Chapter

The Anatomy, Histology and Physiology of the Healthy and Lame Equine Hoof

Ramzi Al-Agele, Emily Paul, Valentina Kubale Dvojmoc, Craig J. Sturrock, Cyril Rauch and Catrin Sian Rutland

Abstract

Satisfactory investigations of the equine foot appear to be limited by the histomorphological complexity of internal hoof structures. Foot lameness is considered to be one of the most debilitating pathological disorders of the equine foot. In most species, foot lameness is traditionally linked to hoof deformity, and a set of molecular events have been defined in relation to the disease. So far, there is controversy regarding the incidence of foot lameness in horses, as it is unclear whether it is foot lameness that triggers hoof distortions or vice-versa. In order to develop a better understanding of foot lameness, we review both the healthy and lame foot anatomy, cell biology and vascularisation and using micro-computed tomography show new methods of visualising internal structures within the equine foot.

Keywords: equine, anatomy, histology, healthy, lame, vasculature

1. Introduction

Understanding the basic anatomy of the horse hoof is essential in order to further investigate the structures' involvement in the pathogenesis of lameness and in order to help understand disorders such as lameness and laminitis. This chapter aims to show anatomy and physiology of the hoof and bones of the equine foot and relate these back to lameness and laminitis in the horse.

2. Gross anatomy of the equine hoof

The distal extremities of the domestic mammal are encased inside a keratinised capsule [1], which takes the form of a hoof capsule in ungulates and a claw in carnivores [2]. This insensitive horny structure encloses the distal part of the second phalanx (also known as the middle phalanx or short pastern bone), the distal phalanx (also known as the coffin bone or the pedal bone) and the navicular bone, in addition to connective tissues including, for example, the distal interphalangeal joint, medial and lateral hoof cartilage, with the terminal end of the deep digital flexor tendon and navicular bursa [1, 3–5]. These structures are connected to each other in order to provide a coherent and resilient structure within the foot (**Figure 1**) [6].

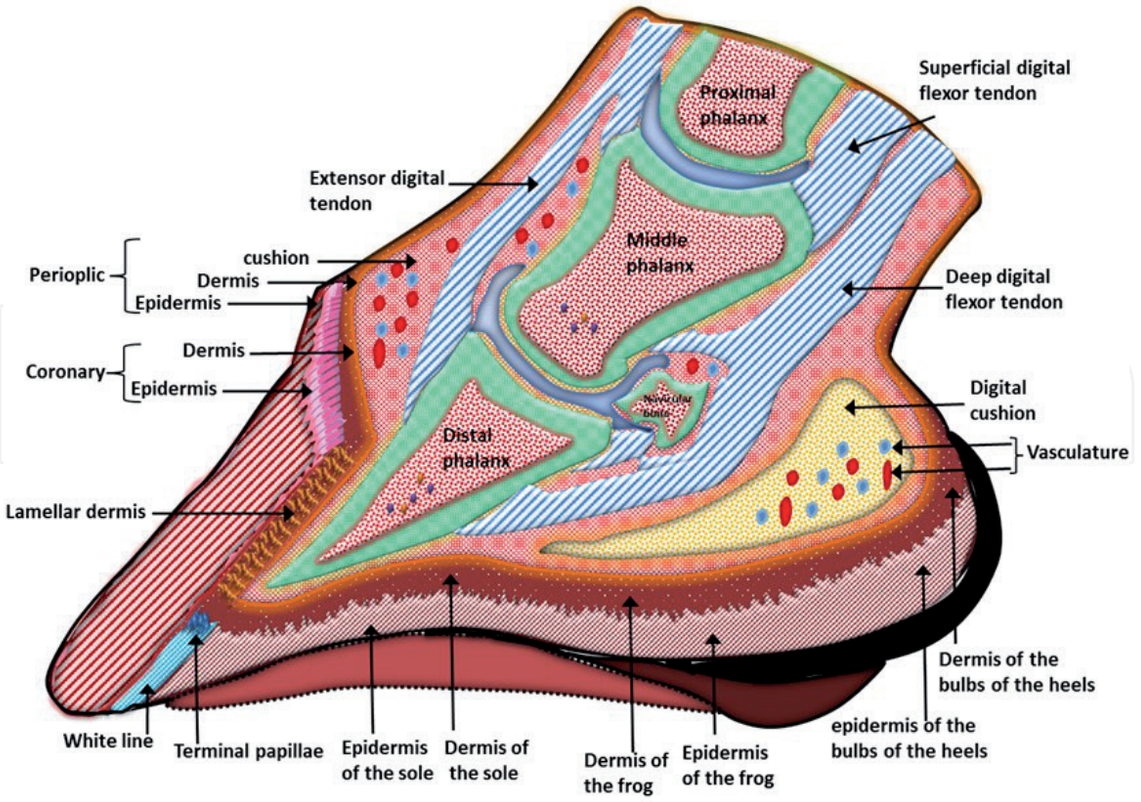

Figure 1.
Schematic drawing of a sagittal section of equine hoof. Schematic diagram illustrating the entire structure of the horse hoof. Figure adapted from Budras et al., [7].

The hoof is composed of horn, derived from epidermal tissue which has been keratinised to a varying extent [8]. Horn is largely arranged into a series of parallel microscopic tubules, interconnected by intertubular horn [9]. This structure plays a substantial role in load-bearing, and encapsulates almost the entire circumference of the foot, curling inwards towards the rear to form the bars which provide additional support to the heels [10]. Encasing the palmar/plantar surface of the foot is the sole, which is concave and has a similar, but softer and more flexible, composition to the hoof wall [10]. The hoof joins to the skin at the coronet where it is protected by a waterproof band of soft tubular horn, the periople [11]. Connecting the periphery of the sole to the hoof wall is the white line, which is highly elastic and derived from the epidermal lamellae. Composed of supple, incompletely keratinised horn, the frog is an elastic structure which is essential for shock absorption, blood circulation, and in slip prevention [10]. The frog extends inwards to the digital cushion which, being composed of poorly vascularised adipose tissue embedded in a fibroelastic mesh, is involved in shock absorbance and possesses blood pumping properties [6, 10]. The digital cushion is segregated from the deep digital flexor tendon (DDFT) by the presence of the distal digital annular ligament [10].

The bones of the equine foot comprise the third phalanx (P3; also called the distal phalanx), the second phalanx (P2), and the navicular bone. P3, also referred to as the pedal or coffin bone, is the foot's principal bone, occupying its most distal position, and attaching to the hoof capsule via the lamellar and solar coria [6]. P3 supports and stabilises the hoof capsule, and is highly porous due to the prolificacy of nutrient foramina [6]. P2, or short pastern, forms the proximal interphalangeal, or pastern, joint with the first phalanx (P1), and the distal interphalangeal, or coffin, joint with P3 [10]. Its short, nearly cuboidal, composure makes P2 resilient to a broad range of stresses [6]. The navicular, or distal sesamoid bone, is a small, smooth bone located caudal to the distal interphalangeal joint. Coated ventrally in

smooth fibrocartilage, it has a pulley-like role, allowing the DDFT to glide smoothly under the distal interphalangeal joint without interference from other bones [10]. The navicular synovial bursa and distal synovial sheathes further aid the smooth action of the DDFT as it secretes synovial fluid which lubricates the area [10].

