

## **TUTORIAL ARTICLE**

# **Clinical anatomy and physiology of the normal equine foot**

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## **INTRODUCTION**

The forces of evolution have produced in the equine foot a miracle of bioengineering. However, despite being a success in its natural environment, the equine foot becomes a common site of disease and injury when subjected to the demands of human domestication. A sound knowledge of the anatomy of the equine foot (Fig 1) is necessary to understand the pathophysiology, diagnosis and treatment of its disorders. In the last issue (August 1992), Smith and Schramme (p 177) described the use of contrast agents to locate with precision the degree of penetration and the extent of damage to deeper structures after wounding to the palmar/plantar frog.

## **THE HOOF**

The hoof is a highly keratinised epidermal structure without blood vessels or nerves. It is much like any other structure derived from epidermis (such as horn or hair) in that it is a product of the continual cell division of a single germinative layer of basal cells, located at the dermoepidermal junction. Separating the dermis from the epidermis is the tough basement membrane (basal lamina) to which the epidermal basal cells are firmly anchored by way of hemidesmosomes. Basal cells, and the adjoining suprabasal cells, are anchored to each other by numerous desmosomes. As the basal cells divide, the newly formed daughter cells begin to differentiate by a process known as keratinisation. The differentiating epidermal cells of the hoof form three distinct histological strata: the *stratum* germinativum (germinal (basal) cells with large nuclei and scant cytoplasm, permanently attached to the basement membrane), the *stratum* spinosum (cells with a spiny 'prickle cell' appearance due to large numbers of desmosomes) and the *stratum* corneum (anuclear, fully keratinised, 'cornified' cells or comeocytes). Mature comeocytes, when cemented together, form a tough protective barrier preventing the passage of water and water-soluble substances inwards and the loss of body fluids outwards. In addition to acting as a permeability barrier, hoof comeocytes have the additional job of ultimately supporting the entire weight of the horse. To accomplish this, comeocytes are arranged in specialised cylindrical tubules or as leaf-like lamellae. Naturally each of these epidermal specialisations is accompanied by a similar, reciprocal, specialisation of the underlying dermis. Thus, each horn tubule is supported by a dermal papilla and each epidermal lamella by its dermal counterpart.

## **THE WALL**

The wall is thickest at the toe (the region of greatest friction) and thins gradually towards the heels. In most fore feet the wall of the medial quarter is thinner than that of the lateral and is more steeply angled. The thickness of the wall is an important consideration when rasping it, when designing horseshoes or when driving horseshoe nails. The angle formed by the dorsal surface of the hoof wall and the ground surface is important for normal activity and is usually in the range of 48-60° (fore foot) and 50-62° (hind foot). The dorsal hoof wall-ground surface angle varies considerably between individuals and bears a close relationship to the angle of the pastern and the shoulder. Sometimes, normal horses can have exactly the same fore and hind dorsal hoof wall angles! It is a principle of farriery to prepare the hoof so that the angle of the dorsal wall is set parallel to the axis of the pastern, rather than to a hoof angle derived from a textbook. Lowering the heels to place the frog on the ground, once considered a tenet of farriery, destroys the correct hoof pastern axis and is no longer acceptable. The angle of the dorsal hoof wall and the pastern should be the same, regardless of the proximity of the frog to the ground. The wall is made up of the following three layers:

## *STRATUM EXTERNUM*

The external layer is an extremely thin layer of tubular horn covering the surface of the wall. Its narrow proximal part is the soft and non-pigmented periople. The periople expands caudally over the bulbs of the heel and approaches the ground surface of the foot. In the hoof wall, only the soft, skin-like, epidermis of the periople develops a granular cell layer (*stratum granulosum*). The cytoplasmic granules after which the layer is named contain keratohyaline. When epidermal cells contain keratohyaline they have elasticity added to their properties of toughness and impermeability. The superficial layer covering the rest of the wall is the stratum tectorium. Because of its high lipid content the stratum tectorium reduces evaporative water loss from the foot. The superficial layer gives the wall its smooth, glossy appearance.

