Hemodynamic Flow Hypothesis for Energy Dissipation in the Equine Foot

by Robert M. Bowker VMD, PhD

DURING LOCOMOTION, THE HORSE'S FOOT IMPACTS THE GROUND WITH A FORCE that often exceeds the weight of the animal by severalfold. The distribution of these forces during ground contact and the stance phase have been studied biomechanically by various methods during different gaits and under various lameness conditions.

SUMMARY

Previously, little or no mention has been made of an axial (towards the center) projection of the cartilage into the substance of the digital cushion. We observed in our research that this axial projection had a relatively constant relationship to the epidermal (outwardly visible) bars and was comprised of either cartilage or both fibrocartilage and fibrous connective tissue being interwoven into the digital cushion.

Our investigations into the anatomy of the cartilage have also revealed the presence of a unique vascular network coursing through the internal cartilages. These anatomical observations, along with recent biomechanical studies on the equine foot, have enabled our laboratory to formulate an alternate hypothesis of how energy is dissipated within the equine foot at ground impact.

Our hypothesis proposes that the high transient energy forces produced within the horse's foot are dissipated via the rapid flow and movement of blood through an extensive and tortuous vascular network of small caliber veno-venous anastomoses present within the cartilages and at other strategic regions within tissues of the equine foot.

This hemodynamic flow hypothesis relies upon the biomechanical principles of hydraulic fluid theory as it relates to the impedance (resistance) of such fluid movement that develops when it is forced to flow through small vessels.

Furthermore, the efficiency of this mechanism is dependent upon the individual conformation of the cartilages and the structural composition of a horse's digital cushion.

Any dysfunction in this hemodynamic flow mechanism may partially explain many of the insidious lameness conditions that develop during normal locomotion of the equine athlete. Such a disturbance will result in greater transient energies being subsequently transmitted to bone and other sensitive tissues within the digit rather than being dissipated by this hemodynamic mechanism.

Whatever the loads are and however they are distributed at impact, they must be dissipated rapidly to minimize the potentially adverse affects on the bone and connective tissues within the foot.

The function of the foot in regards to energy dissipation has been subject to speculation. Descriptions of foot anatomy during health and disease or its physiological responses during contact have not been well documented.

The laminar attachments between the hoof wall and P3 (the distal phalanx or coffin bone) and the digital cushion—along with the respective ligamentous connective tissues—have all been mentioned as having potentially significant roles in the anti-concussive mechanisms of the foot.

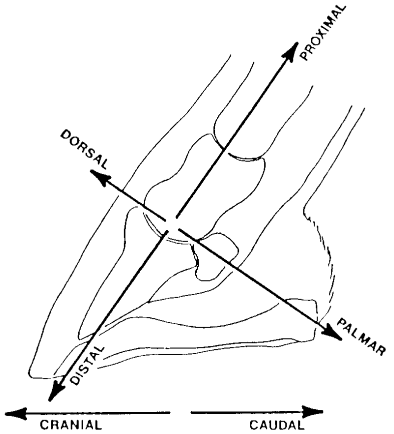
Reports have also discussed the potential roles of the suprascapular ligament, the elasticity of the suspensory ligaments associated with the proximal sesamoid bones, and the ligaments and joints of the digit itself.

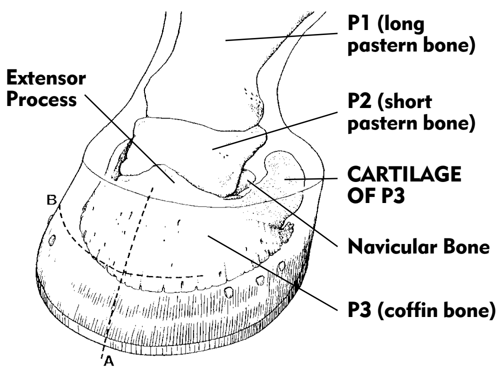
When the frequency and amplitude of vibration on P2 (pastern bone) are measured, and then compared to those recorded at the hoof wall, it is obvious that the forces are greatly decreased. This suggests a dampening role of these vibration energies by the laminar attachments and underlying dermis.

Vascular relationships to the ungual cartilage

Our new expanded anatomy of the equine digit suggests that the cartilages form an internal structural support system for the caudal foot and potentially prevent its collapse at ground impact.