Along with the DDFT, which descends from the deep digital flexor muscle in the forearm to the flexor surface of P3, the superficial digital flexor tendon (SDFT) forms part of the back tendon pair, thus enabling flexion of the interphalangeal joints [10, 11]. Descending from the superficial digital flexor muscle in the forearm, the SDFT attaches to the proximal surfaces of P1 and P2 [10]. Responsible for the extension of the interphalangeal joints is the common digital extensor tendon (CDET also known as m. extensor digitorum communis in the fore limb and m. extensor digitorum longus on the rear limb) [11]. Stemming from the long digital extensor muscle proximal to the knee, the CDET descends the leg dorsally, terminating at the extensor process of P3 with projections into P1 and P2 [10].

While the DDFT and SDFT permit flexion of the foot's interphalangeal joints and the CDET allows their extension, the presence of lateral and medial collateral ligaments limits the joints' adduction and abduction respectively [11]. The collateral ligaments attach to notches on the distal and proximal edges of P1 and P2 correspondingly in the case of those of the proximal interphalangeal joint, and on the distal and proximal edges of P2 and P3 respectively for those of the distal interphalangeal joint [11]. The position of P3 is also maintained by three pairs of chondral ligaments, attaching to the medial and lateral cartilages of P3 [10]. The navicular bone is held in place by the navicular suspensory ligaments which anchor to the distal edge of P1, just dorsal to the collateral ligament attachments, and converge at the navicular bone, forming the distal navicular ligament which terminates at P3 [10].

The coria are the richly vascularised and innervated dermal regions lying between and supporting the skeletal structures and the epidermal hoof capsule [4]. The coronary corium runs along the proximal edge of the hoof wall, with each hoof wall tubule growing around small, finger-like papillae projecting from the coronary corium which provide nourishment to the proliferative epidermal cells, maintaining hoof growth [8]. The solar corium is similar in structure and function to the coronary corium, with papillae enabling the growth of the sole [8]. The lamellae of the lamellar corium, commonly referred to as the sensitive or the dermal lamellae, form, together with the epidermal/insensitive lamellae of the inner hoof wall with which they interlock, the suspensory apparatus of the third phalanx, suspending P3 within the hoof capsule [4]. Distal to each dermal lamella is a set of papillae, the terminal papillae, which form the soft, elastic white line which binds wall to sole [8].

The macroscopic ridge-like primary lamellae, of which there are some 550–600 epidermal/dermal interlocking pairs in parallel descent within each foot, provide a large surface area between the epidermis and the dermis for the suspension of P3 [9]. Each primary lamella bears a further 150–200 microscopic secondary lamellae and, collectively, the primary and secondary lamellae create a surface area for attachment of around 0.8 m^2 (**Figure 2**) [9].

Between the dermal and epidermal tissues of the foot lies the basement membrane (BM), a strong, uninterrupted sheet of extracellular matrix [8]. Epidermal basal cells are attached to the basement membrane (BM) on its border with the hoof epidermis [8]. On its inner, dermis-bordering side, a vast array of collagen-rich connective tissue strands projecting from the periosteum of P3 intertwine with the BM's lattice, ensuring the structural integrity of the dermal structures [8]. The BM is folded into ridges along the longitudinal axes of the primary lamellae, forming the secondary lamellae, and the coronary and terminal papillae, increasing the surface area for the attachment of proliferative epidermal basal cells [12].

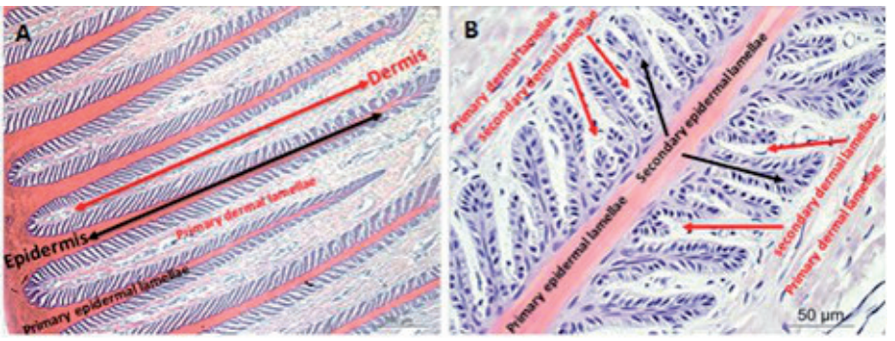

Figure 2.
Haematoxylin and eosin stained lamellae within the horse hoof.

3. Vasculature of the foot

In addition to the bones, ligaments, tendons and other soft tissues of the foot, the vasculature is essential in the equine foot. The blood vessel system is a vital part of transport of dissolved gases, nutrients, waste, signalling chemicals such as hormones, and immune cells to and from other organs [13]. The vast vascular network underlying the hoof capsule and coursing through the bones, fed through branches from the medial and lateral digital arteries and returning to general circulation via the medial and lateral digital veins (**Figure 3**) [9].

The vascular blood supply of the hoof originates from the common palmar digital artery and the dorsometatarsal artery, these main branches giving rise to medial and lateral palmar/plantar digital arteries (**Figure 4**) [14, 15]. In the hind limb, the small plantar common digital arteries contribute to form the digital arteries. At the level of second phalanx, there are branches nourishing to the heel bulbs and coronary region [1].

The vascular arteries of the dermis are divided into three independent arterial blood supplies: the dorsal coronary corium; the palmar/plantar portion of the coronary corium and laminar corium; and the dorsal laminar corium and solar corium, as the blood flow is reversely directed from the distal part to the proximal part within the dermal lamina (also termed lamella/lamellae and lamellar in the

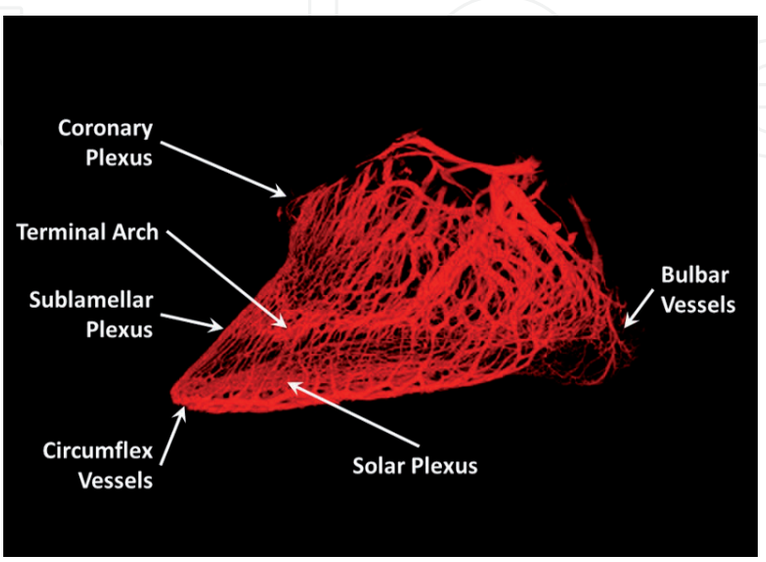

Figure 3.
Vascularisation of the equine foot. Reconstruction of the vasculature of the equine foot from CT images, showing the coronary, sublamellar and solar plexuses, the terminal arch, the circumflex vessels of the sole, and the bulbar vessels.

