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.

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.
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

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

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

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

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

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

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

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

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

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

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

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

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

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
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

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.

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 does 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 Bernoulli’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 paracanal veins and then through the cartilages.

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.”
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 than 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.

Robert Bowker is professor of anatomy at the College of Veterinary Medicine, Michigan State University. He is consulting editor for Hoofcare & Lameness.

Acknowledgement

The author would like to thank the American Quarter Horse Association for financial support and Ms. B. Schmidt and J. Carey for technical assistance.
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).

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 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 harshness 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 (IVC). In addition, microscopically, venous venous anastomoses (VVAs, or shunts between veins) were found to be present.