1. Introduction

Every day, clinicians change the point of breakover of a foot, add a wedge or a pad to a shoe, or resect part of a hoof capsule. All of these change the way the foot functions in some manner. We make some of these changes because that is what we were instructed to do in school, because it may have worked for us before, or because it makes sense to us—but how often do we actually think about the underlying biomechanical principles involved? This report discusses some aspects of function of the front foot of the horse. It is written from the perspective of a clinician trying to incorporate scientific developments in the biomechanics of the horse’s foot into clinical practice. It is not intended as a comprehensive review of all the biomechanical studies that have addressed the function of the equine digit. Readers who would like an in-depth review of digital biomechanics are referred to several recent excellent articles.1–4

Understanding how the foot works in this manner undoubtedly improves one’s ability to treat the more complicated foot problems in horses; however, the subject is fascinating in its own right. The most important aspects of foot function are related to the hoof and the distal interphalangeal joint. Therefore, this article will briefly discuss the anatomy of these structures, aspects of foot function at rest and at the trot, and briefly explore how some common manipulations used therapeutically may affect function. As clinicians, we tend to be very good at qualitative ideas such as the biomechanical concepts explored in this article. Fortunately for us, it appears to work well much of the time. However, there are occasions when the outcome of a biomechanical event is the result of two different determinants that function in an opposite manner to each other, and therefore, the result is the balance of the two. In such circumstances, without quantifying both effects, it is not possible to determine the net result. Therefore, excessive reliance on qualitative concepts can lead to overinterpretation or misinterpretation of the facts.

The majority of studies have examined the kinetics and kinematics of locomotion of horses at rest, at the walk and trot, and measured strains present in various tissues. These scientific studies have examined the position of the different elements of the distal limb in relation to each other and the ground, the force applied to the ground surface of the foot, strains in the hoof capsule and in major tendons and ligaments, and the biomechanical properties of some of the tissues in the foot. From this information, given specified assumptions and other static measurements, more information may be calculated. Last, using experimental data of the forces applied to the foot and the biomechanical properties of the tissues, finite element analysis models have been
developed to determine what is happening with respect to movement and forces within some of those tissues that cannot currently be directly measured.

2. Anatomy of the Hoof and Distal Interphalangeal Joint
The hoof is the integument of the foot, and as such, it is composed of three layers: the epidermis, dermis, and subcutaneous tissue. It is also divided into 5/6 regions: the limbic (perioplic), coronary, parietal (lamellar), solar, and cuneate/bulbar regions. The hoof capsule is formed by the stratum corneum of the epidermis of all these layers. The wall is formed by the stratum corneum of three layers—the limbic, coronary, and parietal—and these layers are called the stratum externum, stratum medium, and stratum internum, respectively. Each region of the hoof is highly specialized. The stratum medium of the wall is formed from tubular and intertubular horn. The structure, size, and density of the horn tubules vary with which zone of the wall they are located. The moisture content of the wall similarly varies, being drier more superficially and more hydrated in the deeper layers. The interdigitations of the lamellae are highly specialized and provide a very large surface area of contact between the epidermis and adjacent dermis. The frog is much softer than the wall and sole, and the underlying subcutaneous tissue is greatly modified to form the digital cushion. Therefore, the wall is well adapted to weight-bearing, the sole adapted to protecting the underlying soft tissues and weight distribution, and the frog and digital cushion adapted to permit expansion of the foot and participate in damping of vibrations.

The distal interphalangeal joint (DIPJ) is a complex joint with three articulations: (1) between the middle and distal phalanx, (2) between middle phalanx and the distal sesamoid (navicular bone), and (3) between the distal phalanx and the distal sesamoid. There is very little movement between the distal phalanx and the distal sesamoid, so they are frequently treated as one unit and will be so for the remainder of this discussion. The distal interphalangeal joint is a ginglymus joint. However, because the sagittal groove on the middle phalanx is very shallow and the opposing ridge on the distal phalanx very low, it also permits significant rotation and movement in the frontal plane.