## *STRATUM MEDIUM*

The middle layer is composed of very prominent tubular and intertubular horn which comprises the bulk of the hoof wall. Its proximal part is excavated to form the coronary groove in which lies the convex coronary corium. The surface of the coronary groove has numerous openings, or sockets, into which fit the long tapering papillae of the overlying coronary corium (Fig 4). In the dark hoof, except for the inner lamellar layer, the middle layer is pigmented. Despite popular opinion, the mechanical properties of the equine hoof do not depend upon whether or not it is pigmented (Leach 1980). The horn tubules arise from the germinal epidermis (*stratum germinativum*) the covers the sides and shoulders of the dermal papillae. The intertubular horn is elaborated from the germinal epidermis between papillae and in the dark hoof contains melanin pigment.

The papillae of this region are elongated and are orientated parallel to the long axis of the hoof wall, at an oblique angle to the ground surface (Fig 4). This orientation results in the horn tubules being elaborated in a similar relationship to the ground surface. The horn tubules are visible on the surface of the hoof wall as very fine longitudinal lines. Each tubule consists of a hollow medulla containing cellular debris surrounded by a dense, lightly pigmented, cortex of keratinised cells.

## *STRATUM INTERNUM (LAMELLATUM)*

The internal layer is always non-pigmented. The inner surface of the hoof wall consists of 600 keratinised primary epidermal lamellae which extend from the coronary groove to the ground surface (Fig 4). Each keratinised primary epidermal lamella bears 100-150 non-keratinised secondary epidermal lamellae. They interlock with the primary and secondary lamellae of the lamellar corium. Distally, at the heels, the lamellae are reflected axially as the lamellae of the bars.

Recent research has shown that the fully keratinised primary epidermal lamellae arise on the inner shoulders of the coronary groove and once formed undertake a 6-8month journey to the ground surface, slowly sliding past the stationary spinous and basal cells of the adjoining secondary epidermal lamellae (Leach and Oliphant 1983).

Apparently, primary lamellae move distally, past the stationary cells of the secondary epidermal lamellae (which are firmly anchored to their basement membrane) by breaking desmosomal connections (Fig 6). It is assumed that the desmosomes, joining the moving parts to the stationary parts of the epidermal lamellae, break and reform in a staggered ratchet-like manner, so that the keratinised cells can move distally yet still support load.

The membranes between lamellar epidermal cells are extensively folded and interconnected by numerous desmosomes. Between each half desmosome is a powerful adhesive substance which bonds the adjoining cell membranes tightly together. Within the cytoplasm countless tonofilaments (composed of keratin) radiate from the desmosomes and form bundles of tonofibrils. By crisscrossing the cell, tonofibrils form an internal cytoskeleton which adds to the mechanical strength of the epidermal cell while retaining flexibility. Epidermal cells change shape in response to the tensile stresses of weight bearing and locomotion. The spaces between cell junctions form canals. (interfacial canals) which are conspicuously large in epidermal tissue. Because the epidermis is avascular these take on the function of capillaries and bring nourishment to the vital epidermal cells. It is essential that the hoof wall epidermis, along with the basement membrane at the dermo-epidermal junction, the connective tissue of the lamellar corium and the periosteum of the parietal surface of the distal phalanx all remain unified. If a junctional disruption between these elements occurs, the hoof-distal phalanx bond fails, with serious pathological consequences within the hoof capsule (eg laminitis).

Although there is no evidence (no increase in thickness, no mitotic figures) that cells of the secondary lamellae contribute much to the primary lamellae in the distal two thirds of the normal foot, the reverse is true in abnormal conditions. The basal cells are capable of rapid proliferation when the wall is

damaged (surgical wall stripping, puncture wounds) or if the keratinised parts of wall are separated from the generative layer as in laminitis.

