THE FIVE INFLUENCIAL FACTORS FOR A HEALTHY HOOF AND THE IMPACT OF THE TWIN™ SHOE ON IT: A LITERATURE REVIEW

BART HALSBERGHE, JANUARY 2020

DVM, DECVSMR (Equine), DABVP (equine practice), cert. ISELP, cVMA, cVSMT, CERT

Contents:

1. INTRODUCTION

Shoeing horses has a long tradition. Originally, the main reason for applying shoes to horses was to protect the feet against excessive wear.[1,2] Over the years, numerous types of shoes and corrective farriery techniques have been developed in an attempt to influence performance or as a therapeutic aid to treat lameness.[1] However, the way in which horses are shod are still similar to the techniques of centuries ago, no matter what the purpose of the shoes.[1,3]

The past two decades have provided equine veterinarians and farriers with new information relating to limb biomechanics and the effects of various farriery methods.[1] The back half of the hoof seems to play a major role in overall hoof health.[4] Changes to this area may then affect the way the hoof copes with impact and may be beneficial or deleterious, affecting soundness.[4] The purpose of this paper is to review the influencing factors affecting the health of the hoof as well as the effects of current farriery techniques on stress and strain within the distal limb. With this knowledge in mind, we will discuss how the TwinÔ Shoe has a positive impact on those factors.

2. FACTORS INFLUENCING HOOF HEALTH

2.1 HOOF MECHANISM

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.[5] The hoof mechanism describes the changes in the hoof geometry (deformation) that occur during locomotion (loading and unloading of the foot/limb) (figure 1).[6]

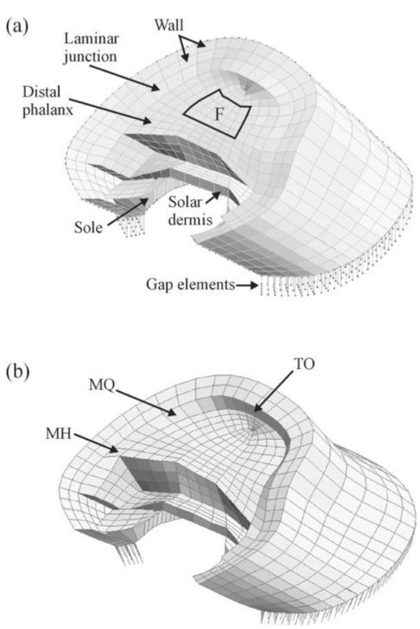

Figure 1: (a) A complete finite-element model with component layers and structures labeled, representing the unloaded hoof. (b) The same model showing global hoof capsule deformation (exaggerated) representing the loaded hoof. Reprinted from Thomason JJ, Mclinchey HL, Faramarzi B et al. Mechanical behavior and quantitative morphology of the equine laminar junction. 2005, The Anat Rec 2005; Part A, 283A: 366-379.

Under load bearing conditions, the dorsal hoof wall rotates palmar/plantar-distal (caudo- ventral) about the distal phalanx (Coffin bone (P3)), the quarters flare outward, the sole and frog move downward and the heel expands (figure 2).[6,7,8,9] Heel expansion occurs regardless of the loading pattern, but more heel expansion occurs when pressure is applied directly to the frog and sole.[10]

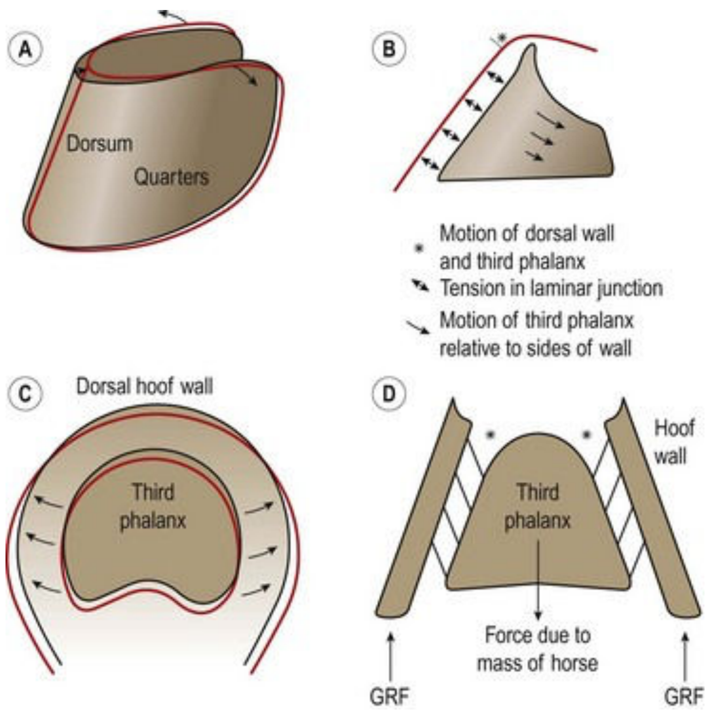

Figure 2: Schematic drawing of the hoof mechanism phenomenon. The solid black line represents the unloaded hoof wall, the solid red line shows the change in shape that occurs during weight-bearing. Reprinted from Douglas JE, Biddick TL, Thomasson JJ, and Jofriet JC. Stress/strain behaviour of the equine laminar junction. J Expl Biol 1998; 201: 2287-2297.

The exact mechanism by which the hoof deforms and expands under load is unknown and different theories exists, all of them having certain limitations.[8,11,12,13] Based on the results of finite-element modeling it now seems that the main contributor to the hoof mechanism is the cone-like shape of the hoof capsule itself.[8,14] Other contributors to the hoof mechanism are the descend of the distal phalanx (P3) or coffin bone within the hoof capsule, frog pressure, and lowering of the middle phalanx (P2) or short pastern bone, which are represented in the older pressure and depression theories.[14]

- The pressure theory (Clark 1809, Lungwitz 1883) suggests that the tissues of the digital cushion are trapped between the foot's descending axial skeleton and solar components during loading.[11,12] The sole and the frog as such compress the digital cushion and thereby apply pressure to force the cartilages and hoof wall outward.[11,14]

- The depression theory (Coleman 1805, Peters 1883) indicates that, during impact, the forces transmitted through the laminar attachments of the hoof wall are redirected and dissipated as the middle phalanx (P2) is lowered.[11,12,15] Lowering of middle phalanx pushes the hoof wall and the cartilage outward.[11,12,15]