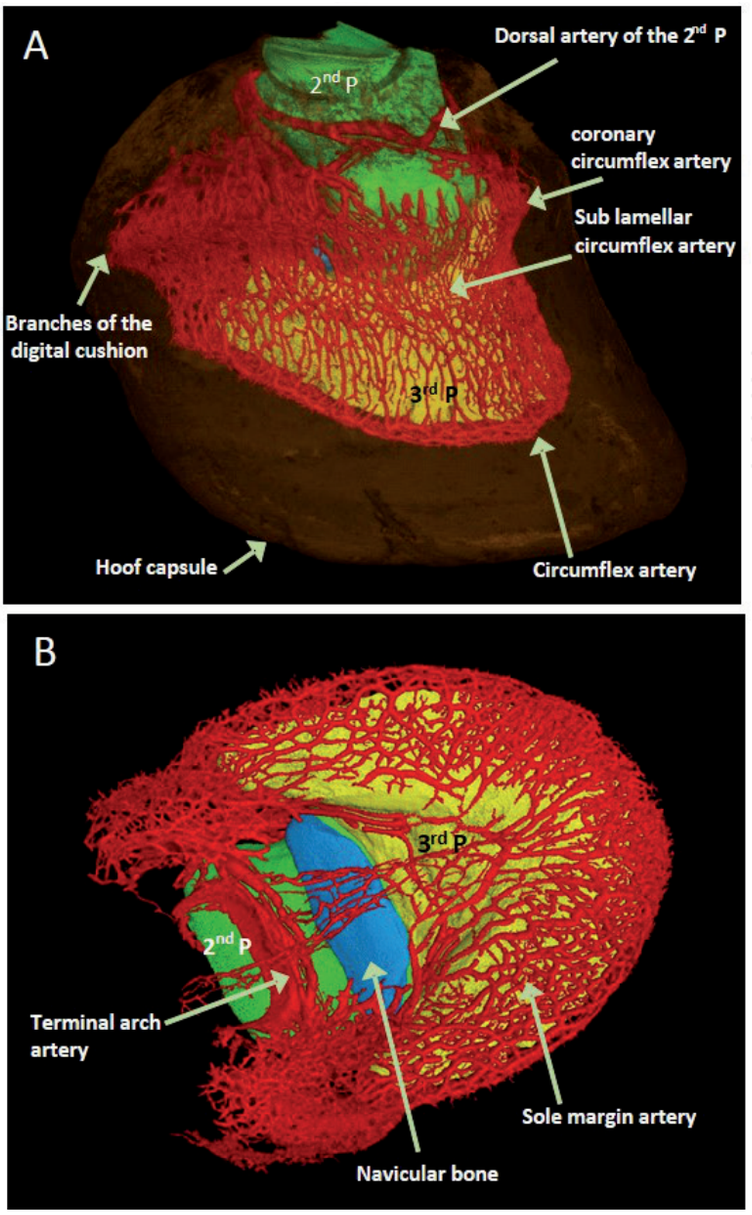

Figure 4.
Reconstruction of micro CT image illustrating vascularisation of equine foot. Computed tomography (CT) scan images showing the three-dimensional reconstruction of arterial supply of equine foot. (A) Shows arteries distributed throughout the dorsal surface of the distal phalanx and anastomoses located proximally with vessels of the coronet and distally forming the circumflex artery. (B) Represents the arteries distributed in the sole margin.

literature) [4]. The terminal branches of the blood supply enter the distal phalanx from the medial and lateral aspects and then form several anastomoses within the bone to make the terminal arch. At this arch, there are 8–10 blood vessels emerging distally to nourish the sole margin [1]. This is a highly important organisation of blood vessels in equine feet as the terminal arch and its branches are protected by the bony canal that can be altered in chronic laminitis, leading to ischemia and a decrease in the growth rate of the corium [16].

The capillary network of the equine digit is complex due to the fact that the dorsal and palmar parts of the foot have different blood supplies and drainage routes [2]. For instance, the blood vessels of the dorsal lamella pass through the distal phalanx and the blood supply of these portions is directed in the distal to the proximal way, while the palmar lamella is from the proximal circumflex to dorsal lamella [17]. Thus, haemorrhage from the sublamellar circulation can result in the rotation of P3, as is observed in the case of founder [16, 18, 19]. Consequently, the blood vessels of

the equine foot are predisposed to local vasoconstriction and the development of ischemic disease as the arteries from the plexus have thicker walls with small lumens and are unable to auto-regulate the volume variations that are involved in contraction of smooth muscle as well as encompassing arteriovenous shunts [18].

The equine hoof veins are divided into three groups depending on their location: wall dermis veins, which are separated into proximal and distal regions; coronary dermis veins; and frog and sole dermis veins [1]. The dermal lamella is drained by: the coronary vein; the independent superficial vein; the proximal branch of the caudal hoof vein; and the circumflex vein. The toe and quarters are drained via the circumflex vein [2, 20]. An additional feature of the blood circulation of the equine foot is the anastomoses of arteries and veins, which are blood vessels forming shunts [21]. Each dermal papilla in the periople, coronary band, frog, sole and terminal papillae contain a meshwork of anastomosing arteriovenous vessels located at the base of the papillae. These anastomoses are able to withdraw approximately 50% of the whole limb blood flow, and thus can be involved in ischemia due to blood flow diversion [22]. This could explain the relationship between laminitis and ischemia [3].

4. Bone physiology

Bone is a complex, dynamic tissue that has the ability to grow ontogenically, to repair after damage, and to adaptively respond to a variety of exogenous and endogenous stimuli [23]. Composed of a mineralised organic matrix in which the cells responsible for its formation and rejuvenation are embedded, osseous tissue, through its unique physiological and biochemical properties, enables bones to perform a multitude of functions within the animal's body. The organic matrix, or osteoid [24], is formed principally of type-I collagen (around ~95% type-I [25]) which affords the bone its tensile strength, alongside trace amounts of other collagens, in addition to non-collagenous proteins whose predominant purpose is to permit the mineralisation of the matrix. The chief mineral salt found in osseous tissue is a form of hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] which, bound to the matrix proteins, renders the tissue resistant to compressive forces [23].

The bone is structured into either cortical or trabecular bone. Cortical, or compact, bone forms the dense outer proportions of the bone and, in the human, accounts for 80% of the total skeletal mass [23, 26]. Cortical osteons (**Figure 5**), or Haversian systems, are tubular structures consisting of a central channel (Haversian canal), through which a nerve and blood supply are provided,

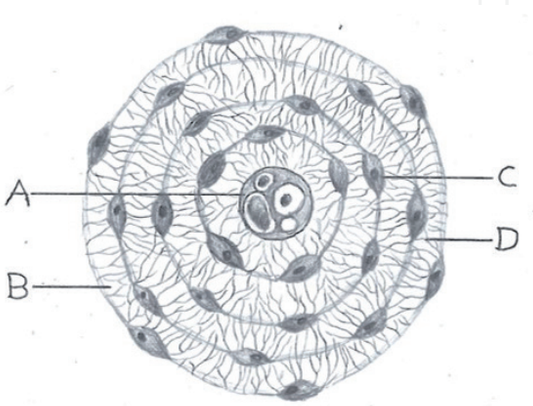

Figure 5.
Schematic of a cortical osteon. (A) Represents a Haversian canal incorporating a neurovascular bundle, (B) a lamella, (C) a lacuna containing an osteocyte, and (D) canaliculi.

surrounded by coaxial lamellae of mineralised bone matrix which incorporate a number of voids, in the form of lacunae and canaliculi, inhabited by cells [23]. The remaining 20% of the osseous tissue is in the form of trabeculae (from the Latin *trabs*, meaning "beam" [27]) which provide structural support, in a buttress-like manner, to the surrounding cortex. Trabecular osteons, or packets, are similar in their lamellar architecture to those of the cortex, but are smaller in size and semi-lunar in shape [23]. This hierarchical design, a common (if not omni-existent) phenomenon in biological materials, provides bones with the physical strength they need to fulfil their roles in structural support, the protection of underlying organs, and in providing leverage to muscles and tendons, facilitating movement [23, 28, 29].