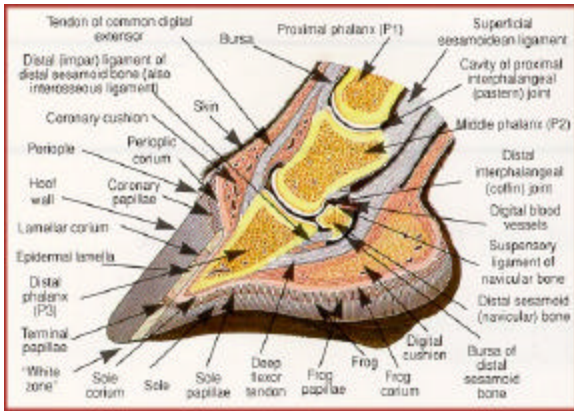


Fig 1: Diagrammatic view of longitudinal section of the equine

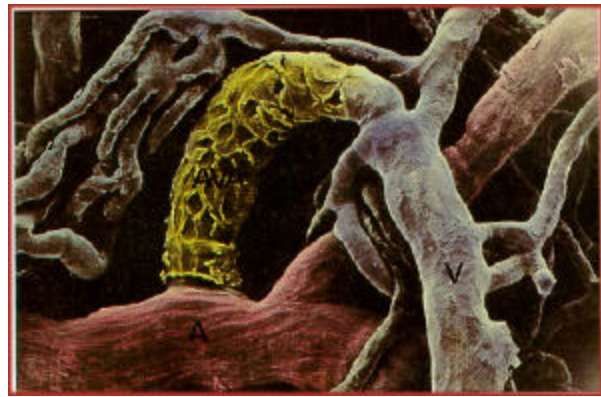


Fig 2: Scanning electron micrograph of AVA connecting artery (A) to vein (V) in the microcirculation of a dermal lamella. AVAs were identified by their characteristic surface morphology. AVA distribution and density (500 AVAs/cm<sup>2</sup> of lamella) are compatible with their proposed role in the ischaemia of developmental laminitis

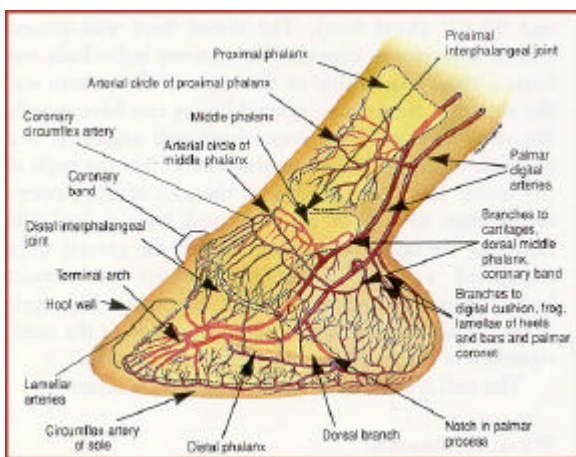


Fig 3: Diagram of the arteries of the equine digit. The lamellar arteries of the toe arise from arteries (themselves branches of the terminal arch) which perforate the dorsal artery supplies branches to the corium of the dorsal hoof wall which anastomose with the proximal lamellar arteries

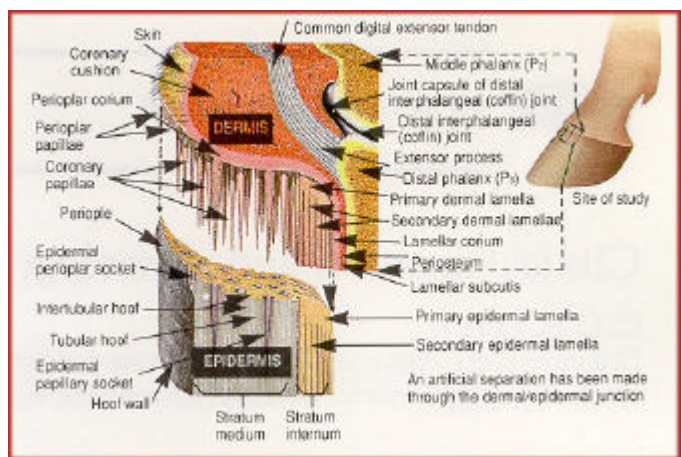


Fig 4: Expanded diagrammatic view of coronary region of the equine foot

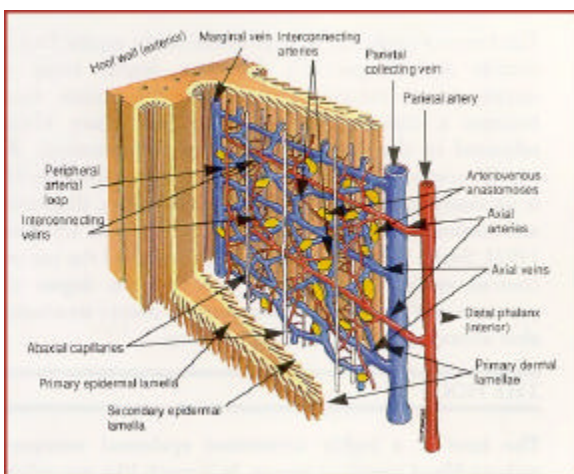


Fig 5: Diagram of the equine hoof wall lamellar (laminar) microcirculation. AVAs connect artery to vein throughout the lamellar circulation but are larger and more frequent near the tips of the primary epidermal lamellae