From impact to mid-stance, force is progressively applied, causing the whole hoof to change shape or deform. Weight of the body pushing down on the distal phalanx (P3) causes the bone to pull down on the hoof wall at the toe via the laminar junction.[14] Under this force, the wall is dragged down and also moved backward because it is inclined to the vertical to start with, and the lower part of the wall may dish a little. At the coronet, the amount of motion may be 1 to 3 mm.[14] This motion tends to push the quarters into the ground, but the ground pushes back, which forces the quarters to move outward rather than downward, causing them to flare.[14] The heels are carried along with the quarters to some extend.[14] The heels are also compressed in a vertical direction as they are pressed into the ground.[14]

By mid-stance the hoof is maximally deformed for the step. The degree of deformation is dependent on the peak force at midstance.[14] The sole has also flattened (moved down), the small amount of motion of the sole is likely not because it is being pushed down from above, but because it is being pulled out and down from the sides.[14] The sole is a low dome, arching between the quarters on either side.[14] As the quarters flare, they pull outward on the edges of the sole, tending to flatten its domed shape.[14] The sole can be compared to a drum skin that is attached to the wall at the white line.[14] When you push on a taut drum skin, it resists your push, not because of the air pressure on the far side of it, but because it is stretched across the barrel of the drum and transfers the push to the edges of the barrel.[14] In a similar manner, upward pressure on the sole is resisted at the white line primarily, and not generally by the sole being pushed up toward the coffin bone.[14,16] This means that the white line has the important mechanical function of bracing the sole against the wall, in addition to providing a seal to prevent infection from entering the foot.[14,16] It makes sense for the coffin bone not to press down on the sole over most of its area.[14] For one reason, a blood vessel that is important in the supply to the cells that make the white line runs around the lower edge of the coffin bone.[14] Continuous pressure on it might obstruct the blood flow in it.[14] For another, the sole grows down from a layer of cells on its inner surface.[14] If those cells were continually under pressure, growth abnormalities of the sole would be likely.[14] As such the forces go out to the wall, via the white line, and to the coffinbone via the laminar junction.[14] From mid-stance to breakover, deformation relaxes as the force subsides and the hoof begins to resume its unloaded shape.[14]

High displacements of the hoof wall are seen towards the coronary band. With only a little displacement in the weight bearing border of the toe, gradually increasing towards the heels. Maximum hoof wall deformation at the coronet is seen in the dorsal toe and the quarters.[17] As mentioned before, the proximal dorsal wall moves inward and downward, the coronary band moves outward at the quarters, and the sole and frog move downward.[17] Displacement of the weight bearing borders are comparably small with very little movement at the toe and most movement at the heels.[17] Hoof wall displacements closer to the coronary band are significant higher than in the corresponding segment more distally.[17]

Although the above described heel expansion theory is now widely accepted, some studies have shown that heel contraction can take place.[18] It has been shown that heel displacement is influenced by the geometry of the hoof.[19] Horses with a steeper hoof angle, narrow heels and prominent bars with narrow/small frog (upright/contracted foot) have less heel expansion compared to horses with low heels, less developed bars and large frogs.[9,15,20] As such steeper hoofs or stiffer and have less shock absorption at impact.[20] A more recent finite-element model has looked at the effect of loading and unloading of the heels and its relationship to heel expansion/contraction.[8] This research suggest that change in shape of the sole (concavity) and whether or not the bars are weight bearing effects the amount of expansion/contraction of the heels.[8] Unloading of the heels is responsible for contraction and heels seemed to be unloaded in horses with flat soles and high/weight bearing bars.[8] If contraction is related to heel unloading and it is a cause of pain, then it is likely to be self-proliferating due to voluntary unloading of the heels.[8]

In a shod horse, the weight is born relatively evenly over the area that the shoe contacts firm ground,[21] with dominant stress areas occurring in the bars, the outer layers of the proximal hoof wall, and in hoof horn material surrounding nail fixation, particularly the 3rd nail, and in hoof horn material surrounding side clips.[17] 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.[21] 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.[8,21] Long toe and low heels increases the stress on the dorsal proximal hoof wall at the level of the coronet band.[9]

A proper functioning hoof mechanism can not be underestimated as it plays a role in absorbing shocks and circulation.[19,22] The hoof capsule, together with the joints of the distal limb, provides flexibility of the distal limb.[23] A diminished function of one of these components may increase loading of others, possibly exceeding the normal physiological capacity and therefore leading to injury.[23]

2.2 VASCULAR SUPPLY OF THE DIGIT

Many have pondered the mechanics of the circulation of blood through the horse foot.[24] Bouley's insightful observations in 1851 described the horse's foot as an additional heart working as "a pushing and sucking pump".[24,25]

The "pushing" phase (venous return to the heart) comes from descent of bones, tendons, and cartilage into the semi-rigid hoof capsule, compressing the corium and the blood vessels contained within during loading of the foot.[24] The low resistance veins and lymphatic vessels are more affected by the pressure than the thick-walled arteries, the blood in the three venous plexi (coronary, dorsal and palmar venous plexus) is squeezed into the digital veins.[4,5,24] There is a secondary pumping action of venous blood out of the foot as the foot unloads and the hoof capsule contracts (negative pressure in the digital cushion falls away).[4] For a pump to operate effectively, no back flow must occur. Prevention of (retrograde) arterial flow during loading of the foot occurs secondary to closure of the medial and lateral digital arteries at the level of the extremities of the navicular bone (reducing blood flow to the sole and toe) and proximal to it (reducing blood flow to the quarters and heels) .[24,26,27,28] This occlusion is due to tension in the deep digital flexor tendon (DDFT) compressing the arteries. Closure of the coronary arteries occurs only during heavier loading secondary to global compression of the corium between bone and hoof as the distal phalanx (P3) vertically descends into the hoof capsule and the middle phalanx (P2) rotates back/palmar (coffin joint flexion).[24]

The "sucking" phase" (arterial blood flow to the digit) comes from unloading the foot/digit.[24,26,27,28,29] Arterial blood enters the foot and venous blood is prevented from flowing back into the foot by valves.[4,5,30]