The remodelling and general renewal of the bone is mediated by three cell types: osteoblasts, osteoclasts and osteocytes [30]. Osteoblasts are mononucleated cells formed by the differentiation of mesenchymal stem cells, and are responsible for the synthesis of osteoid and its subsequent mineralisation [25]. They reside principally in the endosteum—the vascularised cellular lining of the internal proportions of the bone, covering the walls of the Haversian canals, and the trabeculae and medullary cavity where it separates the bone matrix from the marrow [31]—and, alongside their incompletely-differentiated precursors and fibroblasts, the cambial layer of the periosteum [23]—a vascularised and innervated structure consisting of an outer fibrous layer comprising fibroblasts, collagen and elastin, and the discrete inner cambium that coats the bone's exterior [32]. Osteoclasts are multinucleated macrophagic cells derived from phagocytes in the haematopoietic bone marrow, and carry out bone resorption in localised areas of the bone surface to which they adhere upon activation [21]. Osteocytes, which inhabit the lacunae of the osteons and have multiple cytoplasmic processes which traverse the osteons' canaliculi, are the result of the terminal differentiation of osteoblasts that have become entrapped within the bone matrix that they have synthesised [25]. They act as mechanoreceptors, communicating with the osteogenic/osteolytic cells via gap junctions at the extremities of their cytoplasmic processes, and play a regulatory role in the bone synthesis/resorption cycle [25].

Concomitant to the physical need for the bone to be able to remodel for general maintenance, repair, and for increasing structural strength in response to stimuli, are the roles in pH balance and mineral homeostasis that the synthesis/resorption cycle affords [23]. While under normal physiological circumstances the pH of blood and extracellular fluid is maintained within narrow parameters by the removal and excretion of protons by the kidneys and lungs, a multitude of physiologically adverse conditions (e.g. kidney disease or severe exercise) can lead to acidosis [33]. The basicity of hydroxyapatite renders bone an emergency reservoir for base, buffering the acidity with the products of osteoclastic resorption. This mechanism is enabled by the osteoclast's stimulation at low pH, a peculiarity from a general cellular point of view, and the osteoblast's synergistic inhibition [33]. In a similar vein, bone acts as a reservoir for calcium and phosphorus, making them available for the maintenance of mineral homeostasis. Calcium and phosphorus are vital for a plethora of biological functions, and their homeostasis is under the endocrine regulation of the parathyroid glands, thyroid gland, and the kidney which, through the intermediary of parathyroid hormone, calcitriol (1,25-dihydroxyvitamin D, a hormone derived from vitamin D), and calcitonin respectively, affect the intestinal absorption, renal reabsorption and bone synthesis/resorption mechanisms [24, 34]. The parathyroid glands, which express Ca^{2+}-sensing receptors, secrete PTH in response to a reduction in circulating calcium ions. Parathyroid hormone acts in the kidney to decrease phosphate and increase calcium reabsorption, and in the bone by stimulating osteocytic and osteoclastic activity [34].

Bone also acts as reservoir for growth factors and cytokines, which are released during bone resorption and take effect either locally or systemically [14]. Along with the effects that these growth factors and cytokines may exert on other tissue cell types, such as the endothelial cells of the vasculature, they play important roles in bone formation and resorption, including: insulin-like growth factors, transforming growth factors, and bone morphogenic proteins as growth factors promoting osteogenesis; epidermal growth factor, granulocyte-macrophage colony-stimulating factor, macrophage-colony stimulating factor, and tumour necrosis factor as growth factors stimulating osteolytic resorption; platelet-derived growth factor and fibroblastic growth factor which have contributory effects to both bone formation and resorption; prostaglandins and leukotrienes as osteolysis-stimulating cytokines; and interleukins that may directly or indirectly stimulate either bone formation or resorption depending on the interleukin family in question [35].

Strong links exist between the skeletal and vascular systems and, along with a strong vascular and nerve presence in the periosteum, numerous neurovascular bundles enter the bone through nutrient foramina, descend and ascend the canals of Haversian systems, and enter medullary cavity through Volkmann's Canals [36]. The two systems are interdependent in that the bone relies on the vasculature for the delivery of oxygen and nutrients and that, modulated by osteoblasts, haematopoiesis takes place in the bone marrow [37].

5. Morphological changes and pathologies in the foot

The external morphology of the hoof capsule is indirectly associated with the function and shape of the internal segments of the hoof [38]. Dyson and colleagues [39] drew attention to the fact that, despite differences in the orientation of the distal phalanx between horses, mainly associated with changes in direction of the dished solar border, the morphology of the distal phalanx is unaffected by the external features of the hoof capsule. It is worth noting here that hoof shape can be altered when trimming and shoeing are considered [40]. The impact of trimming/shoeing on the hoof capsule shape has been explained [41] and the researchers demonstrated that the formation of the hoof wall is physically connected to the loading of the lower limb, thus protecting its optimal balance on the ground [42]. Therefore, the geometrical tendency of the foot components determines the ability of the internal structures to respond to loading through the bearing phase of the stride cycle [43].

The distal phalanx is attached within the hoof capsule through the suspensory apparatus [44], which connects the entire parietal surface of the distal phalanx to the lamellar structures of the internal hoof wall [11]. Preliminary work on equine lamellar connection found that this attachment provides the mechanism by which the weight is transferred between the distal phalanx and the epidermal laminae of the hoof wall [45]. This connection, or attachment, has a substantial role in the biomechanics of healthy foot performance, and may lead to foot lameness if damaged [41]. Indeed, the failure of the connection between the epidermal laminae and the underlying basement membrane of the dermal lamellae would weaken the suspensory apparatus of the distal phalanx [46]. Unsurprisingly, changes in the basement membrane of the suspensory tissue have been suggested to signal the first step of laminar failure [47]. While other research reported that lesions in the basement membrane appear before any clinical signs of foot lameness [48]. The dislocation of the distal phalanx, followed by its rotation, applies pressure, first on the sole at the palmar border of the distal phalanx and, secondly, on the coronet or upper area of the lamellae by the extensor process of the distal phalanx [49]. These deflections lead to impaired blood flow into the basal layers of the hoof wall [18], and can lead

to an inhibition of the growth rate of the hoof capsule, affecting its shape over time and induced osteolysis of bone trabeculae in chronic stages [50]. A number of hoof shapes can arise from this chronic condition, including sheared heels, crushed heels, club foot, long-dished toe, and high-heel foot [49, 51].

One of these chronic conditions is the lamellar wedge that develops alongside laminitis and a result can be an anatomical displacement of the distal phalanx within the hoof capsule [52], is a direct consequence of the failure of the suspensory apparatus of the distal phalanx [53]. However, the molecular events involved in the lamellar wedge condition are broadly unknown [54]. In chronically laminitic horses, the lamellar wedge appears as an abnormal horny mass, that is formed between the inner hoof wall and the epidermal lamellae, and is linked to the slight rotation of the distal phalanx [55]. The separation of the distal phalanx inside the capsular wall can change the sole shape to become convex rather than be concave, due to differential growth of the proximal hoof wall portion [55]. The structural and physical appearance of this abnormal keratinized material is comparable to the white line tissue, and is therefore proposed to be an ectopic white line [56]. It was therefore thought that a large quantity of the ectopic white line could be able ultimately to prohibit the straight and normal growth of the hoof capsule (**Figure 6**) [57].