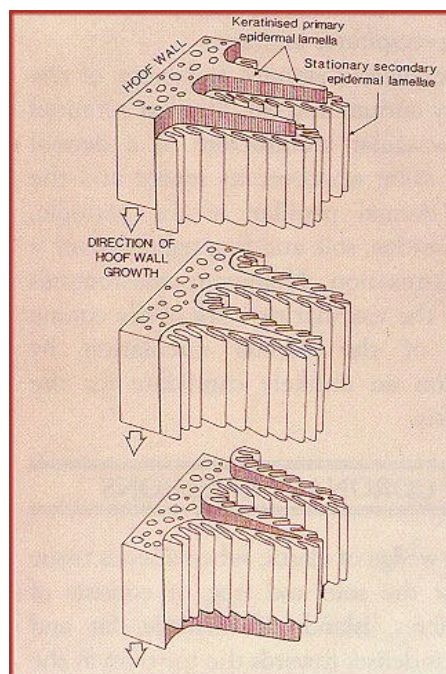


Fig 6: Diagram showing how the hoof wall and the primary epidermal lamellae side past the stationary cells of secondary epidermal lamellae

## THE CORIUM

The highly vascular and sensitive corium or dermis (popularly the 'quick') underlies the hoof and consists of a dense matrix of tough connective tissue containing a network of arteries, veins and capillaries and sensory and vasomotor nerves. All parts of the corium except for the lamellar corium have papillae which fit into openings in the subjacent hoof. The lamellar corium has dermal lamellae which interlock with the epidermal lamellae of the inner layer of the wall and bars. The corium provides the hoof with nourishment and blends into subcutis which, in turn, blends into the modified periosteum of the parietal surface of the distal phalanx. A dense, fibrous, matrix of connective tissue connects the lamellar basement membrane of the dermo-epidermal junction to the periosteal surface of the distal phalanx and suspends the distal phalanx from the inner wall of the hoof capsule (the hoof•istal phalanx bond).

### *THE CORONARY CORIUM*

The coronary corium lies in the coronary groove immediately below the perioplic corium. Its inner surface is attached to the extensor tendon and the cartilages of the distal phalanx by the subcutaneous tissue of the coronary cushion (Fig 4). The coronary cushion contains the coronary vascular plexus. Collectively, the coronary corium and the germinal epidermal cells which rest upon its basement membrane are known as the 'coronary band'.

The stratum medium is nourished by the coronary corium. If the stratum germinativum overlying the corium is injured, a defect may result in the wall which will be carried distally. If the coronary corium and the associated epidermal basal cells are severely damaged, the coronary papillae are replaced with a cicatrix of scar tissue. A permanent wall defect (wall crack) results which will always be refractory to treatment.

### *THE LAMELLAR CORIUM*

The lamellar corium consists of about 600 primary *dermal* lamellae each of which is subdivided into between 100 and 200 secondary dermal lamellae (Fig 4). The deep surface of the corium blends with the periosteum of the third phalanx and the lower abaxial (outer) surfaces of the cartilages and contains the lamellar arteries, veins, arteriovenous anastomoses and capillaries.

### *THE DERMAL MICROCIRCULATION*

Numerous arteriovenous anastomoses (AVAs) connect the axial arteries and veins of the dermal lamellae (Pollitt and Molyneux 1990). AVAs are present throughout the dermal lamellae but are larger and more numerous around the axial vessels close to their bases (Figs 2 and 5). Studies with the transmission electron microscope show that these AVAs are richly innervated by autonomic vasomotor nerves and their associated peptidergic nerves, have thick walls of smooth muscle and a specialised, characteristically tall, endothelium (Molyneux, Haller, Mogg and Pollitt 1993). They obviously play a significant role in the control of the dermal microcirculation of the equine digit in relation to thermoregulation and pressure modulation and if their normal function is disturbed for long enough are probably the source of the ischaemic damage to epidermal cells which apparently precipitates laminitis.

AVAs are equally numerous around the bases of the papillae of the coronary corium and the lamellar terminal papillae. In fact the vascular architecture of a dermal papilla is basically the same whatever its source and the blood vessels of the dermal papillae of the periople, coronary band, distal laminae, sole and frog regions share a common structural organisation. Numerous anastomoses between all divisions of the vascular network of the equine foot make blockage of the dermal circulation by intravascular coagulation an unlikely candidate for the primary cause of laminitis.

