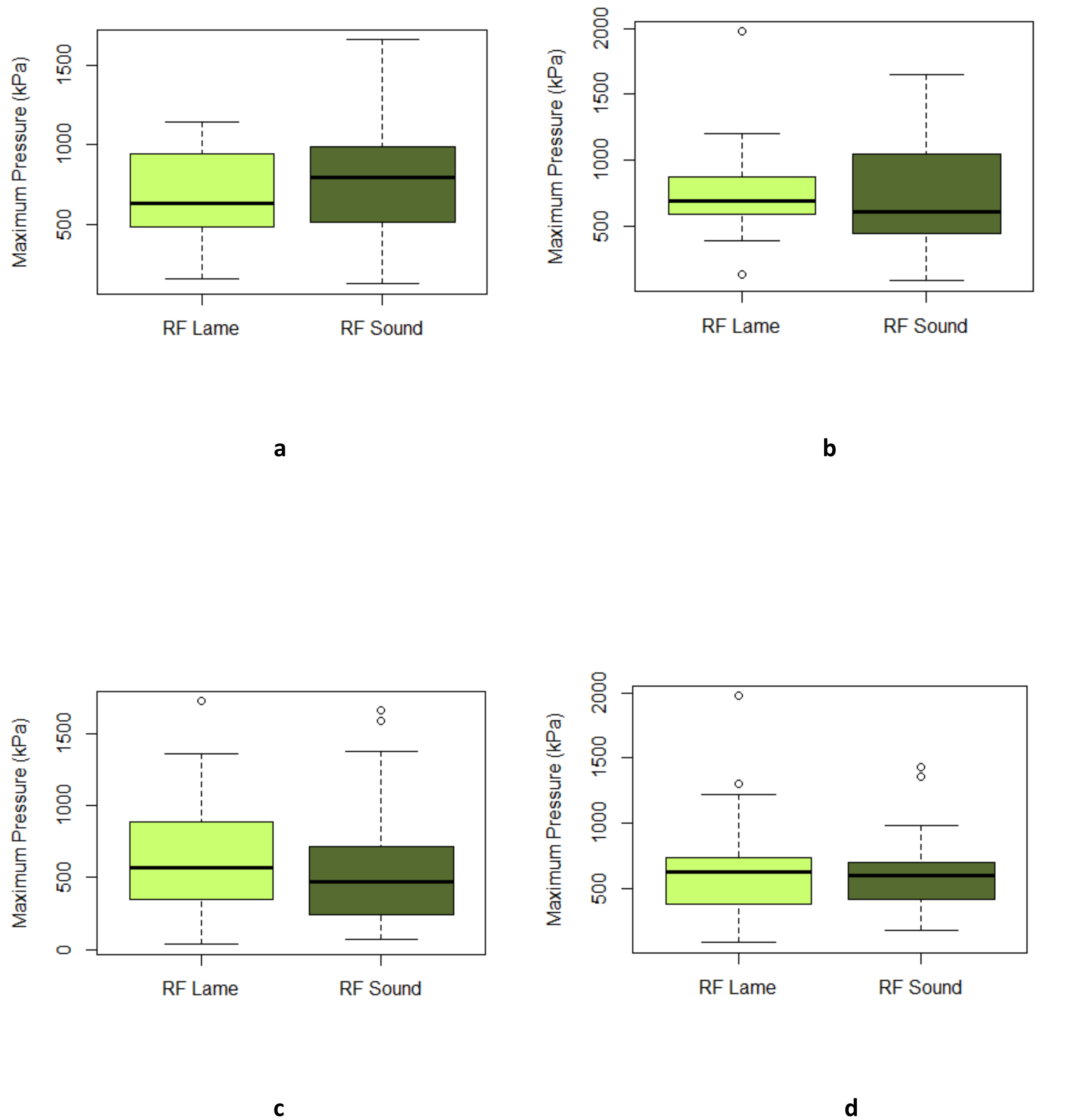


Figure 5.4a-d: Boxplots showing maximum static pressures (kilopascals (kPa)) for different foot quadrants of RF lame limbs in the current study (n=19 horses) and RF sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant, c quadrant, d palmaromedial quadrant

5.5.3.2 Quadrant analysis dynamic pressure data

Similar to static pressure mat data, for unilateral and bilateral forelimb lameness there was no significant difference in the loading of the lame or lame limbs (Table 5.14 and 5.15). When lame and non-lame or lame and non-lame limbs were compared, again, these did not have significant differences in their loading pattern except for the maximum pressure in the dorsomedial quadrant of the bilateral group where the lame limb was loaded more than the non-lame limb (Table 5.15).

Table 5.14 Dynamic mean quadrant pressure data from lame and non-lame feet of unilaterally lame horses (n=11)

Pressure (kPa)	**Foot Quadrant**	**Non-lame Mean (95% CI)**	**Lame Mean (95% CI)**	**P Value**
Mean	Dorsolateral	677.2 (562.4, 791.9)	652.9 (529.2, 776.6)	0.75
	Dorsomedial	429.5 (362.7, 496.3)	488.4 (405.3, 571.4)	0.23
	Palmarolateral	480.7 (365.5, 595.9)	502.7 (371.6, 633.9)	0.78
	Palmaromedial	375.2 (291.5, 458.9)	400.8 (321.2, 480.4)	0.63
Maximum	Dorsolateral	1853.0 (1546.4, 2159.6)	1860.1 (1545.1, 2175.2)	0.97
	Dorsomedial	1242.1 (993.7, 1490.4)	1369.9 (1203.6, 1536.2)	0.35
	Palmarolateral	1533.6 (1176.4, 1890.7)	1491.9 (1201.1, 1782.7)	0.84
	Palmaromedial	1181.6 (868.4, 1494.8)	1215.2 (988.2, 1442.3)	0.85

95% CI = 95% confidence intervals; ; kPa=kilopascals

Table 5.15 Dynamic quadrant pressure data from lame and non-lame feet of bilaterally lame horses (n=17)

Pressure (kPa)	**Foot Quadrant**	**Non-lame Mean (95% CI)**	**Lame* Mean (95% CI)**	**P Value**
Mean	Dorsolateral	647.3 (569.8, 724.8)	664.7 (610.1, 719.4)	0.70
	Dorsomedial	478.1 (402.1, 554.1)	550.4 (468.8, 632.0)	0.18
	Palmarolateral	495.6 (415.9, 575.2)	559.6 (445.4, 673.7)	0.34
	Palmaromedial	359.3 (290.4, 428.3)	370.4 (282.7, 458.1)	0.84
Maximum	Dorsolateral	1802.7 (1541.2, 2064.1)	1901.9 (1714.1, 2089.7)	0.52
	Dorsomedial	1363.0 (1161.2, 1565.0)	1642.6 (1430.5, 1854.7)	0.05
	Palmarolateral	1680.4 (1392.0, 1968.8)	1785.7 (1513.2, 2058.3)	0.58
	Palmaromedial	1120.8 (921.8, 1319.8)	1112.5 (852.9, 1372.1)	0.96

*95% CI = 95% confidence intervals; kPa=kilopascals * the limb listed as lame is that which had the more clinically significant lameness*

The recorded pressures for different foot quadrants in dynamic pressure mat data were compared between lame limbs from the current study and sound limbs from subjects in Chapter 3 section 3.5.4.2. In the LF no significant differences were identified in the loading of foot quadrants in sound and lame limbs (Figures 5.5a-d).

In the RF dorsomedial quadrant sound horses exerted significantly greater pressure than the lame cohort (Figure 5.6b). No other significant changes were identified between lame and sound RF quadrant loading (Figures 5.6a, c and d). The pattern was similar for maximum quadrant pressures (Figures 5.7a-d and 5.8a-d).

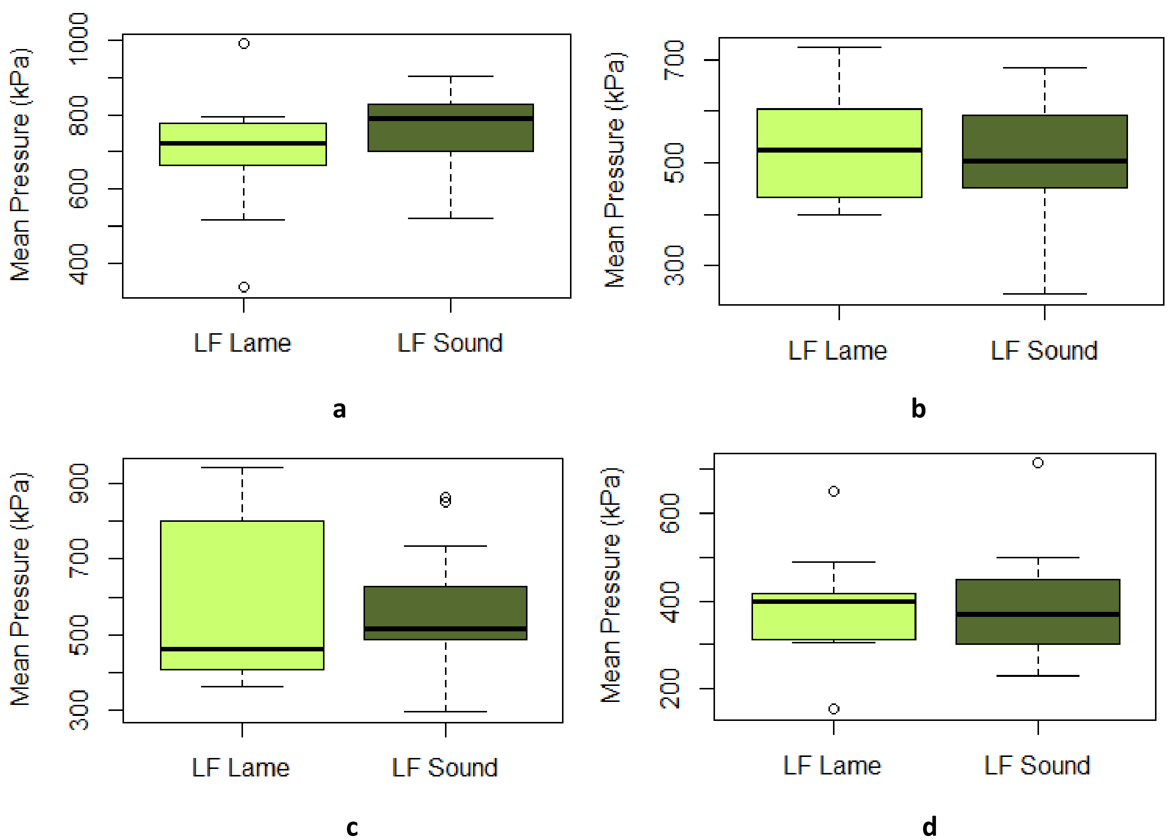
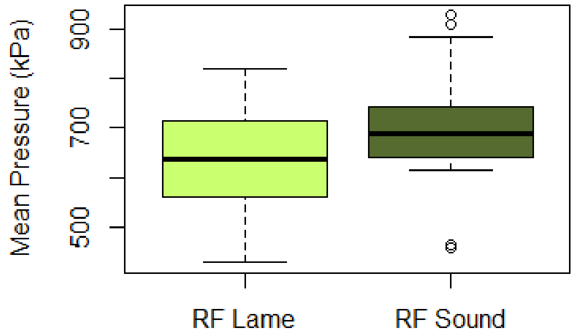


Figure 5.5a-d: Boxplots showing mean dynamic pressures (kilopascals (kPa)) for different foot quadrants of left fore (LF) lame limbs in the current study (n=9 horses) and left fore sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant; d bottom right palmaromedial quadrant.



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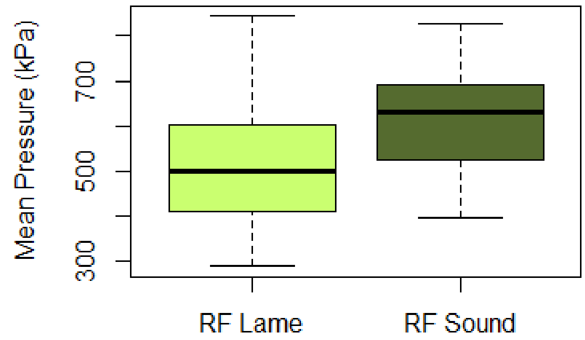

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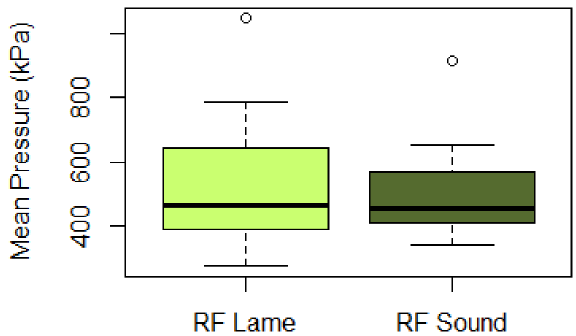

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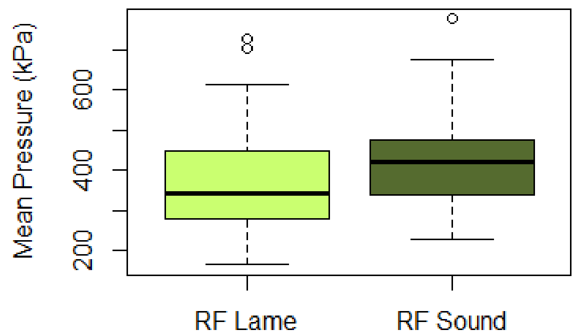

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Figure 5.6a-d: Boxplots showing mean dynamic pressures (kilopascals (kPa)) for different foot quadrants of right fore (RF) lame limbs in the current study (n=19 horses) and right fore sound limbs in Chapter 3 (n=69 horses). a dorsolateral quadrant; b dorsomedial quadrant (lame and sound significantly different, p=0.04); c palmarolateral quadrant; d palmaromedial quadrant.

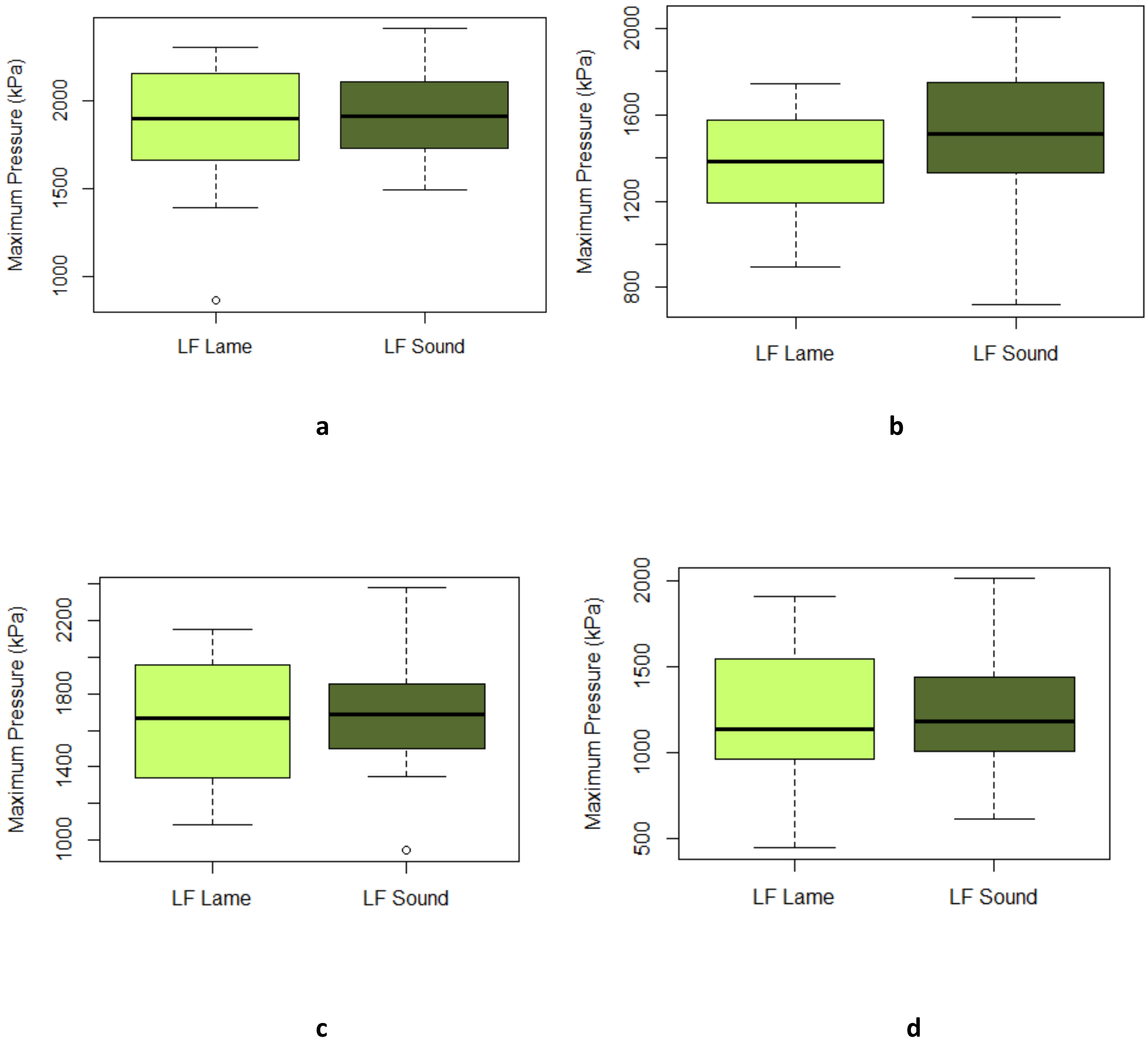
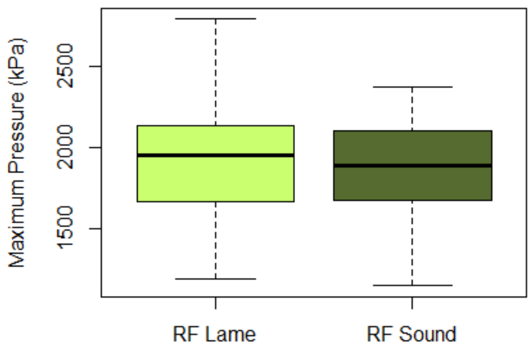


Figure 5.7a-d: Boxplots showing maximum dynamic pressures (kilopascals (kPa)) for differen foot quadrants of LF lame limbs in the current study (n=9 horses) and LF sound limbs in Chapter 3 (n=61 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant; d palmaromedial quadrant.



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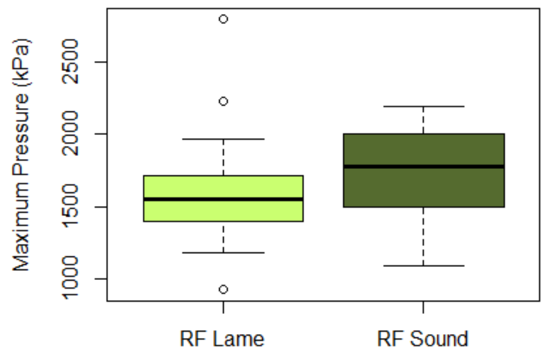

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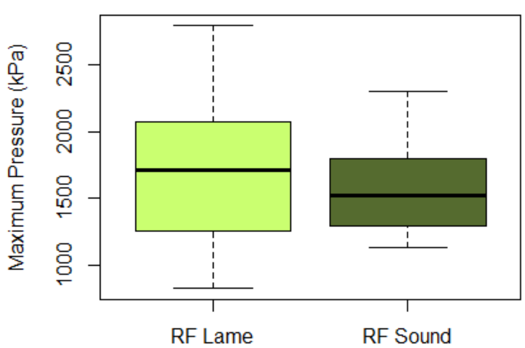

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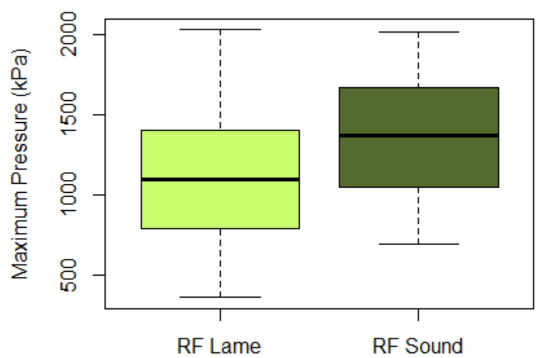

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Figure 5.8a-d: Boxplots showing maximum dynamic pressures (kilopascals (kPa)) for different foot quadrants of RF lame limbs in the current study (n=19 horses) and RF sound limbs in Chapter 3 (n=61 horses). a dorsolateral quadrant; b dorsomedial quadrant; c palmarolateral quadrant; d palmaromedial quadrant.

5.5.3.4 Estimation of variability of pressure mat data

In order to ascertain the amount of variability within the pressure mat data collected in this study, the coefficient of variation was calculated for right and left fore lame limbs, both static and dynamic quadrant pressures. Results are displayed in Table 5.16.

Table 5.16: Coefficient of variation of pressure mat quadrant data from left fore and right fore lame limbs

	Static		Dynamic	
Limb and Condition	**Mean CoV (%)**	**Maximum CoV (%)**	**Mean CoV (%)**	**Maximum CoV (%)**
Left Fore Lame	61.6	57.5	50.6	45.3
Right Fore Lame	51.1	56.4	46.5	45.1

CoV=coefficient of variation

5.5.4 Magnetic resonance imaging findings

Findings from MRI scans demonstrated that ND was the most common cause of foot lameness in this study population (Table 5.17), followed by distal interphalangeal joint (DIPJ) disease. Navicular disease (ND) and DIPJ disease almost always affected both forelimbs, this was also true of just under half of all DDFT lesions (Table 5.17). Distal phalanx (P3) fractures only occurred unilaterally. In the LF a median of two findings (IQR: 1.8-3.0) were identified per horse and in the RF a median of 2.5 findings (IQR: 2.0-3.0) were identified per horse.

Table 5.17: Breakdown of diagnoses based on magnetic resonance imaging findings from the study population (n=28 horses)

MRI findings	**Number Left Fore**	**Number Right Fore**	**Number Bilateral**
Navicular disease	12	10	10
Primary DDFT lesions	3	7	3
DIPJ disease (+/- collateral ligament disease)	7	8	6
P3 Fracture	2	1	0
No significant findings	3	2	0

DDFT = deep digital flexor tendon; DIPJ = distal interphalangeal joint; P3 = distal phalanx; MRI = magnetic resonance imaging

Table 5.18: Median (interquartile range) foot measurements for the most common magnetic resonance imaging findings (n=20 horses)

Limb	**Foot Measure**	**Navicular Disease Median (IQR)**	**Deep Digital Flexor Tendon Lesion Median (IQR)**	**Distal Interphalangeal Joint Disease Median (IQR)**
Left Fore	LHWA (°)	73.0 (69.1-76.9)	72.6 (71.4-76.4)	68.9 (67.6-72.7)
	DHWA-HA (°)	2.0 (-0.9-5.8)	6.8 (2.9-9.6)	7.9 (0.8-12.0)
	BBL (cm)	12.7 (11.9-13.7)	13.6 (13.3-13.8	13.7 (13.1-13.9)
	Width (cm)	13.4 (12.6-14.5)	14.2 (13.8-14.7)	14.4 (14.0-16.0)
	FRA-Toe (cm)	4.7 (4.3-4.9)	4.4 (4.3-4.4)	4.9 (4.7-5.3)
Right Fore	LHWA (°)	75.7 (73.9-79.0)	79.8 (77.4-80.8)	80.3 (75.8-81.5)
	DHWA-HA (°)	7.0 (5.3-9.7)	11.4 (6.4-13.9)	13.5 (11.6-15.3)
	BBL (cm)	13.0 (12.1-13.9)	13.2 (12.6-14.1)	13.3 (12.8-13.9)
	Width (cm)	13.6 (12.5-14.6)	14.5 (12.9-15.0)	14.2 (14.0-14.9)
	FRA-Toe (cm)	4.5 (4.3-5.0)	4.4 (4.4-4.8)	4.5 (4.4-4.8)

LHWA = lateral hoof wall angle; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width BBL = bearing border length; COR = centre of rotation; IQR=interquartile range

Table 5.18 shows that DHWA-HA is lowest for ND in the LF and RF, but highest for DIPJ disease in the LF and for P3 fracture in the RF. Results of DHWA-HA for the RF are higher than that of LF across all lameness diagnoses. ND, as well as having the lowest DHWA-HA, had the lowest BBL and hoof width for both forelimbs. LHWA was the lowest in LF DIPJ issues, but conversely was the highest result for RF for the same diagnosis. FrA-Toe had the lowest result for DDFT in the RF, and similarly it was lowest for DDFT and P3 fractures (also 4.36cm (IQR: 4.25-4.47) in the LF. None of the above differences between MRI categories were statistically significant.

The dorsolateral quadrant was subject to the greatest static pressure in limbs affected by ND (LF and RF) and DIPJ disease (RF only) (Table 5.19). For LF limbs with DDFT lesions, the dorsolateral quadrant was subject to lower pressures than all other quadrants. In RF limbs with DDFT lesions, the dorsomedial quadrant was subject to greatest loading. The same pattern was evident for LF limbs with DIPJ lesions. These differences were not statistically significant.

Table 5.19: Mean static foot quadrant pressure result for the most common magnetic resonance imaging findings (n=20 horses)

Limb	Foot Quadrant	Navicular Disease mean kPA (95% CI)	Deep Digital Flexor Tendon Lesion mean kPa (95% CI)	Distal Interphalangeal Joint Disease mean kPa (95% CI)
Left Fore	Dorsolateral	717.3 (622.6-775.7)	463.2 (412.0-489.9)	766.7 (687.3-856.0)
	Dorsomedial	539.8 (426.2-605.3)	432.9 (410.1-462.4)	423.6 (411.5-578.1)
	Palmarolateral	483.2 (418.9-617.2)	462.8 (362.8-478.6)	506.3 (405.1-593.2)
	Palmaromedial	405.0 (291.7-445.5)	366.4 (321.1-382.7)	336.7 (268.9-407.1)
Right Fore	Dorsolateral	623.4 (556.4-681.3)	562.6 (554.6-647.4)	623.7 (508.3-731.4)
	Dorsomedial	496.3 (361.7-550.9)	428.0 (367.9-506.5)	445.3 (418.6-597.6)
	Palmarolateral	374.2 (301.3-574.9)	464.8 (422.2-502.6)	410.8 (371.2-548.9)
	Palmaromedial	349.7 (272.8-412.2)	392.4 (253.7-475.6)	338.2 (310.5-357.9)

95% CI = 95% confidence intervals; kPa=kilopascals

Table 5.20: Mean dynamic foot quadrant pressure result for the most common magnetic resonance imaging findings (n=20 horses)

Limb	Foot Quadrant	Navicular Disease median kPA (IQR)	Deep Digital Flexor Tendon Lesion median kPA (IQR)	Distal Interphalangeal Joint Disease median kPA (IQR)
Left Fore	Dorsolateral	262.4 (206.0-328.8)	203.0 (195.2-352.3)	233.7 (184.3-331.3)
	Dorsomedial	187.6 (149.8-275.2)	318.8 (246.5-364.5)	315.6 (230.0-372.0)
	Palmarolateral	210.8 (155.9-304.0)	273.9 (153.2-308.8)	157.1 (97.4-210.8)
	Palmaromedial	108.7 (87.0-310.1)	262.7 (211.9-276.6)	163.1 (91.9-223.0)
Right Fore	Dorsolateral	300.6 (165.9-383.5)	193.0 (114.3-243.3)	227.3 (213.7-267.8)
	Dorsomedial	264.9 (223.8-396.5)	201.9 (174.2-211.8)	200.0 (168.9-254.4)
	Palmarolateral	198.5 (171.1-224.3)	154.9 (65.9-226.8)	142.6 (133.4-223.1)
	Palmaromedial	159.1 (134.2-322.2)	136.8 (76.1-162.8)	180.0 (154.8-225.4)

IQR = interquartile range; kPa=kilopascals

For both limbs and across ND, DDFT lesions and DIPJ disease, the dorsolateral quadrant was shown to be subject to higher dynamic pressures than any other quadrants, much as has been found in sound horses (Chapter 3 section 3.5.4). Lower pressures were recorded in the DDFT group for the dorsolateral quadrant compared to the ND and DIPJ groups for both RF and LF limbs. The palmaromedial quadrant was subject to the lowest pressures in all groups. Although in RF DIPJ and LF and RF ND the dorsomedial quadrant was subject to greater pressures than the palmarolateral quadrant, this pattern was reversed for LF DIPJ and RF and LF DDFT cases. None of the differences in dynamic pressure measures between MRI findings were statistically significant.

Table 5.21: Average duration of lameness (days) at the time of hospitalisation for the most common magnetic resonance imaging findings (calculated as time of recorded onset to date of hospitalisation) (n=20 horses)

Limb	**Navicular Disease Median Days (IQR)**	**Deep Digital Flexor Tendon Lesion Median Days (IQR)**	**Distal Interphalangeal Joint Disease Median Days (IQR)**
Left Fore	52.0 (34.5-158.2)	90.0 (61.5-126.5)	40.0 (35.5-44.5)
Right Fore	44.5 (33.50-81.3)	96.0 (60.5-126.5)	109.0 (75.3-203.8)

IQR = interquartile range

As previously described the time from onset of lameness to hospitalisation for lameness investigation in the current study was wide-ranging. Table 5.21 demonstrates that overall the DDFT lesions were the most chronic conditions at the time of hospitalisation in the LF. DIPJ had the longest interval between onset and hospitalisation for the RF but the shortest interval for LF. ND had the shortest interval in the RF.

5.5.4.1 Pedobarographic statistical parametric mapping results

Three horses showed a significant ($p<0.05$) difference in the way they loaded contralateral forelimbs. Figure 5.9 demonstrates the findings from a horse which horse had bilateral navicular disease findings on MRI and had been referred for investigation of a bilateral lameness where the RF was lame than the LF and showed greater loading over the frog region in the RF. Figure 5.10 shows the findings from a horse which had been referred to the Philip Leverhulme Equine Hospital for investigation of a unilateral left fore lameness and showed less loading in the midsection of the lateral sole of the right fore compared with the left fore. MRI revealed a fracture of P3 in the LF and no significant pathology in the RF. A third horse was referred for investigation of a bilateral forelimb lameness where the RF was the lame limb, in this case greater pressure was exerted on the lateral heel and lateral hoof wall of the left fore than the right fore. MRI findings identified DIPJ disease in the RF (Figure 5.11).