3. Aspects of Distal Forelimb Function in the Stationary Horse
In a standing horse, the weight (mass times acceleration of gravity) borne by the limb is supported by the ground, which opposes the weight with an equal and opposite force. This force exerted on the hoof by the ground is the ground reaction force (GRF). At rest, both of these forces are approximately vertical. The weight of the horse is not uniformly distributed across the ground surface of the foot. By using a complex pressure transducer system, the distribution of the GRF on the ground surface of the foot has been examined under various conditions. It has been shown that in a shod horse, the weight is borne relatively evenly over the area that the shoe contacts firm ground. In a barefooted horse that has just been trimmed and is standing on firm ground, weight-bearing is increased compared to the untrimmed state and ground contact is present over...
the frog but is not necessarily evenly distributed around the perimeter of the foot. In a barefooted horse that has been at pasture and then stood on firm ground, the weight-bearing is primarily at the heel and toe. The pattern of weight-bearing at the toe has been shown to vary; it is either spread broadly across the toe from the toe-quarter junction on one side to the other or restricted to the toe-quarter junctions without any weight-bearing at the center of the toe. When a horse is placed on a surface that deforms to the shape of the foot, the weight-bearing area becomes much larger and is broadly distributed across the center of the ground surface of the foot.

The mechanical interaction between the horse and the ground is measured with force plates that do not differentiate between weight-bearing by different parts of the foot but renders a single value. It is represented as a vector (GRFV). Vectors have a direction and magnitude. This vector represents the summation of all the forces acting on the foot. Measurements made this way can be broken into three components representing the three orthogonal planes: vertical, craniocaudal, and mediolateral. As such, they have a point of action. This point of action is given several names: point of force, point of zero moment, and center of pressure. This article will use the latter because its meaning is more intuitive to most people. At rest, the vertical component of the GRFV is much greater than either of the two horizontal components.

The weight of the body borne by the limb is transmitted through the limb by the skeletal system. The question that arises is, how is this force transmitted from the skeletal system to the ground? Based on clinical evidence, it has been assumed that the lamellae suspend the distal phalanx within the hoof capsule. In horses with laminitis in which the lamellae are severely damaged, the distal phalanx displaces within the hoof capsule. Additionally, it is possible to remove the majority of the sole in a horse for therapeutic reasons, and the horse is able to bear weight on the wall without the distal phalanx displacing. As such, it creates an extensor moment that is opposed by an equal and opposite moment, the flexor moment, generated by the force in the deep digital flexor tendon so that the foot is stationary.

The force exerted through the skeletal system is acting through the center of rotation of the distal interphalangeal joint. Therefore, the GRF creates a moment about the distal interphalangeal joint. A moment is the tendency to cause rotation of a body about an axis. This moment created by the GRF will cause the joint to dorsiflex (hyperextend) if unopposed; this moment is the extensor moment. In this case, the axis is the center of rotation of the distal interphalangeal joint. The magnitude of the moment is the product of the force and the length of the moment arm. The force is the magnitude of the GRFV. The length of the moment arm is the shortest distance between the line of action of the GRFV and the center of rotation of the DIPJ (i.e., the moment arm is perpendicular to the line of action of the GRF). Because the foot is in a stable position flat on the ground, the extensor moment must be opposed by an equal and opposite moment, which is the flexor moment. The flexor moment is the product of the force in the deep digital flexor tendon and the length of the moment arm, which is the shortest distance from the center of rotation of the DIPJ to the tendon.

4. Aspects of Distal Forelimb Function at the Trot

So far, this description has covered the dynamics of the foot of a horse standing at rest, but what about the foot of a horse that is walking or trotting? The stride is divided into flight and stance, and this discussion will be confined to the stance phase. At the beginning of the stance, the limb is fully protracted, with the foot out in front and the limb almost fully extended. After the foot comes to rest, the body continues to move forward and the trunk descends. As it does so, the metacarpophalangeal joint (MCPJ) dorsiflexes (hyperextends) and the distal interphalangeal joint flexes; that is, they are rotating in opposite directions. At midstance, the limb is vertical and the MCPJ dorsiflexion and the
DIPJ flexion have peaked. After midstance, the limb moves toward full retraction. As it does so, the MCPJ decreases (but is still dorsiflexed) and the DIPJ changes from flexion to dorsiflexion so that at the beginning of breakover, both joints are dorsiflexed.