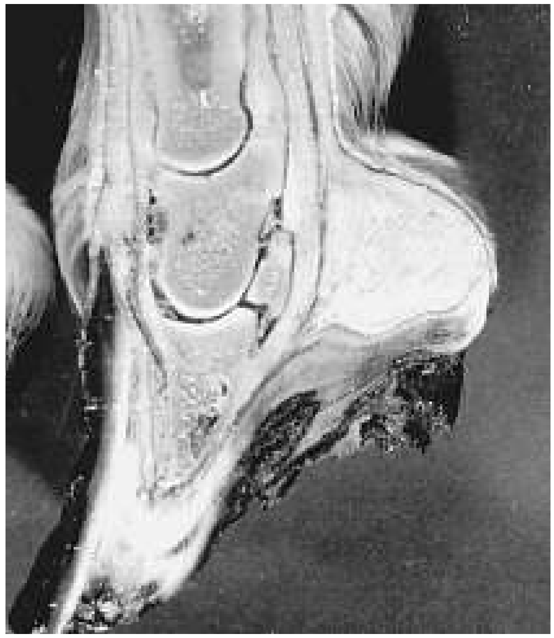
This structural framework of the cartilage and its unique venous system, coupled with their positional relationship to the hoof wall pillars, form the basis of the hemodynamic flow hypothesis of energy dissipation to be presented here.





Top Figure: Directional terminology for describing structures in the equine foot. (Doug Leach diagram)

Bottom Figure: A simplified drawing of the foot. The dashed line at "A" represents a longitudinal, or sagittal, section cut through the hoof. The line a "B" (parallel to the ground surface) represents a transverse section.

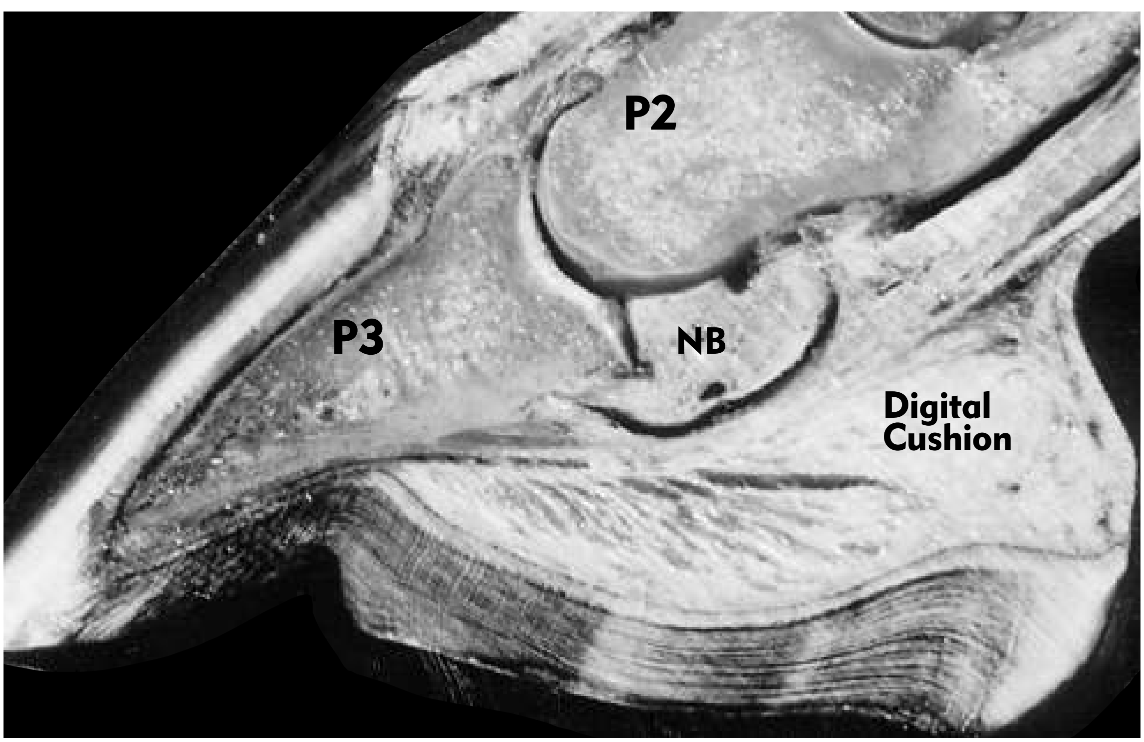


Front foot (abnormal) cut in sagittal section. This horse's foot and lower leg show several problems that were probably quite obvious to its owner and caused lameness. What wouldn't have been obvious is that the digital cushion has been displaced and is filling the bulbs of the heels, without any cushioning of P3. Some anatomy texts divide the digital cushion into a "digital cushion", proper, which overlies the frog and helps protect P3, and the "bulbar cushion", located in the caudal part of the foot and often filling the bulbs of the heel. (Horse Science model)