## THE DIGITAL AND CORONARY CUSHIONS

The digital cushion is a wedge of elastic subcutaneous tissue underlying the coria of the sole and frog. It consists of collagen and elastic fibres, islands of cartilage, fat and modified skin glands. It is denser towards the toe than at the heels where it supports the bulbs. The cushion plays an important part in shock absorption. The coronary cushion is a thickened layer of elastic subcutaneous tissue underlying the coronary corium and attaching it to the digital extensor tendon and the cartilages of the distal phalanx.

The cartilages of the distal phalanx are hyaline in younger animals but are changed to fibrocartilage in the adult. Ossification may occur, producing the unsoundness known as sidebone. The palmar venous plexus, on inner axial surfaces of the cartilages, communicates freely through foramina in the cartilage with the coronary plexus on the outer abaxial surfaces. These venous plexuses are drained by the digital veins and are of considerable importance in the surgical resection of the cartilages for the relief of sidebone and quittor; quittor is a purulent infection of the cartilages.

## **THE ACTION OF THE HOOF**

In essence, the hoof is a flexible structure which yields under the pressure of the impact with the ground, dissipating the concussion in a depression, compression and lateral expansion of the various parts. The compression raises the pressure in the venous plexuses, which are acting as hydraulic shock absorbers, and forces the blood proximally into the digital veins. Strategic valves prevent the return of the blood into the foot when it is off the ground.

## **THE BLOOD SUPPLY**

### *DIGITAL ARTERIES*

The medial and lateral digital arteries arise by division of the medial palmar artery (common digital artery) between the suspensory ligament and the deep digital flexor tendon and enter the digit on the abaxial surfaces of the proximal sesamoid bones of the fetlock (Fig 3). Opposite the proximal phalanx each digital artery gives rise to a branch which forms, with the artery of the opposite side, an arterial circle around the bone. At the level of the proximal interphalangeal joint, the digital arteries send major branches to the heels which supply the digital cushion, frog, lamellar corium of the heels and bars and the palmar perioplic and coronary coria. Opposite the middle of the second phalanx, each digital artery again branches and forms an artery which runs deep to the cartilages and the extensor tendon, and connects with the artery of the opposite side, to form an arterial circle around both the second phalanx and coronary band. This coronary circumflex artery supplies the digital extensor tendon, distal interphalangeal joint and supplies numerous branches to the coronary corium and proximal lamellae of the toe and dorsal quarters.

Proximal to the navicular bone each digital artery gives off a dorsal branch which passes through the notch or foramen in the palmar process of the distal phalanx and, running in the parietal groove on the dorsal surface of the distal phalanx, supplies the lamellar coria of the quarters and heels and anastomoses with the palmar part of the circumflex artery of the sole.

Each medial and lateral digital artery sends branches to both the proximal and distal borders of the distal sesamoid (navicular) bone. The branches anastomose with each other and form direct cross connections between medial and lateral digital arteries above and below the distal sesamoid bone. The proximal artery runs in the suspensory ligament of the distal sesamoid bone and its branches enter the proximal edge of the bone through fine vascular foramina. Along the distal border a similar anastomotic arterial network runs in the distal interosseous (impar) ligament and its branches bifurcate and enter the distal sesamoid bone through fine vascular foramina or adjacent to (but separate from) the 3-5 synovial fossae which characterise the distal border. The synovial fossae appear as small radiolucent inverted bottle- or flask-shaped areas along the distal border of the bone.

The careful and elegant work of Hertsch and Dammer (1988) using arterial injections of contrast medium and 'fine focus' radiography has unequivocally shown that each synovial fossa is lined with synovial membrane and connects directly with the distal interphalangeal (coffin) joint. Indeed, contrast medium injected into the coffin joint will not only outline the capsule of the joint but the synovial fossa of the distal sesamoid bone as well. Histological sections through the region show branches of the distal artery running, through connective tissue, palmar to the synovial membrane of the fossa (Poulos and Smith 1988). Several branches of the distal artery enter the bone independently of the synovial fossae. The terminal part of the digital artery enters the solar canal of the distal phalanx via the paired sole foramina and unites with the artery of the opposite side to form the terminal arch deep within the bone. Branches of the terminal arch (4-5 mid-dorsally and 8-10 distally, near the solar border) radiate outwards through foramina in the dorsal surface of the distal phalanx and supply the lamellar corium and, after forming the circumflex artery, the corium of the sole.