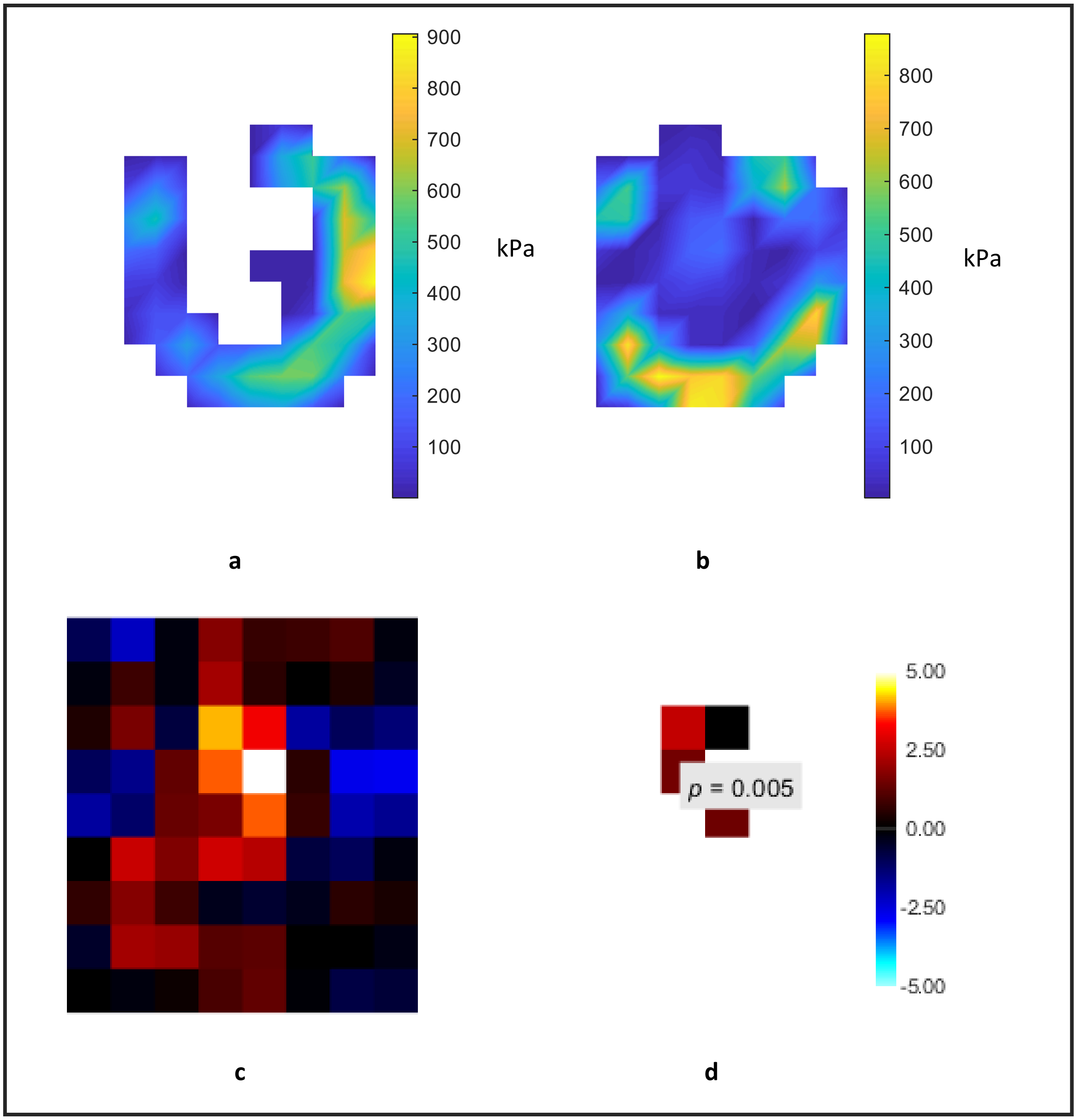

Figure 5.9: An example of greater pressure over the frog region in the right fore than the left fore. Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs. a is a plot of the mean pressure distribution of the left forelimb strikes, b is a plot of the mean pressure distribution of the right forelimb strikes, c is a plot of the inference between the left and right forelimbs and d plots the areas of significant differences in loading between left and right forelimbs. In this horse plots a and b indicate that the loading over the frog region (and indeed much of the solar surface of the foot) is less in the left fore than the right fore. A cluster of pixels that are significantly different (p=0.005) between limbs is demonstrated in d; comparison with c indicates the location is the central or frog region of the sole. The colour of the pixels in this cluster indicate a positive change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means that there is greater pressure in the right fore than the left fore. kPa=kilopascals

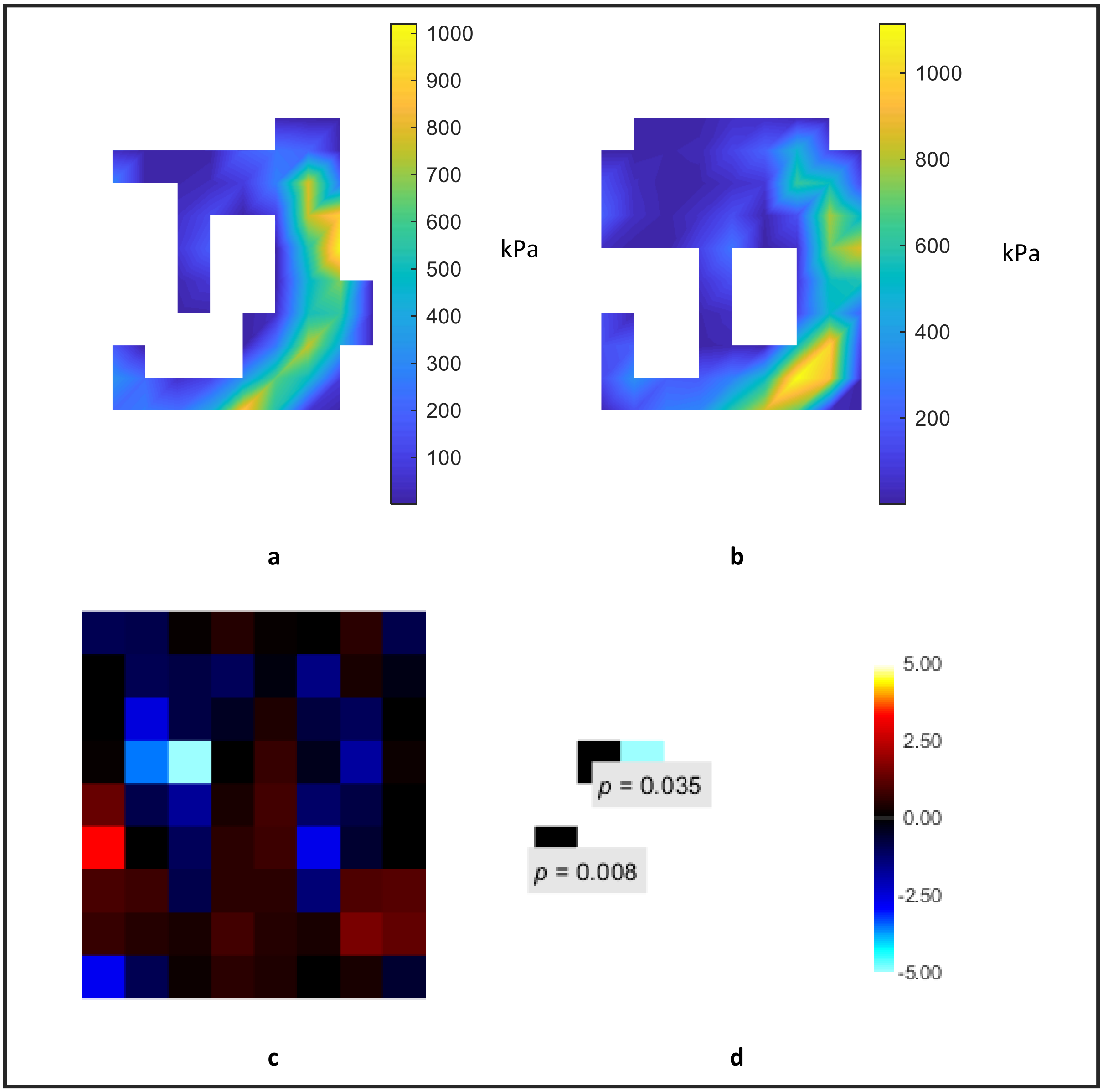

Figure 5.10: An example of decreased loading over the midsole region in the right fore compared with the left fore. Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs. Mean pressure in left fore and right fore are shown in plots a and b. A plot of the difference between left and right forelimbs is shown in c and d plots the areas of significant differences identified in c. In this horse plots a and b shows less loading in the midsection of the lateral sole of the right fore compared with the left fore. A two-pixel cluster that is significantly different between limbs is demonstrated in d (p=0.035); comparison with c indicates the location is the midsection of the lateral sole. The colour of the pixels in these clusters indicate negative change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means that there is less pressure in the right fore than the left fore. The single pixel difference (p=0.008) was not deemed to be a meaningful change due to affecting a very small area. kPa=kilopascals

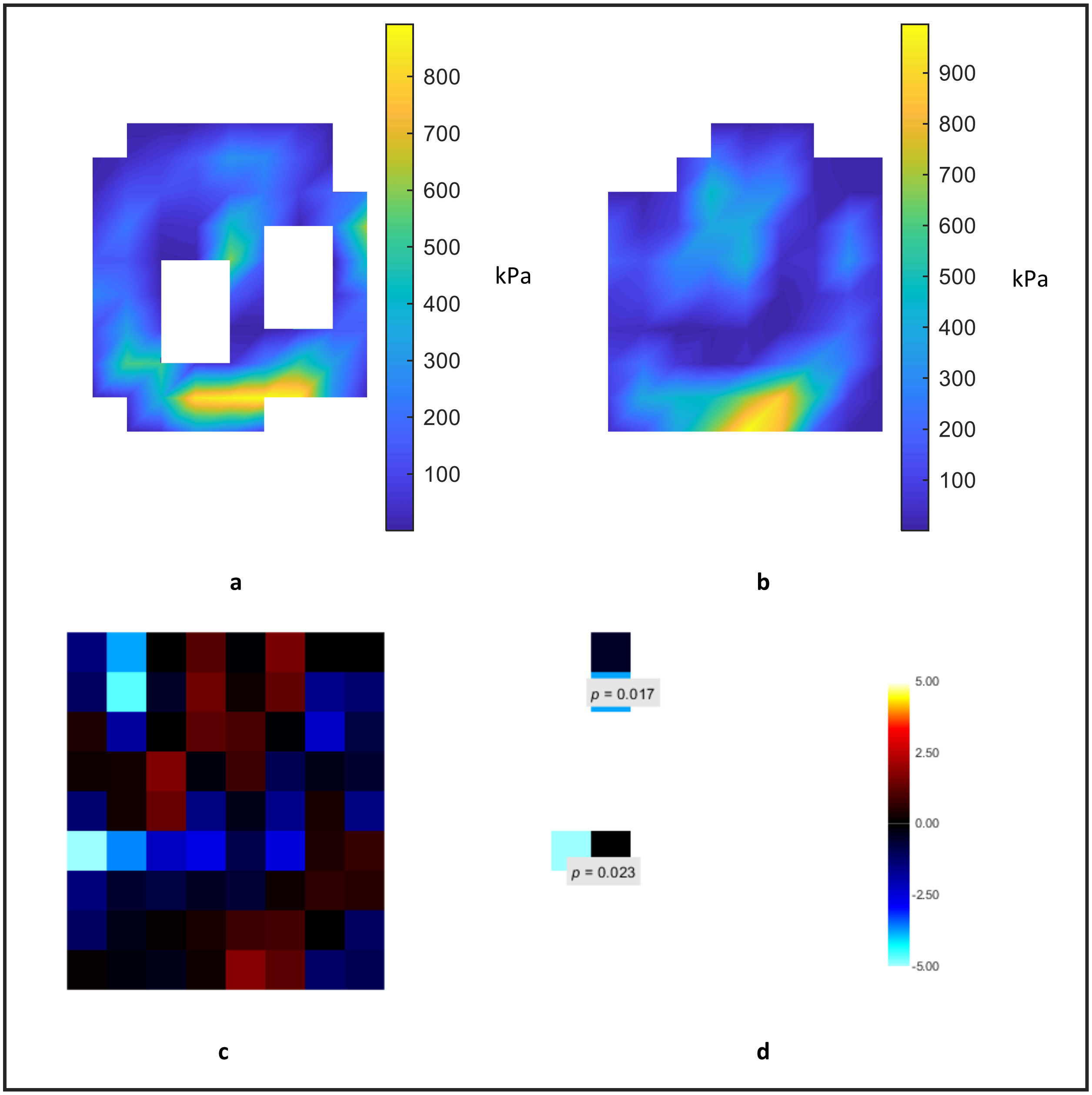

Figure 5.11: An example of where greater pressure was exerted over the lateral heel and lateral hoof wall of the left fore compared with the right fore. Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs. Mean pressure in left fore and right fore are shown in plots a and b. A plot of the difference between left and right forelimbs is shown in c and d plots the areas of significant differences identified in c. In this horse plots a and b show that greater pressure is exerted on the lateral heel and lateral hoof wall of the left fore than the right fore. Two, two-pixel clusters that are significantly different between limbs are demonstrated in d; comparison with c indicates the location is the lateral heel (p=0.017) and lateral hoof wall (p=0.023). The colour of the pixels in these clusters indicate negative change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means that there is less pressure in the right fore than the left fore. kPa=kilopascals

5.6 Discussion

This study examined the foot shape and loading patterns of lame limbs from a cohort of horses referred to the Philip Leverhulme Equine Hospital for investigation of lameness localised to the foot. The aim of the study was to unpick how foot shape and loading differed between different MRI findings. Feet with ND were shown to have a small and upright shape compared with other foot pathologies (Table 5.14). Pressure mat data demonstrated that in some cases the feet of lame limbs were loaded less than those of sound limbs, but this was not a universal finding. Few significant differences were identified between contralateral limbs.

5.6.1 Foot shape and loading in lame vs sound limbs

In the current study population, RF lame limbs had a longer HL and more acute HA than in RF limbs than the sound study population of Chapter 3. The acute HA may indicate that the lame limbs suffer poor dorsopalmar foot balance compared with sound limbs, since the more acute the HA is, the more likely it is to have a larger difference to DHWA. The suggested 'ideal' in terms of dorsopalmar foot balance is parallelism of DHWA and HA, though a small difference (up to a maximum of 5°) between these angles may still be acceptable (Turner, 1992; Balch, White and Butler, 1993). Alternatively, the longer HL may indicate a more upright foot shape in the lame limb due to chronic unloading as described previously (Back *et al.*, 1995a; Wiggers *et al.*, 2015). This latter view would also be supported by the fact that the lateral DHWL:HL is smaller in the lame cohort of RF than the sound cohort. The cross-sectional nature of this study means it is not possible to draw any conclusions about causality of foot shape in lame horses.

RF LHWA had a significantly more acute angle in sound horses and MHWA a more acute angle in lame horses. This difference was much greater in lame horses (c. 8°) than sound horses (c. 2°). Such asymmetry within feet of lame limbs indicates poor mediolateral balance. There was no difference between the feet of LF sound and LF lame limbs. The difference in findings from LF and RF may be related to the fact that the majority of horses in this study the RF was the affected (or more affected) limb. The low number of LF lame horses as well as the small overall sample size in this study may have affected the results and power for identification of differences between LF lame and LF sound feet.

Published literature has a variety of findings with respect to foot shape and balance in horses with specific lameness diagnoses. It is hard to decipher what conformation contributes to or is the result of lameness events (Wright, 1993; Dyson *et al.*, 2011; Parkes, Newton and Dyson, 2015). Holroyd and others found that horses with ND and DDFT lesions had, on average, a lower solar angle of P3 than other horses with foot pain that underwent MRI examination (2013). Another study found that horses with ND more commonly had low heel or broken back hoof-pastern axis than upright feet, whilst the opposite was true of horses diagnosed with DDFT lesions (Parkes *et al*., 2015). The findings from these studies resonate with those of the current study.

Static quadrant foot pressures were higher in the LF sound limbs than LF lame limbs for the dorsolateral and palmaromedial quadrants, though the opposite was true of dorsomedial and palmarolateral quadrants. Sound RF limbs exerted greater pressures than lame limbs in dorsolateral, dorsomedial and palmaromedial quadrants. Relative unloading of lame limbs compared with sound limbs reflects the findings of previous force plate and pressure mat studies (Buchner, Obermuller and Scheidl, 2001; Rhodin *et al.*, 2013; Pitti *et al.*, 2018). The quadrants that are loaded more in lame limbs than in sound limbs in the current study may indicate a reduction of mediolateral sway in lame limbs as described in recent studies (Pitti *et al.*, 2018; Egan *et al.*, 2021) and consequent increased loading of particular regions of the foot.

Comparison of quadrant pressures from dynamic data collection demonstrated that LF dorsolateral and palmarolateral quadrants were loaded more heavily by sound horses than lame horses. The RF dorsomedial quadrant was loaded significantly more by sound horses than lame horses. Where pressure exerted over foot quadrants was lower in lame limbs than sound limbs, this corroborated the findings of the static pressure mat data from this study as well as previous studies that lame limbs will be unloaded compared with sound limbs (Buchner, Obermuller and Scheidl, 2001; Rhodin *et al.,* 2013). However, compensatory loading of lame limbs at walk is poorly understood, with no parameters validated for objective lameness assessment in this gait (Serra Bragança *et al.*, 2020). Reasons for this include that in a horse with unilateral lameness, the biomechanics of the contralateral (sound or non-lame) limb are altered, sometimes making lameness hard to identify. Additionally, parameters that are valuable for lameness or symmetry assessment in trot exist at a lower magnitude at walk, making them harder to detect and where variability exists, validate. The bi- and tri-pedal support available at walk compared with only bipedal at trot also provides greater opportunity for compensatory loading. This may result in greater variation between individual gait patterns of lame horses when assessed in walk rather than trot (Buchner *et al.*, 1996a, 1996b; Serra Bragança *et al.*, 2020). Similarly, the higher speed and frequency of strides at trot increase the forces and consequently pain experienced by a lame horse at trot over walk (Serra Bragança *et al.*, 2020).

Three of the 28 horses in this study had significant differences in pressure distribution between contralateral forelimbs. Two of these horses had been referred for investigation of bilateral forelimb lameness where the RF was the more clinically affected limb. However, in the case suffering from ND, higher pressure was observed in the RF. This may reflect the findings of a previous study (McGuigan and Wilson, 2001) which found that horses suffering from ND exerted greater forces from the DDFT onto the NB in early stance than healthy horses.

A lameness case diagnosed with DIPJ disease in the RF had significantly lower loading of the lame limb (RF) lateral heel and lateral hoof wall. Similarly, the lateral hoof wall of the lame limb was unloaded in a unilaterally lame horse identified with a P3 fracture on MRI. Both of these examples support those of previous studies that have found reduced loading in the lame limb (Buchner *et al.*, 2001; Rhodin *et al*., 2013).

One cause of the lack of detectable difference in foot loading between affected and unaffected limbs may be that the majority of the study population (17/28) were bilaterally lame, and therefore horses were attempting to unload both limbs simultaneously. Similarly, in unilateral lameness cases, the non-lame limb is compensating for lameness in the contralateral limb, and therefore the non-lame limb is unlikely to be loaded as it would be in a sound animal. The small sample size may have compromised the statistical power, preventing detection of significant changes. The median interval between lameness onset and hospitalisation was 83 days. Many horses' lameness severity may have reduced during this time due to rest and administration of analgesia (none were under analgesic treatment at the time of hospitalisation). Collection of pressure mat data in walk rather than trot may also have impacted the results, since detection of compensatory loading can be difficult and variable in walk (Serra Bragança *et al.*, 2020).

5.6.2 Magnetic resonance imaging findings

In this study, the most common diagnosis following MRI was ND, followed by DIPJ disease (osteoarthritis and/or ligament damage). Holroyd and others reported ND and DDFT lesions as the most common findings at MRI, whilst Parkes and others found the most common pathologies at MRI were those affecting sesamoidean ligaments and 'other' (Parkes *et al.*, 2015). Differences in categorisation of MRI findings in different studies may influence reported disease prevalence, as often there is more than just a single abnormality at MRI examination. In this study on average each limb had two MRI findings per limb.

In general the same pathologies were detected on MRI in both forelimbs, even in horses referred due to a unilateral lameness. This has been reported previously and suggests a level of subclinical lameness in the sound (or less clinically affected) limb (Sherlock *et al*., 2008; Smith, 2015).

The current study found that average DWHA-HA, BBL and width were lowest for ND compared with other MRI findings in LF and RF. Previous studies have also reported that ND can result in a small or 'boxy' foot due to chronic unloading of the affected limb(s) (Back *et al.*, 1995a; Wiggers *et al*., 2015). However, it opposes the findings of another study that examined measures of foot shape by MRI (Holroyd *et al.*, 2013) and found ND and DDFT lesions were associated with low solar angle (<13°) compared with other lesions detected at MRI. The current study did not collect data on the solar angle of affected horses, however DHWA-HA was larger for those limbs with a primary DDFT lesion, which may be representative of a low heel and low solar angle.

RF lateral DHWA-HA was greater than the LF for all MRI findings. This may be due to a higher prevalence of RF lameness in the study population and related poor dorsopalmar foot balance. Lowest LHWA was found in horses with DIPJ lesions in the LF, and highest for this MRI finding in the RF. The shortest FrA-Toe distance was identified for primary DDFT lesions in both limbs.

Horses with DDFT and RF DIPJ lesions had an interval of around 90 days between lameness onset and hospitalisation. These can be considered chronic events and may well have influenced foot shape by the time of data collection. The duration of lameness in limbs affected by ND and LF limbs affected by DIPJ disease was approximately the length of a shoeing cycle. We know from results of Chapter 3 and published literature that foot shape can change significantly over the course of a shoeing cycle. However, less is known about the speed at which changes due to lameness occur. Given that the feet affected by ND and LF DIPJ had around half the time from onset to hospitalisation in which to change compared with the DDFT and RF DIPJ counterparts, it may be that their foot shape is less representative of changes caused by lameness.

DDFT lesions appeared to cause different loading patterns compared with joint disease (ND and DIPJ disease). This was particularly marked in the results of static pressure mat data, with the dorsolateral quadrant subject to the lowest amount of loading in LF limbs affected by DDFT lesions. However, in both RF limbs with DDFT lesions and LF limbs with DIPJ disease the dorsomedial quadrant pressures were higher than the dorsolateral.

Dynamic pressure data showed that although lame horses load the dorsolateral quadrant less than sound horses, as discussed above, this quadrant is still subject to the highest pressures in horses affected by foot lameness. The difference between limbs affected by DDFT lesions and joint disease was also demonstrated by the fact that the dorsolateral quadrant in limbs with DDFT lesions was loaded on average less than limbs affected by ND and DIPJ. There is no data with which to compare these findings.

5.6.3 Demographics of study population

The age of horses in the current study (mean 11.4 years) was similar to that identified in other referral populations of horses with foot lameness (Blunden *et al.*, 2006; Sherlock, Mair and Blunden, 2008; Parkes, Newton and Dyson, 2013). Horses aged 6-15 years have been found to be at greater risk of foot pain than those under five years of age (Parkes *et al*., 2013).

The findings of the current study do not really align with others that found that TB-crossbreds are more likely to suffer foot pain than WBs (Parkes *et al.*, 2013). In the current study population the low number of TB and TBX were amalgamated into a single category. There is a similar number of animals in this group as there are WBs. The most numerous breed in the current study population was native, which has not previously been reported in the literature. This is likely to represent the referral demographic of the region in which this study took place. The demographics of horses recruited to Chapter 3 support this; in this population native breeds were also the most common (37.6%). The number of WBs and TBs comprising the study population were also similar in both study populations (18.3% and 17.2% in Chapter 3), though there was a much lower proportion of ISHs in the current study, compared with Chapter 3. The age, height and estimated weight of the horses recruited to Chapter 3 (10.7 years; 154cm; 561.6kg) were very similar to that of the current study. Gender demographics were somewhat different. The current study had over 50% mares, whilst in Chapter 3 less than one-third of the study population were mares.

5.6.4 Limitations

This study suffered several limitations: the population was recruited in a single year from one referral hospital in the North-West of England, hence it is not representative of the general UK equine population nor all referral populations in the UK or abroad. There was a median gap of 83 days between the reported onset of lameness and the date of hospitalisation. Although this is less than that described in other studies (Parkes *et al*., 2015), it may have impacted the foot loading pattern and foot shape measured at the time of hospitalisation. There was an average gap of 28 days between the last foot-trimming or shoeing date and hospitalisation. These data were unavailable for six horses and were extremely varied; some horses had been trimmed the day before hospitalisation whilst others had not been trimmed for 70 days. Consequently foot shape measured in the study may not be fully representative of lameness-related changes. As described in Chapter 4, longitudinal studies are required to truly unravel the relationship between foot shape and lameness in horses.

Clinical histories from both the referring veterinarian and those collected on admission to the referral hospital were used to categorise horses into bilateral and unilateral lameness groups and to define which limb was more clinically affected. It is known that lameness assessment by veterinarians can be highly subjective (Keegan *et al.*, 2010). Objective lameness data were available for each horse at the time of hospitalisation. However, the huge variability in duration of lameness amongst the study population as well as many different lameness raters in referring veterinarians mean that formal quantification of agreement between subjective and objective lameness was felt to be of little value and therefore was not pursued. Lameness assessments were often performed following administration of diagnostic analgesia in affected horses. A number of different individuals (referring veterinarians and hospital clinicians) performed this administration. Different methods of administration may have had different efficacies and impacted the lameness category horses were given.

This study had a small number of subjects. The RF was the most clinically affected limb in both unilateral and bilateral groups. This difference in numbers of LF and RF lameness may have affected the results of comparison with feet of sound horses.

The coefficient of variation of foot quadrant pressures for LF and RF lame limbs was high (>5%) (Beauchet *et al.*, 2009; McClymont *et al.*, 2016). This may be the result of data collection outside of laboratory conditions, as well as the relatively small number of foot strikes collected per limb and condition. This high level of variability may have affected the findings of the study.

5.6.5 Conclusions

This study found that ND, DIPJ and DDFT lesions were the most common findings at MRI examination in a population of horses with lameness localised to the foot. Some horses with P3 fractures were also diagnosed this way. Horses with ND appeared to have a more upright, boxy foot shape than horses in other disease categories. Foot loading may change in horses with lameness, resulting in the relative unloading or increased loading of various foot regions. Further longitudinal studies examining equine foot shape, loading and MRI findings are indicated in order to further elucidate the complex relationship between these factors and provide a greater opportunity for early diagnosis of foot lameness. Until the pathological aspects of shape and loading have been identified it is not possible to design effective treatment regimes, particularly as regards remedial farriery, which is a commonly prescribed course of action in cases of lameness localised to the foot.

Chapter 6

Demographics, Hardness, Resistance to Penetration and Moisture Content of a Sample of Synthetic Equine Arenas in North-West England and North Wales

6.1 Introduction

There has been a dramatic increase in the availability and use of synthetic arena surfaces by equestrians in recent decades. However, use of these surfaces has also been linked to lameness events in horses (Murray *et al.*, 2010b; Egenvall *et al.*, 2013) and little is understood about their impact on training and performance. Construction, location and constituents of arena surfaces as well as their response to different weather conditions, age and user traffic have all been highlighted as factors which affect surface properties and consequently the safety of the surface (Burn and Usmar, 2005; Burn, 2006; Murray *et al.*, 2010a; Murray, *et al.*, 2010b; Peterson *et al.*, 2012). The greatest body of research on equine surfaces exists in relation to racetracks and racehorses due to the considerable economic losses associated with racehorse injuries (Peterson *et al.*, 2012; Holt *et al.*, 2014). However, little is known of the applicability of this research to a general equine population.

Surface properties of individual arenas have important implications for the horses using them. Surfaces that are too hard can result in impact injuries, whilst surfaces that are too soft or deep can lead to fatigue and are associated with an increased injury risk in racehorses (Hill *et al.*, 1986; Mohammed, Hill and Lowe, 1991) as well as dressage horses (Murray *et al.*, 2010b). Synthetic surfaces whose functional properties can be altered under different conditions are considered to present a risk of injury to horses using them (Hobbs *et al.*, 2014). Moisture content has been shown to be a major factor in surface conditions, influencing the hoof-surface interaction (Ratzlaff *et al.*, 1997; Peterson and McIlwraith, 2008). Similarly hardness of human sports surfaces has been shown to be affected by drainage and compaction secondary to usage (Brosnan and McNitt, 2009). Frequency of maintenance is another important factor in arena properties; the literature shows that less frequent maintenance can be detrimental to surface performance with associated risks to equine users (Kai *et al.*, 1999; Peterson and McIlwraith, 2008; Murray *et al.*, 2010b). Arena surface constituents can affect the result of maintenance with certain methods (Tranquille *et al.*, 2015).

Research in to arena surfaces has taken the form of laboratory studies, horse-surface interaction studies, surface construction data, epidemiological studies, rider evaluations and testing using specific objective measurement devices (Murray *et al.*, 2010b; Tranquille *et al.*, 2012; Holt *et al.*, 2014; Lewis *et al.*, 2015; Northrop *et al.*, 2016; Hernlund *et al.*, 2017). The Clegg hammer has been used in previous studies to evaluate surface hardness or density (Clegg, 1976, 2012; Holt *et al.*, 2014) and is considered the most commonly used measure of surface performance in North America (Hobbs *et al.*, 2014).

The Longchamps penetrometer is a close relation to a dynamic penetrometer, or 'going-stick'. Penetrometers are generally used to assess turf or dirt tracks (Murphy, Field and Thomas, 1996), though they have been used previously in arena surface studies (Blundell, 2010). Since the load exerted (1kg weight) by a penetrometer is small, the result of the penetrometer is likely to represent the response of the track to the breakover stage of equine locomotion (Peterson *et al.*, 2012).

This study gathered information relating to arena characteristics and construction information through an interview questionnaire performed on owners of sound horses recruited to Chapter 3. Objective surface testing was carried out on a subset of the arenas identified in the questionnaire to establish the hardness, resistance to penetration and moisture content in these arenas in winter and summer conditions.

6.2 Hypotheses

i. *Arena characteristics in the study population will be consistent with those of previous studies in the UK*
ii. *Arena hardness, resistance to penetration and moisture content will be variable between different arenas and between different seasons within arenas*
iii. *Arena setting and construction will influence hardness, resistance to penetration and moisture content*

6.3 Aims

- *Describe the variation in hardness, resistance to penetration and moisture content of a subset of arenas in different UK seasons and how this is influenced by arena characteristics*

6.4 Study design

As part of an interview questionnaire performed on the owners of 93 sound horses (see Chapter 3), data were collected on arena surfaces used regularly by horses recruited to the study. Arena users were asked about the individual arena surface constituents and construction. Arena users were asked for their perception of surface conditions in normal, wet and hot or dry weather. Ten respondents were located on the same yard; 44 responses were collected for 34 arenas (Figure 6.1).

Of those arenas that were used regularly, permission was requested from yard owners for arena surface testing with a Clegg hammer, Longchamps penetrometer and collection of samples from which moisture content could be calculated. The owners of eleven arenas agreed to the testing, which was carried out once in December and once in June for each arena. Since recruitment (for Chapter 3) was ongoing from June 2017 to October 2018, data were collected in December 2017, June 2018 and December 2018.

Six arenas existed in pairs at three different premises: two premises had one indoor and one outdoor arena (Table 6.3 arenas 3 and 4, 8 and 9), whilst the third premises had two outdoor arenas (Table 6.3 arenas 10 and 11).

6.4.1 Arena testing methodology

A systematic sampling method as used in previous studies of arena surfaces (Northrop *et al.*, 2016) was designed to test areas where we expected higher usage (e.g. track, centre line, corners) as well as lesser usage, with an equal distribution over every surface (Figure 6.1a). A total of 31 separate points per arena were chosen for data collection. A further 4 to 6 locations at the gate were tested (Figure 6.1c). Areas that required testing by were measured out using strides (1 stride = 1 metre). This was then checked against a 100m surveyor's tape to ensure the accuracy of position of the testing areas. Where more than one instrument was used in the same area, the operator ensured the two measurements did not occur in identical places and therefore influence one another (Figure 6.1d). A pilot study was carried out on the Philip Leverhulme Equine Hospital arena surface. This was used to optimise the equipment and testing protocol prior to the main study.

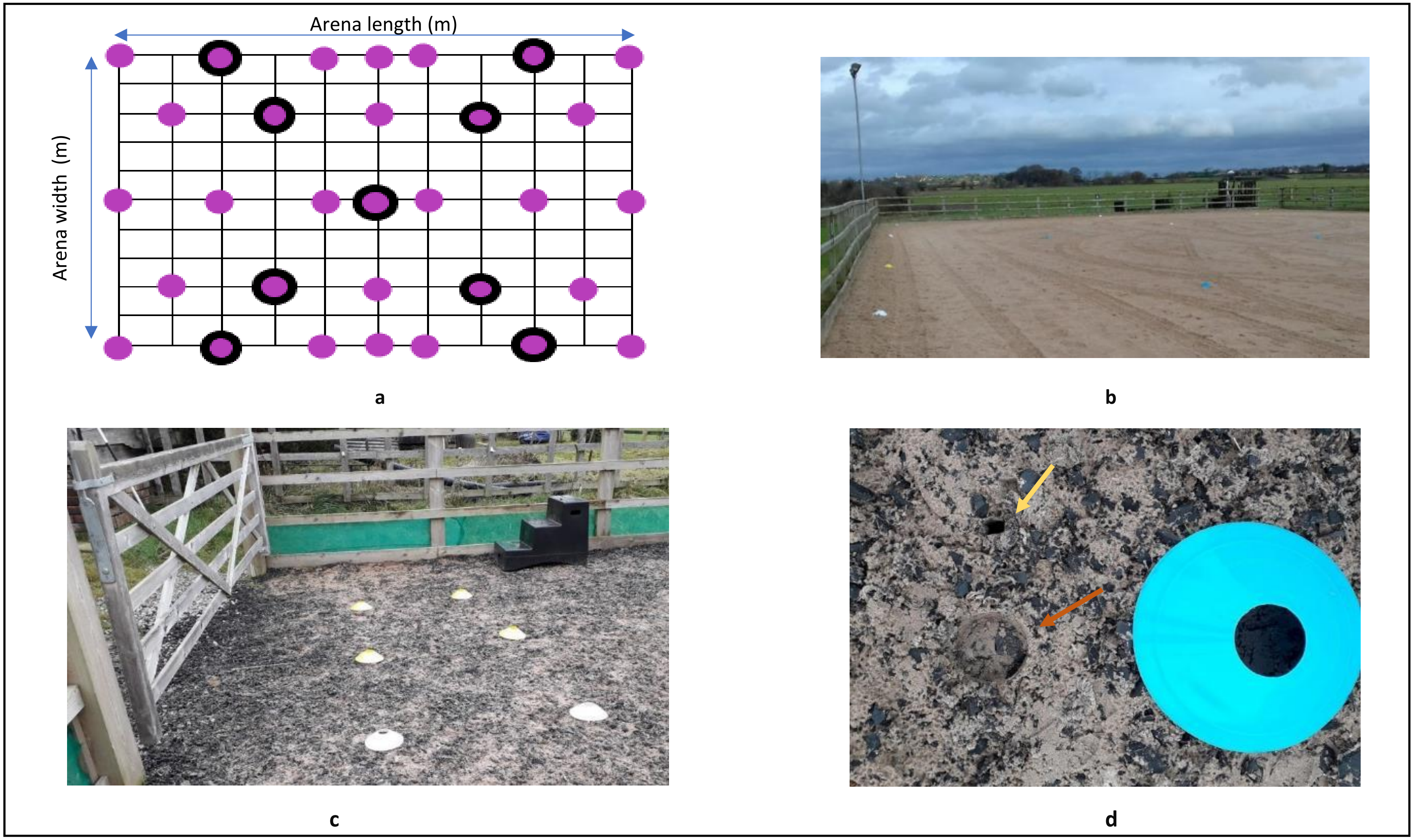

Figure 6.1a-d: Photographs and diagrams illustrate the methodology and equipment used to collect data from arena surfaces. a demonstrates the distribution of testing areas (based on stratified sampling method) for Longchamps penetrometer and Clegg hammer (purple circles) and moisture content sample collection (purple circles with outer rim of black) on a 10x10 grid. b demonstrates markers for data collection laid out in an arean as per diagram a, ready for data collection. c indicates the testing of gate area: 4-6 locations were sampled at gates, depending on the size of the gateway. d shows Clegg hammer (orange arrow) and Longchamps penetrometer (yellow arrow) imprints in separate places, next to marker.

a b c d

Figure 6.2a-d: Photographs showing equipment used to obtain surface hardness and total penetration depth data. a shows a Clegg hammer with drop weight (left side) connected to a hollow guide tube (right side); b shows the Clegg hammer result display. c shows the top of the pin of the Longchamps penetrometer, with scale for reading measurements during testing (blue arrow) and the 1 kilogram weight (red arrow); d the 1 metre length (green line) that the weight is dropped on the 1cm² pin during testing.

a

b

$$\text{Moisture content (\%)} = \frac{(\text{wet sample (g)} - \text{dried sample(g)})}{\text{dried sample(g)}} \times 100$$

c

Figure 6.3a-d: Photographs and equation demonstrating equipment and method used to calculate moisture content of samples collected from arena surfaces. a is a photograph of the equipment (trowel, ziplock bag, markers to show location on arena for sampling) used to gather and store the arena surface samples until they could be processed in the laboratory. b arena surface material in foil tray being weighed. c shows the calculation used to work out the percentage moisture content of samples collected from arenas.