5.1 Lameness

Foot lameness is a physical impairment of a limb that has a negative effect on the freedom of movement of the animal [58, 59]. It is accompanied by clinical signs linked to a disturbance of locomotion that is related to hoof pathologies that can be caused by infection, environmental and/or genetic causes [60, 61]. Lameness can also manifest itself in pain and lesions that, in turn, lead to an abnormal gait [62, 63] with undesirable consequences on performance [64] and welfare [65]. This disruption in gait originates from involuntary and voluntary exertions to diminish the level of discomfort and/or pain that are the result of damage or injury of ligaments, muscles, nerves or integument [59, 60], or could be due to asymmetric and/or uneven feet promoting the development of foot lameness [66].

Virtually all ungulate animals can be affected by foot lameness [67–70]. However, our knowledge concerning the aetiology of the condition is often related to the economic implications of the animal in our society [58, 62]. Foot lameness is classified into acute and chronic types depending on the severity of lesions and the

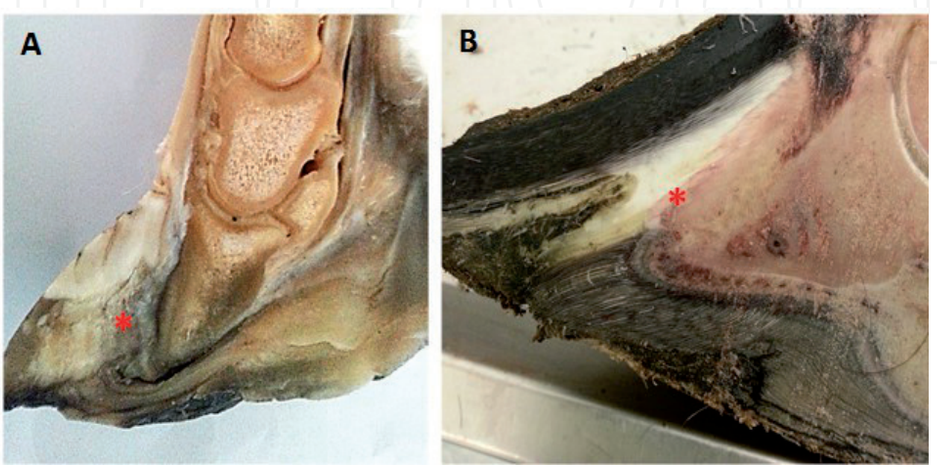

Figure 6.
*The anatomical displacement (indicated by *) of the distal phalanx. (A, B) Longitudinal section of two laminitic feet shows lamellae wedge inside the hoof capsule indicates (*) abnormal tissue, which changed the shape of hoof capsule.*

time requirement for healing, if healing is possible [71]. In dairy cows it represents the most important financial and welfare problem faced by the industry [60], as it is responsible for a drop in reproductive efficacy, a decrease in milk production, and increased culling rates [5, 69]. Similarly, in horses, foot lameness is a significant and predominant medical disorder which accounts for about to $1 billion in losses annually for the equine industry in the United States of America [72, 73]. In the UK, the maintenance of each horse is estimated to cost about £2660 annually and much of this in the treatment of foot lameness [74]. Foot lameness in the horse is the most prevalent and frequent medical issue, affecting about 11% of the general equine population in the UK in 2011 [75]. This rose significantly in 2012 to 18.6% [76] and was thought to be due to factors such as differing foot balance, shoeing and trimming techniques. Some subpopulations however, seem to be more affected than others as, for example, it is estimated that nearly 33% of dressage horses in the UK suffer from foot lameness [69]. The clinical diagnosis of foot lameness in the equine population is subdivided into scores ranging from 0 to 5 depending on the degree of the condition, with 5 being the worst outcome [77].

Lame horses adapt their gait to compensate for the pain originating from damaged tissues or foot lesions [78–80]. Accordingly, foot lameness is considered to be one of the most common signs of kinetic disorder affecting the musculoskeletal system [30]. As forelimb foot lameness is more common than hind limb foot lameness [81], it has been suggested that conformations of the distal limbs may have a substantial impact in the development of front and rear limb foot lameness [66]. The relatively high prevalence of forelimb foot lameness [81] which reaches to more than 75% of equine foot lameness being found in a forelimb particularly in breeds such as Thoroughbred horses and 40% in Standardbred racehorses [82]. This may be explained by that fact that the centre of gravity of the horse is closer to the front limbs than the rear limbs, as the loading ratio is spread approximately 60% forelimbs: 40% hind limbs [66]. Other research [80] has shown that horses with severe foot lameness in the front limb display an untrue foot lameness in the contralateral rear limb, whereas horses with a real rear limb foot lameness exhibit an incorrect foot lameness in the ipsilateral front limb.

Although the aetiology of equine foot lameness is still an active research area, recent efforts have also tried to determine whether the hoof shape is a disposing factor for foot lameness-causing lesions. The investigation of variations between foot lameness and non-foot lameness affected horses [51], demonstrated that the angle between the capsular wall and the ground is larger in the lame horse with an enlarged heel, curved or misshapen coronary band, that diverging growth lines can occur, and that the tubular horns differ from non-lame horses. It was suggested that hereditary influences and trimming are factors contributing to the asymmetrical shape of the hoof [83, 84].

In chronic foot lameness, the hoof capsule of the lame foot can be more distorted than in the non-lame one [85], as a result of altered loading forces applied to the hoof, hence affecting the shape of the hoof and the internal structures of the foot [86, 87]. These variations in the shape of the capsule are triggered by biological sources causing autolysis of the collagen fibres connecting the epithelium to the bone [68]. The role of these fibres is to support and suspend the weight of the horse via the distal phalanx, as well as to maintain the shape of the capsule constant [88, 89]. Another cause that could lead to hoof distortion is the ability of the foot to produce keratinous material proximally [90]. A number of chronic foot lameness states can be related to sheared heels causing palmar foot pain and hoof deviation [34]. Sheared heels are considered as one of the main causes of foot lameness in the equine genus, which results from an abnormal stride and persistent uneven weight bearing [91]. This leads to higher soft tissue strains that predispose the hoof capsule to deformation [92].

The hoof conformation seems to be a two-way process whereby the hoof shape is a key factor in foot lameness [54, 93] and foot deformation can arise as a consequence of foot lameness [85]. However, there has been little evidence showing that malformation is one of the predisposing factors for foot soreness and foot lameness. Dyson and colleagues [39] highlighted that, despite the differences in the shape of the distal phalanx between horses, lameness is mainly associated with changes in the direction of the dorsal hoof wall. For example, constant shoeing has an impact on the way in which the hoof grows and can, over time; result in a different foot conformation/capsular shape, which can have an effect on foot lameness [15, 40]. Recent bovine work using micro CT has shown that lame cows can present with additional bone growth on the distal phalanx [94]. It is important to remember that comparative findings in other animals could provide crucial evidence which may be applicable to horses and is therefore a further consideration for work in this area.

The methodologies which are used are also being developed over time and giving new insights into anatomy and physiology. In a recent study looking at foals with osteomyelitis it was shown how important newer techniques such as CT could be used to compliment traditional radiography whilst also providing novel information about disorders [95], the emerging evidence indicating that CT may be superior at detecting osseous changes in general in comparison to traditional techniques. The number of studies comparing MRI methods to more traditional methods is also highlighting the knowledge that can be gained in not only osseous tissue but also in soft tissue. For example in recent studies in equine limbs lesions where MRI was considered against retrospective patient data/ultrasonography radiography [96, 97]. In addition anatomical knowledge and imaging are becoming increasingly important for new discoveries and techniques in relation to stem cell and gene therapy as highlighted by recent studies using gene therapy to treat equine lameness [78, 98].