Physiological studies of the foot's vascular (blood) system have contributed further to our understanding that these vessels are responsive to a wide variety of neuro-active substances.

In previous studies of the cartilage of P3, only brief mention is made of the presence of several foramina (tunnel-like openings) for the passage of veins to connect the inner venous plexus of the foot with veins at the coronet (coronary plexus).

Punctuating the "floor" of the cartilaginous/fibrous framework along the semilunar line of P3 are tributaries draining the solar plexus underneath P3 towards the venous channels of the cartilages. This



Hind foot (normal), cut in the sagittal section. Preserved hoof specimen make excellent anatomy study aids, but the limitations of the view include exclusion of the cartilages. In this view, however, it is easy to access the location of the digital cushion; under a portion of P3 and extending continuously to the bulbs of the heels. (Horse Science model)

structure, we believe, plays a major role in energy dissipation when the hoof impacts the ground.

The venous vasculature associated with the cartilage has been described in several classic anatomy papers. The veins can be divided into two groups of vessels. The deep veins drain the more internal portions of the foot, such as P3, the navicular bone and the digital cushion, while the superficial veins are associated with the hoof wall epidermis (outer portion).

A second network of veins under P3 drains into the cartilage area before emptying into the inner venous plexus at the coronet. The ungual cartilages separate the outer coronary plexus (located inside the coronet area, close to the skin surface) from the inner venous plexus. Interestingly, more tributaries are found in feet having thicker cartilages than in those with thin cartilages.

In feet with thin cartilage, the veins are located axially to (inside of) the cartilage. In the thick cartilage feet, the veins must travel a greater distance through the cartilage.

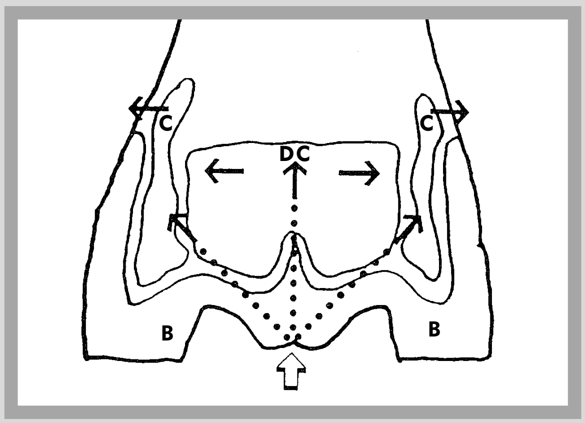
These observations of an extensive but minute network of veins within the vascular channels of the cartilages, and the revelation of their close association with the hoof wall pillars, suggest a critical function for these small vessels beyond the mere distribution of nutrition to and from the perfused tissues.

Small capillary-like vessels, or veno-venous anastomoses, exit the large central vein within the vascular channel and eventually

Traditional Theories of Energy Dissipation in the Equine Foot

Two ideas have emerged and prevailed over the last century to describe the mechanisms of energy redistribution and dissipation in the foot during ground impact.

The digital cushion is usually mentioned for its purported "energy absorption" properties in relation to frog impact. The veins and other foot vasculature (blood drainage system) are usually described as serving to "evacuate" blood from the foot. The digital cushion is described as part of a foot "blood pumping" mechanism, which encourages the return of venous blood from the digit upward in the leg.



Traditional theory of the role of the frog and digital cushion in energy absorption during ground contact.

One idea, called the **pressure theory,** implies that, at impact, the sole and the frog (with its spine) compress the digital cushion and thereby apply pressure to force the cartilages outward (abaxially) while the digital cushion simultaneously serves as a shock absorber.