6.4.1.1 Surface hardness testing

Surface hardness was tested using a Clegg Hammer (Clegg, 1976), as described by Richards (1994). This instrument consists of a hollow guide tube, and a 50mm diameter hammer fitted with an accelerometer (Figure 6.2a and b). A digital display shows the results of each drop, in units of gravities (Clegg, 2012; *Clegg Hammer*, 2021). The harder the surface, the greater gravities result will be (*Clegg Hammer*, 2021). A range of Clegg hammer weights and drop heights have been used to test different sports surfaces in the past. In this study a Clegg hammer of mass 2.25kg and drop height of 0.45m was used. The 2.25kg hammer has been shown to have a higher kinetic energy than its 0.5kg counterpart, and consequently to provide more reliable data (Hannaford and Fox, 2001), as well as a more accurate reflection of the hardness of the entire surface rather than just the top layer(s). In this study the hammer was dropped four consecutive times in each location and the reading taken from the fourth drop. This is the same as the original procedure outlined by Clegg (1976) which has been used in previous studies on equine arena surfaces as well as other sports surfaces (Setterbo *et al.*, 2011; Clegg, 2012; Holt, 2013).

6.4.1.2 Surface resistance to penetration testing

Surface resistance to penetration was measured using a Longchamp's penetrometer. A penetrometer was originally developed to test the 'going' of racetracks and consists of a 1kg weight which is dropped from a 1m height onto a 1cm^2 pin (Figure 2c and d). On racetracks it is usually dropped three consecutive times. However, it has not been used in many studies of arena surfaces (Blundell, 2010) and so to reduce the variability of the data in this project it was dropped five consecutive times in each location, as described previously (Blundell, 2010). The difference between the first and 5th drops was used for data analysis. Measurements are recorded from the scale on the metal pin (Figure 6.2c); a larger number indicates greater penetrability of the surface. In this study total penetration depth in centimetres is reported in the results.

6.4.1.3 Moisture content testing

Samples of 100-300g of surface material were collected from nine locations in the arena for further study. Due to time constraints, only five samples were collected from some arenas; the number of samples taken from each arena is detailed in the results. Statistical power calculations were not undertaken to determine the number of samples to be collected. Moisture content of surfaces has been shown to be associated with surface hardness as well as other surface properties. These samples were collected in sealable bags to prevent changes in moisture content during transportation (Figure 6.3a), and then processed as described in Racing Surfaces Testing Laboratory protocol ASTM D2216 (Babbitt, 2014). Percentage moisture content is calculated following processing of the samples (Figure 6.3).

6.4.2 Data analysis

Data were prepared for analysis using Microsoft® Excel® Version 2003 12624.20466 for Windows. Data analysis was carried out using R Studio for Windows (R version 3.5.2 (2018-12-20) "Eggshell Igloo" Copyright © 2018). Data were displayed as median and interquartile range (IQR) when non-normally distributed; mean and 95% confidence intervals (CI) when normally distributed. Paired Wilcoxon signed rank tests were used to compare June and December surface testing and moisture content results. For analysis of arena characteristics and surface testing, the Kruskal-Wallis test was used to test the statistical significance of differences in median values of continuous dependent variables and between categories of categorical independent variables. Where these findings were significant, pairwise Wilcox rank sum tests were used to discover where the significant differences existed, with results corrected for multiple comparisons within the software, using the Bonferroni method. The Mann-Whitney U test was used to calculate difference between continuous dependent variables and binary independent variables. Significance was set at $p<0.05$ unless otherwise stated.

6.5 Results

6.5.1 Questionnaire

The vast majority of horses recruited to the study (81/93, 86.0%) were reported to be exercised on a synthetic arena surface at least once weekly. For the horses that did use an arena regularly, since a number of horses were located on the same premises, 34 arenas were described. These arenas were most commonly on livery yards (17/34, 50.0%). The remaining arenas were on privately-owned yards (8/34, 23.5%), training and competition yards (5/34, 14.7%), rehabilitation centres (2/34, 5.9%) and riding stables (2/34, 5.9%). Outdoor arenas were more common (28/34, 82.4%) than indoor (6/34, 17.6%).

Details on arena construction and composition were available for 27 arenas, which had a median length of 60m (IQR: 40-60) and width of 30m (IQR: 20-35). The most common surface constituents were sand and rubber (10/27, 37.0%) and sand and fibre (10/27, 37.0%). Sand, rubber and fibre mixtures (4/27, 14.8%), sand-only (2/27, 7.4%) and woodchip surfaces (1/27, 3.7%) were also reported. Only three surfaces had wax in the surface mixture. Most arenas were reported to have a base (22/27, 81.5%), one arena did not have a base and for the remaining four arenas, the person who completed the questionnaire did not know whether the arena had a base or not. Of those with a base, limestone was the most common material (11/22, 50.0%). A membrane was reported for 15 arenas (55.5%), with the remaining 12 reporting no membrane (44.5%). The year of construction was known for 20 arenas, with mean time since construction being 6.6 years (95% CI: 4.4-8.7).

Arena usage was available for 27 arenas: the median number of horses using an arena per day was 10 (IQR: 3-13.5; range 1-56 horses per day). Information on arena maintenance was available for 30 arenas (Table 6.1). Harrowing was the most popular choice of arena maintenance. Only a single arena was watered, regardless of weather conditions. There was a range of frequency of arena maintenance (Table 6.1) from daily maintenance to every six months or more, and one owner described that the arena was only maintained when someone complained to the yard owner.

Table 6.1: Description of arena maintenance method and frequency as reported by respondents to the questionnaire (n=34 arenas)

Arena Maintenance	**Number of Arenas**
Method	
Harrowing	24
Rolling	3
Levelling	2
Grading	1
Watering	1*
Unknown/data not available	4
Frequency	
Daily	5
Weekly	9
Fortnightly	3
Monthly	4
Less than once per month	9
Unknown/data not available	4

**one arena used watering in the summer in addition to harrowing*

Horse owners were asked to describe how they perceived the arena surface when riding on it in different weather conditions (Figure 6.4). Where arena users were answering for more than one horse, only a single response was taken per person to avoid duplication. By far the most common descriptions used were that arenas were level and uniform across all weather conditions, though these descriptions were more common in normal weather than in wet or hot and dry conditions (Figure 6.4). Boggy, firm and waterlogged conditions were reported more commonly in wet weather. Hot or dry conditions were accompanied by increased reporting of arenas feeling deep, and these conditions were the only reported cause of dustiness. Arenas that were sloping as well as those that were uneven had similar results across all weather conditions. Arenas were less commonly described as patchy in hot and dry conditions than in normal or wet conditions.

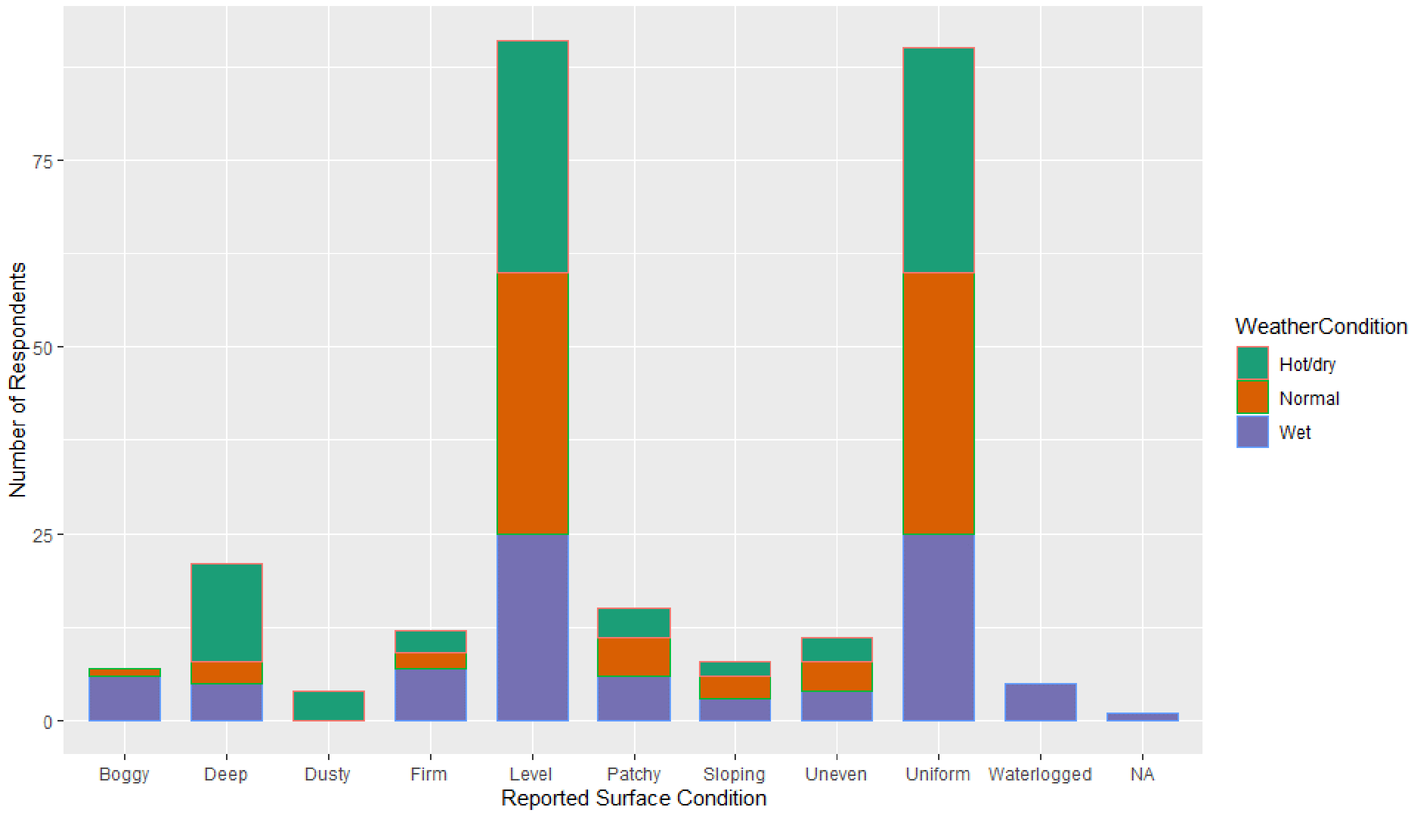

Figure 6.4: Bar graph depicting the results of respondents who reported the condition of the arena in different weather conditions (n=44 respondents)

As shown by Table 6.2, in most cases where the arena surface was perceived to have a negative condition (i.e. not described as level and uniform) the affected areas were unavoidable. Indeed, only boggy or waterlogged areas had a higher number of respondents reporting the area was avoidable, and that they avoided it.

Table 6.2: Illustrating questionnaire results which detail the frequency with which arena surface condition was perceived to be other than level and uniform, whether the affected area(s) were avoidable and avoided when exercising horses (n=24 respondents)

Arena Surface Perception	**Area Avoidable**		**Area Avoided**	
	Yes	No	Yes	No
Patchy	4	11	4	11
Uneven	0	11	0	11
Deep	4	17	4	17
Sloping	0	8	0	8
Firm	0	12	0	12
Boggy	5	2	5	2
Dusty	0	4	0	4
Waterlogged areas	4	1	3	2

6.5.2 Surface Testing

Of the 34 arenas described as being used by recruited horses, a subset of 11 were tested using equipment as described above. Table 3 describes the key characteristics of each surface.

Table 6.3: Characteristics of arenas included in surface testing (n=11)

Arena	Indoor or Outdoor	Premises type	Length (metres)	Width (metres)	Surface Materials	Base Material	Membrane	Age (years)	Use (horses per day)	Maintenance Method	Maintenance Frequency (days)
1	Outdoor	Livery Yard	60	25	Sand and fibre	Limestone	No	6	4	Rolling	42
2	Outdoor	Livery Yard	60	30	Sand and fibre	Unknown	Yes	1	2	Grading	3
3	Outdoor	Riding Stables	60	20	Sand and fibre	Unknown	No	1	39	Rolling	1
4	Indoor	Riding Stables	42	21	Sand and wax	Unknown	Yes	4	56	Harrowing	1
5	Outdoor	Livery Yard	60	20	Sand and rubber	Crushed concrete	No	5	1	Harrowing	30
6	Outdoor	Privately-owned Yard	40	25	Sand and fibre	Limestone	Yes	17	3	Harrowing	180
7	Outdoor	Privately-owned Yard	40	20	Sand and rubber	Limestone	Yes	1	3	Harrowing	14
8	Outdoor	Training/Competition Yard	70	40	Sand and fibre	Limestone	Yes	1	10	Harrowing	3
9	Indoor	Training/Competition Yard	60	30	Sand and fibre	Limestone	Yes	5	12	Harrowing	3
10	Outdoor	Training/Competition Yard	40	35	Sand, rubber and fibre	Limestone	Yes	7	10	Harrowing	1
11	Outdoor	Training/Competition Yard	80	46	Sand, rubber and fibre	Limestone	Yes	12	10	Harrowing	1

There was a lot of variation in surface hardness, as measured by the Clegg hammer, between individual arenas in both December and June (Table 4). Most arenas showed a significant change in surface hardness between December and June (Table 4); with the surface of six arenas being less hard in June than in December. Three arenas showed no significant difference between the two time points.

Table 6.4: Surface hardness results December and June (n>31 areas sampled per arena)

Arena (areas sampled)	Hardness (Gravities)		
	December Median (IQR)	**June Median (IQR)**	**P value**
1 (n=40)	155.5 (134.2-167.1)	129.5 (92.5-155.2)	**<0.001**
2 (n=37)	125.0 (116.0-136.0)	143. (124.0-154.0)	**<0.001**
3 (n=37)	108.0 (91.0-117.0)	141.0 (123.0-153.0)	**<0.001**
4 (n=37)	136.0 (117.0-148.0)	127.0 (101.0-142.0)	**0.03**
5 (n=37)	96.0 (85.0-106.0)	100.0 (87.0-110.0)	0.91
6 (n=35)	115.0 (92.5-142.5)	118.0 (88.0-142.0)	0.38
7 (n=37)	84.0 (76.0-94.5)	59.0 (54.0-68.0)	**<0.001**
8 (n=37)	45.0 (40.0-49.0)	44.0 (38.0-49.0)	**0.02**
9 (n=37)	129.0 (123.0-135.0)	109.0 (97.0-112.0)	**<0.001**
10 (n=40)	110.0 (99.0-123.0)	101.5 (88.7-118.0)	0.24
11 (n=31)	107.5 (97.0-121.2)	91.0 (80.2-119.0)	0.04

**Significant difference between indoor and outdoor arenas on the same site in December (p<0.001) and June (p=0.007)*

Results from Longchamps penetrometer testing in December showed mild variation in resistance to penetration between arenas, which was also seen in June (Table 6.5). Only three arenas showed a significant difference between December and June (Table 6.5), of which two showed increased and one showed decreased values in June, compared with December.

Table 6.5: Surface resistance to penetration results from December and June (n>31 areas sampled per arena)

Arena (areas sampled)	Total Penetration Depth (cm)		
	December Median (IQR)	**June Median (IQR)**	**P value**
1 (n=40)	2.5 (2.0-3.0)	2.5 (1.9-3.0)	0.71
2 (n=37)	5.0 (3.0-6.5)	4.5 (3.5-6.0)	0.38
3 (n=37)	3.0 (2.5-3.5)	2.5 (2.0-3.5)	0.58
4 (n=37)	2.0 (1.5-2.5)	2.5 (1.5-4.0)	**<0.001**
5 (n=37)	2.0 (1.5-3.0)	2.0 (1.0-3.0)	0.53
6 (n=35)	2.5 (2.0-3.5)	2.5 (2.0-3.5)	0.55
7 (n=37)	4.5 (2.5-5.5)	4.5 (3.5-6.0)	0.33
8 (n=37)	2.5 (2.0-3.5)	1.5 (1.0-2.5)	**<0.001**
9 (n=37)	2.5 (2.0-3.0)	3.5 (3.0-4.0)	**0.02**
10 (n=40)	2.5 (2.0-3.5)	2.5 (2.0-3.0)	0.42
11 (n=31)	3.0 (2.5-3.5)	3.0 (2.5-3.5)	0.26

IQR = interquartile range

A wide range of percentage moisture content values was recorded, both between arenas and between seasons in the same arenas (Table 6.6). There was considerable variation between arenas in terms of percentage moisture content calculated from samples taken in December. This was partly due to the inclusion of both indoor and outdoor arenas; the two indoor arenas had median moisture content of <5%, whilst all outdoor arenas had median moisture content of >12%, and in most cases >20% (n=6/9; Table 6.6).

Table 6.6: Results of moisture content analysis of samples from the arenas in June and December (n=9 samples per arena unless otherwise specified)

	Moisture Content (%)		
Arena	**December Median (IQR)**	**June Median (IQR)**	**P value**
1	12.1 (7.9-14.8)	2.8 (2.7-3.7)*	0.06
2	26.3 (26.0-27.5)	4.9 (4.3-5.8)	**0.008**
3	51.0 (43.0-59.1)*	9.1 (8.0-11.8)	0.06
4	4.3 (1.7-4.4)*	0.5 (0.5-0.8)	0.06
5	26.9 (24.4-28.3)	2.7 (2.0-3.2)	**0.004**
6	16.8 (15.0-18.2)	4.9 (3.5-6.1)	**0.004**
7	18.2 (17.6-19.0)	1.1 (0.7-2.3)	**0.004**
8	27.1 (22.9-28.9)	0.2 (0.0-0.3)	**0.004**
9	0.3 (0.3-0.6)	0.1 (0.0-0.2)	**0.02**
10	21.6 (20.2-24.9)	1.5 (1.4-3.5)	0.06
11	21.2 (17.8-22.7)	2.8 (2.5-2.9)	0.06

IQR = interquartile range; n=5 moisture samples per arena*

There was some variation in moisture content in June, though this was less extreme than that of December (Table 66). The two indoor arenas had a moisture content of <1% in June, whilst all outdoor arenas had a moisture content of <10%, although for six outdoor arenas it was >2%. Six arenas showed a significant reduction in moisture content in June compared with December; these were all outdoor arenas. For outdoor arenas 10 and 11 on the same premises, there was no significant difference between the moisture content of both arenas in either December or June.

6.5.3 Intra-arena variability

As well as looking at variation between arenas, the coefficient of variation for each arena was calculated to give an indication of the intra-arena variation (Table 6.7). Many arenas showed a difference in variability across their surface between June and December.

Table 6.7 Coefficient of Variation for moisture content, hardness and resistance to penetration results for each arena

	Moisture Content Coefficient of Variation (%)		Hardness Coefficient of Variation (%)		Resistance to Penetration Coefficient of Variation (%)	
Arena	**December**	**June**	**December**	**June**	**December**	**June**
1	36.2	27.1	30.3	31.1	33.3	37.8
2	6.1	41.9	14.9	16.0	41.4	33.2
3	17.8	38.3	16.2	14.7	38.5	59.7
4	115.4	112.4	24.6	31.7	24.5	37.3
5	27.0	37.5	28.5	37.2	50.9	53.4
6	12.7	34.0	30.5	28.6	40.2	35.3
7	7.57	78.2	14.1	24.2	47.5	30.7
8	20.7	113.7	20.6	21.2	32.4	29.3
9	53.5	103.5	11.8	11.3	48.3	72.5
10	14.5	60.7	18.2	16.2	36.0	32.3
11	16.4	24.7	16.8	31.2	27.0	25.4

CoV = Coefficient of Variation

6.5.4 Association between arena surface characteristics and surface testing results

When Clegg hammer results were compared between premises types, in both June and December, livery yards and riding stables had significantly harder arena surfaces than training and competition yards or privately-owned yards (Table 6.8). Sand and rubber surfaces were significantly less hard than all other surface constituents in this study. The sand-only surface was significantly harder than all other arena constituents in December, though this was only true of sand and rubber and sand, rubber and fibre surfaces in June.

Table 6.8 Hardness and total penetration depth results from June and December by arena location and surface constituents (n=11 arenas)

Yard or Surface Factor	Hardness (Gravities)		Total Penetration Depth (cm)	
	December Median (IQR)	**June Median (IQR)**	**December Median (IQR)**	**June Median (IQR)**
Yard Type				
Livery	124.5 (100.0-151.0)[a,b]	123.5 (100.0-149.0)[a,b]	2.5 (2.0-3.5)	3.0 (1.6-4.0)[a]
Privately-owned	93.0 (81.3-114.8)	75.0 (59.0 – 117.3)	3.5 (2.0-5.0)	3.5 (2.5-5.0)[a]
Riding Stables	116.5 (104.2-136.0)[a,b]	131.0 (110.0 – 148.8)[a,b]	2.5 (2.0-3.0)[a]	2.8 (2.0-3.5)
Training/competition	108.0 (73.5 – 125.0)	93.0 (64.0-115.0)	3.0 (2.0-3.5)[a]	2.5 (2.0-3.5)[a]
Surface Constituents				
Sand	136.0 (117.5-148.0) [c,d,e]	127.0 (101.0-142.0) [c,e]	2.0 (1.5-2.5)[c,d,e]	3.0 (2.-3.5)
Sand and Fibre	117.0 (91.0-137.0)[c]	118.0 (85.0-145.0)[c,e]	2.5 (2.0-3.5)	3.0 (2.0-4.0)
Sand fibre and rubber	108.0 (97.0-122.0)[c]	99.50 (83.8-118.0) [c,d]	3.0 (2.5-3.5)	2.5 (2.5-3.0)
Sand and rubber	88.0 (79.5-100.5)	85.0 (59.3-100.0)	2.8 (2.0-4.5)	3.5 (2.0-4.5)

[a]significantly different from privately-owned yards (p<0.05); [b] significantly different from training yards (p<0.05) [c]significantly different from sand and rubber surfaces (p<0.05); [d]significantly different from sand and fibre surfaces (p<0.05); [e].significantly different from sand, rubber and fibre surfaces (p<0.05). p values have already been adjusted for multiple comparisons using the Bonferroni method therefore p<0.05 is considered significant; IQR = interquartile range

Longchamps penetrometer readings from June demonstrated that arena surfaces on privately-owned yards had the lowest resistance to penetration (i.e. highest penetration depth); significantly lower than that of riding stables or livery yards (Table 6.8). Arenas at training and competition yards had significantly higher resistance to penetration than that of livery yards. In December, arenas on privately-owned yards and training and competition yards had significantly lower resistance to penetration than those on livery yards or riding stables.

In terms of surface constituents, no significant difference was identified between different constituents in June. However, in December the sand-only arena had a significantly lower penetration depth than all other arena constituents (Table 6.8).

In both June and December, surfaces with a limestone base were less hard than those with a different base material (Figure 6.5a and 6.6a). Waxed surfaces were significantly harder than non-waxed surfaces and indoor surfaces were harder than outdoor (Figure 6.5b, 6.6b, 6.5c and 6.6c). The presence of a membrane in the arena construction was associated with reduced hardness in June results; no significant difference was observed in December (Figure 6.5d and 6.6d).

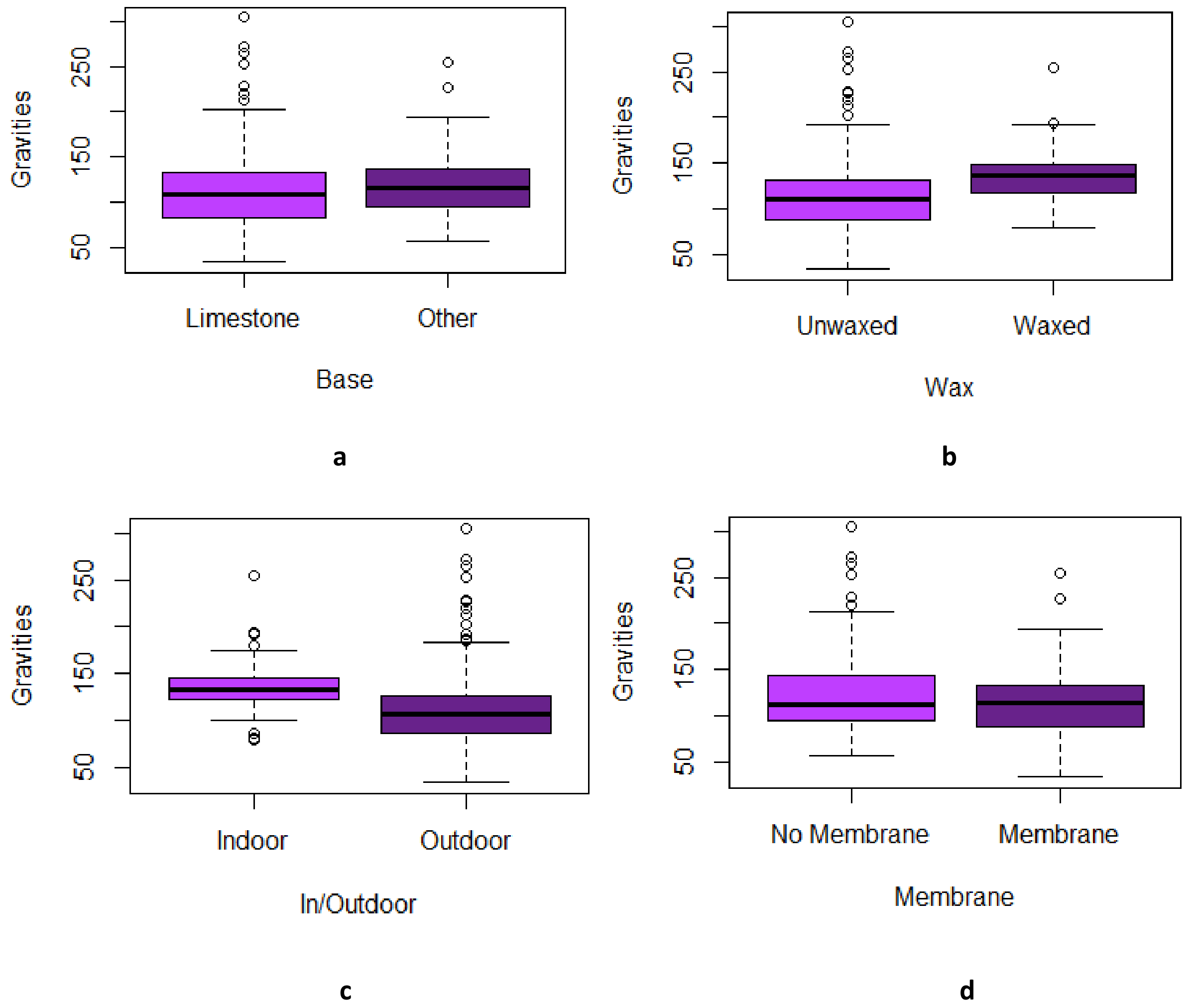

Figure 6.5a-d: Boxplots showing arena surface hardness (as measured by a Clegg hammer) results for December. a: base material (p=0.01), b: wax in surface mixture (p<0.001), c: indoor or outdoor arena (p<0.001) and d: presence or absence of surface membrane (p=0.06).

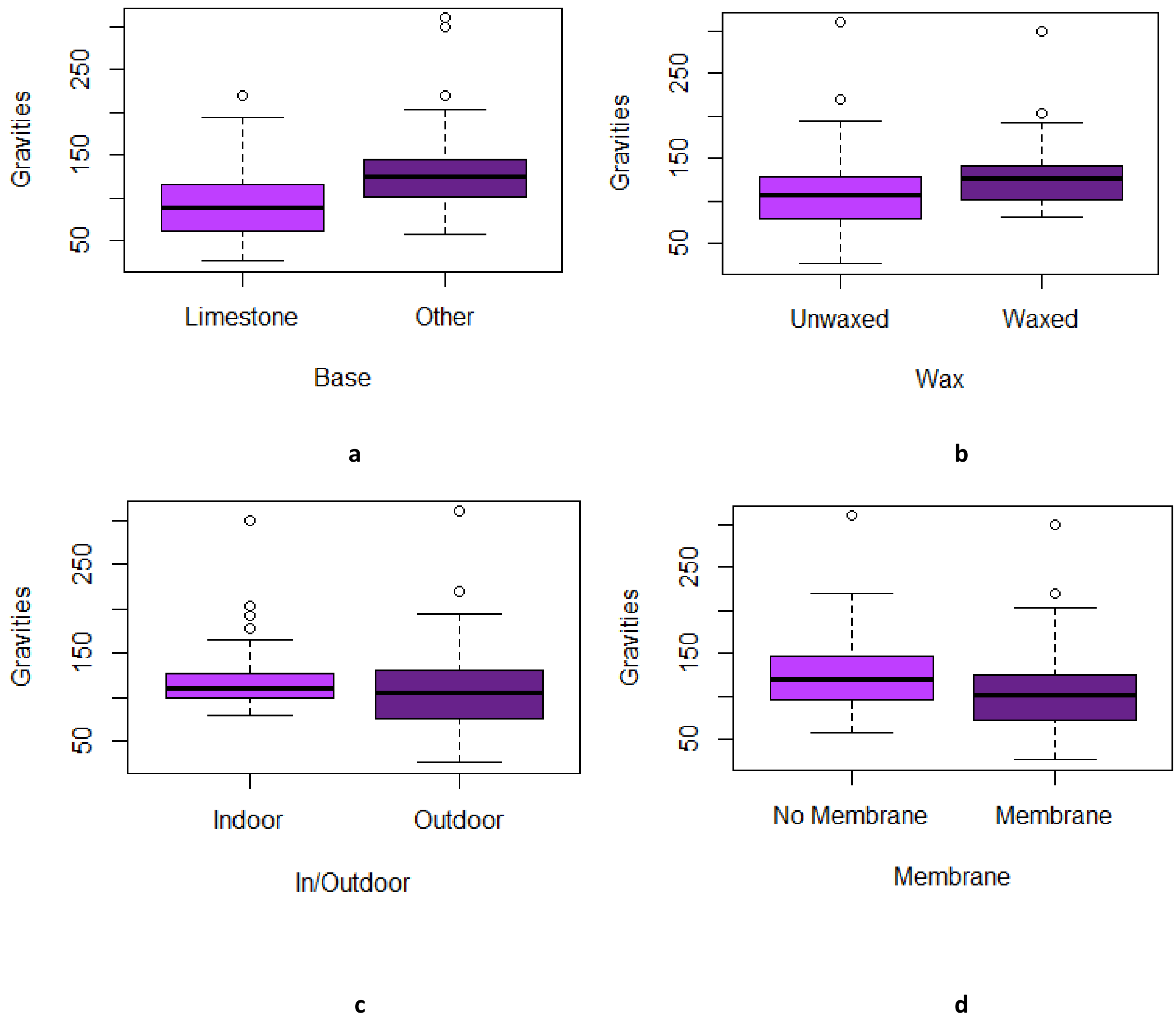

Figure 6.6a-d: Boxplots showing arena surface hardness (as measured by a Clegg hammer) results for June. a: base material (p<0.001), b: wax in surface mixture (p<0.001), c: indoor or outdoor arena (p=0.02) and d: presence or absence of surface membrane (p<0.001).