6. Conclusions

There is no doubt that understanding the anatomy, histology and physiology of the equine foot and limb is essential in treating a wide range of disorders. Advances in technology such as magnetic resonance imaging, computed tomography and other imaging techniques also play a role in assisting both anatomical knowledge and understanding equine conditions [99]. Coupled with more traditional techniques recent research has used these techniques to show bone conformation and growth, vascularisation and a number of other factors which could help inform us about anatomy and limb disorders. Although much is known about equine anatomy and histology, more is being discovered in both the normal and pathologically affected horse. In addition, new information from cellular and molecular studies is advancing not only the anatomical and histological sides but also the physiology and function of the equine limbs and the disorders they are prone to.

Acknowledgements

The work was funded by PetPlan, Waltham, The Ministry of Higher Education and Scientific Research of Iraq, Western Scholarship and The University of Nottingham School of veterinary Medicine and Science. We also thank Mr. Craig Sturrock CIPB, Hounsfield Building, University of Nottingham with whom the computed tomography imaging was carried out. Catrin Rutland Orcid: 0000-0002-2009-4898. Cyril Rauch Orcid: 0000-0001-8584-420X.F. Emily Paul Orcid: 0000-0001-8518-4205.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

Nomenclature observes Nomina Anatomica Veterinaria terminology [100].

Acronyms and abbreviations

BM	basement membrane
CDET	common digital extensor tendon
CT	computed tomography
DDFT	deep digital flexor tendon
P1	first phalanx
P2	second phalanx
P3	third phalanx
SDFT	superficial digital flexor tendon.

Author details

Ramzi Al-Agele[1,2], Emily Paul[1], Valentina Kubale Dvojmoc[3], Craig J. Sturrock[4], Cyril Rauch[1] and Catrin Sian Rutland[1*]

1 School of Veterinary Medicine and Science, University of Nottingham, Leicestershire, UK

2 Department of Anatomy, College of Veterinary Medicine, University of Diyala, Iraq

3 Veterinary Faculty, University of Ljubljana, Ljubljana, Slovenia

4 CPIB, The Hounsfield Facility, School of Biosciences, University of Nottingham, Leicestershire, UK

*Address all correspondence to: catrin.rutland@nottingham.ac.uk

References

[1] Bragulla H, Konig HE, Liebich H-G. Veterinary Anatomy of Domestic Mammals: Textbook and Colour Atlas. Germany: Schattauer Verlag; 2007

[2] Konig HE, Liebich H-G. Veterinary Anatomy of Domestic Mammals: Textbook and Color Atlas. Germany: Schattauer; 2007

[3] Stewart J. Understanding the Horse's Feet. UK: The Crowood Press; 2013

[4] Pollitt CC. The anatomy and physiology of the suspensory apparatus of the distal phalanx. Veterinary Clinics of North America: Equine Practice. 2010;**26**(1):29-49

[5] Budras KD, Sack WO. Anatomy of the Horse. UK: Manson Publishing; 2012

[6] Davies HMS, Philip CJ, Merritt JS. Functional anatomy of the equine digit: Determining function from structure. In: Floyd AE, Mansmann RA, editors. Equine Podiatry. Missouri: Saunders Elsevier; 2007

[7] Budras K-D, Sack WO, Rock S. Anatomy of the Horse: An Illustrated Text. Germany: Schlütersche; 2003

[8] Pollitt CC. Anatomy and physiology of the inner hoof wall. Clinical Techniques in Equine Practice. 2004;**3**(1):3-21

[9] Pollitt CC. Microscopic anatomy and physiology of the hoof. In: Floyd AE, Mansmann RA, editors. Equine Podiatry. Missouri: Saunders Elsevier; 2007. pp. 90-101

[10] Goody PC. Horse Anatomy: A Pictorial Approach to Equine Structure. 2nd ed. London: J. A. Allen; 2000

[11] Davies HMS, Philip C. Gross anatomy of the equine digit. In: Floyd AE, Mansmann RA, editors. Equine Podiatry. Missouri: Saunders Elsevier; 2007. pp. 1-24

[12] Pollitt CC. The basement membrane at the equine hoof dermal epidermal junction. Equine Veterinary Journal. 1994;**26**(5):399-407

[13] Stapor P, Wang X, Goveia J, Moens S, Carmeliet P. Angiogenesis revisited—role and therapeutic potential of targeting endothelial metabolism. Journal of Cell Science. 2014;**127**(Pt 20):4331-4341

[14] Delany AM, Canalis E. The metastasis-associated metalloproteinase stromelysin-3 is induced by transforming growth factor-beta in osteoblasts and fibroblasts. Endocrinology. 2001;**142**(4):1561-1566

[15] Baxter GM. Adams and Stashak's Foot Lameness in Horses. UK: John Wiley & Sons; 2011. pp. 516-520

[16] Floyd A, Mansmann R. Equine Podiatry. USA: Elsevier Health Sciences; 2007

[17] Collins JN, Galuppo LD, Thomas HL, Wisner ER, Hornof WJ. Use of computed tomography angiography to evaluate the vascular anatomy of the distal portion of the forelimb of horses. American Journal of Veterinary Research. 2004;**65**(10):1409-1420

[18] Hood DM, Grosenbaugh DA, Mostafa MB, Morgan SJ, Thomas BC. The role of vascular mechanisms in the development of acute equine laminitis. Journal of Veterinary Internal Medicine. 1993;**7**(4):228-234

[19] Orsini JA. A fresh look at the process of arriving at a clinical prognosis part 1: Laminitis. Journal of Equine Veterinary Science. 2011;**31**(4):194-201

[20] Mishra PC, Leach DH. Extrinsic and intrinsic veins of the equine Hoof wall. Journal of Anatomy. 1983;**136**:543-560

[21] Pearson OM, Lieberman DE. The aging of Wolff's "law": Ontogeny and responses to mechanical loading in cortical bone. American Journal of Physical Anthropology. 2004;**39**(Suppl):63-99

[22] Pollitt CC. The role of arteriovenous anastomoses in the pathophysiology of equine laminitis. In: Proceedings of the Thirty-Seventh Annual Convention of the American Association of Equine Practitioners. 1992. pp. 711-720

[23] Clarke B. Normal bone anatomy and physiology. Clinical Journal of the American Society of Nephrology. 2008;**3**(Suppl 3):S131-S139

[24] Petersen OH, editor. Lecture Notes on Human Physiology. 5th ed. Oxford: Blackwell Publishing; 2007

[25] Bayliss L, Mahoney DJ, Monk P. Normal bone physiology, remodelling and its hormonal regulation. Surgery (Oxford). 2012;**30**(2):47-53

[26] Iolascon G, Napolano R, Gioia M, Moretti A, Riccio I, Gimigliano F. The contribution of cortical and trabecular tissues to bone strength: Insights from denosumab studies. Clinical Cases in Mineral and Bone Metabolism : The Official Journal of the Italian Society of Osteoporosis, Mineral Metabolism, and Skeletal Diseases. 2013;**10**(1):47-51

[27] Stevenson A, Waite M, editors. Concise Oxford Dictionary. 12th ed. Oxford: Oxford University Press; 2011

[28] Gao HJ. Application of fracture mechanics concepts to hierarchical biomechanics of bone and bone-like materials. International Journal of Fracture. 2006;**138**(1-4):101-137