The second idea, termed the **depression theory,** indicates that, during impact, the forces transmitted through the laminar attachments of the hoof wall are redirected and dissipated as the middle phalanx (short pastern bone, or "P2") is lowered. P2 pushes the hoof walls and the cartilage outward.

Both theories propose that the blood is pumped from the foot at impact.

Each idea has certain strengths in explaining the apparent abaxial (outward) deflection of the cartilages and caudal (posterior) foot and the depression (or sinking groundward) of the metacarpal-phalangeal (fetlock) joint when the foot makes ground contact. However, the actual mechanisms of how energy is dissipated remains uncertain, since both ideas rely upon the belief that the digital cushion somehow "absorbs energy" before it forces the cartilages outward.

Previous notions on the energy dissipation mechanisms of the equine foot have focused upon the pressure and the depression theories. However, several studies have implied major weaknesses in these two ideas.

In one study, a pressure transducer implanted within the digital cushion of horses during various gaits recorded a negative pressure within the digital cushion, rather than a positive pressure during ground contact and stance phases. Such an observation is, we believe, counterintuitive to the notion that the digital cushion forces the cartilages outward when the foot is on the ground.

The actual role of the frog during ground contact is still uncertain and perhaps will remain controversial, since surgical ablation (removal) of the frog doe not affect the horse's ability to trot or canter. This implies that the hoof wall and sole are adequate as weightbearing tissues for the horse.

re-enter it without passing into the surrounding tissue. This indicates that they may serve to attenuate the transient peak energies occurring within the foot during ground impact. Such a vascular network would greatly increase the functional length of the vessels which would be important at certain times.

At such times, according to basic laws of hydraulic flow theory (Poiseuille's Law and Bernouilli's Principle), increased blood flow would be forced into these small veno-venous anastomotic vessels. This increased volume of blood would encounter an opposing resistance and thereby reduce the impact energies that would be transferred to bony and connective tissues of the limbs.

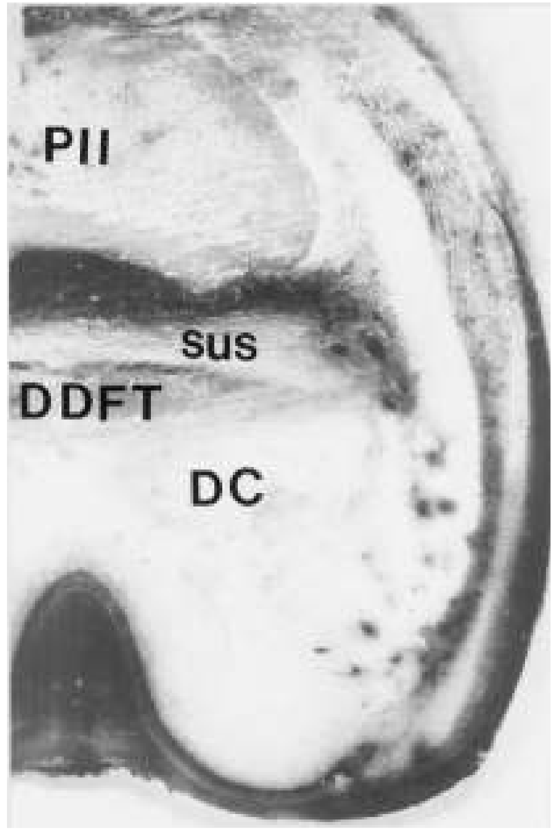
Our hypothesis on energy dissipation in the equine foot has evolved as a result of examination of numerous feet. The transient peak impact energies are hypothesized to be normally dissipated simultaneously by two events: 1) during ground impact, the pillars of the hoof wall (bars and palmar hoof wall at the quarters) force the cartilages to rotate outward (abaxially) by virtue of the cartilages' axial projection being pushed upward (proximally) by the bars to create the negative pressure within the digital cushion; and 2) the impact energy will be transmitted through the pillars of the hoof wall to the cartilages and then to the fluid in the vascular network within the vascular channels the cartilages, specifically the veno-venous anastomoses.

These two events will 1) produce an increase in venous blood flow through the caudal foot and 2) create a negative pressure in the foot, enabling this vasculature to be refilled with venous blood.

At ground contact, the positive reactive forces via the heel and the pillars of the hoof wall act upon the axial projections of the cartilages to rotate the vertical section of the cartilages outward. This action transfers the impact energies through the pillars to the cartilages. Such an outward rotation would occur coincidentally with hoof expansion after initial ground contact.