There was a significant difference in Longchamp penetrometer readings between those arenas that did or did not have a membrane in the surface; those with a membrane had lower resistance to penetration in both December and June (Figures 6.7d and 6.8d). In December, waxed surfaces had a significantly higher resistance to penetration, whilst outdoor surfaces had a lower resistance to penetration (Figures 6.7b and 6.8c). Base material did not significantly affect the resistance to penetration in either June or December (Figures 6.7a and 6.8a).

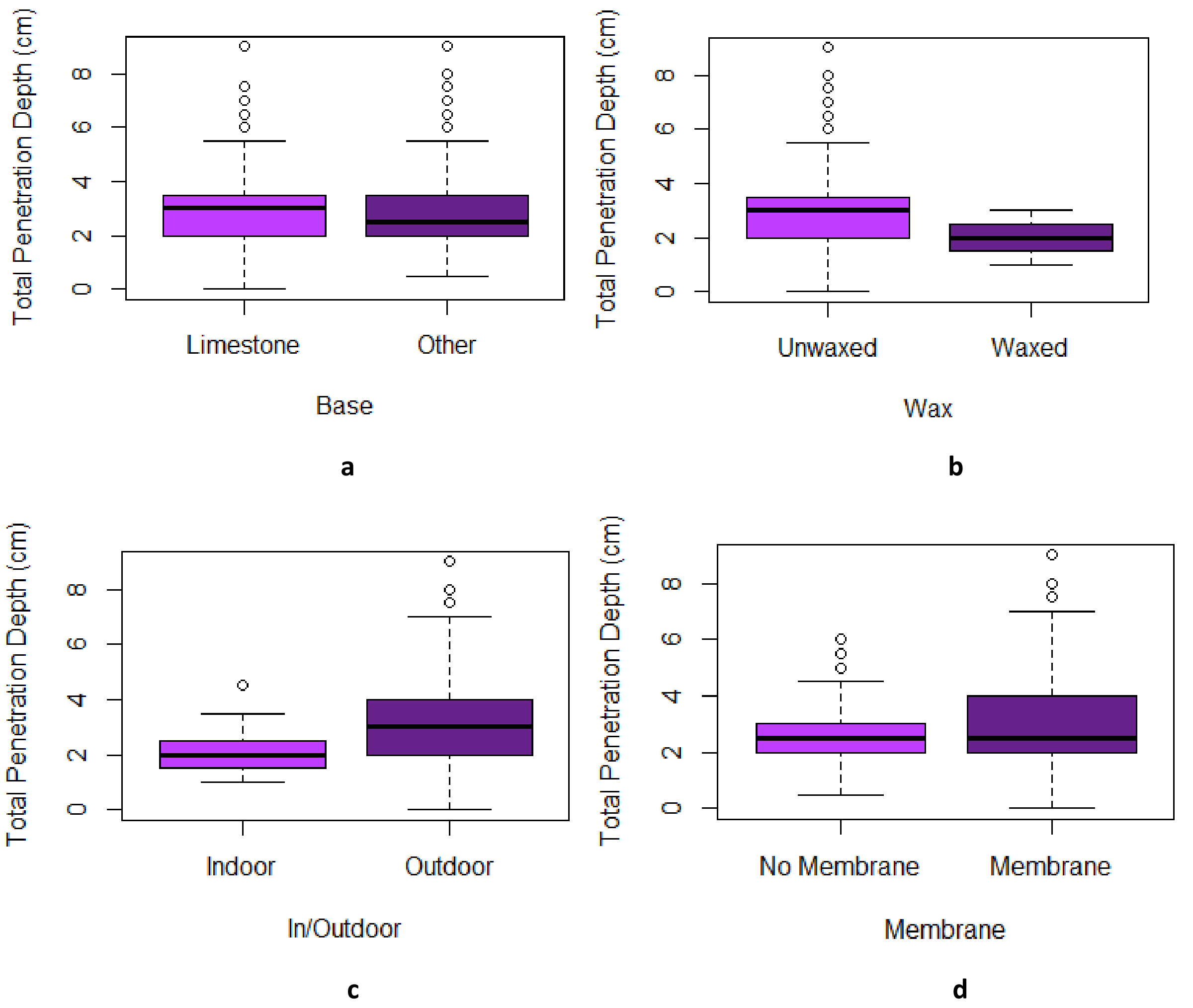

Figure 6.7a-d: Boxplots showing arena surface total penetration depth (as measured by a Longchamps penetrometer) results for December. a: base material (p=0.24), b: wax in surface mixture (p<0.001), c: indoor or outdoor arena (p<0.001); d: presence or absence of surface membrane (p<0.001)

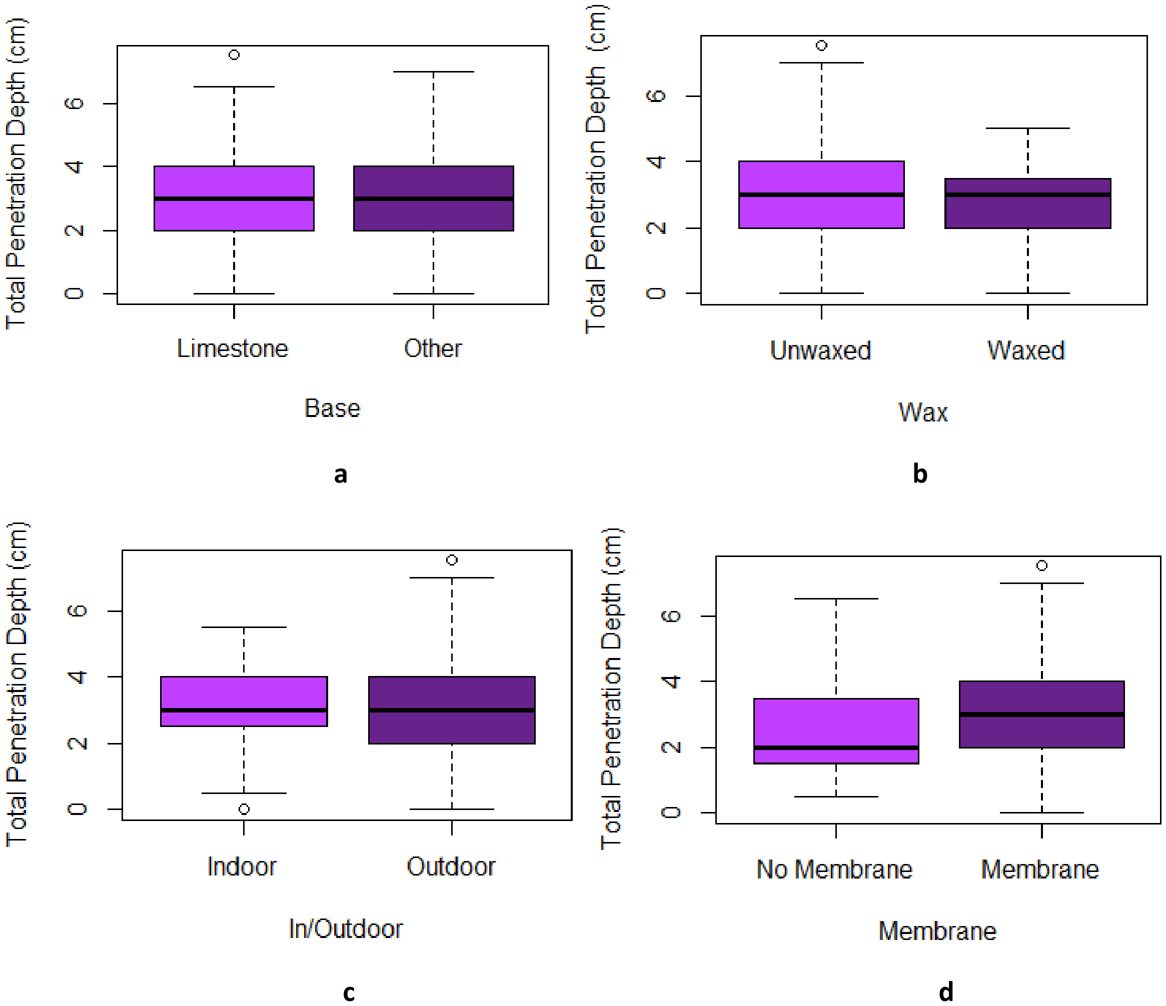

Figure 6.8a-d: Boxplots showing arena surface total penetration depth (as measured by a Longchamps penetrometer)results for June. a: base material (p=0.68), b: wax in surface mixture (p=0.29), c: indoor or outdoor arena (p=0.17); d: presence or absence of surface membrane (p<0.001)

In June, arenas on training and competition yards had significantly lower moisture content than those on livery yards, privately-owned yards and riding stables (Table 9). This pattern was not observed in December. The moisture content for sand-only arenas was significantly lower than sand and rubber as well as sand, rubber and fibre arenas (p<0.001 in both cases) in December (Table 9). No significant difference was identified between the moisture content of arena surface constituents in June.

Table 6.9: Moisture content results for different yard types and surface constituents, June and December

Yard or Surface Factor	Moisture Content (%) December median (IQR)	Moisture Content (%) June median (IQR)
Yard Type		
Livery	25.3 (14.8-27.1)	3.3 (2.4-4.6)[b]
Privately-owned	17.6 (16.8-19.0)	3.3 (1.1-4.8)[b]
Riding Stables	28.8 (4.3-49.0)	6.5 (0.5-9.0)[b]
Training/Competition	21.4 (15.5-23.5)	0.3 (0.0-1.6)
Surface constituents		
Sand	4.3 (1.7-4.4)[c,e]	0.5 (0.5-0.8)
Sand and Fibre	19.6 (12.1-27.3)	3.6 (0.2-6.4)
Sand, Fibre and Rubber	21.4 (18.5-22.9)	2.6 (1.5-3.3)
Sand and Rubber	20.6 (19.0-26.9)	1.1 (2.0-2.8)

[b] significantly different from training yards ($p<0.05$) [c]significantly different from sand and rubber surfaces ($p<0.05$); [d]significantly different from sand and fibre surfaces ($p<0.05$); [e].significantly different from sand, rubber and fibre surfaces ($p<0.05$). p values have already been adjusted for multiple comparisons using the Bonferroni method therefore $p<0.05$ is considered significant; IQR = interquartile range

The use of limestone as a base material was significantly associated with reduced moisture content in both June and December (Figures 6.9a and 6.10a), and the same was true of those surfaces with wax in their mixture (Figures 6.9b, 6.10b) and surfaces that were indoor (Figures 6.9c and 6.10c). In June, the presence of a membrane was significantly associated with reduced moisture content (Figure 6.9d); the same trend was seen in December, but this was not significantly different (Figure 6.9d).

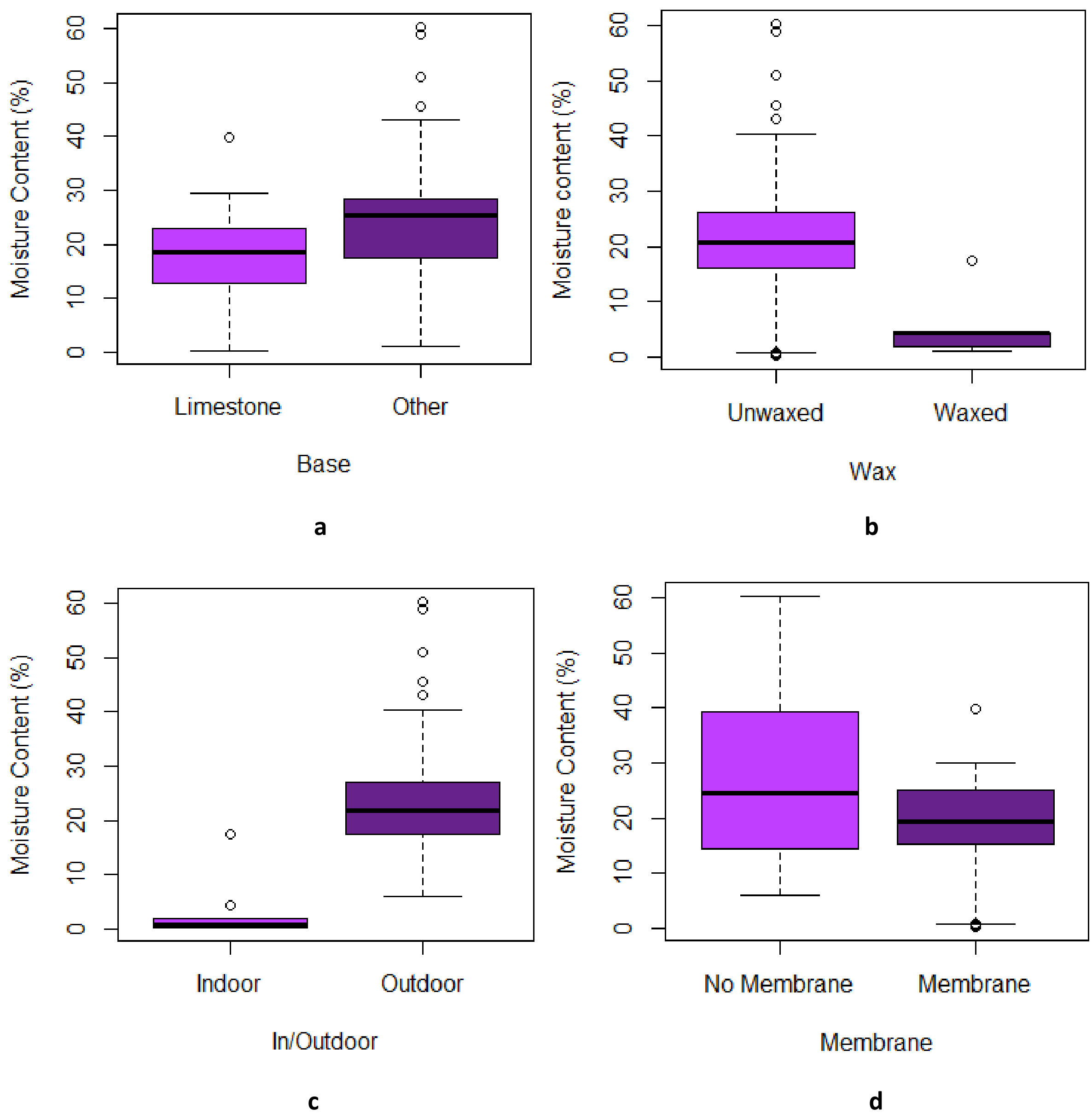

Figure 6.9a-d: Boxplots showing moisture content results from December by a: base material (p=0.002), b: wax in surface mixture (p=0.006), c: indoor or outdoor arena (p<0.001); d: presence or absence of surface membrane (p<0.08)

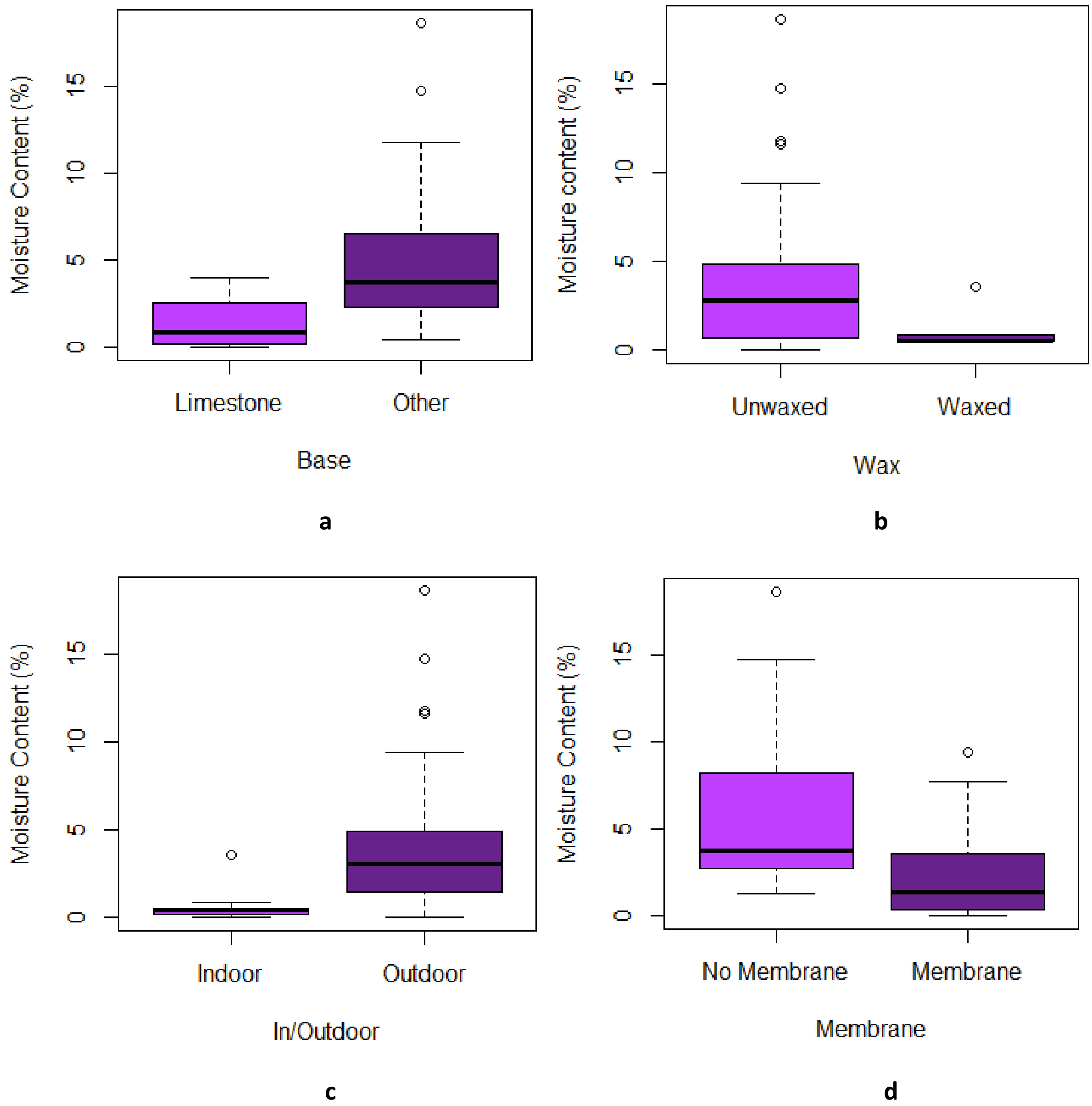

Figure 6.10a-d: Boxplots showing moisture content results from June by a: base material (p<0.001), b: wax in surface mixture (p=0.05), c: indoor or outdoor arena (p<0.001); d: presence or absence of surface membrane (p<0.001)

6.6 Discussion

This chapter answered the hypotheses set out in section 6.1: the study established that the arena characteristics of this study were similar to other published literature in the UK. Differences were identified in arena hardness, resistance to penetration and moisture content between arenas and seasons. The significant impact of arena construction factors on hardness, resistance to penetration and moisture content was also demonstrated.

6.6.1 Characteristics of arena surfaces used by a cohort of sound horses

Results of the interview questionnaire revealed that outdoor arenas were much more common than indoor, accounting for 82.1%. Average arena age (6.6 years) was also similar to that reported in a previous study (median 5 years, IQR: 1-8 years) (Murray *et al.*, 2010a). Livery yards were the most common premises type included in the current study, followed by privately-owned premises. This current study was conducted using convenience sampling, this may not reflect the true situation in North-West England and North Wales. In a study of dressage riders a greater proportion of arenas were on privately-owned premises (Murray *et al.*, 2010a).

Sand and rubber has previously been reported to be the most common surface mixture (Murray *et al.*, 2010a), however in this study, sand and rubber and sand and fibre both represented the same proportion of arenas. The only waxed surface was an indoor arena, in keeping with the literature; wax is purported to prevent drying out and subsequent dustiness, which can become a problem in indoor surfaces (Murray *et al.*, 2010a). The median length of arenas in the current study was 60m and width 30m, which is larger than that previously reported, where the study sample comprised a greater proportion of privately-owned arenas (Murray *et al.*, 2010a). This may reflect the space available on private premises. A higher proportion of arenas were reported to have a base compared with previous studies (Murray *et al.*, 2010a), whilst a smaller number of respondents were not aware of whether arenas had a base or not. This may be due to increased owner interest and awareness of arena characteristics at the time of the current study. As in a previous study, limestone was the most reported base material (Murray *et al.*, 2010a).

In the current study, the median number of horses using an arena per day was greater than that previously reported (Murray *et al.*, 2010a); likely due to the higher proportion of livery yards in the current study. The reported frequency of maintenance was highly variable in this study, from daily to more than six-monthly intervals. No respondent detailed that arenas were maintained in response to a particular number of users, in spite of the fact that previous studies on both dressage arenas and racetracks have identified that increased usage between maintenance events poses an increased risk of injury to horses using such surfaces (Parkin *et al.*, 2004; Verheyen *et al.*, 2005; Parkin, 2007; Murray *et al.*, 2010b). Surfaces can become more compacted and offer less in the way of energy return to the limb with increased usage per maintenance event, which may contribute to this increased risk of lameness (Kai *et al.*, 1999; Setterbo *et al.*, 2013). Such changes depend on the individual constituents and construction of each surface.

In terms of the method of surface maintenance, harrowing was the most reported method in the current study, though grading, rolling and levelling were also listed. This author is not aware of any other literature reporting rates of grading, rolling or levelling. A previous study demonstrated that although harrowing significantly decreased vertical deceleration and vertical load in waxed sand and fibre surfaces, the same effect was not seen on sand and rubber surfaces (Tranquille *et al.*, 2015). This highlights that appropriate maintenance methods are required for each individual arena and its properties. In the current study watering was reported for just a single arena which suggests it is a highly unusual practice.

6.6.2 Surface perception

The rate of surfaces being perceived as patchy, uneven, or sloping were fairly similar across all three weather conditions considered, suggesting that these features are inherent to the surface rather than caused by too little or too much moisture.

Boggy and waterlogged conditions were reported most in wet weather conditions. This suggests a failure in the drainage aspect of the surface, which may be related to base material or other construction factors (Jackson Arenas, 2009; Murray *et al.*, 2010a). Surfaces were reported to be firm most commonly in wet conditions. This fits the consensus that increased moisture content of arena surfaces leads to greater adhesion between (sand) particles and consequently increased shear resistance. Ideal surface moisture content has been postulated to be 8-17%; increases from this may increase the hardness of the surface (Barrey, Landjerit and Walter, 1991; Ratzlaff *et al.*, 1997).

Conversely, dry sand has low shear resistance and hence surfaces which become too dry may provide a less stable surface for horses to work on, increasing their risk of injury (Murray *et al.*, 2010b). Deep surfaces can increase the horse's effort, causing fatigue and increased rate of injury (Hill *et al.*, 1986; Mohammed, Hill and Lowe, 1991). In the current study, some arenas were described as deep during hot or dry weather conditions, which is a cause of concern with respect to injury risk for horses using the surface. Similarly, the fact that watering arenas was only reported for one arena suggests that arena owners are not taking necessary steps to ensure consistency in moisture content of arena surfaces, despite the implications associated with its variability.

As well as how they perceived the surfaces, horse owners and riders were asked whether they were able to and if they did avoid the affected areas. Boggy and waterlogged areas were the only ones where most riders described being able to avoid the affected areas. Where arenas were patchy, uneven, deep, sloping, firm and dusty, the vast majority if not all riders were unable to avoid the affected areas. This maybe because these conditions are more likely to affect the entire surface rather than just certain regions. To the authors’ knowledge no previous studies have examined how avoidable certain surface conditions are.

6.6.3 Objective surface testing

Objective testing of surface hardness revealed large inter-arena differences, with some surfaces measuring three-times the hardness of others, which was similar during both June and December. The majority of arenas showed a significant difference in hardness between June and December, with six surfaces less hard in June than in December. Moisture content has been reported to be an important driver of surface hardness. Higher moisture content leads to greater cohesion between sand particles, increasing the shear resistance of a surface and consequently its stability (Ratzlaff *et al.*, 1997; Chateau *et al.*, 2010; Murray *et al.*, 2010a). Weather conditions in June are likely to have led to surfaces being dryer, and so reduced moisture content may be a reason for this reduction in hardness (Barrey, Landjerit and Walter, 1991; Ratzlaff *et al.*, 1997). One of the arenas that had lower hardness in June had a waxed surface; higher temperatures are more likely to be nearer the melting point of the wax, which may result in a reduction of surface hardness. The three arenas that had higher hardness in June are more difficult to explain since it would be expected that the moisture content to be lower at this time of year, as described above. However, it is possible that other factors such as ageing, usage or maintenance factors were the cause of this change, rather than seasonality and moisture content.

Testing of surface resistance to penetration with a Longchamps penetrometer revealed less variation between surfaces than the surface hardness results. The Longchamps penetrometer has not been extensively used to study resistance to penetration of synthetic arena surfaces and may be affected by layering of such constructions (Blundell, 2010; Hobbs *et al.*, 2014). Resistance to penetration of three arenas was significantly different in June compared with December. Of these, one outdoor arena showed an increase in resistance to penetration in June compared with December (i.e. a lower reading in June compared with December) and two indoor arenas showed a decrease in resistance to penetration in June, which was accompanied by an increase in hardness as measured by the Clegg hammer. It may be that reduced surface moisture has in turn reduced the shear resistance of the surface, or that the difference in usage in summer is contributing to the surface condition. Similarly, the changes may not be representative of seasonality or weather conditions but of surface ageing. For the one indoor arena with wax in the surface mixture, it is also possible that there was increased laxity of the wax in summer, due to higher temperatures that are closer to the melting point of the wax.

Moisture content calculated from surface samples taken at the time of surface testing revealed a huge range of results, particularly in December. Unsurprisingly, given the common prevailing weather conditions in June and December in the UK, moisture content was always lower in June than December. This difference was significant in six arenas. However, very few arenas had a moisture content within what has been stated to be the optimum of 8-17% either in December or June (Barrey, Landjerit and Walter, 1991; Ratzlaff *et al.*, 1997). Variation outside these recommended limits has been reported to alter surface hardness and elastic rebound provided to the foot at impact, which may either result in horses being subject to surfaces that are too hard, or those that increase muscle fatigue and consequently the risk of injury (Barrey, Landjerit and Walter, 1991). Although as described above increased moisture content can lead to increased shear resistance and stability of a surface, when surfaces become saturated with water, shear strength reduces again (Hobbs *et al.*, 2014). Since each arena will have its own optimal moisture content and similarly the optimal properties for some equine activities will be different from that of others (Hobbs *et al.*, 2014), it is hard to know for certain the implications of the moisture content results recorded in this study. Despite this, the evidence of large variation in moisture content between seasons is concerning since it likely presents a risk to horses using these arenas. Since data were only collected at the extremes of summer and winter seasons, it is not possible to know whether surface conditions stabilise between seasons or not. Given the effects of climate change, such as more intense rainfall and more frequent, hotter heatwaves which are already being seen in the UK (Met Office) , it may be that the moisture content and associated changes in arena properties are subject to increasingly severe disturbances in relatively short periods of time. It has previously been concluded that such sudden changes in the conditions of a surface may increase the risk of injury, where a horse is not adapted to using surfaces with a range of different conditions (Murray, *et al.*, 2010b).

As well as inter-arena variation and differences between seasons, intra-arena variation was shown to be relatively high across all arenas tested in this study and was often subject to considerable change between seasons. A previous study which assessed spatial variation of a number of surface properties across a single surface identified peak load and moisture content as the main factors of interest (Northrop *et al.*, 2016).

6.6.4 Relationship between construction and surface properties

Analysis was performed on the relationship between hardness, resistance to penetration and moisture content results and characteristics of the arena surfaces. Yard type and surface constituents were both significantly associated with surface hardness in both December and June. Sand and rubber surfaces were significantly less hard than all other surfaces in December and June. This may indicate the role that rubber plays in reducing surface hardness. Previous studies have identified that the addition of rubber to a surface may improve the elasticity, as well as reducing evaporation from a surface (Jackson Arenas, 2009; Murray *et al.*, 2010a). A study on the mechanical properties of different surface compositions found the sand and rubber surfaces had the lowest maximum vertical deceleration of the surface types tested (Tranquille *et al.*, 2013). In December sand-only surfaces were significantly harder than all other surface constituents tested. There was only one sand-only arena in the study, so this may reflect particular properties of this single arena.

Arenas with a limestone base had significantly lower hardness than those with another material base. Arena manufacturers recommend limestone as a base due to its superior drainage properties (Jackson Arenas, 2021) arenas with a limestone base were also shown to have a significantly lower moisture content in this study, regardless of season. Outdoor surfaces were significantly less hard than indoor surfaces. Given that only two indoor surfaces were tested in this sample, this result may reflect properties of those individual arenas, particularly since one of these arenas is sand and wax. Sand-only surfaces have previously been reported to pose a greater risk of equine lameness than other constituents (Murray *et al.*, 2010b), though it is not known if there is a causal link. Conversely four outdoor arenas had rubber in their mixture. The addition of rubber to a surface can reduce compaction (Hobbs *et al.*, 2014), therefore preventing the surface from becoming hard with use compared with other constituent materials. The arena with a waxed surface was significantly harder than non-waxed surfaces in both June and December and had a lower moisture content than non-waxed surfaces. These findings may be related to the melting point of waxes used in such surfaces. The presence of a surface membrane was associated with reduced hardness in June, but a reversal of this trend that was not statistically significant was seen in December. This may indicate the role a membrane plays in drainage of arena surfaces and associated moisture content.

Resistance to penetration results showed that arenas on privately-owned yards were significantly more penetrable than on most other yard types. Sand-only surfaces were the least penetrable of all surface types in December. This may reflect the above results of surface hardness by yard and surface constituent type.

Training and competition yards had significantly lower moisture content than all other types of arena in June. This may be because all arenas in this category had a limestone base which is postulated to have superior drainage properties compared with other base materials. Similarly, these arenas were all reported to be maintained regularly (at least every three days), which may have an impact on the drainage of the arena. Alternatively, since these four arenas were located in pairs on two premises, it may be that these particular areas were subject to lower rates of rainfall compared with other arenas in the population tested as part of this study. Historical weather data was not examined as part of this study, however, so no conclusions can be drawn about this. The moisture content of sand-only arenas was significantly lower than sand and rubber as well as sand, rubber and fibre arenas in December. As described above, since only a single arena was sand-only, and this particular arena was indoor, this is likely to have resulted in the lower moisture content due to protection from rainfall.

6.6.5 Limitations

For the questionnaire aspect of this study, rider and horse factors may have affected the responses, particularly with respect to surface condition perception. A previous study of top level show-jumpers identified that subjective data collected from riders contributed over 30% of the variation in the dataset (Hernlund *et al.*, 2017). This study had a range of horses and riders which has likely added even more variation. A complete set of data on construction and maintenance of the surfaces was not available since a number of horse owners at livery yards did not know these details and yard owners were not always willing to provide these details when contacted or did not respond to contact. There may have been some selection bias since horses and owners were recruited to the study for a study on foot shape and lameness as described in Chapter 3 of this thesis. Hence it could be reasonable to assume that these owners were more motivated about prevention of lameness than the general equestrian population. As a result, these owners may have been more aware of surface characteristics and maintenance and therefore provided more information about the surfaces that they used. They also may have chosen to house their horses at sites with good quality and well-maintained arena surfaces. Similarly, it is possible that those yard owners that were interested in the properties of their arena surfaces and prevention of lameness events may have been more willing to facilitate testing of their arena surfaces, resulting in the better constructed and maintained arenas being tested.

Although when carrying out surface testing the primary researcher attempted to test all arenas immediately after they had been maintained using a harrow or other method, in most cases this was not possible in order to also test the arena at a time convenient to arena owners and users. Likewise, it was not possible to test all arenas at the same time or on the same day. Due to changes in temperature and rainfall this may have affected some of the results. Date and time of testing were recorded in all instances. Usage of arenas between maintenance and testing may have affected the results from affected arenas. Additionally, although the aim was to collect samples to test moisture content from nine separate sites in the arena, in some cases time did not allow for collection of the full number, in these instances five samples were collected. This may have reduced the representativeness of the moisture content results in these instances.

Where testing of two surfaces occurred on one site, the samples collected from the first site had to be stored until testing of the second surface had been completed, then both were processed on return to university buildings. This, as well as the time during transport, may have caused some changes in temperature and consequently evaporation of moisture from the surface material. All samples were stored in sealed plastic bags to limit the amount to which this may have influenced the eventual moisture content results. Weather data from the weeks prior to data collection were not included in this study..