2.3 SHOCK ABSORPTION OF THE DIGIT

Several structures in the limb are believed to attenuate impact shock.[31] Viscoelastic deformation of the hoof wall damps the frequency and maximal amplitude of the vibrations.[8,15,31] Soft tissues inside the hoof attenuate the higher deceleration frequencies transmitted to the distal phalanx, while the interphalangeal joints attenuate the deceleration amplitude.[31,32] Blood flow in the digital circulatory system contributes to absorption of concussion in the hoof as well.[31,33] Finally, shock is also attenuated by structures in the joints, including subchondral bone and articular cartilage, as it is transmitted proximally in the limb.[31]

During the impact period (concussion period) high-amplitude accelerations are observed during approximately the first 30-50 msec of stance.[23,34] The total period of concussion is approximately the period of muscle latency, which implies that the events at concussion cannot be modulated actively by muscle contraction.[23] As such the more proximal structures of the limb are thought to be important in the damping of the second period of loading (mid-stance).[23,35]

The hoof wall is well adapted to weight-bearing, the sole is adapted to protecting the underlying soft tissues and weight distribution, and the frog and digital cushion are adapted to permit expansion of the foot and participate in damping of vibrations.[21] It has been shown experimentally that the hoof attenuates around 67% of the ground impact deceleration at trot and that shoeing increases the amplitude of the impact vibrations compared to the unshod condition.[36] This attenuation is proposed to occur mainly within the laminar junction.[14,36] However, the results of one finite-element model predict that most of the attenuation takes place in the hoof wall itself rather than the laminar junction.[8] Hoof capsule deformation is proportional to the capacity of the hoof to stored elastic energy.[8] More energy is absorbed elastically when the center of pressure (CoP) is located caudally, indicating that a heel first landing would be expected to maximize energy absorption.[8] The horse may be able to control hoof capsule deformation by controlling the CoP location, avoiding potentially painful deformation.[8] Absorption of the load impulse energy by the capsule would be expected to reduce the amount of impulse energy transmitted to the distal limb joints, thus protecting them from damage.[8] A heel first landing would be expected to promote caudal loading of the hoof and because a caudally located CoP increases the compliance and therefore the predicted capacity of the hoof to absorb impulse energy, then this provides a biomechanical reason for the preference of this hoof landing style.[8]

The forces are transmitted through the hoof wall, laminar junction and P3 and redirected and dissipated as P2 is lowered.[11,12,15] The digital cushion acts as a restraint to the displacement of the second phalanx (sling theory) or as a passive structure that allows flexibility of the caudal two thirds of the foot (passive theory).[13] Regional displacement of the digital cushion occurs principally along distal and palmar vectors in response to vertical loading.[13] Concussion is further absorbed by hemodynamics.[11,15] The particular distribution of blood vessels within the foot suggest that fluid damping of the shock oat impact occurs throughout the toe region, around the coronet, and especially within and between the hoof cartilages.[37] That may be another reason why horses tend to land further toward the heel as they increase their speed.[37] The hemodynamic flow theory (Bowker 1998) explains the fluid dampening effect of the blood vessels in the back of the hoof.[11,12,38] Bowker theorizes that forces are transmitted through the bars and palmar hoof wall at the quarters and redirected and dissipated as the ungular cartilages and their extensive vascular network are activated.[11,12,38] The observations of an extensive but minute network of veins within the foot but especially within the vascular channels of the cartilages, and the close association of the latter with the hoof wall pillars (bars and palmar hoof walls at the quarters), suggest a critical function for these small vessels in shock absorption, beyond the mere distribution of nutrition to and from the perfused tissues.[11,12] During ground impact, the pillars of the hoof wall and the downward movement of the bony column (P2) force the cartilages to rotate outward (abaxially).[11,12] This can be explained by virtue of the cartilages' axial projection being pushed upward (proximally) by the bars and the palmar rotation of P2 pushing the hoof wall and cartilages outwards.[11,12,39] This creates a negative pressure within the digital cushion.[11,12,39] As such an outward rotation occurs coincidentally with hoof expansion after initial ground contact.[11,12] The impact energy will force the venous blood into and through the numerous veno-venous anastomoses present within the cartilages and in accordance with hydraulic fluid theory it will dissipate these high impact energies (hydraulic resistance to flow through the microvasculature dissipates the high-frequency energy waves).[11,12]

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 bones and ligaments within the foot.[11,12] Greater blood flow through the ungular cartilages and the palmar foot is increased by the high negative pressure within the digital cushion during ground impact.[18]

2.4 BIOMECHANICS OF THE DISTAL LIMB

2.4.1 Kinetics

2.4.1.1 Normal Horse Impact phase

When viewed from the side hoof contact with the ground is classified as heel-first, flat- footed, or toe-first. For a horse with well-balanced feet, the heels usually contact the ground first.[6,40] The way the hoof contact the ground is influenced by limb, gait, speed, farriery, and lameness.[6] The hind limbs show a greater tendency to heel first contacts than the forelimbs and heel first contact is exaggerated during high-speed locomotion.[6,41] For gaits and movements in which the hoof approaches the ground with a downward rather than a forward trajectory, such as piaffe, toe first contact is normal.[6] The way the hoof contacts the ground is also affected by the way the hoof is trimmed.[6] The horse's proprioceptive awareness of hoof orientation seems to be based on the internal geometry of the hoof rather than the shape of the hoof capsule.[6] The more acute the hoof angle (low hoof angle), the higher the frequency of toe first contact, whereas heel-first contacts are more prevalent with a more upright hoof angle.[6,42] With certain type of lameness, a characteristic manner of hoof contact occurs as a means of reducing pain by shifting the load away from the affected structures.[6]

During the impact phase (the moment the hoof contacts the ground), the hoof undergoes rapid deceleration, and this is associated with a wave of concussion that travels up the horse's limb.[6] During this period high-amplitude accelerations are observed during approximately the first 30-50 msec of stance.[23,34] The impact phase is potentially the most damaging phase of the stride for the hard tissues (bones and joints).[6]

Concussion is markedly attenuated by structures within the hoof and by flexion of the joints.[12,32,36] The hoof is particularly important in this regard because the soft tissues within the hoof filter out some of the potentially damaging high frequency vibrations.[6] Up to two thirds of the impact shock may be dissipated within the hoof before it reaches the coffin bone.[6,36] As the shock wave travels proximally through the limb, concussion is further attenuated by the coffin, pastern, and fetlock joints so that only 12% of the concussive force reaches the cannon bone.[36] Concussion is higher on hard ground, which results in faster vertical deceleration of the hoof, and on surfaces that prevent the hoof from sliding forward.[6] When the hoof is able to slide forward a little at impact, it has significant effect on terms of absorbing concussion.[34]