As the limb moves through the stance phase of the stride, the GRFV changes and these changes reflect the different phases of the stride. The magnitude of the vertical component of the GRFV is very low immediately after the foot contacts the ground, increases as the horse bears more and more weight, and then decreases so that it is again very low when just before the foot leaves the ground. In the forelimbs, the horizontal component of the GRFV is, for approximately the first 60% of the stride, in the opposite direction to the movement of the horse, that is, it is a braking force. During the last 40% of the stride, the horizontal component of the GRFV is in the same direction as the movement of the horse, that is, it is a propulsive force.

The strains in the flexor tendons, accessory ligament of the deep digital flexor tendon, and suspensory ligament reflect the magnitude of the GRFV and the angulation of the metacarpophalangeal and distal interphalangeal joints. The strains in the superficial digital flexor tendon and the suspensory ligament are greatest at the point of maximal weight-bearing and maximal dorsiflexion of the metacarpophalangeal joint. The strain in the deep digital flexor tendon (measured proximal to its attachment to its accessory ligament) does not increase as much as that in the superficial flexor tendon or the suspensory ligament because as the metacarpophalangeal joint dorsiflexes, the distal interphalangeal joint flexes, that is, the tendency for the tendon to stretch around the metacarpophalangeal joint is offset, at least partially, by its tendency to shorten around the distal interphalangeal joint. The accessory ligament of the deep digital flexor is under greatest tension when both these distal joints are dorsiflexed but before the magnitude of the GRFV has decreased markedly.

Based on the kinematic and kinetic events of the stride, stance is divided into three phases. The first is the impact phase, which begins at first contact and is defined by the presence of shock waves present in the distal limb and is associated with landing and initial loading of the limb. The support phase begins at the end of the impact phase and ends at heel lift-off. It is the phase of the stride when the limb bears maximal load and the period before and after maximal loading. Its beginning is actually a continuation of the initial loading of the limb that begins at first contact but without the vibrations of impact. Its ending at heel-off signifies the kinematic event because the unloading of the limb continues until toe-off. Breakover begins with heel-off and ends with toe-off. The end of breakover is like the impact phase in that it is associated with shock wave vibrations, but they are of considerably lower magnitude.

The impact phase, which lasts 25 to 50 milliseconds, is further subdivided into two parts associated with two collisions. The first is the impact of the foot with the ground, which only lasts a few milliseconds followed by a second, which involves the impact of the weight of the body and limb of the horse with the foot. These two impacts overlap to some degree and set up a series of irregular shock waves associated with the deceleration of impact.

Moments about the distal interphalangeal joint of a horse trotting are a function of the magnitude of the GRFV, the center of pressure, and the tension in the deep digital flexor tendon. Although the center of pressure at first contact is often at the heels or lateral quarter, because it moves very quickly toward the center of the foot and because the magnitude of the GRFV is low, this phase of the stride has received little attention. During the support phase of the stride, when the center of pressure is in a relatively constant position in the center of the foot and dorsal to the center of rotation of the distal interphalangeal joint, the extensor and flexor moment arms are relatively constant, and therefore the force in the deep flexor tendon directly reflects the magnitude of the GRFV. Towards the end of the support phase the tension in the distal portion of the deep digital flexor tendon and its accessory ligament increases so that the flexor moment increases. At the same time the magnitude of the ground reaction force is decreasing. Consequently, the center of pressure moves towards the toe, which lengthens the extensor moment arm such that the extensor moment equals the flexor moment and the foot remains flat on the ground. The heels lift off the ground when the flexor moment exceeds the extensor moment (which occurs because the center of pressure can move no further dorsally once it is at the dorsal margin of the toe).

The distal limb has developed to absorb the energy associated with impact and the loading of the limb. It is known that impact vibrations are largely dampened by the time they have propagated to the proximal phalanx. The evidence indicates that the tissues that absorb the energy are the soft tissues of the hoof, for example, the lamellae and underlying dermis/subcutaneous tissue and the articular cartilage of the distal joints. Additionally, the structure of the digital cushion and the collateral cartilages and their associated venous plexuses suggest that a hemodynamic damping mechanism is present in the palmar half of the foot. The impact associated with loading of the limb by the weight of the trunk is also dampened by the combined action of the musculotendinous structures and the two distal joints in the limb, which, by extending the period over which the load is applied, decreases the maximum force on the distal limb. Dorsiflexion of the metacarpophalangeal joint is associated with an increase in length of supporting...
tendons and ligament. The tendons are structured to store energy as they stretch and release it as they shorten, and the muscles are designed to dampen vibrations within the tendons. However, despite these protective mechanisms, excessive, repetitive strains can potentially damage tissues within the digit during either impact or loading.