6.6.6 Conclusions

Synthetic arena surfaces are commonly used by horse riders in the North-West of England and North Wales. The majority of arenas are outdoor and sand fibre or sand rubber are the most common surface constituents. Perceived undesirable changes in arena properties are relatively common, these may have implications for the injury risk of horses using these surfaces. Hardness, resistance to penetration and moisture content showed some seasonal variation. Moisture content of arenas was almost always outside of recommended limits. Factors such as wax in the surface mixture, base material and presence of a membrane were shown to influence surface hardness, resistance to penetration and moisture content. Further studies are required to establish the effect of seasonality and ageing on different arena types and how the effect of prevailing weather conditions can be mitigated to reduce the risk of musculoskeletal injuries to horses.

Chapter 7

General Summary

7.1 Introduction

The studies presented in this thesis represent the first major investigation into longitudinal foot shape changes and the relative impacts of farriery and lameness. The studies included address the influence of foot-trimming, signalment factors such as height and breed, work pattern, discipline, arena surface usage and stable management on foot shape and loading. A significant amount of previous research has occurred in the pursuit of understanding risk factors for equine lameness, and how both the healthy and pathological limb or foot should look and move. Conversely, although farriery is a critical cog in the machine of maintaining optimal foot shape and health, there is a paucity of studies examining the role of the farrier in manipulating foot shape and loading for the better. Consequently, farriery still remains more an art than a science, despite its significant impact on equine health and welfare.

7.2 Cross-sectional study of sound horses

Previous studies have examined foot shape using digital photographs or radiographs. Only a limited number of these have done so around trimming or shoeing by a farrier and most have focussed on a single breed of horse and horses in the same management system. Chapter 3 of this thesis reports on a study of the general equine population in the North-West of England and North Wales in order to capture results that were representative of the UK equine population. The data collected enabled assessment of the impact of environmental and genetic factors on hoof shape, in order to answer hypothesis *iii*, Chapter 3. The breed and gender demographic of the study population, as well as stable management aspects reflected the findings of other surveys carried out across the UK equine population (Wylie *et al.*, 2013; Blue Cross, 2018). Similarly, as found in these studies, hacking or leisure was the most common discipline of horse in the study population. However, this study had a slightly more competitive equine demographic than previous equine surveys conducted in the UK in the last 10 years (Wylie *et al*., 2013; Blue Cross, 2018).

On veterinary observation, many horses were affected by at least one hoof abnormality, of which imbalance was the most common (Chapter 3). There were large differences between veterinary-observed and owner-reported hoof abnormalities, as has been recorded previously in aged horses (Ireland *et al.*, 2012). Foot shape findings from this sample of horses largely reflected the findings of previous studies, though examination of the medial view of the foot added a new dimension that has not been studied before. This revealed medial and lateral differences in foot shape, highlighting that feet should not be treated as though they are symmetrical. Similarly, this study supported that of Caldwell (2017) by finding that geometric proportionality did not exist pre-trimming nor was it achieved post-trimming by a farrier. This calls in to question whether the aims of such a trimming protocol are even achievable and if so, whether they would be beneficial to any horse on which it can be achieved.

As well as asymmetry between medial and lateral aspects of the individual feet, contralateral forelimbs were shown to be different from one another. This has been previously reported in the context of increased lameness risk or reduction of competitive lifespan (Ducro *et al.*, 2009), however numerous studies fail to address RF and LF limbs as different. Here it was identified in a population of sound horses. Again, most horse owners in this study were unaware of these asymmetries, which reflects the findings of previous studies and potentially the view of owners that mild asymmetries are not significant (Dijkstra *et al.*, 2018).

Contralateral asymmetries were also observed in foot loading, where significant differences between forelimb pairs were common. Comparison of foot quadrants as well as use of a novel, topological approach in equine pressure mat studies enabled understanding of changes in distribution of load over the foot surface in response to foot-trimming by a farrier. Indeed, trimming was shown to change the nature of these differences from greater loading in the toe region pre-trimming, to in the frog region post-trimming. This may reflect the observed foot shape changes: decreased length at the toe and elongation of measurements over the centre of sole (COR-COP, COR-FrA distances) which indicate palmar heel migration post-trimming as also reported a previous study (Caldwell, 2017).

A number of intrinsic and extrinsic factors were shown to significantly influence foot shape in the study population, from breed and height to individual farrier and discipline. Some findings indicated longer toe length and lack of parallelism between the toe and heel may be related to horses that were used for hacking or leisure riding, as opposed to different disciplines. Although this may indicate infrequent foot care by a farrier or poorer foot balance in leisure horses, it is also possible that other horse or environmental factors were the cause. When tested as part of a multivariable model, shoeing frequency was not a significant factor in any foot shape measure. Further work on shoeing frequency and horse discipline are required to understand this relationship. The answers appeared to be clearer with respect to the influence of various factors on foot imbalance. Horses shod by a farrier who had completed or enrolled in further education had 18-times the odds of avoiding mediolateral imbalance compared with horses shod by a farrier that had never enrolled in further education (Chapter 3, Table 3.15). The trend was the same for dorsopalmar imbalance but with a reduced effect size ((odds ratio = 3); Chapter 3, Table 3.15). This may indicate the importance of continuing professional development and further education in the farriery industry, if it is to move towards a more evidence-based profession in the future.

Although management factors were shown to be significantly associated with foot shape, direct correlations between foot shape and pressure mat data were very few and, where they did exist, weak ($r<0.40$). This may simply demonstrate the complexity of the foot shape and foot loading relationship and that a change in one element does not necessarily lead to an expected change in another, as identified by previous work (Van Heel *et al.*, 2005).

7.3 Longitudinal study of sound horses

Having addressed changes around a single trimming event in sound horses, Chapter 4 followed a number of those horses longitudinally. Sound horses showed increases in DHWL over time with variable accompaniment of reduction of LHWA, as also described in a shorter study (Van Heel *et al.*, 2005). Over consecutive shoeing cycles DHWA-HA decreased in the LF; the opposite finding to that of another study that occurred over three consecutive shoeing cycles (Caldwell, 2017)

Of the horses that became lame during the study period, LF lame feet had a greater DHWA-HA than lame RF counterparts, as well as a steeper LHWA. Similarly, the two LF lame limbs were significantly different from 26 LF sound limbs; lame feet had a larger DHWA-HA indicating poorer dorsopalmar foot balance. Conversely LHWA was steeper in lame LF feet than sound LF feet, which may indicate a shift to a more upright, boxy shape due to chronic unloading of lame limbs. No significant differences were identified between lame and sound RF feet at the end of this study.

Changes in loading over the study period showed that lower pressures were exerted at the end of the study compared with the start in sound horses. In lame limbs this was also the case pre-trimming, though the reverse was observed post-trimming. Increased foot loading in lame limbs when compared to their previous sound selves may correspond to the counterintuitive findings of McGuigan and Wilson (2001), that lame limbs are not always unloaded in the way we would expect. Results of individual lame horses provided a mixed picture, with some horses unloading a lame limb and others overloading it although limited numbers of lame horses made clear patterns unobtainable.

Statistically significant correlations between foot loading and foot shape measurements were again very rare. However, a finding from this study: increased DHWL and decreased loading of the frog at the end of the study, is the reverse of the difference observed pre-post trimming in Chapter 3. Thus, even if they may not be directly comparable, consistent changes that occur together may clarify foot shape and loading relationships that exist.

7.4 Cross-sectional study of horses with foot lameness

To further build on the findings of Chapters 3 and 4, Chapter 5 enabled exploration of a cohort of lame horses with lameness localised to the foot. Foot shape measurements of RF lame limbs exhibited signs of poor dorsopalmar and mediolateral imbalance. LF lame limbs were generally larger dimensionally than LF sound limbs from Chapter 3; this may have simply been due to the breed and height of horses in the two groups. When average foot measures were assessed by MRI finding, those affected by navicular disease displayed a boxy, upright shape in comparison to DDFT lesions and DIPJ disease.

Static and dynamic pressure mat results for foot quadrants indicated a degree of unloading of lame limbs in comparison to sound limbs, though this trend was not observed consistently. Reduced mediolateral sway in lame limbs has previously been documented, which may be a cause of increased cranio-caudal loading and may reduce the expected difference between lame and sound limbs (Pitti *et al.*, 2018; Egan *et al.*, 2021). Simultaneous unloading of bilaterally lame limbs as well as the various compensations available in walk (Serra Bragança, Rhodin and van Weeren, 2018) may also have influenced the results obtained.

As a cross-sectional study, this study still cannot resolve the chicken-and-egg quandary that continues to concern veterinarians and farriers alike as regards foot shape and loading in foot lameness events. However, this is the first known study to examine both shape and loading in a cohort of lame horses under-going MRI investigation. This study was also the first to examine LF and RF lame limbs as separate entities, demonstrating that RF lame feet suffered poorer dorsopalmar foot balance than LF lame feet. This reiterates the findings of Chapter 4 that LF and RF lame limbs can behave differently from each other, as well as from their sound counterparts. These findings are unsurprising since LF and RF differences were shown in the sample of sound horses in Chapter 3, however they should be used to support the treatment of LF and RF as different individual limbs in future studies, to avoid missing key findings that relate to laterality, as has likely occurred in the past.

7.5 Arena surfaces questionnaire and testing

A study into the arenas commonly used by a cohort of sound horses in the North-West of England and North Wales and the subsequent objective testing of a subset of these arenas revealed that most horses used an arena regularly (Chapter 6). Many arenas suffered undesirable changes in surface properties following different weather conditions, of these many changes were not able to be avoided by horses using the arenas. Although most owners were aware of arena maintenance, there was an enormous range in the frequency in which it was carried out, as well as in the method used. For no arena was the frequency of maintenance reported to be associated with a specific volume of equine (or other user) traffic.

Seasonality appeared to have a significant impact on arena hardness, resistance to penetration and moisture content. Moisture content has previously been shown to be a key factor in a number of surface properties (Hobbs *et al.*, 2014; Northrop *et al.*, 2016) and that was reinforced in the current study. Arena construction factors such as the material used for base, presence of a membrane and arena surface constituents were also shown to have an effect on the outcomes of surface testing.

7.6 Limitations

As referred to in greater detail in the discussion section of individual chapters, the studies comprising this thesis suffered several limitations. In every chapter convenience sampling was used, which may have resulted in various biases in the subjects studied and consequently the data collected. Similarly, this study occurred exclusively in the North-West of England and North Wales, and therefore has unknown relevance for different regions of the UK or different countries.

Recruitment and retention of privately-owned horses to both cross-sectional and longitudinal studies was extremely challenging. The resulting small sample sizes may have impacted the results observed, due to biases or lack of statistical power. It became clear when carrying out this study that farriers should receive financial compensation for their professional time if involved in similar studies in the future. The self-employed and often lone-working character of this industry offers little freedom for individuals to dedicate their time to assist in scientific studies in the course of their day-to-day work. Additionally, this may facilitate the recruitment of a broader cross-section of farriers, rather than only those who are engaged enough in the cause of science to contribute.

This study cannot provide any conclusive answers to the question of how to prevent foot lameness in the horse, or what is optimal foot shape and loading, but it is a start. Larger scale longitudinal studies of a range of equine demographics are required to understand the foot shape and foot loading relationship and how these features affect or are affected by lameness events. The role of arena surfaces in equine lameness events has been highlighted in recent decades and hence the exploration of this aspect added valuable information in the understanding of the usage of such surfaces and how they change over time and different seasons. Further studies are required to understand the effects of seasonality and ageing on arena surface properties. Additionally, more evidence regarding the effectiveness of various maintenance methods and when they should be applied to ensure surface consistency would benefit owners and users of arenas to apply the best possible practice. Longitudinal studies of arena surfaces are also required to quantify arena degradation over time and understand the influence of weather conditions and maintenance procedures on arena properties, in order to prevent equine lameness events.

7.7 Concluding remarks and future work

Overall, the studies reported in this thesis have enabled a logical analysis of foot shape and loading from a single trimming event in sound horses to the longitudinal study of horses that both remained sound and became lame, finishing with horses already suffering with a lameness localised to the foot. The findings corroborate previous studies that several factors influence foot shape and the occurrence of hoof abnormalities. Of these, farriery has a major impact, but equine demographics and stable management are also highly relevant.

By providing a uniquely topographical analysis of foot loading in the horse the studies in this thesis have allowed us as researchers to see beyond a single value per foot strike. Consequent observation of patterns in foot shape and loading in study subjects both at a single trimming event and over a long period of time indicated the existence of previously elusive foot loading and shape associations. Assessment of lame and sound horses revealed that foot loading is not as simple as being symmetrical in sound horses and asymmetrical in lame horses nor decreased loading in lame limbs and increased in sound limbs. Such findings should be taken forward to future work and hopefully lead to more concrete answers regarding optimal foot shape and prevention of lameness in the horse.

Future work should maintain left and right forelimbs as separate groups for data analysis, whether sound or lame horses are being investigated. If foot shape is examined, both medial and lateral sides should be measured as these can behave differently, which may have implications for foot care. This thesis has proven that the pSPM method can be used on equine pressure mat data, it is the author's hope that other researchers will use this tool in future to examine foot-loading differences between and across equine populations.

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Appendix 1

14/6/17
Version 8

Horse number

Leahurst Equine Foot Balance and Farriery Study

As part of our research into equine foot balance and lameness, we are conducting a questionnaire into the horses and ponies that will be involved in the study. If you are happy to complete the questionnaire it will provide a lot of very useful information to us regarding the work pattern and management of your horse or pony.

1. General Information

Q1. What is the name of your horse/pony?

Q2. How old is your horse/pony?

years months (approx.)

Q3.What breed is your horse/pony? (if unknown give the type)

Q4. What gender is your horse/pony?

Mare
Gelding
Stallion

Q5. What height is your horse/pony? hh/cm (*delete as appropriate*)

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Horse number

2. Work/exercise

Q6. What activity do you primarily do with your horse/pony?

Dressage	☐	Hunting	☐
Hacking/leisure	☐	Riding School	☐
Show-jumping	☐	Driving	☐
Eventing	☐	Showing	☐
Polo	☐	Riding/pony club activities	☐
Endurance/TREC	☐	Other	☐

If *other* please specify

Q7a. Do you and your horse/pony participate in competitions? (*if no skip to Q8*)

Yes ☐ No ☐

Q7b. If *yes* at what level:

International	☐	National	☐
Regional	☐	Local	☐

Q7c. If *yes* how many years has your horse been competing for?

Q7d. If *yes* how many competitions do you take part in per month?

Q7e. If *yes* how many competitions do you take part in per year?

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Version 8

Horse number [ ]

Q8. What intensity of work does your horse/pony do?

None	
Light (mainly walking)	
Medium (trotting, cantering, low jumps)	
Hard (galloping, high-level dressage, jumping)	

Q9. Is this the usual level of work for your horse/pony?

Yes	
No	

If no why not/what is? [ ]

Q9. How many times per week do you exercise your horse/pony? [ ]

Q10. On average how much time do you spend exercising your horse/pony for per week?

[ ] Hours

Q11. Please describe the different types of exercise that you do with your horse/pony

	Sessions per week	Time (minutes) per session
Lungeing		
Horsewalker		
Flatwork/dressage		
Jumping		
Hacking		
Other		

Is it one hacking session that is changed for lunging/horsewalker?

Q12. How long do you spend 'warming up' before training? (minutes per session)

[ ]

Horse number

Q13a. What surfaces do you work your horse/pony on? (tick all that apply)

Grass		Rubber-based	
Gravel trails		Road (tarmac)	
Sand - based		Other	

If *other* please specify

Q13b. How much time on average per week do you spend using each surface type (minutes)

	Sessions per week	Time (minutes) per session
Grass		
Gravel trails		
Sand-based		
Rubber-based		
Road (tarmac)		
Other		

3. Arena surface information

For the arena surface that you use most commonly:

Q14. Is the arena:

- Indoor
- Outdoor (no roof)
- Outdoor (with roof)

Q15. What size is the arena? ....m?

Q16a. Does the arena have a base?

- Yes
- No
- Don't know

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Version 8

Horse number

Q16b. If *yes* what is the base made of?

- Crushed concrete ☐
- Road planings ☐
- Tarmac ☐
- Limestone ☐
- Don't know ☐
- Other ☐

Q17. Does the arena have a membrane between the base and the surface?

- Yes ☐
- No ☐
- Don't know ☐

Q18. How old is the arena (years)? ....

Q19a. What are the surface constituents?

Sand and rubber	☐	Woodchips	☐
Sand and fibre	☐	Rubber	☐
Sand and PVC	☐	Other	☐
Sand	☐	Don't know	☐

If *other* please specify ....

Q19b.Does the surface have wax in it's mixture?

- Yes ☐
- No ☐

Q19c. If the arena has rubber as a component is it:

- Mixed in ☐
- Top layer ☐

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Version 8

Horse number

Q20a. Would you describe the surface in normal conditions as:

Patchy		Level	
Uneven		Uniform	
Deep		Firm	
Sloping		Other	
Boggy			

Area affected	Avoidable?	Do you avoid it?

Q20b. Would you describe the surface in wet conditions (ie after rainfall) as:

Patchy		Level	
Uneven		Uniform	
Deep		Firm	
Sloping		Other	
Boggy			

Area affected	Avoidable?	Do you avoid it?

Q20c. Would you describe the surface in hot/dry conditions as:

Patchy		Level	
Uneven		Uniform	
Deep		Firm	
Sloping		Other	
Dusty			

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Horse number

Area affected	Avoidable?	Do you avoid it?

Q20d. Do you have any other comments about the condition of the arena surface in normal, wet or dry conditions?

Q21. Where is the arena situated?

Privately owned yard - yours		Livery yard	
Privately owned yard - other		Riding stables	
Training/ Competition yard		Other	

Q22. On average how many horses use the arena per day? ....

Q23. What activities is the arena used for?

Activities		**Activity**	
General purpose (livery)		Showing (ridden)	
General purpose (riding school)		Driving	
Dressage		Jumping (single fence)	
Cross-country		Jumping (grids)	
Lunging		Jumping (course)	
Vaulting		Jumping (loose)	
Horseball		Dog agility	
Showing (in hand)		Non-equestrian (e.g. car boot sales)	

Q24. Are any competitions or events held in the arena? No

Activities	**Times per month**	**Activity**	**Times per month**
General purpose (livery)		Showing (ridden)	
General purpose (riding school)		Driving	
Dressage		Jumping (single fence)	
Cross-country		Jumping (grids)	
Lunging		Jumping (course)	
Vaulting		Jumping (loose)	
Horseball		Dog agility	
Showing (in hand)		Non-equestrian (e.g. car boot sales)	

Horse number

Q25. What method of surface maintenance is used and how often?

Method ____________________

Frequency ____________________

Renovations	**Yes/no**	**Date**
Relaying original surface		
Laying new surface		
Adding roof		
Extension		
Top up of surface material		
Repair to base		
Repair to membrane		

Q26. Do you use different surface types from normal when you go to events/lessons? No

If *yes*, please describe these surfaces and in what circumstances (e.g. for lessons, competitions) you use them?

Surface type	Circumstance	Usage frequency

4. Stabling and Turnout

Q27. Please describe where you keep your horse/pony:

Privately owned yard - yours	☐	Livery yard	☐
Privately owned yard - other	☐	Riding stables	☐
Training/competition yard	☐	Other	☐

If *other* please specify

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Version 8

Horse number [ ]

Q28. Please describe the current stabling and turnout routine for your horse/pony (tick the appropriate one)

At pasture day and night	
At pasture in the day and stabled at night	
Stabled in the day and at pasture at night	
Other	

If *other* please specify

Q29a. If your horse/pony is stabled what bedding do you use?

	No rubber matting	With rubber matting
Straw		
Shavings		
Hemp		
Paper/cardboard		
Other		

If *other* please specify

Q29b. How do you manage the bedding?

Deep litter with daily skipping out		Full muck out daily	
Other			

If *other* please specify

Q30. Approximately how many hours is your horse/pony turned out for per day?

Horse number

5. Diet

Q31. How would you describe your horse/pony's current bodyweight?

Thin	☐	Normal	☐
Slightly overweight	☐	Very overweight	☐

Q32. What forage do you feed your horse/pony? (tick all that apply)

Grass	☐	Hay replacer (hifi/readigrass)	☐
Hay	☐	Silage	☐
Haylage	☐	Other	☐

If *other* please specify

Q33. What hard feed do you give your horse/pony? (tick all that apply)

Chaff	☐	Sugar beet	☐
Alfalfa	☐	Cereals (oats/barley)	☐
Pony nuts/grass nuts	☐	Bran	☐
Coarse mixes	☐	Over 16/veteran mix/cubes	☐
Other	☐	None	☐

If *other* please specify

Q34. Do you currently feed any nutritional supplements?

Hoof supplements (biotin/farrier's formula)	☐	Joint supplements	☐
Oils/High oil supplements	☐	Herbal supplements	☐
Vitamins or minerals	☐	Feed balancers	☐
Other	☐	None	☐

If *other* please specify

Horse number

Q35. Why did you decide to use these supplements?

Recommended by farrier

Recommended by friend

Recommended by veterinary surgeon

Other

If *other* please specify

Q36. If different people recommended different supplements please specify who recommended which

Q37. Do you feel these supplements have had any effect?

Yes No

(hard to say)

If *yes*, what?

6. Foot care and farriery

Q38. What is the name of your farrier?

....

Q39. How long has your horse been treated by this farrier?

years months

14/6/17
Version 8

Horse number ☐

Q40. Is your horse shod?

Yes – front feet only ☐
Yes – all four feet ☐
No ☐

Q41a. If *yes* is this with normal or remedial shoeing?

Normal ☐ Special/ Remedial ☐

Q41b. If *remedial*, which feet are involved?

Front feet only ☐
Back feet only ☐
Left fore ☐
Right fore ☐
Left hind ☐
Right hind ☐
All four feet ☐

Q41c. If remedial, what type of shoe/shoeing technique?

…………………………………………………………… ……………………………

Q42a. On average how often is your horse shod (or trimmed if not shod)?

Every …………………………… Weeks

Q42b. Does the frequency of your horse's shoeing change during the year?

Yes, increases in summer ☐
Yes, increases in winter ☐
No ☐

14/6/17
Version 8

Horse number

Q43. Have you noticed or has your farrier made you aware of any diseases or abnormalities of your horse's feet?

	Yes	No
In the last 6 months		
6 months to 1 year ago		
Between 1 and 2 years ago		
More than 2 years ago		

Q44. If *yes* please tick all of the following that apply

Cracks		Crumbling horn	
Thrush		Prominent growth rings	
Seedy toe		Widened white lines	
Convex soles		Mediolateral imbalance	
Other		Long toe, low heel conformation	

If *other* please specify

Q45a. Have you or your farrier ever implemented any treatment protocol for this?

Yes – currently		Not currently	
Yes – previously		Never	

Q45b. If *yes* please state what this treatment is /was

Q45c. Do you feel that this treatment helped/ is helping?

Yes		No	

Horse number

7. Lameness and Veterinary Care

Q46. What veterinary practice(s) do you use?

Q47. Has your horse suffered from lameness in the past:

	Yes	No
In the last 6 months		
6 months- 1 year ago		
>1 and <2 years ago		
> 2 years ago		

For the most recent lameness event:

Q48. What limb(s) were affected?

Front feet only	
Back feet only	
Left fore	
Right fore	
Left hind	
Right hind	
All four feet	
Other	

If *other* please specify

Horse number

Q49. What region of the limb was affected?

Foot		Cannon bone	
Pastern		Knee	
Fetlock		Hock	
Flexor tendon		Stifle	
Suspensory Ligament		Back	
Other			

If *other* please specify

Q50. Did your horse require veterinary treatment?

Yes ☐ No ☐

Q51. If *yes* did the vet give you a diagnosis?

Yes ☐ No ☐

Q52. Please tick the diagnosis that most fits the lameness issue:

Foot abscess		Muscle damage	
Laminitis		Cellulitis	
Other foot-related lameness		Tendon Injury	
Osteoarthritis		Don't know	
Wound		Other	

If *other* please specify

Horse number ☐

Q53. Is your horse currently on any veterinary-prescribed medication?

Yes ☐ No ☐

Q54. If *yes* what (please list all if more than one)

☐

Q55. How often do you pick out your horse/pony's feet? ....

Q56. Do you apply any treatment(s) to your horse/pony's feet? (please tick all that apply)

Hoof oil	☐	Hoof ointment	☐
Stockholm tar	☐	Hoof hardener	☐
Hoof cream/conditioner	☐	Barrier cream	☐
Other	☐	Hoof filler	☐
None	☐		☐

If *other* please specify ☐

Q57. If yes was this on the recommendation of (please tick all that apply):

Veterinary surgeon	☐	Farrier	☐
Friend	☐	Other	☐

If *other* please specify ☐

Q58. If different treatments were recommended by different people please specify who recommended what:

☐

Horse number

Q59. Please tell us anything else relevant about your horse's feet and foot care in the box below:

Appendix 2

Table 1: Results of univariable screening of independent variables for inclusion into multivariable regression model

Dependent Variable	Independent Variables	P Value	
		Left Fore	Right Fore
Bearing Border Length (cm)	Age	0.18	0.96
Bearing Border Length (cm)	Height	<0.001	<0.001
Bearing Border Length (cm)	Weight	<0.001	<0.001
Bearing Border Length (cm)	Breed	0.03	<0.001
Bearing Border Length (cm)	Gender	0.007	0.1
Bearing Border Length (cm)	Horse Discipline	0.23	0.005
Bearing Border Length (cm)	Exercise intensity	0.53	0.13
Bearing Border Length (cm)	Competes	0.84	0.06
Bearing Border Length (cm)	Previous Lameness	0.14	0.2
Bearing Border Length (cm)	Farrier	0.05	0.01
Bearing Border Length (cm)	Length of time under farrier's care	0.11	0.03
Bearing Border Length (cm)	Lunge Total Minutes (Per Week)	0.06	0.54
Bearing Border Length (cm)	Flatwork Total Minutes (Per Week)	0.35	0.02
Bearing Border Length (cm)	Horsewalker Total Minutes (Per Week)	0.9	0.7
Bearing Border Length (cm)	Grass Total Minutes (Per Week)	0.48	0.14
Bearing Border Length (cm)	Sand Total Minutes (Per Week)	0.39	0.05
Bearing Border Length (cm)	Road Total Minutes (Per Week)	0.18	0.03
Bearing Border Length (cm)	Gravel Total Minutes (Per Week)	0.28	0.07
Bearing Border Length (cm)	Rubber Total Minutes (Per Week)	0.29	0.02
Frog Apex to Toe (cm)	Age	0.73	0.15
Frog Apex to Toe (cm)	Height	<0.001	0.002
Frog Apex to Toe (cm)	Weight	0.002	0.003
Frog Apex to Toe (cm)	Breed	0.009	0.06
Frog Apex to Toe (cm)	Animal Use	0.12	0.01
Frog Apex to Toe (cm)	Competes	0.95	0.14
Frog Apex to Toe (cm)	Farrier	0.01	0.04
Frog Apex to Toe (cm)	Length of time under farrier's care	0.1	0.18
Frog Apex to Toe (cm)	Farrier Higher Education	0.03	0.31
Frog Apex to Toe (cm)	Grass Total Minutes (Per Week)	0.37	0.04
Frog Apex to Toe (cm)	Gravel Total Minutes (Per Week)	0.005	0.03
Width (cm)	Height	<0.001	<0.001
Width (cm)	Weight	<0.001	<0.001
Width (cm)	Breed	0.002	<0.001
Width (cm)	Animal Use	0.44	0.006
Width (cm)	Exercise intensity	0.09	0.01
Width (cm)	Competes	0.39	0.07

Width (cm)	Turnout Hours Per Day	0.28	0.19
Width (cm)	Farrier	<0.001	<0.001
Width (cm)	Length of time under farrier's care	0.34	0.06
Width (cm)	Farrier Years Since Graduation	0.005	0.001
Width (cm)	Flatwork Total Minutes (Per Week)	0.42	0.06
Width (cm)	Gravel Total Minutes (Per Week)	0.04	0.06
Lateral View DHWA-HA	Breed	0.008	0.18
Lateral View DHWA-HA	Horse Discipline	0.89	0.14
Lateral View DHWA-HA	Farrier	0.05	0.01
Lateral View DHWA-HA	Farrier Years Since Graduation	0.004	0.001
Lateral View DHWA-HA	Shoeing Frequency	0.16	0.78
Lateral View DHWA-HA	Farrier Trimming Protocol	0.37	0.06
Lateral View DHWA-HA	Arena Surface Constituents	0.65	0.05
Lateral View DHWA-HA	Horsewalker Average Minutes (Per Week)	0.27	0.09
Lateral View DHWA-HA	Jumping Average Minutes (Per Week)	0.37	0.16
Lateral View DHWA-HA	Grass Total Minutes (Per Week)	0.01	0.46
Lateral View DHWA-HA	Road Total Minutes (Per Week)	0.43	0.16
Lateral Hoof Wall Angle (°)	Height	0.008	0.03
Lateral Hoof Wall Angle (°)	Breed	0.01	0.006
Lateral Hoof Wall Angle (°)	Farrier	0.11	0.003
Lateral Hoof Wall Angle (°)	Length of time under farrier's care	<0.001	<0.001
Lateral Hoof Wall Angle (°)	Farrier Years Since Graduation	0.07	0.52
Lateral Hoof Wall Angle (°)	Shoeing Frequency	0.12	0.66
Lateral Hoof Wall Angle (°)	Farrier Higher Education	0.05	0.004
Lateral Hoof Wall Angle (°)	Turnout Routine	0.03	0.07
Lateral Hoof Wall Angle (°)	Main Arena ID	0.08	0.03
Lateral Hoof Wall Angle (°)	Arena Constituents	0.05	0.78
Lateral Hoof Wall Angle (°)	Horsewalker Average Minutes (Per Week)	0.7	0.02
Lateral Hoof Wall Angle (°)	Jumping Average Minutes (Per Week)	0.07	0.85
Lateral Hoof Wall Angle (°)	Grass Total Minutes (Per Week)	0.85	0.05
Lateral Hoof Wall Angle (°)	Sand Total Minutes (Per Week)	0.67	0.13
Lateral Hoof Wall Angle (°)	Road Total Minutes (Per Week)	0.18	0.05

DHWA-HA=dorsal hoof wall angle-heel angle difference

Table 2: Results of univariable screening of independent variables for inclusion in multivariable logistic regression of hoof imbalance

Hoof Imbalance Outcome	**Independent Variable**	**P Value**
Mediolateral Imbalance	Farrier	0.001
Mediolateral Imbalance	Shoeing Frequency	<0.0001
Mediolateral Imbalance	Length of time under farrier's care	<0.0001
Mediolateral Imbalance	Farrier Years Since Graduation	0.26
Mediolateral Imbalance	Farrier Higher Education	<0.001
Mediolateral Imbalance	Farrier Trimming Protocol	0.03
Mediolateral Imbalance	Contracted Heels	0.77
Dorsopalmar Imbalance	Farrier	0.22
Dorsopalmar Imbalance	Shoeing Frequency	<0.0001
Dorsopalmar Imbalance	Length of time under farrier's care	<0.0001
Dorsopalmar Imbalance	Farrier Years Since Graduation	0.06
Dorsopalmar Imbalance	Farrier Higher Education	0.04
Dorsopalmar Imbalance	Farrier Trimming Protocol	0.13

Table 3: Results of pairwise comparisons of mean pressures (kilopascasl) in each quadrant, static pressure data, pre- and post-trimming (n=69 horses)

Limb	**Trim**	**Quadrant comparison**		**P value**
Left Fore	Pre	Dorsolateral	Dorsomedial	0.29
Left Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Left Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Left Fore	Pre	Dorsomedial	Palmarolateral	**0.004**
Left Fore	Pre	Dorsomedial	Palmaromedial	**0.005**
Left Fore	Pre	Palmarolateral	Palmaromedial	0.67
Right Fore	Pre	Dorsolateral	Dorsomedial	0.47
Right Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Pre	Dorsomedial	Palmarolateral	**<0.001**
Right Fore	Pre	Dorsomedial	Palmaromedial	0.009
Right Fore	Pre	Palmarolateral	Palmaromedial	0.30
Left Fore	Post	Dorsolateral	Dorsomedial	0.20
Left Fore	Post	Dorsolateral	Palmarolateral	**0.004**
Left Fore	Post	Dorsolateral	Palmaromedial	**0.004**
Left Fore	Post	Dorsomedial	Palmarolateral	0.05
Left Fore	Post	Dorsomedial	Palmaromedial	0.09
Left Fore	Post	Palmarolateral	Palmaromedial	0.70
Right Fore	Post	Dorsolateral	Dorsomedial	0.10
Right Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Post	Dorsomedial	Palmarolateral	**0.001**
Right Fore	Post	Dorsomedial	Palmaromedial	0.03
Right Fore	Post	Palmarolateral	Palmaromedial	0.25

Following adjustment for multiple comparisons the threshold for statistical significance in this analysis is $p<0.008$.