Mid-stance phase

In the middle part of the stance phase (mid-stance) the hoof is loaded by the horse's body weight.[6] Mid-stance corresponds closely with the time when the fetlock joint is maximally extended and the vertical ground reaction fore (GRF) reaches its peak value.[6] The amount of fetlock extension is proportional to the magnitude of the peak vertical force.[6] After mid-stance the vertical force declines and the fetlock joint rises.[6] The amount of fetlock extension is important because it determines the amount of strain in the superficial digital flexor tendon (SDFT) and suspensory ligament (SL).[6] Strain on the deep digital flexor tendon (DDFT) is more sensitive to the coffin joint angle and increases as the coffin joint extends.[6,43]

Push off phase

Breakover begins when the heels leave the ground and start to rotate around the toe of the hoof, which is still in contact with the ground.[6] Breakover is initiated by tension in the distal check ligament (DCL) acting through the DDFT, combined with tension in the navicular ligaments.[6]

During most of the stance, a state of equilibrium exist between the torque exerted around the coffin joint by the GRF and the torque exerted on the opposite side of the coffin joint by the DDFT (figure 3).[6] In the later part of the stance phase, the action of the DDFT tends to flex the coffin joint but flexion is resisted by the GRF.[6] As the horse's body moves forward over the grounded foot, the GRF decreases and the tension of the DDFT increases.[6] Eventually, the torque of the DDFT exceeds that of the opposing GRF; this is the moment when the heels are raised around the toe and is eventually pulled of the ground, as the proximal joints flex.[6]

Tension in the DDFT and the consequent pressure on the navicular region are maximal just before the start of breakover.[6] A more acute hoof angle prolongs the duration of breakover.[42] Raising the heels by six degrees delays the onset of breakover, but requires lower forces to initiate breakover.[44]

Healthy hooves, influencing factors 9

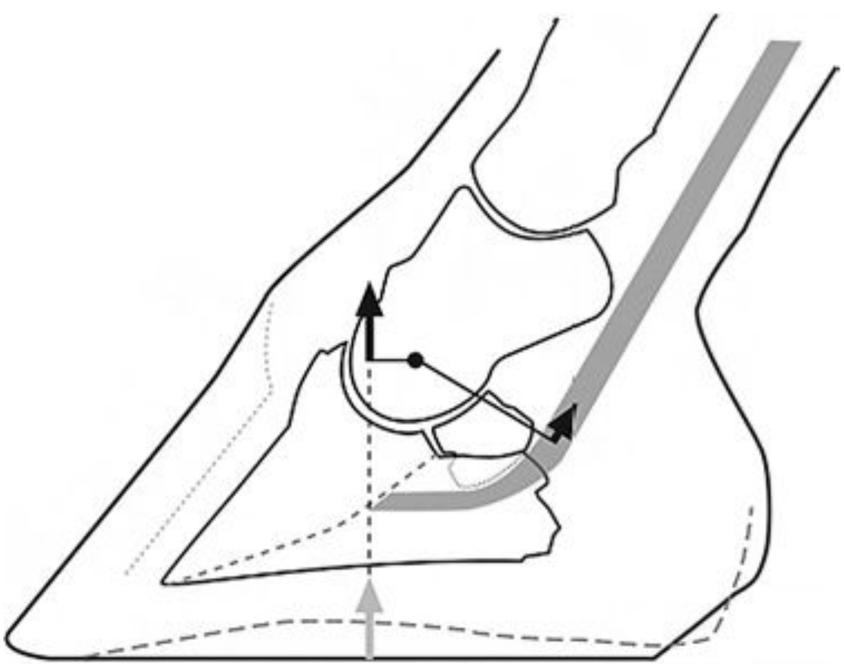

Figure 3: At rest, the ground reaction force (gray arrow) is dorsal to the center of rotation of the distal interphalangeal joint. As such, it creates an extensor moment that is opposed by an equal and opposite moment, the flexor moment, generated by the force in the deep digital flexor tendon so that the foot is stationary. Reprinted from Parks AH. Aspects of functional anatomy of the distal limb, in AAEP proceedings 2012.

2.4.1.2 Lame horse

Horses with navicular disease have abnormal limb-loading force patterns compared with sound horses.[1,45] The peak DDFT force and the peak stress exerted by the DDFT on the navicular bone are similar between normal horses and those with navicular syndrome.[1,45] In early stance, however, the force and stress in the diseased horses are approximately double the values of that in normal horses.[1,45] The increased force and stress are assumed to result from higher forces in the deep digital flexor muscle as the horses attempt to unload their heels.[1,45] This has been confirmed based on a finite- element model.[8] In this model, the horse may avoid or reduce deflection (deformation) of the hoof capsule by moving the CoP forward.[8] Cranial movement of the CoP results in a marked reduction the magnitude of most hoof deflections (deformation) with contraction of the heels instead of expansion.[8] Stored energy in both the capsule and the soft connective tissues of the hoof was also greatly reduced by cranial placement of the CoP.[8] This forward placement of the CoP would result from the increased joint moment caused by the reported increased DDFT tension.[8] This mechanism is thought to result in the classic toe-first gait seen in some horses with navicular disease and is suggested to cause a vicious cycle promoting further damage.[1,45]

2.4.2 Kinematics

2.4.2.1 Coffin (distal interphalangeal) joint kinematics

Alterations in hoof balance are accommodated primarily by changes in angulation and movement of the coffin joint.[6,44,46,47,48]

Coffin joint kinematics during the gait cycle are as followed: the coffin joint flexes in early stance reaching peak flexion around 40% of stance after which it extends as the horse's body continues to move forward over the grounded foot. After the initiation of breakover the coffin joint flexes through the terminal part of stance and into the swing phase.[6] There is less than 5 degrees flexion of the coffin joint in the swing phase.[49] The coffin joint is supported on its palmar aspect by tension in the DCL-DDFT and the navicular ligaments, which limits the amount of coffin joint extension in late stance.[50,51] Increasing the hoof angle is associated with an increase in coffin joint flexion, and to a lesser extend pastern joint flexion and fetlock joint extension.[6] Furthermore there is less pastern and coffin joint extension at breakover.[52] Increased coffin joint flexion is a consequence of reduced tension in the DDFT.[43] Conversely, a more acute hoof angle, by lowering the heel or raising the toe, is associated with more tension in the DDFT, which causes an increase in coffin joint extension (more upright pastern).[6]