This outward rotation of the cartilages most likely is responsible for the negative pressure recorded within the digital cushion during ground contact. Almost simultaneously, the impact energies will force the venous blood into and through the numerous microvessels (veno-venous anastomoses) present within the cartilages from the large central vein within the vascular channels and at other sites of the foot in order to dissipate these high impact energies in accordance with hydraulic fluid theory.

The negative pressure within the digital cushion would enhance the refilling of this "energy dissipation" system of the cartilages. For example, the rapid refilling of the large central vein within the vascular channels of the cartilages would occur as venous blood from underneath P3 (from the solar venous plexus) would flow outward via the tributaries of the large paracunal veins and then through the cartilages.



Front foot (normal) cut in transverse section at P2 level, just above the coffin joint. This view shows the digital cushion filling the heels and extending up to the deep digital flexor tendon. The ungual cartilages extend upward from P3 (not shown in this view) and send projections into the digital cushion. In robust, strong feet, the projection may be continuous through the digital cushion, forming a "shelf" to add strength to the foot. In less robust feet, small islands of cartilage-like material may be found in the digital cushion. In weak feet, the cartilage is thin, with blood vessels passing on its inside edge, not through it, and the digital cushion will be a simple fatty mass. (Robert Bowker photo)

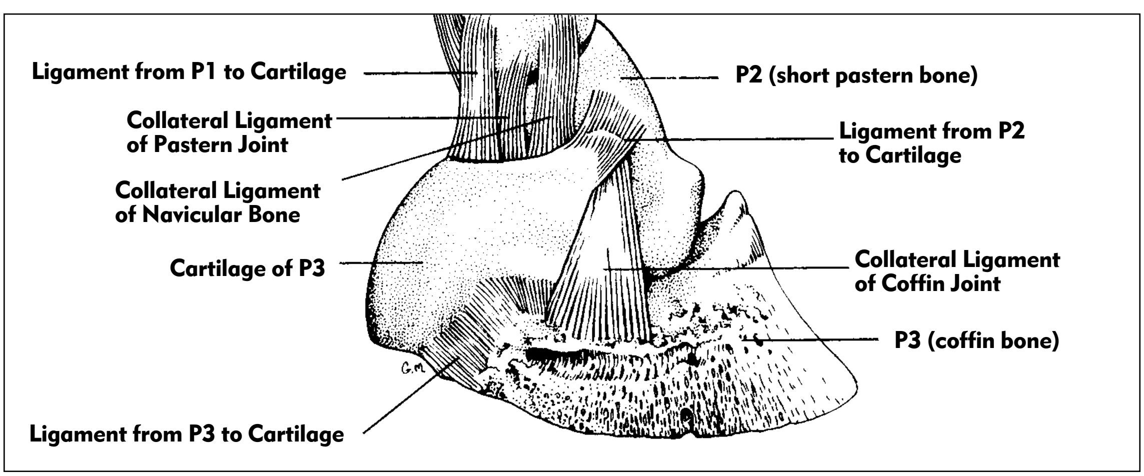
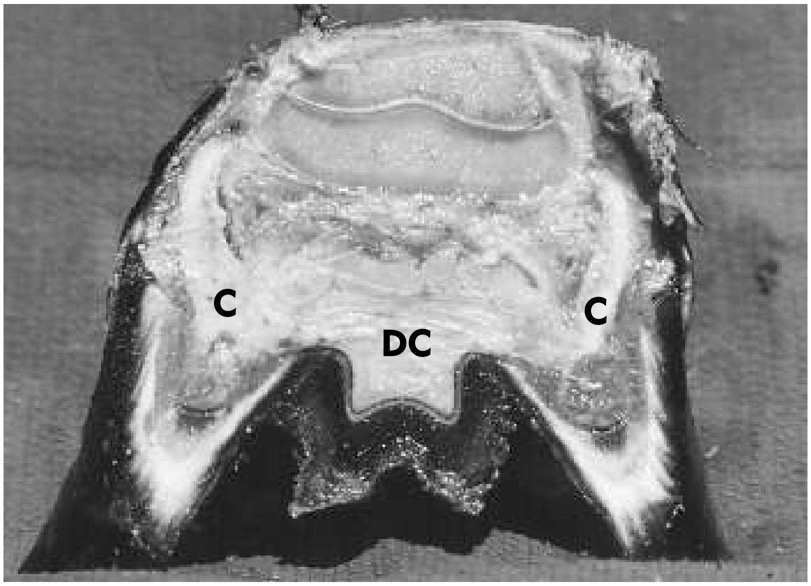
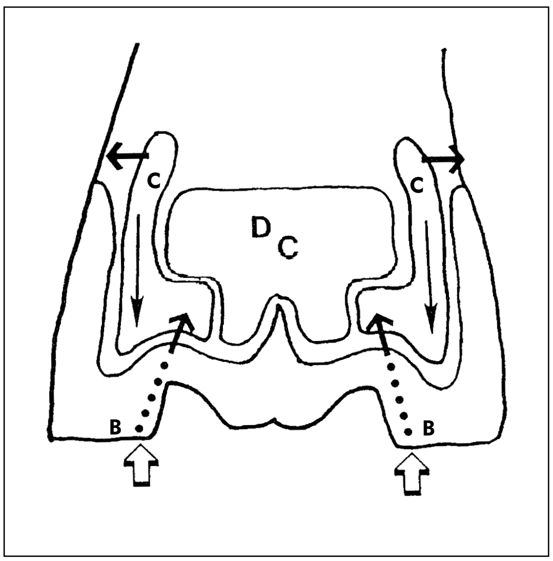