Table 4: Results of pairwise comparisons of maximum pressures (kilopascals) in each quadrant, static pressure data pre- and post-trimming (n=69 horses)

Limb	**Trim**	**Quadrant comparison**		**P value**
Left Fore	Pre	Dorsolateral	Dorsomedial	0.39
Left Fore	Pre	Dorsolateral	Palmarolateral	0.009
Left Fore	Pre	Dorsolateral	Palmaromedial	**0.003**
Left Fore	Pre	Dorsomedial	Palmarolateral	0.04
Left Fore	Pre	Dorsomedial	Palmaromedial	0.01
Left Fore	Pre	Palmarolateral	Palmaromedial	0.93
Right Fore	Pre	Dorsolateral	Dorsomedial	0.97
Right Fore	Pre	Dorsolateral	Palmarolateral	**0.007**
Right Fore	Pre	Dorsolateral	Palmaromedial	0.02
Right Fore	Pre	Dorsomedial	Palmarolateral	0.01
Right Fore	Pre	Dorsomedial	Palmaromedial	0.02
Right Fore	Pre	Palmarolateral	Palmaromedial	0.51
Left Fore	Post	Dorsolateral	Dorsomedial	0.22
Left Fore	Post	Dorsolateral	Palmarolateral	**0.004**
Left Fore	Post	Dorsolateral	Palmaromedial	0.01
Left Fore	Post	Dorsomedial	Palmarolateral	0.99
Left Fore	Post	Dorsomedial	Palmaromedial	0.05
Left Fore	Post	Palmarolateral	Palmaromedial	0.06
Right Fore	Post	Dorsolateral	Dorsomedial	0.05
Right Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Post	Dorsomedial	Palmarolateral	0.03
Right Fore	Post	Dorsomedial	Palmaromedial	0.01
Right Fore	Post	Palmarolateral	Palmaromedial	0.67

Following adjustment for multiple comparisons the threshold for statistical significance in this analysis is $p<0.008$.

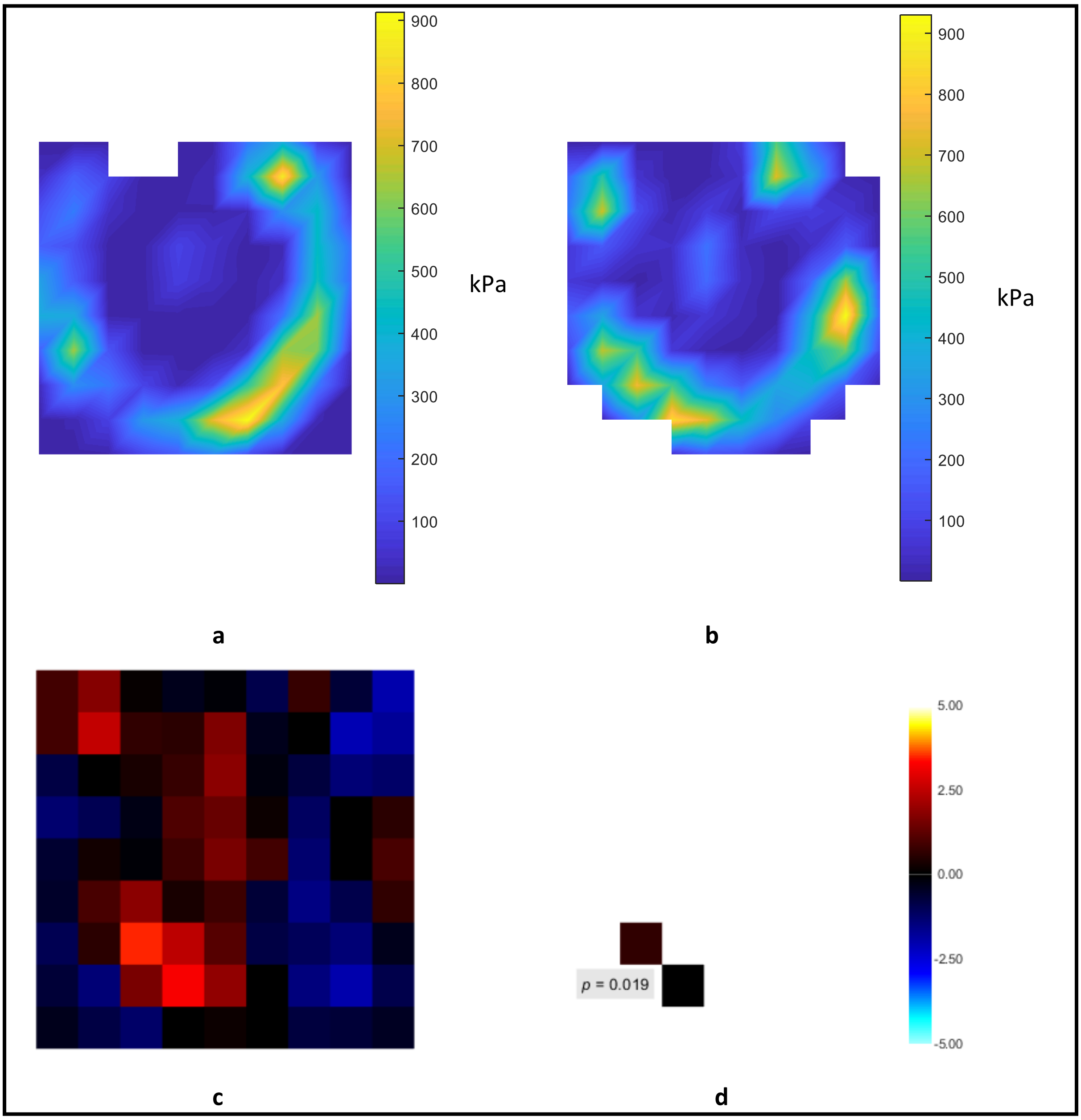

Figure 1: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs pre-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore pre-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate Increased loading of the lateral toe region in the right fore compared with the left fore. A cluster of two pixels that are significantly different (p=0.02) between left and right is shown in plot d. The colour of the pixels indicate a positive change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means higher pressure was exerted in this region on the right fore than the left fore. kPa=kilopascals

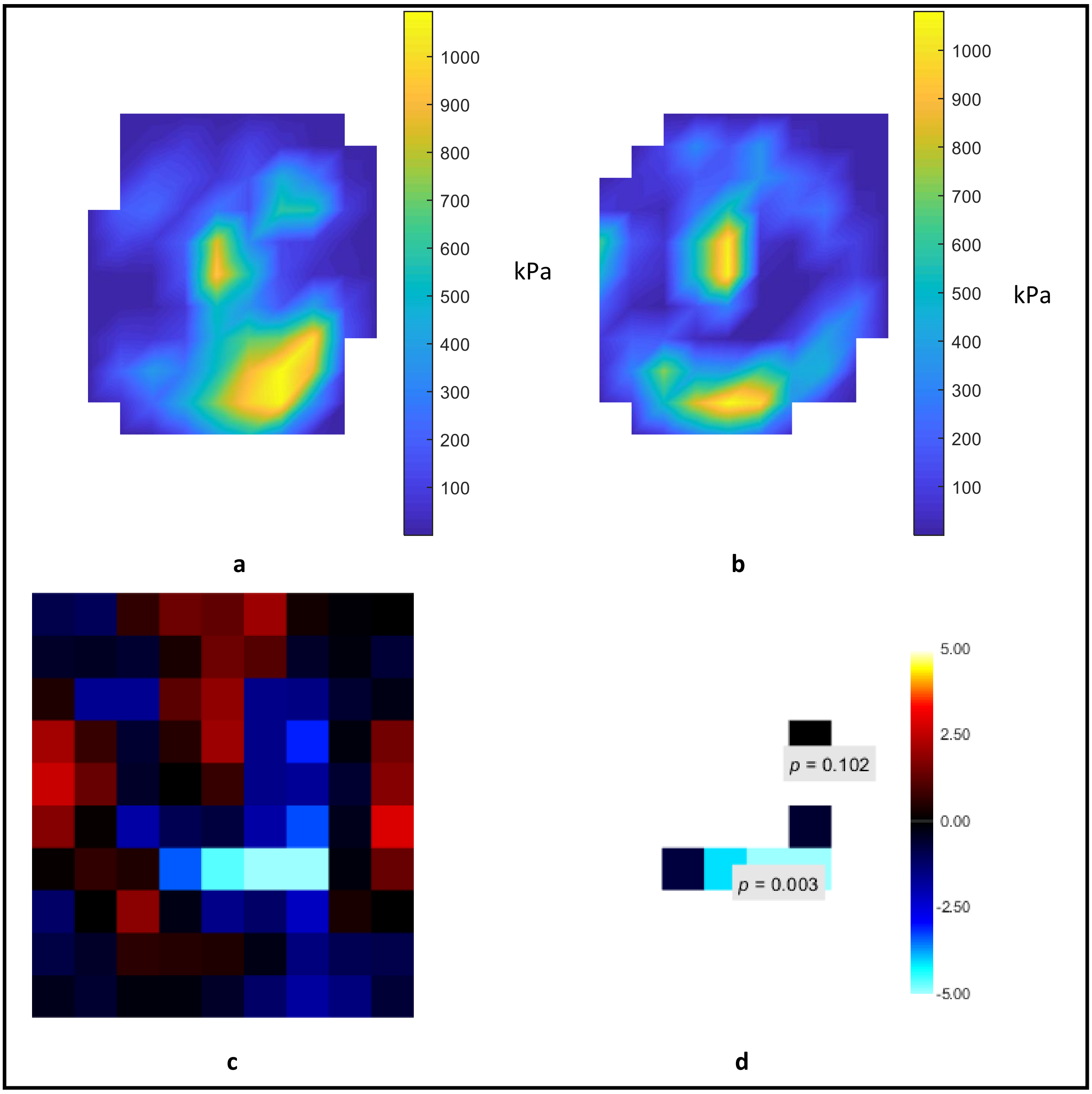

Figure 2: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs pre-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore pre-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate decreased loading of the medial midsole region lateral toe region in the right fore compared with the left fore. A cluster of five pixels that are significantly different (p=0.003) between left and right is shown in plot d. The colour of the pixels indicate a negative change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means lower pressure was exerted in this region on the right fore than the left fore. The single pixel difference also in plot d was p>0.05 so this was not considered significant. kPa=kilopascals

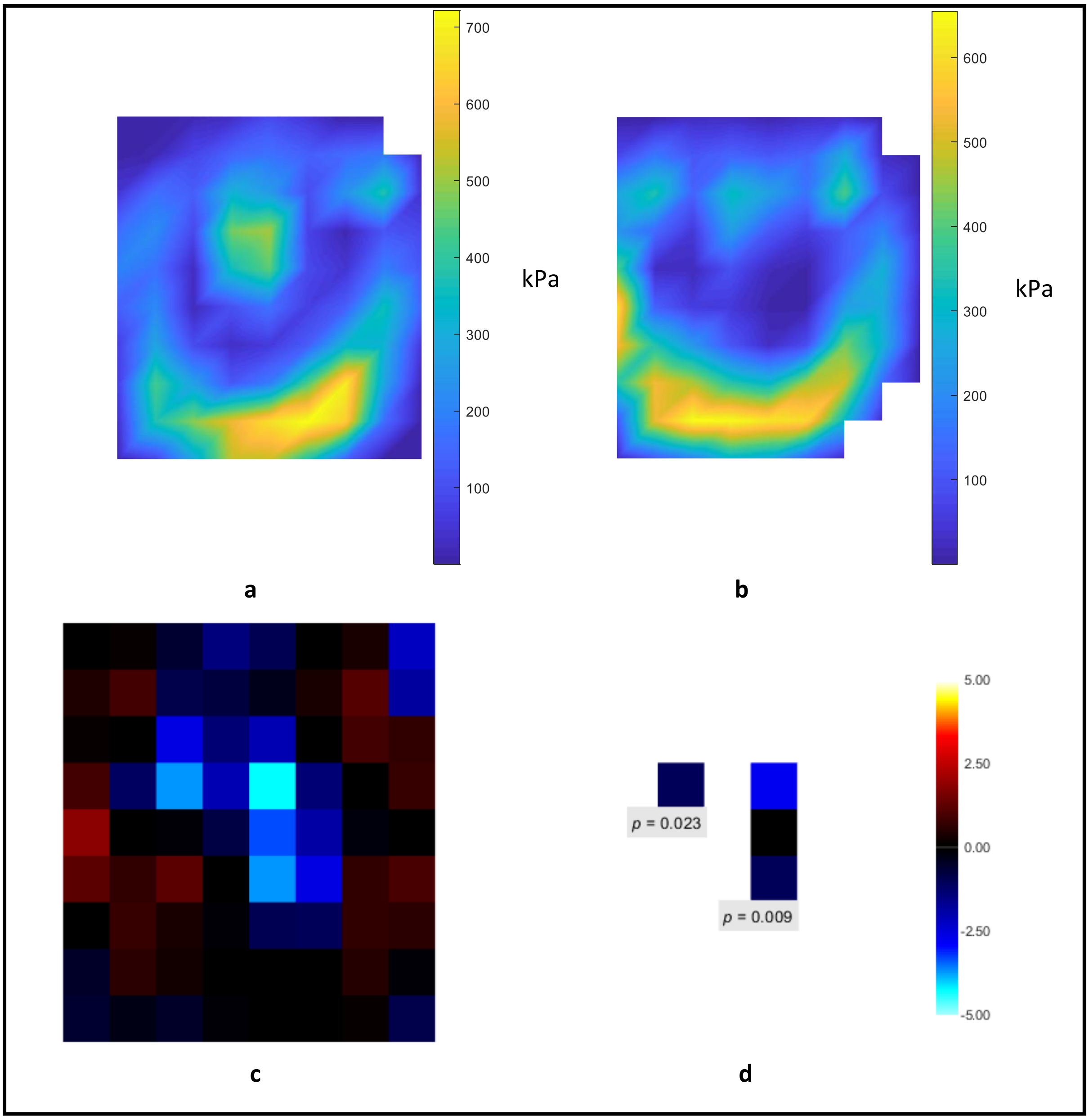

Figure 3: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs pre-trimming. a is a plot of the mean pressure distribution of left fore pre-trim strikes, b is a plot of the mean pressure distribution of right fore pre-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate decreased loading of the frog apex or bridge of the foot region in the right fore compared with the left fore. A cluster of three pixels that are significantly different (p=0.009) between left and right is shown in plot d. The colour of the pixels indicate a negative change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means lower pressure was exerted in this region on the right fore than the left fore. The single pixel difference also in plot d was not considered a meaningful change due to the small area it covered and the location of the change.

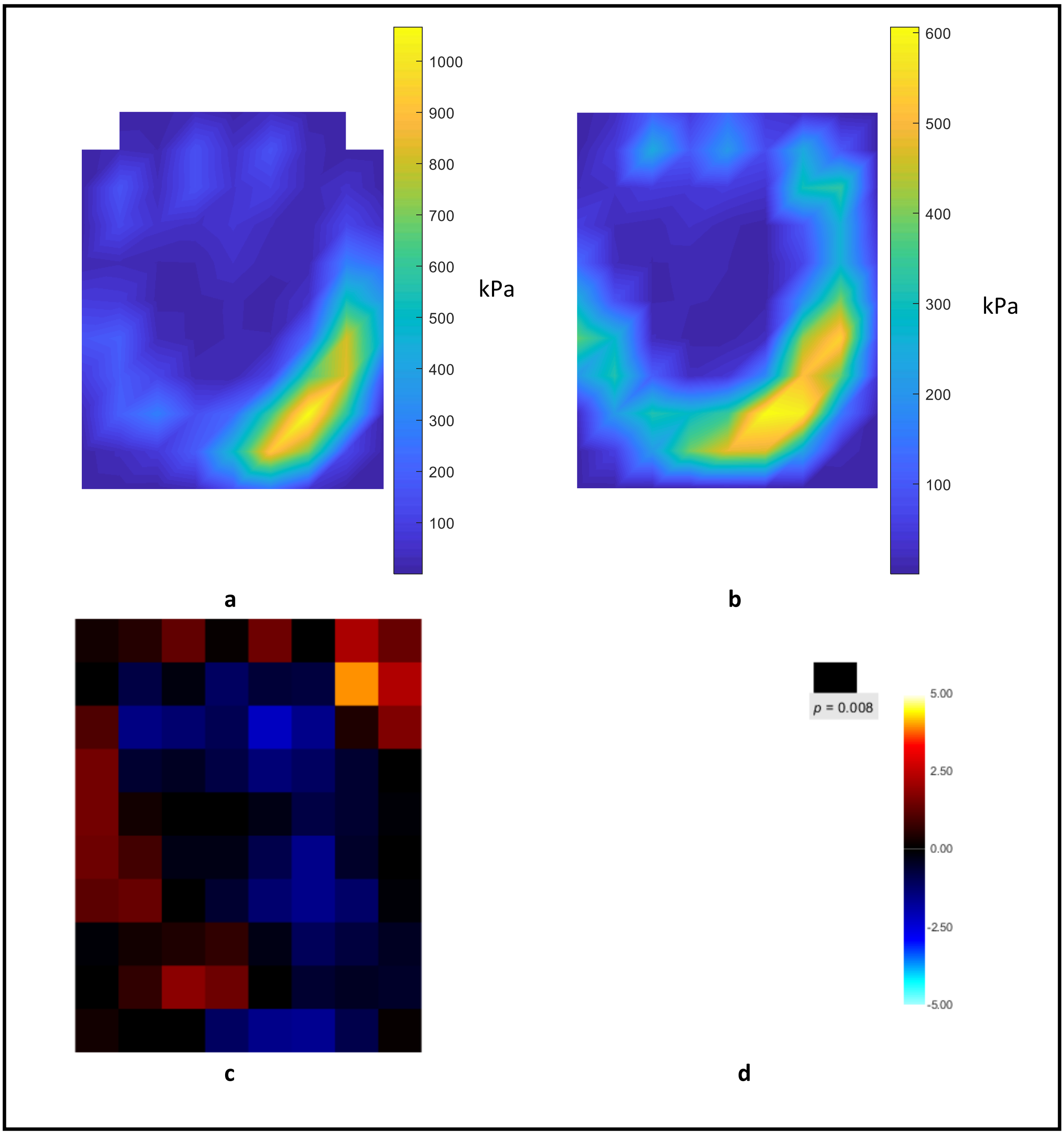

Figure 4: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs post-trimming. a is a plot of the mean pressure distribution of left fore post-trim strikes, b is a plot of the mean pressure distribution of right fore post-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate increased loading of the medial heel in the right fore compared with the left fore. A single pixel that is significantly different (p=0.008) between left and right is shown in plot d. The colour of the pixel indicates a positive change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means greater pressure was exerted in this region on the right fore than the left fore. Although often single pixel changes are not considered meaningful, in this case the pixel clearly affects a specific anatomical location which makes it likely to be a meaningful result. kPa=kilopascals

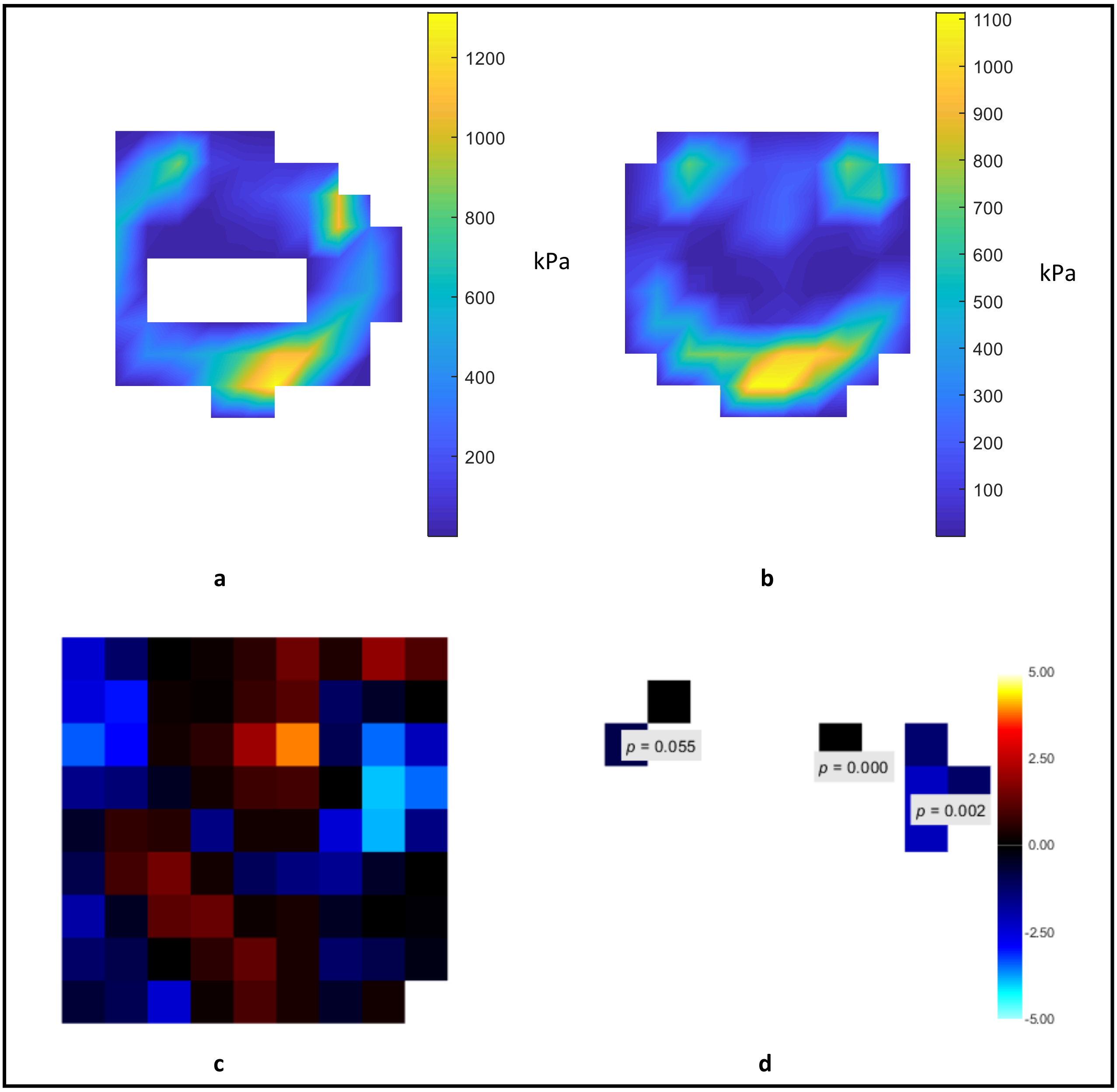

Figure 5: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs post-trimming. a is a plot of the mean pressure distribution of left fore post-trim strikes, b is a plot of the mean pressure distribution of right fore post-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate decreased loading of the medial hoof wall in the right fore compared with the left fore. A cluster of pixels that are significantly different (p=0.002) between left and right is shown in plot d. The colour of the pixel indicates a negative change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means less pressure was exerted in this region on the right fore than the left fore. The two-pixel cluster was p>0.05 and therefore was not considered significant. The single pixel was not considered a meaningful change due to the small area and location. kPa=kilopascals

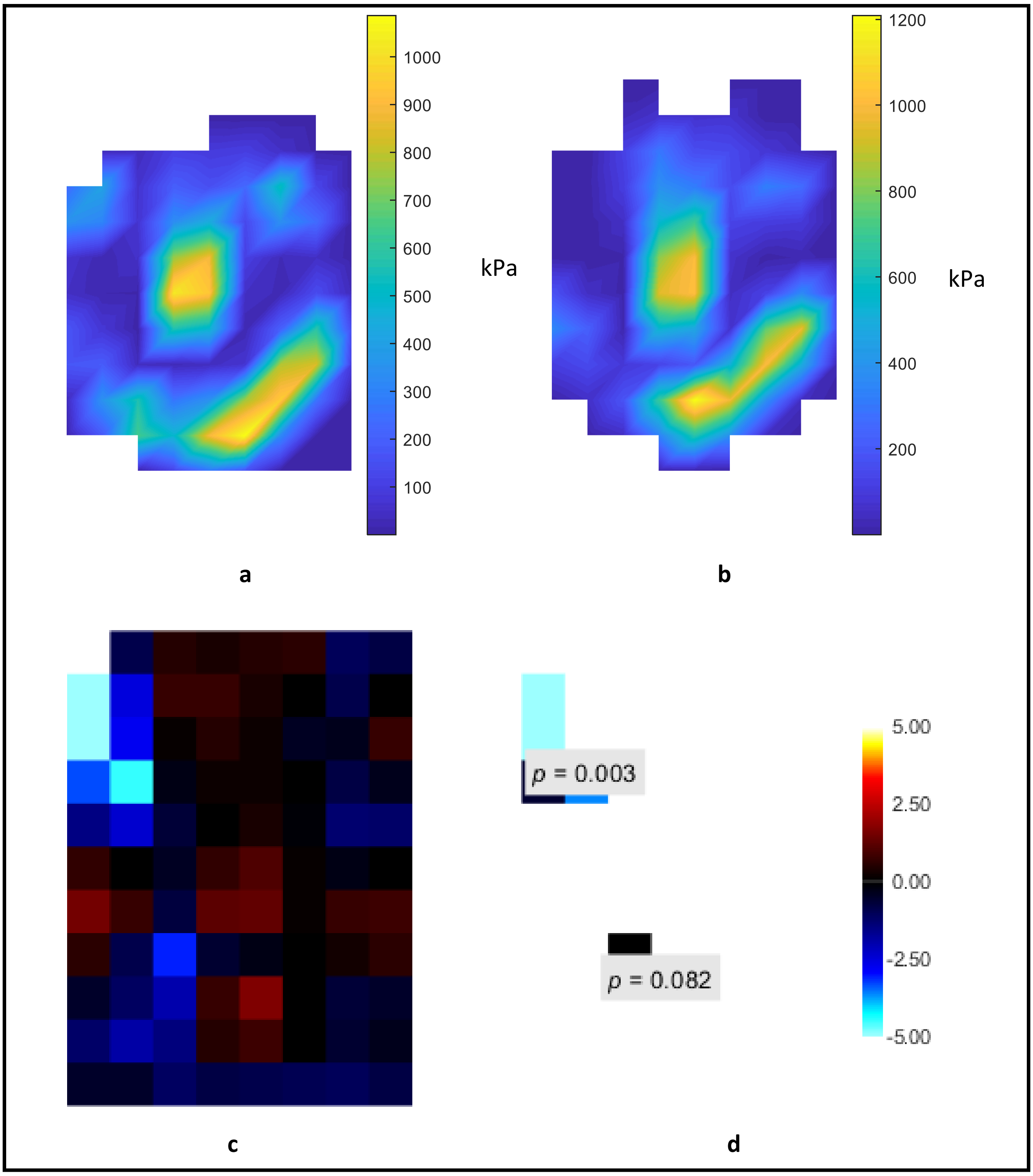

Figure 6: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs post-trimming. a is a plot of the mean pressure distribution of left fore post-trim strikes, b is a plot of the mean pressure distribution of right fore post-trim strikes. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse a and b indicate decreased loading of the lateral heel in the right fore compared with the left fore. A cluster of four pixels that are significantly different (p=0.003) between left and right is shown in plot d. The colour of the pixel indicates a negative change; since the pSPM method involves mapping left fore strikes on to right fore strikes this means less pressure was exerted in this region on the right fore than the left fore. The single pixel change in d was p>0.05 and therefore was not considered significant. kPa=kilopascals

Table 5: Results of statistical analysis of differences between mean dynamic pressures (kilopascals) in each hoof quadrant (n=61 horses)

Limb	**Trim**	**Quadrants being Compared**		**P value**
Left Fore	Pre	Dorsolateral	Dorsomedial	**<0.001**
Left Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Left Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Left Fore	Pre	Dorsomedial	Palmarolateral	0.80
Left Fore	Pre	Dorsomedial	Palmaromedial	**<0.001**
Left Fore	Pre	Palmarolateral	Palmaromedial	**<0.001**
Right Fore	Pre	Dorsolateral	Dorsomedial	**<0.001**
Right Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Pre	Dorsomedial	Palmarolateral	**<0.001**
Right Fore	Pre	Dorsomedial	Palmaromedial	**<0.001**
Right Fore	Pre	Palmarolateral	Palmaromedial	0.09
Left Fore	Post	Dorsolateral	Dorsomedial	**<0.001**
Left Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Left Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Left Fore	Post	Dorsomedial	Palmarolateral	0.04
Left Fore	Post	Dorsomedial	Palmaromedial	**<0.001**
Left Fore	Post	Palmarolateral	Palmaromedial	0.02
Right Fore	Post	Dorsolateral	Dorsomedial	**<0.001**
Right Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Post	Dorsomedial	Palmarolateral	**<0.001**
Right Fore	Post	Dorsomedial	Palmaromedial	**<0.001**
Right Fore	Post	Palmarolateral	Palmaromedial	0.29

Following adjustment for multiple comparisons the threshold for statistical significance in this analysis is $p<0.008$.

Table 6: Results of statistical analysis of difference between dynamic maximum pressures (kilopascals) in each hoof quadrant (n=61 horses)

Limb	Trim	Quadrants being Compared		P value
Left Fore	Pre	Dorsolateral	Dorsomedial	**<0.001**
Left Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Left Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Left Fore	Pre	Dorsomedial	Palmarolateral	0.07
Left Fore	Pre	Dorsomedial	Palmaromedial	**<0.001**
Left Fore	Pre	Palmarolateral	Palmaromedial	**<0.001**
Right Fore	Pre	Dorsolateral	Dorsomedial	0.01
Right Fore	Pre	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Pre	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Pre	Dorsomedial	Palmarolateral	**0.004**
Right Fore	Pre	Dorsomedial	Palmaromedial	**<0.001**
Right Fore	Pre	Palmarolateral	Palmaromedial	**0.007**
Left Fore	Post	Dorsolateral	Dorsomedial	**<0.001**
Left Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Left Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Left Fore	Post	Dorsomedial	Palmarolateral	0.35
Left Fore	Post	Dorsomedial	Palmaromedial	**<0.001**
Left Fore	Post	Palmarolateral	Palmaromedial	**0.003**
Right Fore	Post	Dorsolateral	Dorsomedial	**<0.001**
Right Fore	Post	Dorsolateral	Palmarolateral	**<0.001**
Right Fore	Post	Dorsolateral	Palmaromedial	**<0.001**
Right Fore	Post	Dorsomedial	Palmarolateral	**<0.001**
Right Fore	Post	Dorsomedial	Palmaromedial	**<0.001**
Right Fore	Post	Palmarolateral	Palmaromedial	0.07

Following adjustment for multiple comparisons the threshold for statistical significance in this analysis is p<0.008.