For differences in the palmar angle of the distal phalanx, it was demonstrated that for a 1-degree change in P3 the forces experienced by the DDFT changed by 4%.[53]

2.4.2.2 Fetlock (metacarpophalangeal) joint kinematics

Hoof angulation has shown to influences the fetlock joint angulation to a certain extend.[6] An increased hoof angle, induced by a heel wedge, induces a decrease in the dorsal metacarpophalangeal joint angle (DMPJ) (extension), whereas a decreased hoof angle, induced by a toe wedge, causes an increase in the DMPJ (flexion).[54] Nevertheless, there are other factors that seem to have a greater influence on the fetlock joint kinematics.[55]

Static evaluation of the distal joint angles showed that there was a significant correlation between the DMPJ and the angle of the proximal phalanx/long pastern bone (P1) and middle phalanx/short pastern bone, as well as the length of the long and short pastern bone.[55] The longer the proximal and middle phalanges, the smaller the DMPJ, indicating higher extension in this joint.[55] The more upright the orientation of the proximal and middle phalanges, the greater the DMPJ, meaning less extension in this joint.[55] No correlation was seen between the angle of the dorsal hoof wall and the angle of the distal phalanx with the DMPJ.[55]

Based on these findings[55] as well as earlier findings[56,57] it seems highly probable that the conformation of the proximal locomotor system influences the DMPJ and not the hoof conformation.[55]

2.5 HOOF HORN QUALTIY AND GROWTH

The digit and more specific the hoof is one of the most important structures related to soundness in the horse. This is likely due to the ability of the hoof to attenuate impact vibrations transmitted at ground contact.[36,58] Hoof growth, quality and function as such become important factors as they often affect the usefulness of the horse.[59] Manipulation of hoof growth can also have practical implications for farriers and veterinarians in terms of growing out lesions, producing sufficient horn to properly trim and balance the foot or nailing in to.[60]

Hoof growth is influenced by several factors. These include but are not limited to season[61], age[62,63], gender[61], breed[60], metabolic rate[64], trimming and shoeing[65] and nutrition[62,66]. Average hoof growth for these reasons has a wide range but for a mature horse is around 0.19-0.28 mm/day or 5.7-8.4 mm/month[65,67,68]. Most research has focused on the effects of nutrition on hoof growth and quality, with adequate caloric intake[66] and biotin supplementation[62] being important factor for proper hoof growth.[59] As most horses receive already a well balanced diet with adequate levels of nutrients to support proper hoof growth and quality, other means to further increase hoof growth would be helpful for those hoofs affected by factors beyond our control such as season, age, gender and breed.[59] Whole body vibration (WBV) is a non-invasive, safe and non labor-intensive therapeutic modality that can accelerate hoof growth in the horse.[59]

The exact mechanism(s) of hoof growth itself is still unknown but the following structures seem to play a key role: First of all, the corium, composed of micro-vessels, small nerve fibers and connective tissue, produces or supplies the nutritional products to be used by the basilar and other epidermal cells lining the basement membrane.[59,69] Secondly, the basilar epidermal cells lining the basement membrane, capable of adapting to stress (load) by increasing its surface area through laminar bifurcation of its primary epidermal laminae and subsequently the number of horn forming cells (keratinocytes).[59,69] When we look at these structures involved in hoof growth and adaptation, it is fair to say that increased blood supply, metabolic rate and cellular proliferation and differentiation are all potential mechanisms involved in hoof growth.[59]

3. EFFECTS OF SHOEING

3.1. Hoof (capsule) deformation

Shoeing results in less expansion of the palmar aspect of the hoof when compared with the unshod horse and shoeing attenuates (reduces) contraction of the wall at the heel during the late stages of the stance phase.[10,17] Frog pressure increases heel expansion but heel expansion occurs despite the frog not being in contact with the ground.[10]

Hooves react to type, geometry and form of the horseshoes and their fixation method.[17] Hinterhofer et al. found maximal displacement of the hoof capsule when shod with a regular shoe without clips compared to regular shoe with toe clip, regular shoe with side clips and regular shoe with side clips placed behind the third nail.[17] All models showed higher displacement when nails where loosely fixated in stead of tense fixation.[17] Hinterhofer also found less hoof capsule deformation when heels were raised and increased hoof capsule deformation when heels were lowered.[9]

There is no differences between nailed and glued shoes in maximum heel expansion of the forelimbs, but in the hindlimbs, the maximum heel expansion in glued shoes is smaller than in nailed shoes, this is likely related to the smaller vertical ground reaction force in the hind- than the forelimb.[22] The maximum heel contraction of the glued hoof were smaller than those of the nailed hoof in both fore-and hindlimbs at all speeds.[22] As such Glued on shoes tend to restricts total heel movement more than nailing on shoes, especially at slower speeds.[22]

Naturally, the processes of hoof growth and wear are balanced.[1] This allows an unshod horse to maintain the shape and size of its feet.[1] The shoe of a shod horse prevents the wear of the toe, but not of the heel, and therefore, the angle of both the toe and the heel decrease[70,71] The dorsal hoof angle typically becomes shallower by a means of 3.5 degrees over a period of 8 weeks.[72]

3.2. Shock absorption

Shoeing increases both the maximal amplitude of the vibrations and the frequency of the vibrations caused by hoof strike and transmitted to the bony structures of the leg.[15] As such shoes impaired the dampening function of the hoof.[1,2,15,36]

Higher stresses on the distal bones (coffin bone (P3), short pastern bone (P2), long pastern bone (P1)) were recorded in the shod horses at mid-stance, with most stress on the bone occurring at the solar margin of P3 and distal P1 in both the shod and unshod horses.[73]

Horses shod with regular steel shoes experience higher concussion than unshod horses at the level of the hoof wall (15% increase), but the difference may not be apparent at the level of the first phalanx.[36] Certain types of shoes and shoe/pad combinations, however, may actually reduce concussion at the level of the hoof wall in exercising horses. [36,74,75]