[29] Wegst UG, Bai H, Saiz E, Tomsia AP, Ritchie RO. Bioinspired structural materials. Nature Materials. 2015;**14**(1):23-36

[30] Nakahama K. Cellular communications in bone homeostasis and repair. Cellular and Molecular Life Sciences. 2010;**67**(23):4001-4009

[31] Pazzaglia UE, Congiu T, Sibilia V, Quacci D. Osteoblast-osteocyte transformation. A SEM densitometric analysis of endosteal apposition in rabbit femur. Journal of Anatomy. 2014;**224**(2):132-141

[32] Allen MR, Hock JM, Burr DB. Periosteum: Biology, regulation, and response to osteoporosis therapies. Bone. 2004;**35**(5):1003-1012

[33] Arnett T. Regulation of bone cell function by acid-base balance. Proceedings of the Nutrition Society. 2003;**62**(2):511-520

[34] Peacock M. Calcium metabolism in health and disease. Clinical Journal of the American Society of Nephrology. 2010;**5**(Suppl 1):S23-S30

[35] Kini U, Nandeesh BN. Physiology of bone formation, remodeling, and metabolism. In: Fogelman I, Gnanasegaran G, van der Wall H, editors. Radionuclide and Hybrid Bone Imaging. Berlin Heidelberg: Springer; 2012. pp. 29-57

[36] Stocum DL. Regenerative Biology and Medicine. 2nd ed. London: Elsevier; 2012

[37] Taichman RS. Blood and bone: Two tissues whose fates are intertwined to create the hematopoietic stem-cell niche. Blood. 2005;**105**(7):2631-2639

[38] Moleman M, Heel M, Weeren P, Back W. Hoof growth between two shoeing sessions leads to a substantial increase of the moment about the distal, but not the proximal, interphalangeal joint. Equine Veterinary Journal. 2006;**38**:170-174

[39] Dyson SJ, Tranquille CA, Collins SN, Parkin TDH, Murray RC. An

investigation of the relationships between angles and shapes of the hoof capsule and the distal phalanx. Equine Veterinary Journal. 2011;**43**(3):295-301

[40] van Heel MCV, van Weeren PR, Back W. Compensation for changes in hoof conformation between shoeing sessions through the adaptation of angular kinematics of the distal segments of the limbs of horses. American Journal of Veterinary Research. 2006;**67**(7):1199-1203

[41] Johnston C, Back W. Hoof ground interaction: When biomechanical stimuli challenge the tissues of the distal limb. Equine Veterinary Journal. 2006;**38**(7):634-641

[42] Ramsey G. Equine Hoof Biomechanics. New Zealand: The University of Auckland; 2011

[43] Gunnarsson V, Stefansdottir GJ, Jansson A, Roepstorff L. The effect of rider weight and additional weight in Icelandic horses in tolt: Part II. Stride parameters responses. Animal. 2017;**11**(9):1567-1572

[44] Pollitt C, Collins S. The suspensory apparatus of the distal phalanx in normal horses. Equine Veterinary Journal. 2016;**48**:496-501

[45] Douglas JE, Biddick TL, Thomason JJ, Jofriet JC. Stress/strain behaviour of the equine laminar junction. The Journal of Experimental Biology. 1998;**201**(15):2287-2297

[46] Eades SC. Overview of current laminitis research. Veterinary Clinics of North America: Equine Practice. 2010;**26**(1):51-63

[47] Visser MB, Pollitt CC. The timeline of lamellar basement membrane changes during equine laminitis development. Equine Veterinary Journal. 2011;**43**(4):471-477

[48] Kyaw-Tanner M, Pollitt CC. Equine laminitis: Increased transcription of matrix metalloproteinase-2 (MMP-2) occurs during the developmental phase. Equine Veterinary Journal. 2004;**36**(3):221-225

[49] Redden RF. Hoof capsule distortion: Understanding the mechanisms as a basis for rational management. Veterinary Clinics of North America: Equine Practice. 2003;**19**(2):443-462

[50] Engiles JB, Galantino-Homer HL, Boston R, McDonald D, Dishowitz M, Hankenson KD. Osteopathology in the equine distal phalanx associated with the development and progression of laminitis. Veterinary Pathology. 2015;**52**(5):928-944

[51] Dyson SJ, Tranquille CA, Collins SN, Parkin TDH, Murray RC. External characteristics of the lateral aspect of the hoof differ between non-lame and lame horses. Veterinary Journal. 2011;**190**(3):364-371

[52] Carter RA, Shekk V, de Laat MA, Pollitt CC, Galantino-Homer HL. Novel keratins identified by quantitative proteomic analysis as the major cytoskeletal proteins of equine (*Equus caballus*) hoof lamellar tissue. Journal of Animal Science. 2010;**88**(12):3843-3855

[53] Collins SN, van Eps AW, Pollitt CC, Kuwano A. The lamellar wedge. Veterinary Clinics of North America: Equine Practice. 2010;**26**(1):179-195

[54] Bragulla H, Hirschberg RM. Horse hooves and bird feathers: Two model systems for studying the structure and development of highly adapted integumentary accessory organs—The role of the dermo-epidermal interface for the micro-architecture of complex epidermal structures. Journal of Experimental Zoology Part B. 2003;**298b**(1):140-151

[55] Pollitt CC. Equine laminitis. Clinical Techniques in Equine Practice. 2004;**3**:34-44

[56] O'Grady SE. A fresh look at white line disease. Equine Veterinary Education. 2011;**23**(10):517-522

[57] Kuwano A, Katayama Y, Kasashima Y, Okada K, Reilly JD. A gross and histopathological study of an ectopic white line development in equine laminitis. The Journal of Veterinary Medical Science. 2002;**64**(10):893-900

[58] Archer S, Bell N, Huxley J. Foot lameness in UK dairy cows: A review of the current status. In Practice. 2010;**32**:492-504

[59] Animal WC. In: ACM MG, editor. Physiotherapy: Assessment, Treatment and Rehabilitation of Animals. UK: Blackwell Publishing; 2016. pp. 73-84

[60] O'Callaghan K. Lameness and associated pain in cattle—challenging traditional perceptions. In Practice. 2002;**24**(4):212

[61] Weishaupt MA. Adaptation strategies of horses with lameness. Veterinary Clinics of North America: Equine Practice. 2008;**24**(1):79-100

[62] Bicalho RC, Oikonomou G. Control and prevention of foot lameness associated with claw lesions in dairy cows. Livestock Science. 2013;**156**:96-105

[63] Green LE, Hedges VJ, Schukken YH, Blowey RW, Packington AJ. The impact of clinical lameness on the milk yield of dairy cows. Journal of Dairy Science. 2002;**85**(9):2250-2256

[64] Mulling CK, Green LE, Barker Z, Scaife J, Amory J, Speijers M, editors. Risk Factors Associated with Foot Foot Lameness in Dairy Cattle and a Suggested Approach for Foot Lameness Reduction. World Buiatrics Congress; 2006

[65] Broster C, Burn C, Barr A, Whay H. The range and prevalence of pathological abnormalities associated with foot lameness in working horses from developing countries. Equine Veterinary Journal. 2009;**41**:474-481

[66] Wiggers N, Nauwelaerts SLP, Hobbs SJ, Bool S, Wolschrijn CF, Back W. Functional locomotor consequences of uneven forefeet for trot symmetry in individual riding horses. PLoS One. 2015;**10**(2):e0114836