Table 7: Correlation between foot quadrant static mean pressure (kilopascals) and solar foot measures pre- and post-trimming (n=69 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
FrA-Toe (cm)	Dorsolateral	-0.12	0.34	0.09	0.46	0.28	0.02	0.02	0.87
	Dorsomedial	-0.09	0.49	0.02	0.89	0.08	0.51	0.10	0.44
	Palmarolateral	-0.16	0.19	0.01	0.92	0.12	0.34	0.06	0.64
	Palmaromedial	0.20	0.10	0.09	0.48	0.06	0.62	0.11	0.39
BBL (cm)	Dorsolateral	-0.18	0.14	0.03	0.81	0.04	0.75	0.15	0.22
	Dorsomedial	-0.16	0.20	0.06	0.63	0.18	0.14	0.17	0.19
	Palmarolateral	-0.09	0.45	-0.02	0.89	0.06	0.64	0.15	0.23
	Palmaromedial	-0.07	0.54	-0.12	0.32	0.15	0.20	0.15	0.25
Width (cm)	Dorsolateral	-0.27	0.03	0.007	0.96	0.01	0.92	0.02	0.85
	Dorsomedial	-0.18	0.14	-0.12	0.33	-0.01	0.96	0.23	0.07
	Palmarolateral	-0.02	0.85	0.12	0.32	-0.01	0.96	0.23	0.06
	Palmaromedial	-0.13	0.28	0.13	0.31	-0.09	0.52	0.09	0.46
DHWA-HA	Dorsolateral	0.19	0.12	0.26	0.03	0.19	0.11	0.23	0.06
	Dorsomedial	-0.01	0.93	0.20	0.11	0.14	0.25	0.11	0.37
	Palmarolateral	0.13	0.27	0.11	0.36	0.29	0.02	**-0.32**	**0.01**
	Palmaromedial	0.12	0.31	0.08	0.51	0.04	0.73	-0.03	0.80
LHWA (°)	Dorsolateral	0.23	0.05	-0.18	0.14	0.00	0.99	-0.07	0.55
	Dorsomedial	0.16	0.20	-0.001	0.99	-0.02	0.84	-0.06	0.63
	Palmarolateral	0.12	0.31	0.04	0.77	-0.05	0.70	0.03	0.84
	Palmaromedial	-0.05	0.70	-0.009	0.94	0.10	0.41	0.02	0.87

FrA-Toe = Frog Apex to Toe distance; BBL = bearing border length; Width = Hoof Width; DHWA-HA = difference between dorsal hoof wall angle and heel angle; LHWA = lateral hoof wall angle. p<0.01 considered significant after adjustment for multiple comparisons

Table 8: Correlation between foot quadrant static maximum pressure (kilopascals) and solar foot measures pre- and post-trimming (n=69 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
FrA-Toe (cm)	Dorsolateral	0.04	0.75	0.06	0.66	0.28	0.02	0.12	0.36
	Dorsomedial	0.01	0.91	-0.13	0.30	0.15	0.21	0.05	0.70
	Palmarolateral	-0.05	0.66	-0.10	0.43	0.07	0.56	0.11	0.40
	Palmaromedial	0.25	0.04	0.15	0.21	0.09	0.46	0.21	0.10
BBL (cm)	Dorsolateral	-0.16	0.20	-0.03	0.83	0.07	0.54	0.20	0.11
	Dorsomedial	-0.11	0.38	-0.07	0.59	0.22	0.07	0.14	0.25
	Palmarolateral	-0.08	0.50	-0.05	0.71	0.08	0.51	0.17	0.19
	Palmaromedial	0.09	0.47	-0.06	0.64	0.12	0.34	0.23	0.07
Width (cm)	Dorsolateral	-0.11	0.38	-0.07	0.58	0.07	0.54	-0.02	0.85
	Dorsomedial	-0.17	0.17	-0.20	0.11	**0.36**	**0.008**	0.21	0.10
	Palmarolateral	0.10	0.44	-0.10	0.44	0.15	0.23	0.24	0.06
	Palmaromedial	0.04	0.76	0.14	0.26	0.15	0.23	0.23	0.06
DHWA-HA	Dorsolateral	0.17	0.16	0.15	0.23	0.12	0.32	0.13	0.29
	Dorsomedial	-0.06	0.63	0.20	0.11	0.17	0.16	0.17	0.19
	Palmarolateral	0.14	0.24	0.11	0.39	0.29	0.02	-0.20	0.11
	Palmaromedial	0.08	0.49	0.03	0.83	0.08	0.50	-0.01	0.91
LHWA (°)	Dorsolateral	0.09	0.47	0.08	0.56	-0.08	0.50	0.02	0.84
	Dorsomedial	0.10	0.40	-0.02	0.87	-0.24	0.05	-0.09	0.47
	Palmarolateral	0.12	0.31	-0.02	0.91	-0.05	0.70	0.02	0.43
	Palmaromedial	-0.05	0.70	-0.16	0.24	0.10	0.41	-0.16	0.19

FrA-Toe = Frog Apex to Toe distance; BBL = bearing border length; Width = Hoof Width; DHWA-HA = difference between dorsal hoof wall angle and heel angle; LHWA = lateral hoof wall angle. p<0.01 considered significant after adjustment for multiple comparisons

Table 9: Correlation between foot quadrant dynamic mean pressure (kilopascals) and solar foot measures pre- and post-trimming (n=61 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
FrA-Toe (cm)	Dorsolateral	0.07	0.68	0.21	0.12	0.19	0.18	0.25	0.07
	Dorsomedial	-0.02	0.89	0.23	0.08	0.10	0.48	0.12	0.38
	Palmarolateral	0.05	0.73	0.10	0.47	0.21	0.13	0.16	0.23
	Palmaromedial	-0.06	0.66	-0.02	0.89	0.13	0.36	0.04	0.78
BBL (cm)	Dorsolateral	-0.03	0.85	0.17	0.20	0.11	0.43	0.04	0.77
	Dorsomedial	-0.13	0.37	0.01	0.96	0.02	0.90	-0.07	0.60
	Palmarolateral	-0.22	0.11	-0.10	0.44	-0.04	0.75	-0.07	0.62
	Palmaromedial	-0.10	0.48	-0.11	0.44	-0.03	0.84	-0.08	0.56
Width (cm)	Dorsolateral	-0.19	0.24	0.03	0.81	0.01	0.92	0.09	0.52
	Dorsomedial	0.01	0.94	-0.08	0.56	-0.01	0.96	0.00	1.00
	Palmarolateral	-0.04	0.78	0.15	0.26	-0.01	0.96	-0.14	0.29
	Palmaromedial	0.02	0.91	0.02	0.88	-0.09	0.52	0.01	0.96
DHWA-HA	Dorsolateral	-0.11	0.41	-0.20	0.13	0.31	0.02	0.21	0.13
	Dorsomedial	0.25	0.06	0.20	0.13	0.30	0.03	0.17	0.22
	Palmarolateral	0.12	0.37	0.06	0.68	0.12	0.40	0.13	0.35
	Palmaromedial	0.21	0.12	0.15	0.26	**0.35**	**0.01**	**0.36**	**0.01**
LHWA (°)	Dorsolateral	0.16	0.26	0.25	0.07	0.07	0.61	-0.09	0.49
	Dorsomedial	-0.12	0.40	-0.01	0.95	0.11	0.41	0.23	0.08
	Palmarolateral	0.02	0.90	0.02	0.90	0.06	0.65	0.11	0.43
	Palmaromedial	-0.05	0.72	-0.09	0.49	0.06	0.68	0.09	0.52

FrA-Toe = Frog Apex to Toe distance; BBL = bearing border length; Width = Hoof Width; DHWA-HA = difference between dorsal hoof wall angle and heel angle; LHWA = lateral hoof wall angle. p<0.01 considered significant after adjustment for multiple comparisons

Table 10: Correlation between foot quadrant dynamic maximum pressure (kilopascals) and solar foot measures pre- and post-trimming (n=61 horses)

Foot Measure	**Quadrant**	**Pre -trim**		**Post-trim**		**Pre-trim**		**Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
FrA-Toe (cm)	Dorsolateral	0.05	0.72	0.20	0.14	0.19	0.18	0.23	0.09
	Dorsomedial	-0.01	0.97	0.21	0.11	0.20	0.15	0.13	0.32
	Palmarolateral	0.21	0.13	0.11	0.40	0.29	0.03	0.24	0.07
	Palmaromedial	-0.02	0.90	-0.03	0.82	0.27	0.05	0.04	0.77
BBL (cm)	Dorsolateral	-0.15	0.28	0.09	0.52	0.11	0.41	0.14	0.29
	Dorsomedial	-0.12	0.38	0.02	0.87	0.18	0.18	-0.01	0.93
	Palmarolateral	-0.15	0.27	-0.01	0.92	0.06	0.69	0.07	0.62
	Palmaromedial	-0.11	0.44	-0.11	0.43	0.16	0.24	0.03	0.82
Width (cm)	Dorsolateral	0.07	0.59	0.22	0.11	0.15	0.28	0.24	0.08
	Dorsomedial	0.06	0.65	0.00	0.97	0.27	0.05	0.14	0.30
	Palmarolateral	0.10	0.46	0.16	0.23	0.18	0.19	-0.02	0.90
	Palmaromedial	0.17	0.21	0.00	0.99	0.10	0.47	0.18	0.18
DHWA-HA	Dorsolateral	-0.11	0.43	-0.12	0.37	**0.33**	**0.01**	0.21	0.13
	Dorsomedial	0.24	0.08	0.26	0.05	**0.35**	**0.01**	0.26	0.05
	Palmarolateral	0.11	0.42	0.10	0.45	0.22	0.10	0.10	0.45
	Palmaromedial	0.22	0.11	0.15	0.28	0.25	0.07	**0.36**	**0.01**
LHWA (°)	Dorsolateral	-0.05	0.73	0.08	0.56	-0.09	0.53	-0.05	0.72
	Dorsomedial	-0.21	0.12	-0.02	0.87	-0.10	0.45	0.04	0.78
	Palmarolateral	-0.10	0.47	-0.02	0.91	-0.13	0.35	0.02	0.86
	Palmaromedial	-0.09	0.49	-0.16	0.24	-0.13	0.36	0.02	0.87

FrA-Toe = Frog Apex to Toe distance; BBL = bearing border length; Width = Hoof Width; DHWA-HA = difference between dorsal hoof wall angle and heel angle; LHWA = lateral hoof wall angle. p<0.01 considered significant after adjustment for multiple comparisons

Appendix 3

Table 1: Correlation between foot quadrant static <u>mean</u> pressure (kilopascals) and foot measures pre- and post-trimming at the end of the study period, sound horses (n=26 horses)

Foot Measure	Quadrant	LF Pre -trim		LF Post-trim		RF Pre-trim		RF Post-trim	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	-0.12	0.57	0.04	0.84	-0.003	0.99	0.22	0.30
	Dorsomedial	0.15	0.47	0.04	0.87	0.42	0.04	0.02	0.92
	Palmarolateral	**-0.54**	**0.006**	-0.05	0.81	0.07	0.74	-0.03	0.90
	Palmaromedial	0.08	0.70	0.05	0.81	0.08	0.72	0.01	0.96
DHWL (cm)	Dorsolateral	0.11	0.61	0.00	1.00	0.24	0.24	0.00	1.00
	Dorsomedial	0.02	0.94	0.11	0.60	-0.14	0.49	0.22	0.29
	Palmarolateral	-0.05	0.81	-0.14	0.50	-0.02	0.93	0.20	0.34
	Palmaromedial	-0.20	0.35	-0.29	0.17	0.01	0.96	0.16	0.45
DHWA-HA (°)	Dorsolateral	0.01	0.98	-0.08	0.72	-0.35	0.09	-0.07	0.76
	Dorsomedial	0.35	0.09	-0.37	0.08	-0.10	0.64	0.03	0.89
	Palmarolateral	-0.10	0.63	-0.19	0.36	0.13	0.52	-0.21	0.32
	Palmaromedial	0.30	0.14	0.18	0.39	-0.14	0.51	-0.15	0.47
Width (cm)	Dorsolateral	0.18	0.40	0.37	0.09	0.08	0.69	0.10	0.65
	Dorsomedial	0.06	0.78	0.11	0.63	-0.25	0.22	0.25	0.24
	Palmarolateral	0.13	0.54	0.27	0.22	0.18	0.38	-0.01	0.95
	Palmaromedial	0.20	0.33	0.18	0.43	-0.12	0.58	0.02	0.93
BBL (cm)	Dorsolateral	0.07	0.75	0.25	0.25	0.22	0.29	0.28	0.19
	Dorsomedial	0.07	0.75	0.20	0.36	-0.01	0.97	0.28	0.18
	Palmarolateral	0.03	0.90	0.14	0.50	0.30	0.14	0.18	0.39
	Palmaromedial	0.06	0.78	-0.07	0.75	-0.02	0.92	-0.07	0.73
COR-Toe (cm)	Dorsolateral	0.17	0.40	0.46	0.03	0.25	0.22	0.22	0.30
	Dorsomedial	-0.01	0.97	0.10	0.66	-0.05	0.82	0.14	0.50
	Palmarolateral	0.02	0.94	0.30	0.18	0.38	0.06	-0.04	0.86
	Palmaromedial	0.03	0.90	-0.07	0.75	0.02	0.93	-0.17	0.44

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 2: Correlation between foot quadrant static <u>mean</u> pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, lame horses (left fore n=2 horses, right fore n=3 horses)

Foot Measure	Quadrant	LF Pre -trim		LF Post-trim		RF Pre-trim		RF Post-trim	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	1	1	1	1	-1	0.33	-0.5	1
	Dorsomedial	1	1	1	1	0.5	1	1	0.33
	Palmarolateral	1	1	1	1	-0.5	1	-1	0.33
	Palmaromedial	1	1	1	1	0.5	1	0.5	1
DHWL (cm)	Dorsolateral	-1	1	-1	1	0.5	1	0.5	1
	Dorsomedial	-1	1	-1	1	-1	0.33	-1	0.33
	Palmarolateral	-1	1	-1	1	1	0.33	1	0.33
	Palmaromedial	-1	1	-1	1	-1	0.33	-1	1
DHWA-HA (°)	Dorsolateral	-1	1	-1	1	1	0.33	-0.5	1
	Dorsomedial	-1	1	-1	1	-0.5	1	-0.5	1
	Palmarolateral	-1	1	-1	1	0.5	1	1	0.33
	Palmaromedial	-1	1	-1	1	-0.5	1	-1	1
Width (cm)	Dorsolateral	1	1	1	1	1	0.33	0.5	1
	Dorsomedial	1	1	1	1	-0.5	1	-1	0.33
	Palmarolateral	1	1	1	1	0.5	1	1	0.33
	Palmaromedial	1	1	1	1	-0.5	1	-0.5	1
BBL (cm)	Dorsolateral	1	1	1	1	-0.5	1	1	0.33
	Dorsomedial	1	1	1	1	1	0.33	-0.5	1
	Palmarolateral	1	1	1	1	1	0.33	0.5	1
	Palmaromedial	1	1	1	1	1	0.33	0.5	1
COR-Toe (cm)	Dorsolateral	1	1	-1	1	-0.5	1	1	0.33
	Dorsomedial	1	1	-1	1	1	0.33	-0.5	1
	Palmarolateral	1	1	-1	1	-1	0.33	0.5	1
	Palmaromedial	1	1	-1	1	1	0.33	0.5	1

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 3: Correlation between foot quadrant dynamic <u>mean</u> pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, sound horses (pre-trim n=18 horses, post-trim n=16 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	-0.42	0.10	-0.21	0.45	0.33	0.19	0.58	0.03
	Dorsomedial	-0.32	0.21	-0.37	0.17	-0.23	0.37	0.19	0.50
	Palmarolateral	0.02	0.94	0.08	0.77	0.30	0.25	0.41	0.13
	Palmaromedial	0.21	0.42	-0.09	0.76	0.38	0.13	0.1	0.72
DHWL (cm)	Dorsolateral	0.05	0.84	0.21	0.46	-0.12	0.64	0.37	0.18
	Dorsomedial	0.14	0.59	0.25	0.37	0.30	0.25	0.58	0.03
	Palmarolateral	0.05	0.84	0.19	0.50	0.21	0.43	-0.04	0.88
	Palmaromedial	-0.09	0.74	-0.23	0.42	0.06	0.83	0.18	0.53
DHWA-HA (°)	Dorsolateral	-0.13	0.63	-0.45	0.09	-0.13	0.61	-0.26	0.35
	Dorsomedial	0.24	0.35	-0.11	0.69	-0.14	0.59	-0.17	0.54
	Palmarolateral	-0.43	0.09	0.03	0.93	0.16	0.53	-0.25	0.37
	Palmaromedial	0.31	0.22	-0.38	0.17	-0.08	0.75	0.02	0.95
Width (cm)	Dorsolateral	0.36	0.16	0.28	0.33	-0.22	0.40	-0.16	0.57
	Dorsomedial	0.36	0.15	0.50	0.07	0.19	0.47	0.28	0.31
	Palmarolateral	0.26	0.31	0.11	0.70	-0.09	0.74	-0.05	0.86
	Palmaromedial	0.07	0.80	-0.11	0.72	-0.28	0.27	-0.33	0.23
BBL (cm)	Dorsolateral	0.46	0.06	0.35	0.21	-0.21	0.41	0.05	0.87
	Dorsomedial	0.43	0.09	**0.76**	**0.003**	0.07	0.79	0.18	0.52
	Palmarolateral	0.31	0.23	0.11	0.72	-0.31	0.22	0.11	0.69
	Palmaromedial	0.23	0.37	0.13	0.65	-0.15	0.57	-0.28	0.31
COR-Toe (cm)	Dorsolateral	0.38	0.14	0.28	0.33	-0.38	0.14	0.12	0.68
	Dorsomedial	0.32	0.21	0.67	0.01	-0.01	-0.96	0.15	0.59
	Palmarolateral	0.18	0.48	0.07	0.81	-0.36	0.16	-0.03	0.93
	Palmaromedial	0.10	0.71	0.14	0.63	-0.19	0.47	-0.16	0.56

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 4: Correlation between foot quadrant dynamic <u>mean</u> pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, lame horses (left fore n=2 horses, right fore n=2 horses)

Foot Measure	Quadrant	LF Pre -trim		LF Post-trim		RF Pre-trim		RF Post-trim	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	1	1	1	1	1	1	1	1
	Dorsomedial	1	1	1	1	1	1	1	1
	Palmarolateral	1	1	1	1	1	1	1	1
	Palmaromedial	1	1	−1	1	-1	1	-1	1
DHWL (cm)	Dorsolateral	-1	1	-1	1	1	1	-1	1
	Dorsomedial	-1	1	-1	1	1	1	-1	1
	Palmarolateral	-1	1	-1	1	1	1	-1	1
	Palmaromedial	-1	1	1	1	-1	1	1	1
DHWA-HA (°)	Dorsolateral	-1	1	-1	1	-1	1	1	1
	Dorsomedial	-1	1	-1	1	-1	1	1	1
	Palmarolateral	-1	1	-1	1	-1	1	1	1
	Palmaromedial	-1	1	1	1	1	1	-1	1
Width (cm)	Dorsolateral	1	1	1	1	-1	1	-1	1
	Dorsomedial	1	1	1	1	-1	1	-1	1
	Palmarolateral	1	1	1	1	-1	1	-1	1
	Palmaromedial	1	1	-1	1	1	1	1	1
BBL (cm)	Dorsolateral	1	1	1	1	-1	1	-1	1
	Dorsomedial	1	1	1	1	-1	1	-1	1
	Palmarolateral	1	1	1	1	-1	1	-1	1
	Palmaromedial	1	1	-1	1	1	1	1	1
COR-Toe (cm)	Dorsolateral	1	1	-1	1	-1	1	-1	1
	Dorsomedial	1	1	-1	1	-1	1	-1	1
	Palmarolateral	1	1	-1	1	-1	1	-1	1
	Palmaromedial	1	1	1	1	1	1	1	1

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 5: Correlation between foot quadrant static maximum pressure (kilopascals) and foot measures pre- and post-trimming at the end of the study period, sound horses (n=26 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	-0.13	0.54	-0.02	0.94	0.13	0.55	0.26	0.23
	Dorsomedial	0.18	0.39	0.21	0.34	0.41	0.04	-0.27	0.21
	Palmarolateral	**-0.61**	**0.002**	-0.03	0.89	-0.01	0.98	-0.18	0.41
	Palmaromedial	0.07	0.75	0.06	0.98	0.27	0.20	-0.24	0.27
DHWL (cm)	Dorsolateral	-0.02	0.93	0.11	0.60	0.32	0.11	0.06	0.80
	Dorsomedial	-0.05	0.83	0.00	0.99	-0.14	0.51	0.19	0.38
	Palmarolateral	-0.15	0.49	-0.08	0.71	-0.11	0.60	0.19	0.38
	Palmaromedial	-0.27	0.20	-0.26	0.21	-0.13	0.53	-0.07	0.73
DHWA-HA (°)	Dorsolateral	-0.20	0.35	0.04	0.84	-0.29	0.16	0.05	0.82
	Dorsomedial	0.17	0.41	-0.13	0.54	-0.06	0.76	-0.10	0.63
	Palmarolateral	-0.09	0.67	-0.11	0.61	0.12	0.56	-0.33	0.12
	Palmaromedial	0.21	0.30	0.23	0.27	-0.12	0.56	-0.17	0.43
Width (cm)	Dorsolateral	0.32	0.12	0.33	0.13	0.06	0.78	0.07	0.75
	Dorsomedial	0.07	0.73	-0.03	0.88	-0.32	0.11	0.27	0.20
	Palmarolateral	0.18	0.38	0.48	0.03	0.19	0.37	0.13	0.56
	Palmaromedial	0.24	0.25	0.17	0.46	-0.17	0.41	0.07	0.75
BBL (cm)	Dorsolateral	0.27	0.19	0.25	0.26	0.25	0.23	0.22	0.30
	Dorsomedial	0.10	0.63	-0.09	0.69	0.05	0.82	0.22	0.30
	Palmarolateral	0.02	0.92	0.34	0.12	0.32	0.12	0.45	0.03
	Palmaromedial	0.08	0.70	0.02	0.92	0.01	0.95	0.01	0.95
COR-Toe (cm)	Dorsolateral	0.34	0.10	0.49	0.02	0.31	0.13	0.22	0.31
	Dorsomedial	0.12	0.58	-0.13	0.55	-0.05	0.82	0.01	0.96
	Palmarolateral	-0.01	0.95	0.44	0.04	0.39	0.06	0.11	0.62
	Palmaromedial	0.03	0.89	-0.15	0.52	0.00	1.00	-0.13	0.54

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 6: Correlation between hoof quadrant static maximum pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, lame horses (left fore n=2 horses, right fore n=3 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	1	1	-1	1	-1	0.33	-0.5	1
	Dorsomedial	1	1	1	1	0.5	1	1	0.33
	Palmarolateral	1	1	1	1	-0.5	1	-1	0.33
	Palmaromedial	1	1	1	1	-0.5	1	-0.5	1
DHWL (cm)	Dorsolateral	-1	1	1	1	0.5	1	0.5	1
	Dorsomedial	-1	1	-1	1	-1	0.33	-1	0.33
	Palmarolateral	-1	1	-1	1	-1	0.33	1	0.33
	Palmaromedial	-1	1	-1	1	-0.5	1	0.5	1
DHWA-HA (°)	Dorsolateral	-1	1	1	1	1	0.33	-0.5	1
	Dorsomedial	-1	1	-1	1	-0.5	1	-0.5	1
	Palmarolateral	-1	1	-1	1	-0.5	1	0.5	1
	Palmaromedial	-1	1	-1	1	0.5	1	-0.5	1
Width (cm)	Dorsolateral	1	1	-1	1	1	0.33	0.5	1
	Dorsomedial	1	1	1	1	-0.5	1	-1	0.33
	Palmarolateral	1	1	1	1	0.5	1	1	0.33
	Palmaromedial	1	1	1	1	0.5	1	0.5	1
BBL (cm)	Dorsolateral	1	1	-1	1	-0.5	1	1	0.33
	Dorsomedial	1	1	1	1	1	0.33	-0.5	1
	Palmarolateral	1	1	1	1	-1	0.33	0.5	1
	Palmaromedial	1	1	1	1	0.5	1	1	0.33
COR-Toe (cm)	Dorsolateral	1	1	1	1	0.5	1	1	0.33
	Dorsomedial	1	1	-1	1	1	0.33	-0.5	1
	Palmarolateral	1	1	-1	1	-1	0.33	0.5	1
	Palmaromedial	1	1	-1	1	0.5	1	1	0.33

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 7: Correlation between foot quadrant dynamic maximum pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, sound horses (pre-trim n=18 horses, post-trim n=16 horses)

Foot Measure	**Quadrant**	**LF Pre -trim**		**LF Post-trim**		**RF Pre-trim**		**RF Post-trim**	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	-0.33	0.19	-0.21	0.46	0.21	0.42	0.39	0.15
	Dorsomedial	-0.16	0.53	-0.21	0.46	0.10	0.71	0.22	0.43
	Palmarolateral	-0.16	0.53	-0.07	0.81	0.47	0.05	0.37	0.18
	Palmaromedial	0.15	0.55	-0.06	0.83	0.36	0.16	0.15	0.60
DHWL (cm)	Dorsolateral	-0.13	0.63	0.28	0.31	0.12	0.65	0.57	0.03
	Dorsomedial	-0.04	0.87	0.36	0.19	-0.07	0.79	**0.68**	**0.006**
	Palmarolateral	0.29	0.26	0.11	0.69	0.05	0.85	0.30	0.28
	Palmaromedial	-0.22	0.39	0.07	0.81	-0.07	0.78	0.20	0.47
DHWA-HA (°)	Dorsolateral	-0.07	0.78	-0.43	0.11	0.06	0.82	-0.13	0.64
	Dorsomedial	0.23	0.37	-0.23	0.41	-0.24	0.36	-0.04	0.90
	Palmarolateral	-0.40	0.12	-0.20	0.47	0.15	0.56	0.16	0.57
	Palmaromedial	0.23	0.37	0.02	0.94	-0.16	0.54	0.05	0.85
Width (cm)	Dorsolateral	0.17	0.52	0.24	0.41	0.20	0.44	0.08	0.78
	Dorsomedial	0.25	0.34	0.52	0.06	0.00	1.00	0.01	0.98
	Palmarolateral	0.36	0.16	-0.002	1.00	-0.34	0.19	0.11	0.69
	Palmaromedial	-0.03	0.91	0.27	0.34	-0.32	0.22	-0.40	0.14
BBL (cm)	Dorsolateral	0.22	0.40	0.36	0.20	0.15	0.57	0.05	0.87
	Dorsomedial	0.19	0.46	**0.74**	**0.004**	-0.16	0.53	-0.12	0.66
	Palmarolateral	0.45	0.07	0.34	0.23	-0.34	0.18	-0.06	0.83
	Palmaromedial	0.17	0.52	0.49	0.07	-0.16	0.53	-0.36	0.19
COR-Toe (cm)	Dorsolateral	0.14	0.59	0.24	0.42	0.01	0.96	0.004	0.99
	Dorsomedial	0.14	0.59	0.60	0.02	-0.22	0.40	-0.24	0.39
	Palmarolateral	0.28	0.28	0.26	0.37	-0.38	0.14	-0.14	0.62
	Palmaromedial	0.01	0.98	0.50	0.07	-0.22	0.39	-0.29	0.29

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation; LF = left fore; RF = right fore

Table 8: Correlation between foot quadrant dynamic maximum pressure (kilopascals) and solar foot measures pre- and post-trimming at the end of the study period, lame horses (left fore n=2 horses, right fore n=2 horses)

Foot Measure	Quadrant	LF Pre -trim		LF Post-trim		RF Pre-trim		RF Post-trim	
		r	P value	*r*	P value	*r*	P value	*r*	P value
LHWA (°)	Dorsolateral	1	1	1	1	1	1	-1	1
	Dorsomedial	1	1	1	1	1	1	1	1
	Palmarolateral	1	1	1	1	1	1	-1	1
	Palmaromedial	1	1	−1	1	-1	1	-1	1
DHWL (cm)	Dorsolateral	-1	1	-1	1	1	1	1	1
	Dorsomedial	-1	1	-1	1	1	1	-1	1
	Palmarolateral	-1	1	-1	1	1	1	1	1
	Palmaromedial	-1	1	1	1	-1	1	1	1
DHWA-HA (°)	Dorsolateral	-1	1	-1	1	-1	1	-1	1
	Dorsomedial	-1	1	-1	1	-1	1	1	1
	Palmarolateral	-1	1	-1	1	-1	1	1	1
	Palmaromedial	-1	1	1	1	1	1	-1	1
Width (cm)	Dorsolateral	1	1	1	1	-1	1	1	1
	Dorsomedial	1	1	1	1	-1	1	-1	1
	Palmarolateral	1	1	1	1	-1	1	1	1
	Palmaromedial	1	1	-1	1	1	1	1	1
BBL (cm)	Dorsolateral	1	1	1	1	-1	1	1	1
	Dorsomedial	1	1	1	1	-1	1	-1	1
	Palmarolateral	1	1	1	1	-1	1	1	1
	Palmaromedial	1	1	-1	1	1	1	1	1
COR-Toe (cm)	Dorsolateral	1	1	-1	1	-1	1	1	1
	Dorsomedial	1	1	-1	1	-1	1	-1	1
	Palmarolateral	1	1	-1	1	-1	1	1	1
	Palmaromedial	1	1	1	1	1	1	1	1

LHWA = lateral hoof wall angle; DHWL = dorsal hoof wall length; DHWA-HA = dorsal hoof wall angle – heel angle difference; Width = solar width; BBL = bearing border length; COR = centre of rotation, LF = left fore; RF = right fore

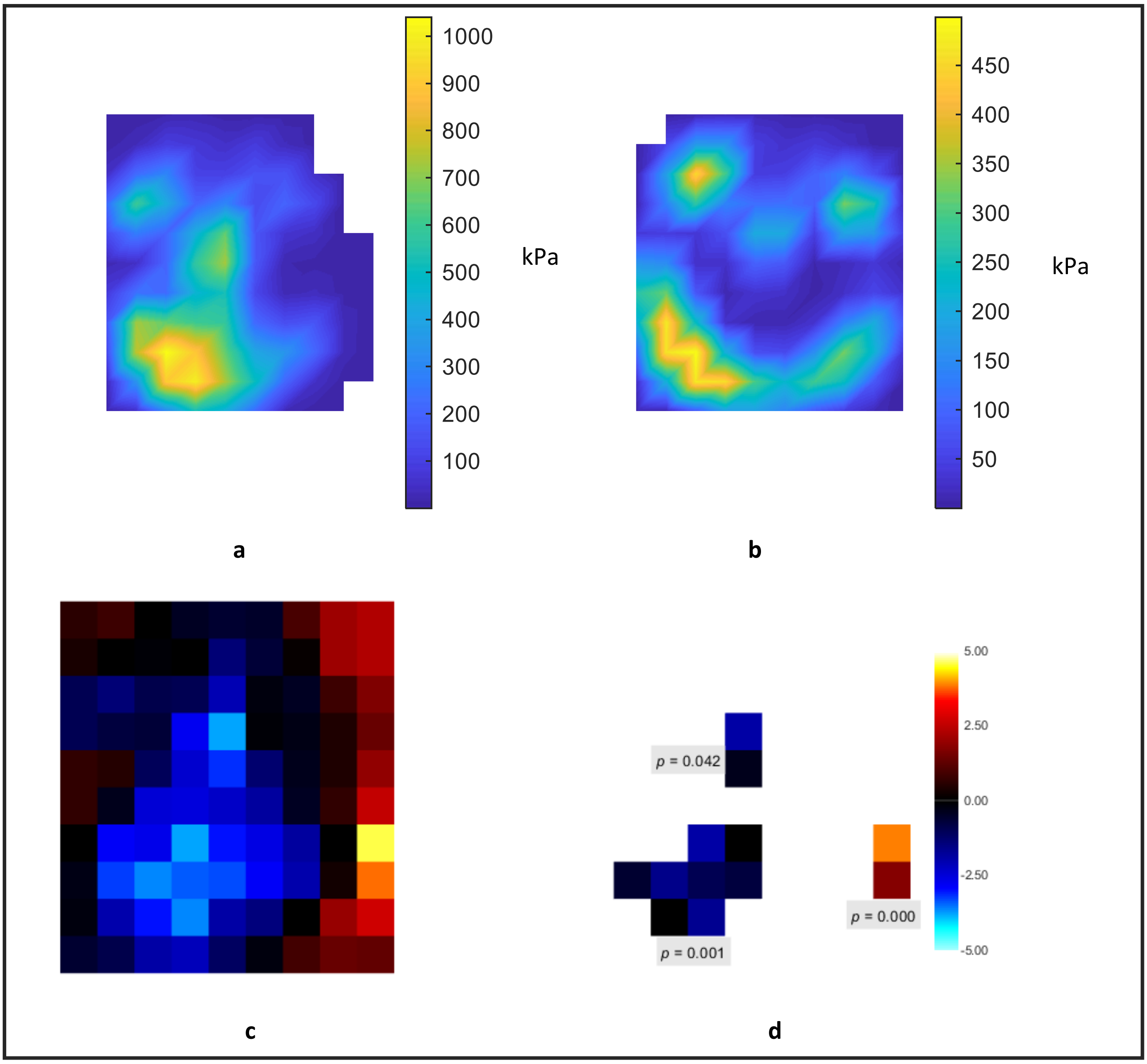

Figure 1: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of left fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of left fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse a and b indicate decreased loading of the toe and frog at the end of the study than the start, and increased loading of the medial hoof wall at the end of the study compared with the start. Clusters of pixels that are significantly different in the toe region (p=0.001), the frog region (p=0.04) and the medial hoof wall (p<0.001) are demonstrated in d; comparison with c enables localisation of these clusters to the regions described. The colour of the pixels in the clusters at the toe and frog indicate a negative change; since the pSPM method involves mapping the start strikes onto end strikes this means that lower pressure was exerted in these regions at the end of the study than the start. For the cluster at the medial wall, the opposite is true. kPa=kilopascals