A reduced shock absorption capability can be explained by the reduced heel expansion in shod horses.[15] This reduced heel expansion causes an alteration in the onset and degree of negative pressure in the digital cushion.[15] In the unshod horse, expansion began about 30 msec after the hoof struck the ground and the pressure decreased rapidly to about -40 kPa.[15] The pressure then remained low until the hoof started rolling over the toe for push off and the pressure returned to normal.[15] When the horse was shod with standard steel shoes the pressure decrease began more than 50 msec after hoof strike (this is after the initial impact phase!!) and the pressure decreased to reach a minimum of -60 kPa, but the low pressure lasted for a shorter time, possibly because the hoof began rolling over the toe sooner.[15] Once the adhesion between the loaded hoof and the shoe was overcome the hoof expanded rapidly, this explains the large change in the pressure inside the digital cushion.[15]

3.3. Joint loading

An upright heel promotes a more pronounced heel-first landing[76], whereas a toe-first landing is seen with a long-toe-low-heel conformation.[42] A similar pattern is seen with wedges: with toe wedges, hoof impact is more dorsal on the lateral side, whereas it occurs more palmar with heel wedges.[52]

Heel elevation increases the pressure within the distal interphalangeal joint (DIPJ) and alters the articular contact area.[1,77] It has been hypothesized that this may lead to greater localized "wear and tear" on the joint surface, possibly predisposing the horse to an increased risk of arthritis.[1,77]

Raising the heels results in flexion of the DIPJ and proximal interphalangeal joint (PIPJ), as well as extension of the metacarpophalangeal joint (MCPJ), whereas toe elevation induces a similar but opposite change.[52,78,79,80,81] The effects on the MCPJ are less pronounced compared to the DIPJ and PIPJ.[1]

Shoeing increases the force exerted on the navicular bone by as much as 14%.[82]

The forelimb center of pressure (CoP) is known to deviate in a palmar direction across a four-to-eight-week shoeing interval.[3,71] The shoe of a shod horse prevents the wear of the toe, but not of the heel, and therefore, the angle of both the toe and the heel decrease, resulting in the palmar movement of the CoP, and an increased loading in the DIPJ and navicular bone.[70,71]

Medio-lateral balance is an important aspect when trimming and shoeing.[1] Elevating one side moves the center of pressure (CoP) towards the elevated side of the foot.[1,81,83] This indicates that the elevated side sustains a higher load, thus supporting the motion that horses with such abnormal medio-lateral imbalance, the change in load distribution may be the reason for structural breakdown between the bulbs of the heels, as well as uneven joint pressure and ligament tension.[1,81,83]

3.4. Tendon and ligament strain

If we look at the effects of shoeing on tendon strains, most of the studies have concentrated on the MCPJ angle and SDFT or SL strain, or on the angle of the DIPJ and DDFT strain as well as the force exerted by the DDFT on the navicular bone.[1] Most studies have demonstrated that heel elevation (heel wedge) decreases strain on the DDFT, does not cause a change in SDFT strain, and increases or does not change the strain in the SL.[1,50,84] Elevating the toe (toe wedge) on the other hand reduced the strain in the SDFT and SL and significantly increased strain in the accessory ligament of the DDFT.[50] Heel elevation decreases the force exerted on the navicular bone by the DDFT by 24%, mainly because of reduction in the extending moment arm of the DIPJ but also as result of a flatter angle of deviation of the tendon around the navicular bone.[1,82]

With hoof growth during a shoeing interval, the angle of the dorsal hoof wall decreases and the length of the toe increases ('long toe, low heel syndrome'), while the center of pressure moves towards the heel.[23,70] Consequently, the moment of force at the DIPJ and hence tension in the DDFT and the pressure on the navicular bursa increase.[23,70]

A preliminary case study in horses at the walk shows that there was a strong similarity in the vertical ground reaction force (GRF) pattern between the shod and unshod conditions during the stance phase.[73] However, at mid-stance, the vertical GRF of the shod condition was approximately 10% higher than the unshod condition (kinetic data).[73] When day looked at the kinematic data they saw slightly more flexion of the PIPJ during impact followed by more extension of the PIPJ during mid-stance and push off in the shod horse.[73] Also there was slightly less flexion of the DIPJ joint at impact but more flexion of the DIPJ during mid-stance and more extension during push off phase of the stance in the shod horse.[73]

Authors (BH) comment: "Although the above described findings are preliminary it may have important implications in regard to the benefit of a normal hoof mechanism. Stresses on the SDFT and suspensory ligament are highest at impact/early stance and mid-stance. A reduction in PIPJ flexion (in barefoot versus shod horses) reduces the stresses on these structures during impact and a reduction in DIPJ flexion at mid-stance (in barefoot versus shod horses) correlates with a reduction in MCPJ extension and as such a reduction on these soft tissue structures at mid-stance as well. Stresses on the DDFT are the highest at push off and pressure on the navicular bone is the highest at push off as well as high during mid-stance because of the lever arm. These stresses are reduced in the barefoot horse versus the shod horse by the decreased extension of the DIPJ during push-off and the decreased flexion of the DIPJ at mid-stance."

4. EFFECTS OF LEG SUPPORT WRAPS

Athletic support wraps (neoprene boot) and polo wraps do not provide shock attenuation.[31] However they do increase the stiffness of the mass-spring system in the horse contributing to unloading the soft tissues.[85,86,87]

5. THE TWIN™ SHOE: BENEFITS BASED ON SCIENCE

5.1. UNRESTRICTED HEEL MOVEMENT

Research performed on the Twin™ Shoe, clearly shows that heel movement (the key variable of hoof deformation) is not negatively affected by the Twin Shoe, compared to the barefoot hoof, whereas a traditional shoe restricts heel movement approximately 36%.[88] A proper functioning hoof mechanism can not be underestimated as it plays a role in absorbing shocks and circulation.[19,22]

> => **Twin™ Shoe: Allows for a normal functioning hoof mechanism and as such proper shock absorption and circulation of the hoof.**

5.2. IMPROVED MEDIO-LATERAL BALANCE

Medio-lateral balance is an important aspect when trimming and shoeing.[1] Elevating one side moves the point of force (point of zero moment) towards the elevated side of the foot.[1,81,83] This indicates that the elevated side sustains a higher load, thus supporting the motion that horses with such abnormal medio-lateral imbalance, the change in load distribution may be the reason for structural breakdown between the bulbs of the heels, as well as uneven joint pressure and ligament tension.[1,47,81,83] Shoeing limits the medio-lateral heel movement.[10,17]