[67] Winter A. Foot lameness in sheep. Small Ruminant Research. 2008;**76**:149-153

[68] Ross MW, Dyson SJ. Diagnosis and management of foot lameness in the horse. Health Sciences. 2010;**36**:549-554

[69] Murray RC, Walters JM, Snart H, Dyson SJ, Parkin TDH. Identification of risk factors for lameness in dressage horses. Veterinary Journal. 2010;**184**(1):27-36

[70] Christodoulopoulos G. Foot lameness in dairy goats. Research in Veterinary Science. 2009;**86**(2):281-284

[71] Vermunt JJ. Subclinical laminitis in dairy-cattle. New Zealand Veterinary Journal. 1992;**40**(4):133-138

[72] Seitzinger AH, Traub-Dargatz J, Kane A, Kopral C, Morley P, Garber L, et al. A comparison of the economic costs of equine foot lameness, colic, and equine protozoal myeloencephalitis (EPM). In: Proceedings of the 9th International Symposium on Veterinary Epidemiology and Economics. 2000:1048-1050. https://naldc.nal.usda.gov/download/45446/PDF

[73] Moorman VJ, Reiser RF II, Peterson ML, McIlwraith CW, Kawcak CE. Effect of forelimb foot lameness on hoof kinematics of horses at a walk. American Journal of Veterinary Research. 2013;**74**:1192-1197

[74] Uprichard K, Boden L, Marshall J. An online survey to characterise spending patterns of horse owners and to quantify. Equine Veterinary Journal. 2014;**46**:4

[75] Cross B. New Survey Reveals UK's Current Equine Healthcare Problems. 2011. Available from: http://www.bluecross.org.uk/2000-84227/new-survey-reveals-uks-current-equine-healthcare-problems-.html

[76] Ireland JL, Clegg PD, McGowan CM, McKane SA, Chandler KJ, Pinchbeck GL. Disease prevalence in geriatric horses in the United Kingdom: Veterinary clinical assessment of 200 cases. Equine Veterinary Journal. 2012;**44**(1):101-106

[77] Wagner BA, Venkataraman S, Buettner GR. The rate of oxygen utilization by cells. Free Radical Biology & Medicine. 2011;**51**(3):700-712

[78] Kovac M, Litvin Y, Aliev R, Zakirova E, Rutland C, Kiyasov A, et al. Gene therapy using plasmid DNA encoding VEGF164 and FGF2 genes: A novel treatment of naturally occurring tendinitis and desmitis in horses. Frontiers in Pharmacology. 2018;**9**:978

[79] Weishaupt MA, Wiestner T, Hogg HP, Jordan P, Auer JA. Compensatory load redistribution of horses with induced weightbearing hindlimb lameness trotting on a treadmill. Equine Veterinary Journal. 2004;**36**(8):727-733

[80] Uhlir C, Lica T, Kubber P, Peham C, Scheidl M, Girtler D. Compensatory movements of horses with a stance phase foot lameness. Equine Veterinary Journal. 1997;**29**:102-105

[81] Keegan KG, Dent EV, Wilson DA, Janicek J, Kramer J, Lacarrubba A, et al. Repeatability of subjective evaluation of lameness in horses. Equine Veterinary Journal. 2010;**42**(2):92-97

[82] Malikides N, McGowan T, Pead M. Equine and canine foot lameness. In: McGowan C, Goff L, Stubbs N, editors. Animal Physiotherapy: Assessment, Treatment and Rehabilitation of Animals. UK: Wiley-Blackwell; 2007. pp. 73-101

[83] French KR, Pollitt CC. Equine laminitis: Congenital, hemidesmosomal plectin deficiency in a quarter horse foal. Equine Veterinary Journal. 2004;**36**(3):299-303

[84] Kummer M, Geyer H, Imboden I, Auer J, Lischer C. The effect of hoof trimming on radiographic measurements of the front feet of normal Warmblood horses. Veterinary Journal. 2006;**172**(1):58-66

[85] Holroyd K, Dixon JJ, Mair T, Bolas N, Bolt DM, David F, et al. Variation in foot conformation in lame horses with different foot lesions. Veterinary Journal. 2013;**195**(3):361-365

[86] Ryan T. Dorsal hoof wall grooving for the treatment of acute laminitis. Journal of Equine Veterinary Science. 2013;**33**:877

[87] Drumond B, Ginelli AMG, Faleiros RR, de Magalhaes JF, Coelhos CS. Hoof capsule distortion and radiographic measurements of the front feet in Mangalarga Marchador horses subjected to athletic training. Pferdeheilkunde. 2016;**32**(2):110-118

[88] Mungall BA, Pollitt CC. Zymographic analysis of equine laminitis. Histochemistry and Cell Biology. 1999;**112**(6):467-472

[89] Pollitt CC. Dysregulation of the lamellar basal epithelial cell in laminitis: Role of the cytoskeleton and cell junctions. In: Equine Laminitis. UK: Wiley Blackwell. Vol. 43. 2016. pp. 167-172

[90] Daradka M, Pollitt CC. Epidermal cell proliferation in the equine hoof

wall. Equine Veterinary Journal. 2004;**36**(3):236-241

[91] O'Grady SE, Castelijns HH. Sheared heels and the correlation to spontaneous quarter cracks. Equine Veterinary Education. 2011;**23**(5):262-269

[92] O'Grady SE. Farriery for the hoof with a sheared heel. Veterinary Clinics of North America: Equine Practice. 2012;**28**(2):381-392

[93] Holroyd K, Dixon JJ, Mair T, Bolas N, Weller R. Is there a relationship between foot conformation and foot lesions in lame horses? Journal of Equine Veterinary Science. 2013;**33**:858-859

[94] Newsome R, Green MJ, Bell NJ, Chagunda MGG, Mason CS, Rutland CS, et al. Linking bone development on the caudal aspect of the distal phalanx with lameness during life. Journal of Dairy Science. 2016;**99**(6):4512-4525

[95] Lean NE, Perkins NR, Ahern BJ. Comparison of conventional radiography and computed tomography as aids in the diagnosis of osteomyelitis in 11 foals. Australian Veterinary Journal. 2018;**96**(7):257-261

[96] Barrett MF, Selberg KT, Johnson SA, Hersman J, Frisbie DD. High field magnetic resonance imaging contributes to diagnosis of equine distal tarsus and proximal metatarsus lesions: 103 horses. Veterinary Radiology & Ultrasound. 2018;**59**(5):587-596

[97] Barrett MF, Manchon PT, Hersman J, Kawcak CE. Magnetic resonance imaging findings of the proximal metacarpus in quarter horses used for cutting: Retrospective analysis of 32 horses 2009-2012. Equine Veterinary Journal. 2018;**50**(2):172-178

[98] Kovac M, Litvin YA, Aliev RO, Zakirova EY, Rutland CS, Kiyasov AP, et al. Gene therapy using plasmid DNA encoding vascular endothelial growth factor 164 and fibroblast growth factor 2 genes for the treatment of horse tendinitis and desmitis: Case reports. Frontiers in Veterinary Science. 2017;**4**:168

[99] Keane M, Paul E, Sturrock C, Rauch C, Rutland C. Computed tomography in veterinary medicine: Currently published and tomorrow's vision. In: Halefoglu A, editor. Computed Tomography—Advanced Applications. Rijeka, Croatia: InTechOpen; 2017

[100] ICoVGAN (I.C.V.G.A.N). Nomina Anatomica Veterinaria. 6th revised edn. 2017. Available from: http://www.wava-amav.org/ [Accessed: December 5, 2017]