In addition to the 12-15 main foramina, the dorsal surface of the distal third of the distal phalanx is perforated by numerous finer foramina (the bone in this region is very porous) and recent evidence (C.C. Pollitt and G.S. Molyneux, unpublished data) shows that many of the vessels within these foramina are arranged anatomically to perform counter-current heat exchange, ie a central artery surrounded by a

sheath of capillaries and venules (similar to the pampiniform plexus of the mammalian testis). This implies that the equine digit is an efficient thermoregulatory organ which is not surprising when the range of equine habitats, from the sub-arctic to the equator, is taken into consideration.

The lamellar corium derives most of its blood supply from the branches of the terminal arch which perforate the distal phalanx. Numerous anastomoses form an arterial lattice beneath and between the epidermal lamellae and blood can flow proximally to the coronary circumflex artery and to the solar circumflex artery.

The circumflex artery of the sole is an anastomosis of all the distal branches of the terminal arch and the dorsal arteries of the distal phalanx and forms a complete arterial loop supplying the corium at the junction of the distal lamellae and peripheral sole close to the sharp solar margin of the bone. All of the arterial blood supply of the sole (except for the angle between the bars and the heels) comes from axially directed arteries branching inwards from the circumflex artery. There are no vascular foramina perforating the solar surface of the distal phalanx (except at the angle). This means that almost the entire corium of the sole is dependent upon a blood supply which arises first on the dorsal surface of the distal phalanx and then curls under the margin of the distal phalanx. The solar corium is sandwiched between the epidermal sole and the unyielding solar surface of the distal phalanx and is therefore prone to damage from compressive forces. If a horse is deliberately forced to stand or walk on the soles of its feet (by overzealous trimming of the ground surface wall) the sharp distal rim of the distal phalanx effectively cuts off the blood circulation to the central solar corium and results in severe lameness and, in some cases, necrosis of the sole.

### *DIGITAL VEINS*

There are three interconnected valveless venous plexuses in the foot. The dorsal venous plexus lies in the deep part of the lamellar corium. The palmar/plantar venous plexus lies in the deep part of the sole corium and on the inner axial surfaces of the cartilages of the distal phalanx. The coronary venous plexus lies in the coronary cushion covering the digital extensor tendon and the outer abaxial surfaces of the cartilages of the distal phalanx. It anastomoses with the palmar/plantar venous plexus via foramina in the cartilages (note that both sides of the cartilages are covered by plexuses of veins).

The three plexuses are drained by the medial and lateral digital veins. Most of the deep veins within the foot are valveless although valves occur in the more superficial coronary, subcoronary and heel veins.

### *REACTIONS OF THE VENOUS BLOOD DURING CONCUSSION*

The hoof is subjected to a range of weight-bearing and locomotor forces. These forces are believed to cause expansion of the frog and to deform all the soft tissue of the hoof, including the digital cushion, the cartilages and the vascular systems. Because the soft tissues of the hoof are encased by the hard keratinised wall which cannot expand substantially (Fischerleitner 1974), the internal deformation of the hoof forces evacuation of the venous blood from the hoof quite quickly. The multiple routes of drainage of the wall and sole venous plexuses, the absence of valves in most veins of the hoof, the presence of valves in the proper digital veins and caudal hoof veins, and the presence of a double layer of venous plexuses on either side of the flexible cartilages are all mechanisms to evacuate the venous blood quickly and to distribute the pressure evenly. The absence of valves would help evacuation by allowing venous blood to take any convenient path. The presence of the valves in the caudal hoof veins and proper digital veins prevents retrograde blood flow to the hoof and thereby ensures the efficient venous return of blood to the heart (Mishra and Leach 1983a, b).

### **THE SKELETON**

The skeleton of the foot consists of the proximal, middle and distal phalanges, the cartilages of the distal phalanx, and the distal sesamoid bone. In transverse section the distal phalanx in the forefoot is semicircular whereas in the hind foot it is oblong craniocaudally. The distal sesamoid bone articulates with both the middle and distal phalanges. In low ringbone, the phalanges are affected in the region of the distal interphalangeal joint and this may interfere with the movement of the joint. Pyramidal disease is a form of ringbone affecting the extensor (pyramidal) process of the distal phalanx. Navicular disease may involve the distal interphalangeal bone, its suspensory ligaments, the navicular bursa and the subjacent deep flexor tendon.

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