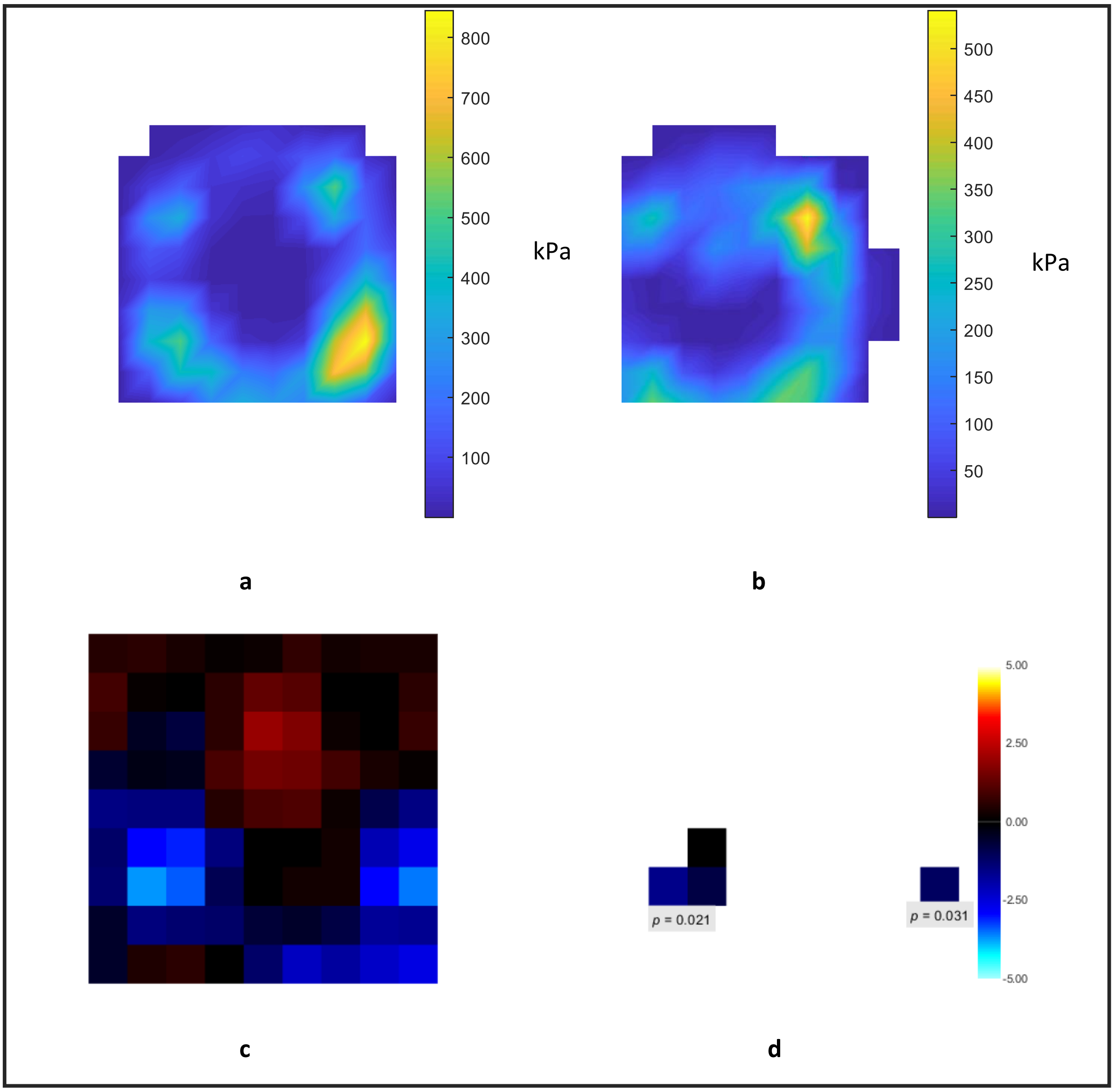

Figure 2: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period in a horse that was lame in the left forelimb at the end of the study. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse a and b indicate increased loading of the lateral toe region at the start of the study compared with the end. A cluster of pixels that are significantly different (p=0.02) between the start and the end of the study is demonstrated in d; comparison with c indicates the location is the lateral toe. The colour of the pixels in this cluster indicate a negative change; since the pSPM method involves mapping start strikes onto end strikes this means that there is less pressure in this region at the end of the study than the start. The single pixel change (p=0.031) at the medial aspect was not considered meaningful. kPa=kilopascals

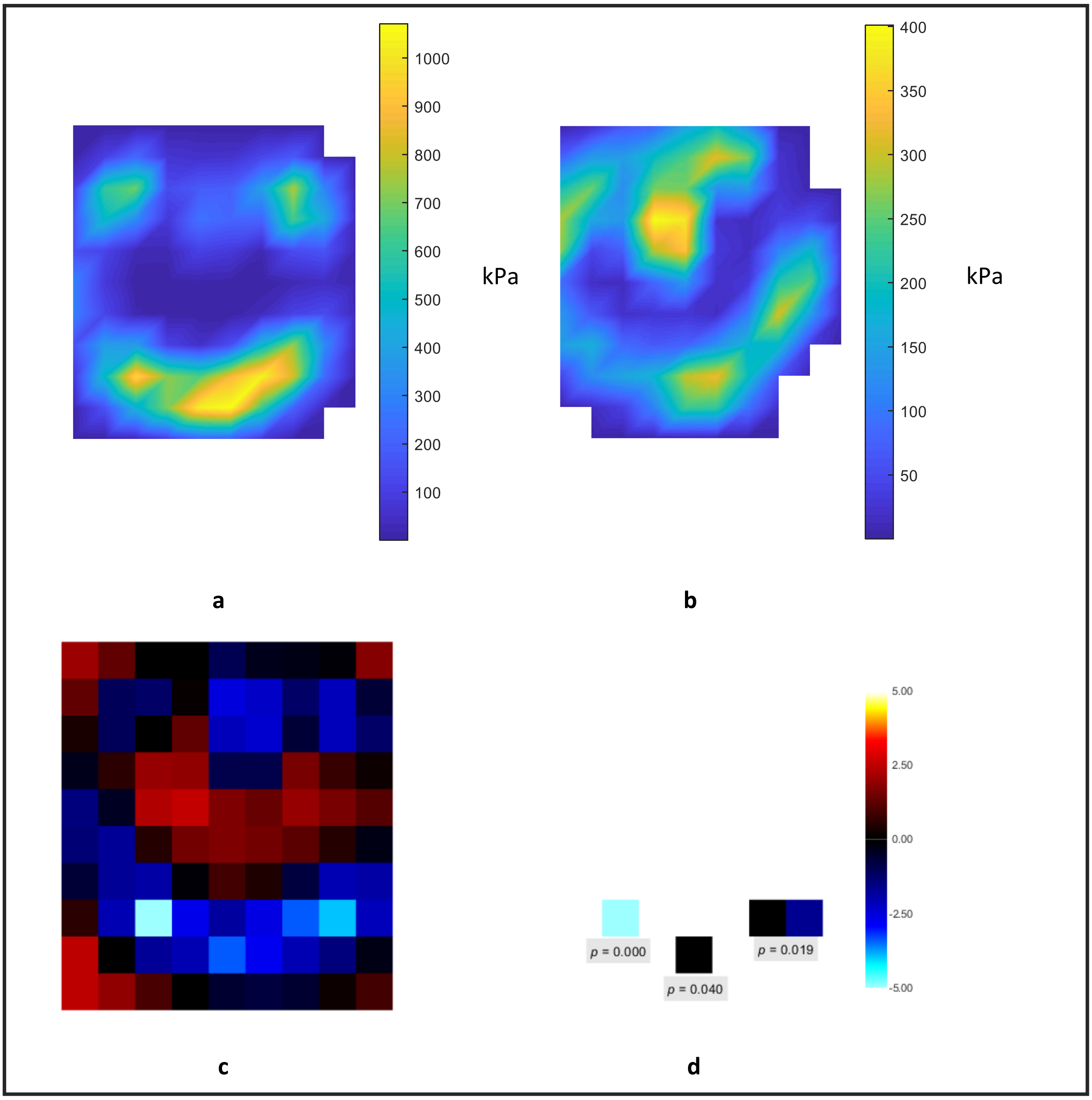

Figure 3: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. in this horse plots a and b indicate greater loading of the medial toe region at the start of the study. A cluster of pixels that are significantly different (p=0.019) between the start and end of the study is demonstrated in d; comparison with c indicates the location is the medial toe region. The colour of the pixels indicates a negative change; since the pSPM method involves mapping start strikes onto end strikes this means there is less pressure in this region at the end than at the start. All other changes were not considered meaningful due to affecting single pixels only. kPa=kilopascals

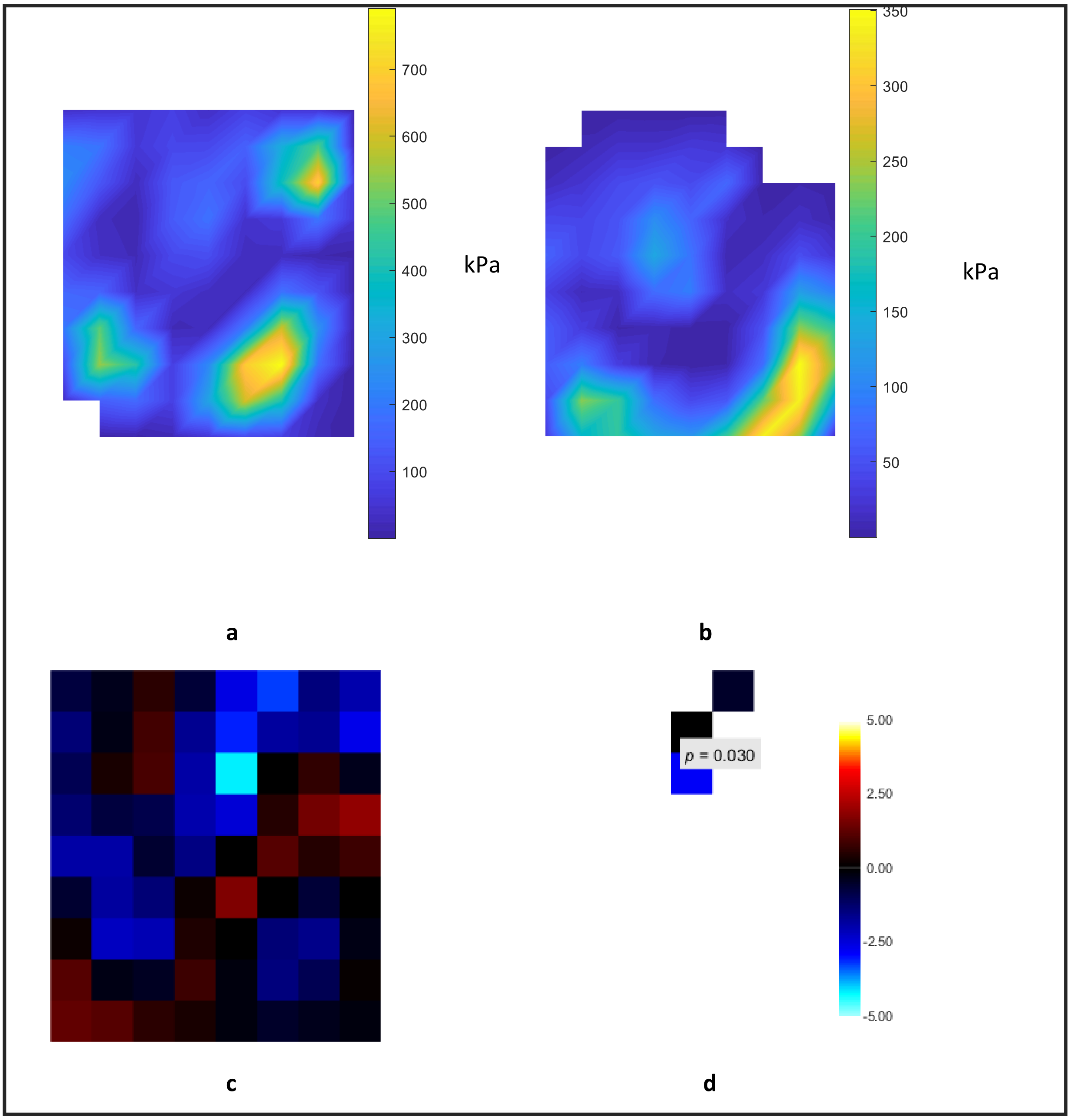

Figure 4: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. in this horse plots a and b indicate lower pressure in the medial heel region at the end compared with the start. A cluster of pixels that are significantly different (p=0.030) between the start and end of the study is demonstrated in d; comparison with c indicates that the location is the medial heel region. The colour of the pixels in this cluster indicate a negative change; since the pSPM method involves mapping start strikes onto end strikes this means there is significantly lower pressure exerted over the medial heel at the end of the study than the start. kPa=kilopascals

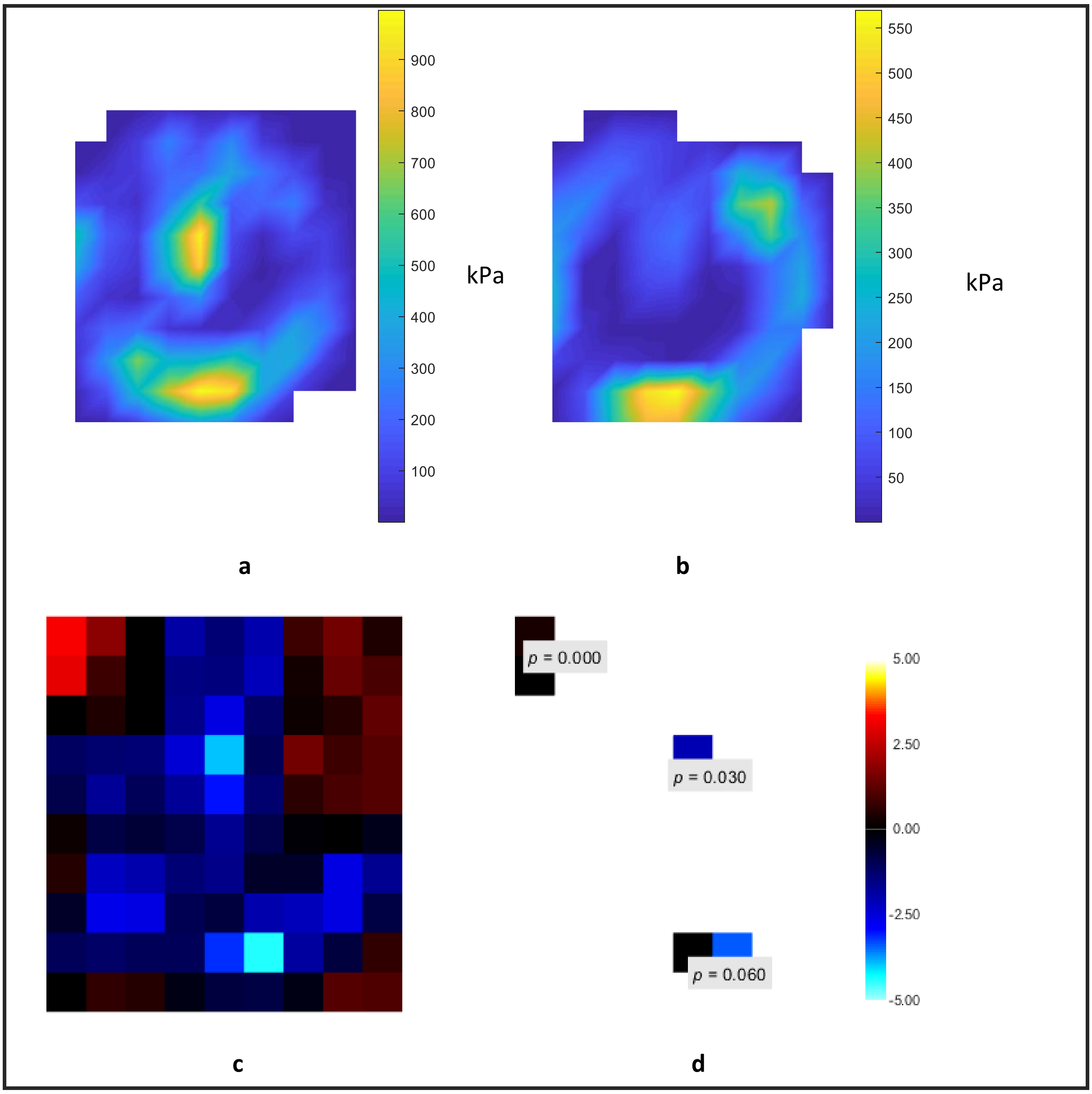

Figure 5: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse plots a and b indicate increased loading of the lateral heel region at the end of the study compared with the start. A cluster of pixels that are significantly different (p<0.0001) between the start and end of the study is demonstrated in d; comparison with c indicates the location is the lateral heel region. The colour of the pixels in the cluster indicate a positive change; since the pSPM method involves mapping start strikes onto end strikes this means there was significantly higher pressure on the lateral heel region at the end of the study than the start (p<0.0001). kPa=kilopascals

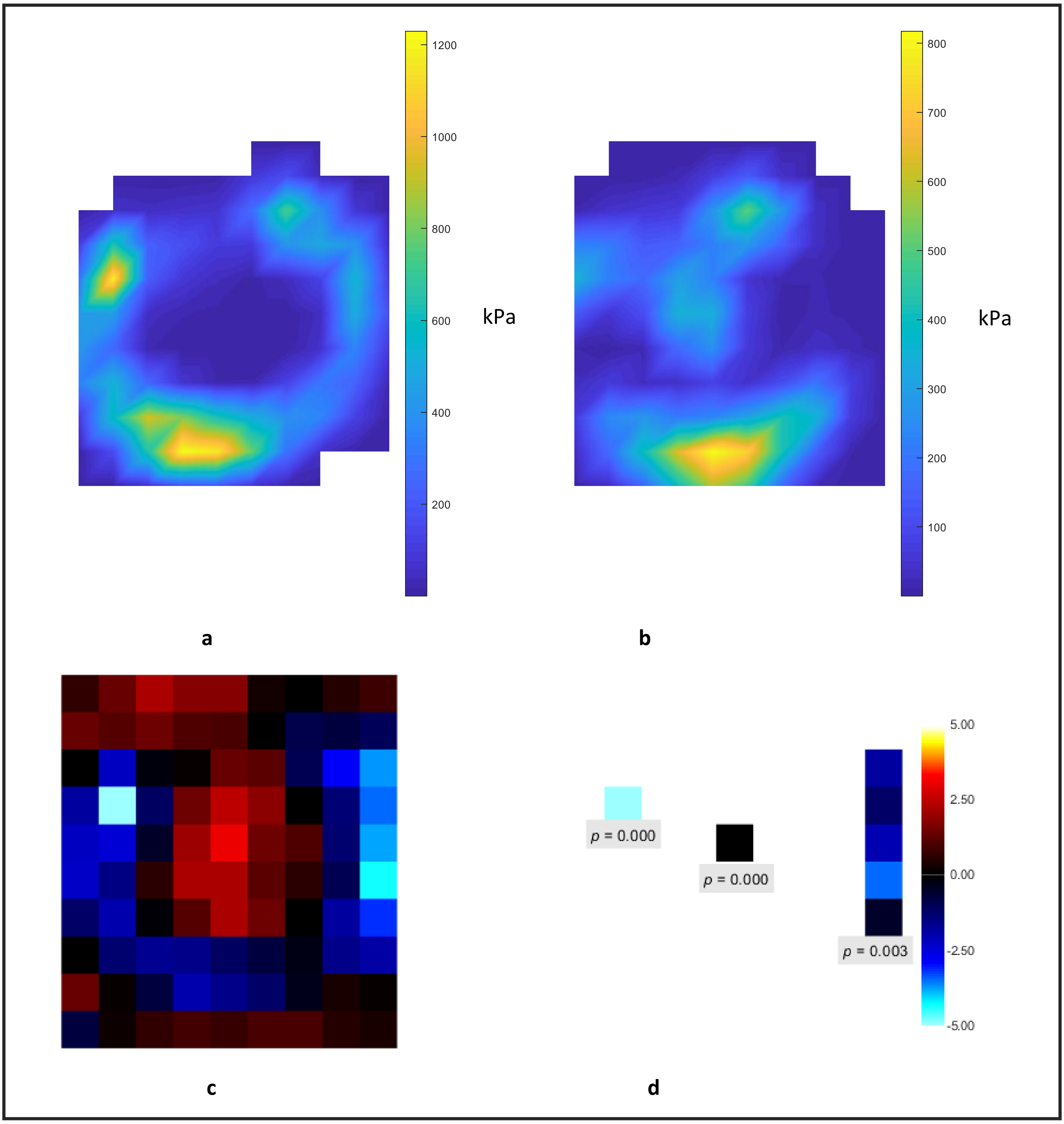

Figure 6: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse plots a and b indicate reduced loading of the medial hoof wall at the end of the study compared with the start. A cluster of pixels that are significantly different are demonstrated in plot d (p=0.003); comparison with c indicates this affects the medial hoof wall region. The colour of the pixels indicate a negative change; since the pSPM method maps start strikes onto end strikes this means there was significantly lower pressure on the medial hoof wall region at the end of the study compared with the start.

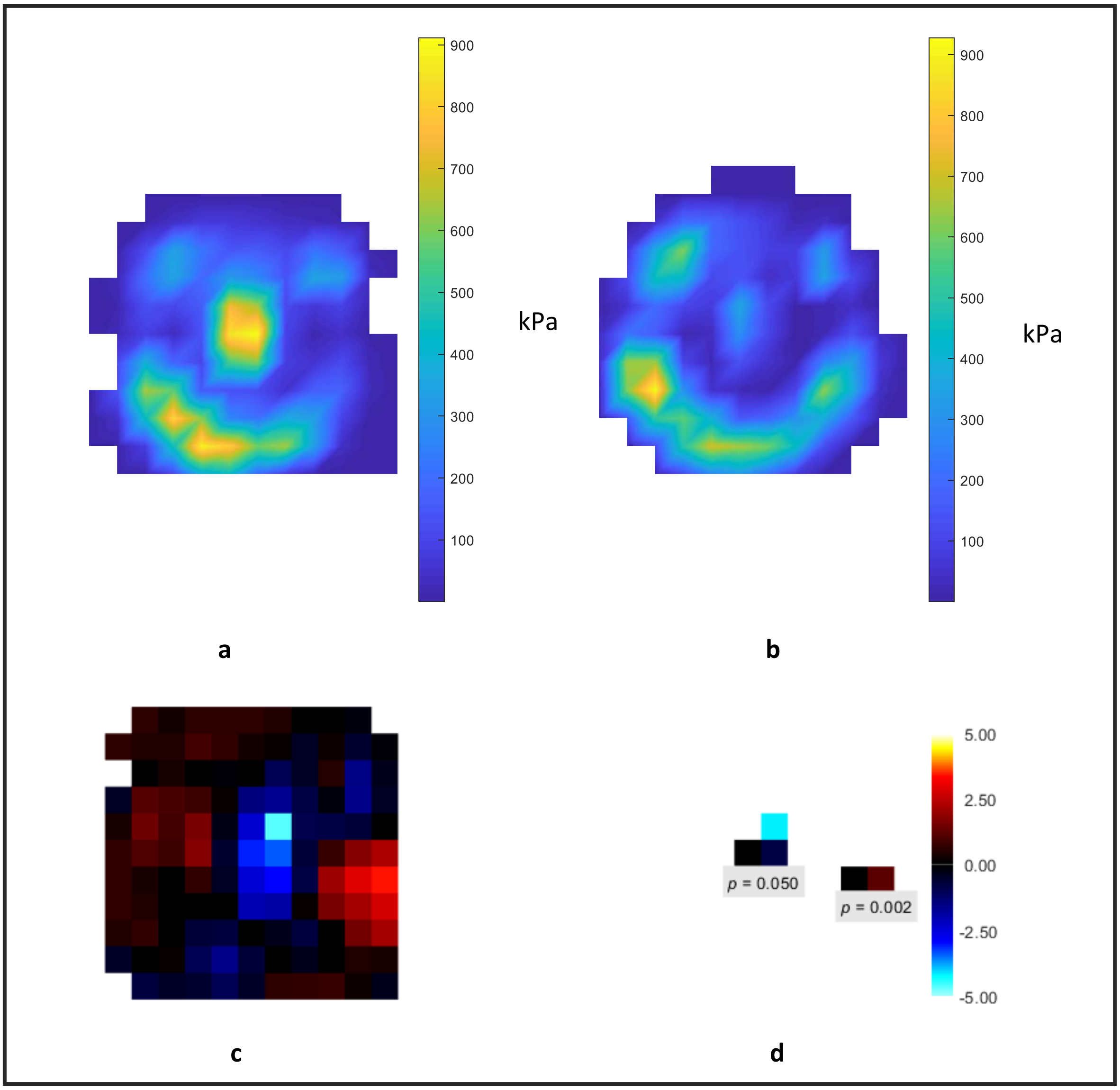

Figure 7: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse plots a and b indicate reduced loading of the frog region at the end of the study compared with the start. Two separate clusters of pixels that are significantly different (p=0.05 and p=0.002) are demonstrated in d; comparison with c indicates they affect the frog and medial hoof wall region, respectively. The colour of the pixels indicates a negative change (p=0.05) and positive change (p=0.002), respectively; since the pSPM method involves mapping start strikes onto end strikes this means that there was significantly lower pressure exerted on the frog region and significantly more pressure exerted on the medial hoof wall region at the end of the study than the start. kPa=kilopascals

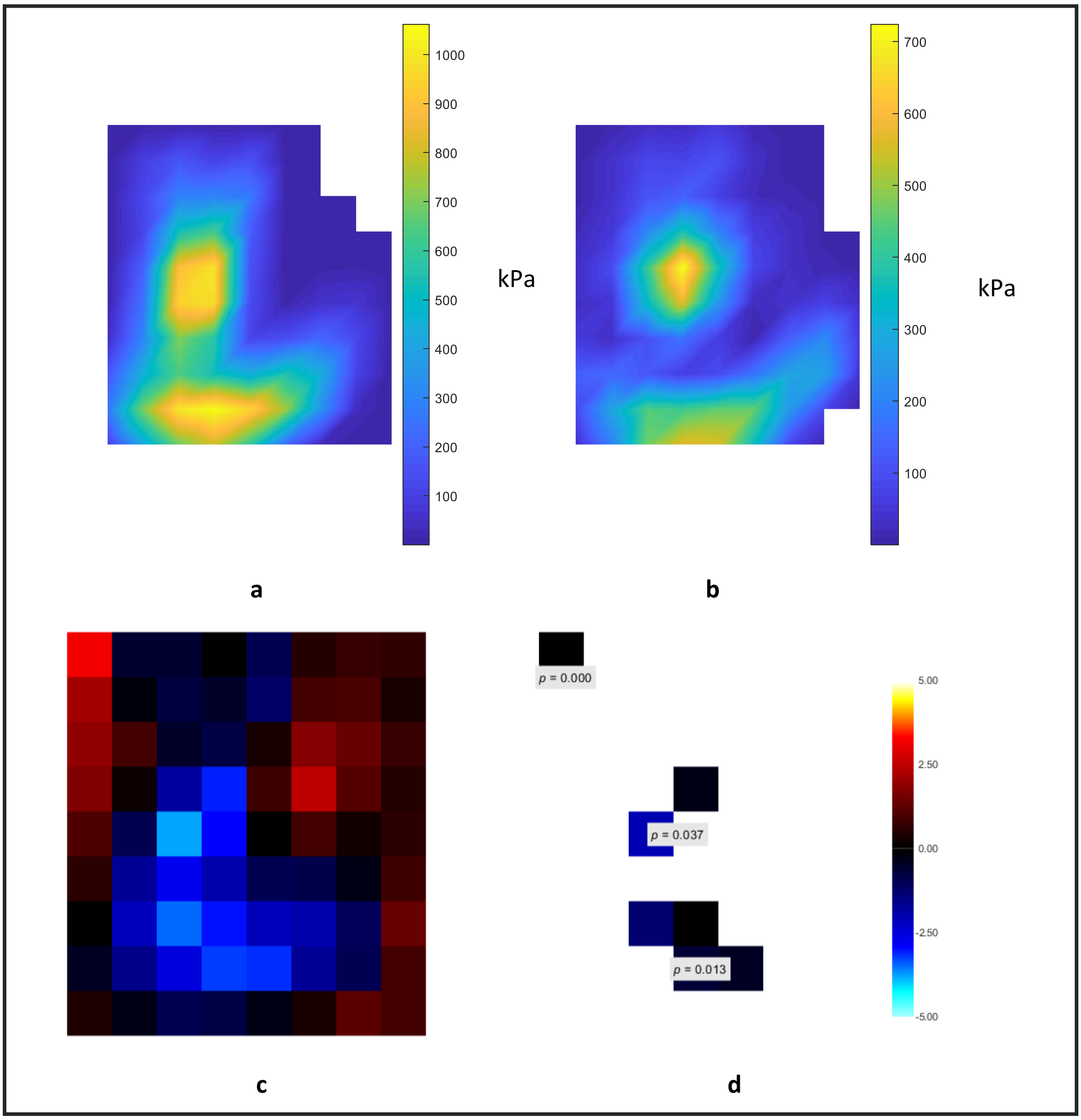

Figure 8: Plots a-d indicate mean pressure and significant differences in loading between the start and end of the study period. a is a plot of the mean pressure distribution of right fore pre-trim strikes at the start of the study, b is a plot of the mean pressure distribution of right fore pre-trim strikes at the end of the study. c is a plot of the difference between start and end and d plots the areas of significant differences in loading between the start and end of the study. In this horse plots a and b indicate decreased loading of the mid- and dorsal regions of the sole at the end of the study compared with the start. Two separate clusters of pixels that are significantly different are demonstrated in plot d; comparison with c indicates they affect the mid- and dorsal regions of the sole. The colour of the pixels indicates a negative change; since the pSPM method involves mapping start strikes onto end strikes this means there was significantly lower pressure exerted onto the mid- and dorsal sole at the end of the study compared with the start. kPa=kilopascals

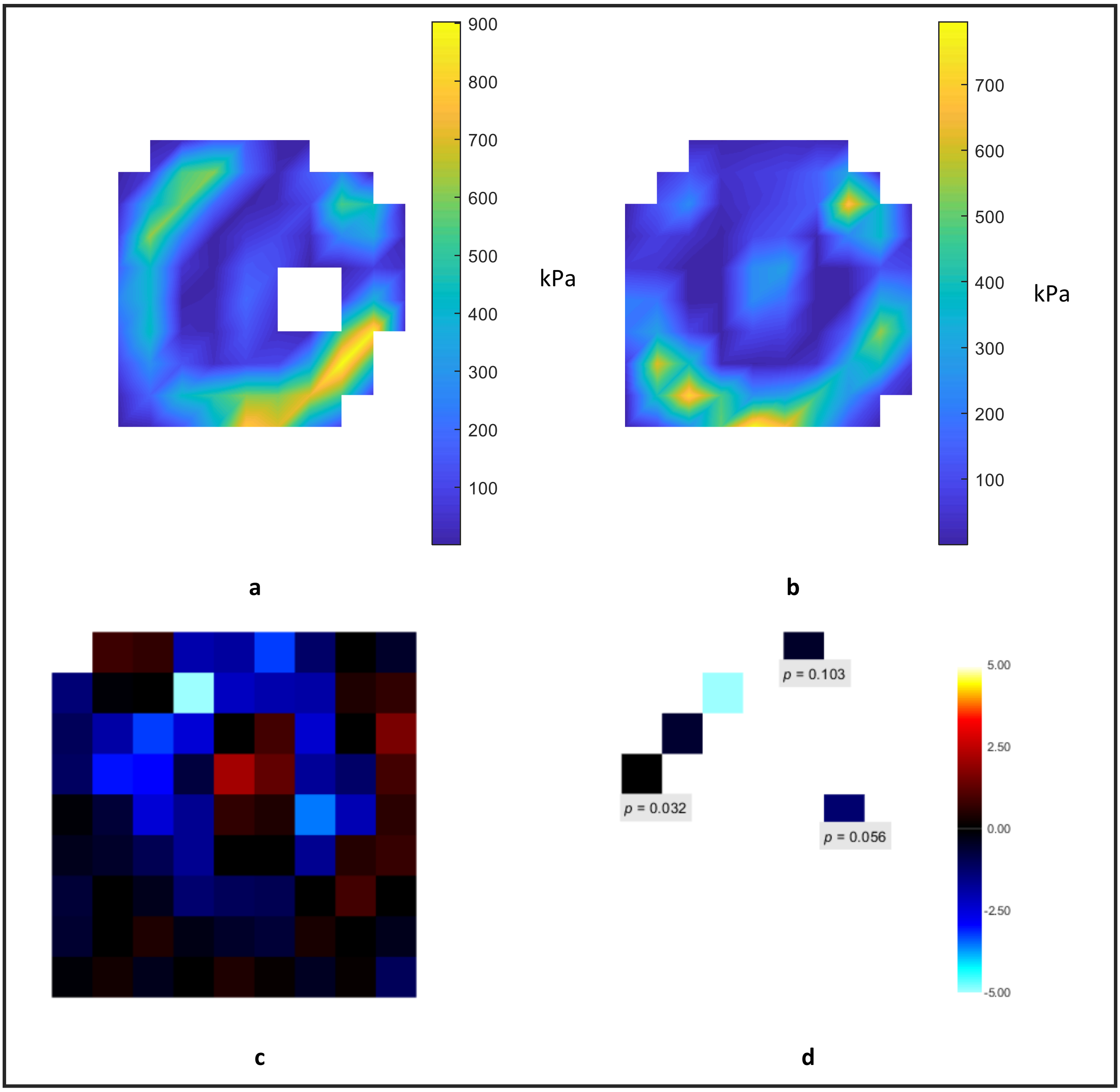

Figure 9: Plots a-d indicate mean pressure and significant differences in loading between left and right forelimbs at the end of the study period. a is a plot of the mean pressure distribution of left fore post-trim strikes at the end of the study, b is a plot of the mean pressure distribution of right fore post-trim strikes at the end of the study. c is a plot of the difference between left and right and d plots the areas of significant differences in loading between left and right. In this horse plots a and b indicate decreased loading of the right fore lateral heel region compared with the left fore. A cluster of pixels demonstrate a significant difference in d; comparison with c indicates this affects the lateral heel region. The colour of the pixels indicates a negative change; since the pSPM method involves mapping left fore strikes onto right fore strikes this means loading of the right fore medial heel is significantly lower than the left fore, post-trim at the end of the study. kPa=kilopascals