However, the Twin™ Shoe, consisting of two separate halves, allows heel movement comparable to the barefoot horse.[89]

> => **Twin™ Shoe: Because the TwinÔ Shoe consist of two separate halves it does not limit medio-lateral heel movement, allowing the hoof two adapt to uneven surfaces and turns and as such balancing the foot from medial to lateral (side-to-side) minimizing uneven joint pressure and ligament tension.**

5.3. CONSTANT DORSAL HOOF ANGLE BETWEEN SHOEING INTERVALS

Naturally, the processes of hoof growth and wear are balanced.[1] This allows an unshod horse to maintain the shape and size of its feet.[1] The shoe of a shod horse prevents the wear of the toe, but not of the heel, and therefore, the angle of both the toe and the heel decrease.[70,71] Typically the dorsal hoof angle becomes shallower by a means of 3.5 degrees over a period of 8 weeks[72] resulting in extension of the DIPJ the palmar movement of the CoP[23,70,71], and an increased loading in the DIPJ, navicular bone, navicular bursa and the DDFT.[23,70,71]

> => **Twin™ Shoe: Because the Twin**O **Shoe moves with the hoof as it expands and contracts there is less excessive wear at the heel compared with a traditional shoe. As such the hoof angle remains more constant between shoeing intervals resulting in decreased force on the DIPJ, navicular bone and navicular bursa and decreased strain on the DDFT.**

5.4. IMPROVED CIRCULATION

The mechanics of the circulation of blood through the horse foot are closely associated with the ability of the heels to expand and contract.[4,24] Research performed on the Twin™ Shoe, clearly shows that heel movement (the key variable of hoof deformation)

is not negatively affected by the Twin Shoe, compared to the barefoot hoof, whereas a traditional shoe restricts heel movement approximately 36%.[88]

> => **Twin™ Shoe: allows for proper circulation of the hoof, which is important for proper hoof growth and quality as well as shock absorption of the hoof.**

5.5. IMPROVED HOOF GROWTH RATE

A proper functioning hoof mechanism can not be underestimated as it play a role in absorbing shocks and circulation.[19,22] It is clear that the mechanics of the circulation of blood through the horse foot are closely associated with the ability of the heels to expand and contract.[4,24] Research performed on the Twin™ Shoe, clearly shows that heel movement (the key variable of hoof deformation) is not negatively affected by the Twin Shoe, compared to the barefoot hoof, whereas a traditional shoe restricts heel movement approximately 36%.[88] Furthermore, increased blood supply, metabolic rate and cellular proliferation and differentiation are all potential mechanisms involved in hoof growth.[59]

> => **Twin™ Shoe: Because the Twin Shoe allows normal heel movement (does not restrict the hoof mechanism), blood circulation to the hoof is maintained compared to barefoot horses and improved compared to traditional shod horses. This in combination with proper cellular proliferation and differentiation from mechanical stimulation allows for an increased hoof growth rate compared to a traditional shoe.**

5.6. IMPROVED SHOCK ABSORPTION

Shoeing reduces the shock absorption capacity of the hoof.[19] The effect depends on the type of material the shoe is made off: the shock absorption properties of steel and that of aluminum are less than that of polyurethane shoes.[19] Horses shod with regular steel shoes experience a 15% higher concussion than unshod horses at the level of the hoof wall.[36]

A reduced shock absorption capability of traditional shoes can be explained by the reduced heel expansion in shod horses.[15] This reduced heel expansion causes an alteration in the onset and degree of negative pressure in the digital cushion.[15] Research performed on the Twin™ Shoe, clearly shows that heel movement (the key variable of hoof deformation) is not negatively affected by the Twin Shoe, compared to the barefoot hoof, whereas a traditional shoe restricts heel movement approximately 36%.[88]

- ⇨ **Twin™ Shoe: because the Twin Shoe does not restrict heel expansion compared to barefoot the shock absorption capacity of the natural hoof is maintained. As such the Twin Shoe provides good shock absorption independent of the material it is made of and as such reduces the forces placed upon the bones and joints at impact.**

5.7. IMPROVED BIOMECHANICS

The dorsal hoof angle decreases in a shod horse versus a barefoot horse over an 8 week cycle[72] resulting in extension of the DIPJ, the palmar movement of the CoP[23,70,71], and an increased loading in the DIPJ, navicular bone, navicular bursa and the DDFT.[23,70,71] Furthermore, a preliminary case study in horses at the walk shows that at mid-stance, the vertical GRF of the shod condition is approximately 10% higher than the unshod condition (kinetic data)[73] and kinematics are altered as well. There is slightly more flexion of the PIPJ during impact followed by more extension of the PIPJ during mid-stance and push off in the shod horse.[73] Also there is slightly less flexion of the DIPJ joint at impact but more flexion of the DIPJ during mid-stance and more extension during push off phase of the stance in the shod horse.[73] Stresses on the SDFT and suspensory ligament are highest at impact/early stance and mid-stance.[6]

A reduction in PIPJ flexion (in barefoot versus shod horses) reduces the stresses on these structures during impact and a reduction in DIPJ flexion at mid-stance (in barefoot versus shod horses) correlates with a reduction in MCPJ extension and as such a reduction on these soft tissue structures at mid-stance as well. Stresses on the DDFT are the highest at push off and pressure on the navicular bone is the highest at push off as well as high during mid-stance because of the lever arm.[6] These stresses are reduced in the barefoot horse versus the shod horse by the decreased extension of the DIPJ during push-off and the decreased flexion of the DIPJ at mid-stance. Lastly, shoeing limits the medio-lateral heel movement compared to barefoot[10,17] However, research[88] has shown that a hoof shod with a Twin™ Shoe acts comparable to the barefoot condition.