Diagram of the ligaments and cartilage of the equine foot. The digital cushion would lie inside the wing of cartilage. When the cartilage ossifies, or becomes "bone-like", the condition is called "sidebone".





Front foot, coronal section, cut through the bulbs of the heels shows the digital cushion clearly and the cartilages.

Bowker's theory of hemodynamic pressure in the foot: When the foot hits the ground, the bars of the heels and pillars of the hoof wall force a small "shelf" of the cartilage outward, creating negative pressure in the digital cushion. Impact is thus transmitted to a complex venous network inside the cartilage, creating more negative energy, which draws blood up from the solar area of the hoof.

This sequence of forcing venous blood through the microvasculature of the cartilages and caudal foot at impact followed by refilling of the "reservoir" of the large vein within the cartilages via larger diameter tributary vessels enables such a system to be replenished prior to the next foot contact with the ground.

The close relationship of the cartilages' axial projection to the epidermal bars of the heels was relatively constant in most well-balanced feet. In short, the bars of the hoof wall were present beneath (distal to) the axial projection of the cartilages.

One noteworthy, but constant exception was in those feet having underrun heels or a long toe-low heel conformation, whereby the wear of the hoof at the angle of the hoof wall and bars (the pillars) was located beneath the bony part of P3 rather than underlying the axial projection of the cartilages. (These are personal observations.)

Thus, in these instances, the proposed hemodynamic mechanism presented here might be bypassed or have minimal effect in dissipating energy, as a greater proportion of the initial shock and vibratory energies would be transmitted directly to the bones and ligaments within the foot. Such a conformation and resultant inefficiency of energy dissipation may be one reason why these horses have clinical foot and/or lameness problems.

Our initial morphological observations suggest that horses having thick cartilages caudal with a greater proportion of the digital cushion being composed of fibrous and/or cartilaginous elastic tissue rather that adipose tissue will potentially have maximal benefit of such a hemodynamic mechanism in the foot for dissipating energy if they have proper hoof conformation.

In horses having thinner cartilages, e.g. the caudal cartilages being <0.200-0.220 inches thick, the negative pressures in the digital cushion may be decreased due (in part) to less abaxial movement of the cartilages, partial expansion of an adipose-laden digital cushion and/or the improper trimming of the hoof wall (pillars) in relation to the cartilages.

Our hemodynamic flow hypothesis may also explain the gradual and insidious onset of many clinical lameness conditions. With decreased blood flow through the cartilages and/or with a fatty digital cushion, less energy will be dissipated, resulting in more energy being transmitted to bone and ligaments within the foot. Eventually, a threshold will be reached wherein clinical signs of lameness will become apparent.

Finally, even with a robust hemodynamic mechanism present in the foot, created either by breed predisposition or by environmental stimulation, the hoof wall must be prepared properly by the farrier and/or veterinarian. He or she must align the hoof wall pillars with the cartilages to maximize such a dissipating system. If this is not done properly, as in the case of underrun heels, eventual lameness problems will probably ensue.