5. Effect of Common Manipulations on Foot Function

The effect of shoeing horses on foot function is well documented. In short, it is known that nailing on steel shoes limits expansion of the foot and causes the magnitude and frequency of impact vibrations to increase. It is also known that some shoe and pad combinations can ameliorate these changes.

Two adjustments to shoeing commonly performed for horses with navicular disease are heel elevation and moving the point of breakover in a palmar direction. Our goal is usually described as taking the pressure off the navicular bone and making breakover “easier.” However, what do they really achieve in terms of the biomechanics discussed above? Elevating the heels causes the distal interphalangeal joint to flex. At rest, elevating the heels moves the center of pressure toward the center of rotation of the distal interphalangeal joint. Therefore, it shortens the moment arm of the GRFV, which means that the tension in the deep digital flexor tendon is reduced (Fig. 2). The reduction in the deep digital flexor tendon pressure tension in conjunction with the change in angle of the deep digital flexor tendon around the navicular bone substantially reduces the pressure on the navicular bone. The biomechanics of the middle of the stride are similar with respect to the position of the center of pressure, but the magnitude of the GRFV and the tension in the deep digital flexor tendon are greater. Therefore, elevating the heels would be protective to the deep digital flexor tendon and navicular bone. However, moving the center of pressure in a palmar direction increases the load on the heels and increases intra-articular pressure. Additionally, flexion of the joint changes the distribution of pressure within the distal interphalangeal joint. Any of these effects of heel elevation are potentially deleterious.

Moving the point of breakover in a palmar direction is thought to improve distal limb function in horses with diseases such as navicular syndrome. Moving the point of breakover in this manner does shorten the extensor moment arm at the initiation of breakover (Fig. 3). Because the flexor moment exceeds the extensor moment when the GRFV can no longer move dorsally, breakover may occur slightly earlier. However, it does not shorten the duration of breakover. Furthermore, it does not decrease the maximal pressure on the navicular bone as might be expected. This is because the pressure on the navicular bone is a function of the tension in the deep digital flexor tendon and the angle at which it bends around the bone. Therefore, maximal pressure on the navicular bone is a balance of decreasing tension in the deep digital flexor tendon as the load on the limb decreases toward the end of the stride, whereas breakover occurs at approximately 65% of the way through the stride, whereas breakover occurs at approximately 85% of stance. These findings would argue against the effectiveness of moving the point of breakover in a palmar direction for horses with navicular disease. However, it appears that rolling the toe smoothes out the breakover process.

In horses with laminitis, in addition to raising the heels and moving the point of breakover in a palmar...
direction, it is common practice to fill the space between the branches of the shoe with a synthetic polymer to promote weight-bearing by the sole. This procedure is also done for horses with other clinical conditions of the foot. Clinical evidence is highly varied, indicating that it appears to improve the lameness in some horses but worsens it in others. However, the scientific evidence behind what it does is minimal. This evidence, discussed above, suggests that it will distribute the force of weight-bearing over a much wider area of the sole. However, finite element analysis suggests that movement of the quarters abaxially during foot expansion pulls at the margins of the sole, causing it to flatten out. Therefore, any device that limits movement of the sole in this manner may either limit foot expansion or place excessive strain on the white line. Intuitively, the thickness and quality of the sole horn may also affect how the foot tolerates this maneuver. However, much remains to be resolved about the effects of this procedure.

The farriery and veterinary professions have made significant advances over the last 25 years in treating many conditions of the horse’s foot, but undoubtedly we still have a long way to go. This progress has received contributions from new scientific knowledge, but much of our progress has been the result of reasoning (sometimes good, sometimes bad) and experience. The author believes that the next step in our progress requires more deliberate thinking by clinicians about concepts such as moving the center of pressure and changing distribution of force into the development of therapeutic plans that involve biomechanical manipulation of the horse’s foot.

References