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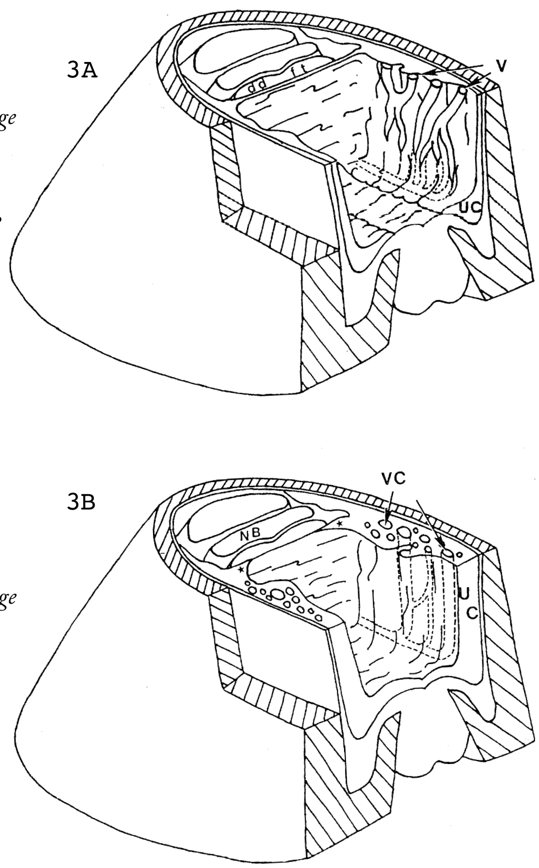
Breed characteristics exhibited in the digital cushion

Figure 3 shows two drawings depicting the shapes observed in horses having thin cartilage (Figure 3A) and thick cartilage (Figure 3B).



A. In the thin-cartilage foot, blood vessels are found on the inner surface of the cartilage, rather than inside the cartilage itself. This may be a sign of a weaker foot.

B. In the thick-cartilage foot, blood vessels are enclosed in foraminae within the cartilage.

Briefly, in horses with relatively thin cartilage, the axial projection and vertical component of the cartilage were usually present, but did not extend as far axially as it did in the feet having thicker cartilage.

Interestingly, horses commonly believed to have "good and healthy", or "problem-free" feet (i.e., Arabian horses) were consistently observed to have digital cushions from both the forelimb and hind limb composed mainly of fibroelastic tissue with fibrocartilaginous rays between the cartilage. They also had relatively thick cartilages rather than a fatty digital cushion and thin cartilages; 13 of 16 Arabian horses had fibroelastic digital cushion with cartilage.

However, the fibrocartilaginous digital cushion, along with a thick UC, was not restricted to only a few breeds as many Standardbred and other horse breeds also were observed to possess this type of cushion, especially in the forelimb.

A range of tissue composition of the digital cushion and the associated cartilages was observed in most breeds. This observation suggests that in addition to a potential genetic predisposition of certain breeds to have a fibrocartilaginous digital cushion, these connective tissues within the foot may be responsive or adaptive to various external stimuli within the environment, such as weight of the horse, concussive forces at ground impact, age, etc.

We also believe that such a fibrocartilaginous digital cushion is beneficial, since most Arabian horses had such a tissue composition within the caudal foot and are perceived to have "healthy feet". Such environmental stimuli may include the degree of hardness of the ground that the foot encounters and weight of the horse, to name only two possible factors. This firmer digital cushion may aid support of the foot when the horse is standing at rest and perhaps when the foot is on soft or more yielding soils to encourage movement of the venous blood to the cartilages.

Also, thin-cartilage feet had fewer vascular channels than feet with thicker cartilage, as much of the vasculature (blood supply) exited the cartilage axially prior to reaching the level of the navicular bone. In horses with thicker cartilage in the rear part of the foot, the axial projections into the digital cushion and along the semilunar line of the distal phalanx were consistently cartilaginous in nature.

Through more proximal (towards the body) levels of the cartilage, the number of vascular channels decreased, as the vessels exited the cartilage to combine and form an inner venous complex (IVP). In addition, microscopically, veno-venous anastomoses (VVAs, or shunts between veins) were found to be present.