⇨ **Twin™ Shoe: Because the Twin Shoe acts comparable to the barefoot condition, bones, joints, ligaments and tendons will be less stressed in horses shod with the Twin Shoe compared to traditional shoes.**

References:

1. Eliashar E. An Evidence-based assessment of the biomechanical effects of the common shoeing and farriery techniques. Vet Clin Equine pract 2007;23: 425- 442.
2. RoepstorffL,JohnstonC,DrevemoS.Theeffectofshoeingonkineticsand kinematics during the stance phase. Equine Vet J Suppl 1999; 30: 279–85.
3. VanHeelMC,MolemanM,BarneveldA,etal.Changesinlocationofcentreof pressure and hoof-unrollment pattern in relation to an 8-week shoeing interval in the horse. Equine Vet J 2005; 37: 536–40.
4. Davies Z. Circulation – the lower limb. In: Davies Z ed. Equine Science. 3rd ed. Hoboken, NJ, USA: John Wiley and sons Ltd, 2018; 102-122.
5. Pollitt CC. Clinical anatomy and physiology of the normal equine foot. Equine Vet Educ 1992; 4(5): 219-224.
6. ClaytonHM.Chapter14:hoofmechanicsduringlocomotion.In:RameyP, Sullivan C, eds. Care and rehabilitation of the equine foot. Lakemont, GA, USA: Hoof rehabilitation Publishing LLC, 2011; 265-279.
7. JordanP,WillneffJ,D`ApuzzoN,etal.Photogrammetricmeasurementof deformations of horse hoof horn capsules, in Proceedings. Videometrics and optical methods for 3D shape measurements, proceedings of SPIE 2001; 204- 211.
8. RamseyG.Equinehoofbiomechanics,inMasterthesis.Auckland bioeningeering institute, University of Auckland, 2011.
9. HinterhoferC,StanekC,HaiderH.Theeffectofflathorseshoes,raisedheels and lowered heels on the biomechanics of the equine hoof assessed by finite element analysis (FEA). J Vet Med A Physiol Pathol Clin Med 2000; 47: 73-82.
10. Roepstorff L, Johnston C, Drevemo S. In vivo and in vitro heel expansion in relation to shoeing and frog pressure. Equine Vet J Suppl 2001; 33: 54–57.
11. Bowker RM. Hemodynamic flow hypothesis for energy dissipation in the equine foot. Hoofcare and Lameness - Issue 70: 36-41.
12. Bowker RM, Van Wulfen KK, Springer SE et al. Functional anatomy of the cartilages of the distal phalanx and digital cushion in the equine foot and a hemodynamic flow hypothesis of energy dissipation. Am J Vet Res 1998; 59: 961-996.
13. Taylor DD, Hood DM, Potter GD, et al. Evaluation of displacement of the digital cushion in response to vertical loading in equine forelimbs. Am J Vet Res 2005; 66(4): 623-629.
14. Davies HMS, Merritt JS, Thomason JJ. Chapter 3: Biomechanics of the equine foot. In: Floyd AE, Mansmann RA eds. Equine podiatry. St. Louis, MO, USA, 2007; 42-56.
15. Dyhre-Poulsen P, Smedegaard HH, Roed J et al. Equine hoof function investigated by pressure transducers inside the hoof and accelerometers mounted on the first phalanx. Equine Vet J 1994; 26(5): 362-366.

16. Thomason JJ, McClinchey HL, Jofriet JC. Analysis of the strains and stresses on the equine hoof capsule using finite element methods: comparison with principal strains recorded in vivo. Equine Vet J 2002; 34: 719-725.
17. Hinterhofer C, Stanek C, Haider H. Finite element analysis (FEA) as a model to predict effects of farriery on the equine hoof. Equine Vet J Suppl 2001; 33: 58-62.
18. Rasch Konstanze. The hoof mechanism – the quintessence of horse hoof biomechanics? In Huftagung der DHG e.V. für Tierärzte und Hufbearbeiter, Tagungsmaterialien 2015.
19. Oosterlink M, Dumoulin M, Can de water E et al. Biomechanische aspecten met betrekking tot hoefbeslag bij paarden. Vlaams diergen tijds 2017; 86: 256-265.
20. Thomason JJ. Variation in surface strain on the equine hoof wall at the midstep with shoeing, gait, substrate, direction of travel, and hoof shape. Equine Vet J Suppl 1998; 26: 86-95.
21. Parks AH. Aspects of functional anatomy of the distal limb, in AAEP proceedings 2012.
22. Yoshihara E, Takahashi T, Otsuka N, et al. Heel movement in horses: comparison between glued and nailed horse shoes at different speeds. Equine Vet J Suppl 2010;38: 431-435.
23. Johnston C and Back W. Science: Overview. Hoof ground interaction: when biomechanical stimuli challenge the tissues of the distal limb. Equine vet J 2006;38 (7): 634-641.
24. Van Eps A, Collins SN, Pollitt CC: Supporting limb laminitis. Vet Clin North Am. Advances in Laminitis - Part 2 2010; 26: 287-302.
25. Bouley MH: Treatise on the organization of the foot of the horse, comprising the study of the structure, functions and diseases of that organ. In: Treatise. Paris: 1851.
26. Pollitt CC. Equine foot studies. Brisbane, Australia: Videovision, information Technology Services, the University of Queensland, 1992.
27. Van Kraayenburg FJ, Fairall N, Littlejohn A. The effect of vertical force on blood flow on the palmar arteries of the horse. In proceedings. 1st ICEEP 1982; 144- 154.
28. Van Kraayenburg FJ. A comparative study of haemodynaomics in the equid digit [MSc thesis]. The university of Pretoria, 1982.
29. Redden RF: Preventing laminitis in the contralateral limb of horses with non-weightbearing lameness. Clin Tech Equne Pract 2004; 3: 57-63.
30. Mishra PC, Leach DH. Extrinsic and intrinsic veins of the equine hoof wall. J Anat 1983; 136: 543-560.
31. Luhmann LM, Wickler SJ, Hoyt DF, et al. Evaluation of shock attenuation in the forelimb of horses wearing boots and wraps. J Equine Vet Sci 2000; 20(8): 503- 510.
32. Lanovaz JL, Clayton HM, Watson LG. In vitro attenuation of impact shock in equine digits. Equine Vet J Suppl 1998; 26: 92-102.
33. Ratzlaff MH, Shindell RM, Debowes RM. Changes in digital venous pressures of horses moving at the walk and trot. Am J Vet Res 1985; 46: 1545-1549.
34. Gustas P, Johnston C, Roepstorff L et al. In vivo transmission of impact shock waves in the distal forelimb of the horse. Equine vet J Suppl 2001; 33:11-15.
35. McGuigan, MP and Wilson, AM. The effect of gait and digital flexor muscle activation on limb compliance in the forelimb of the horse Equus caballus. J Expt Biol 2003; 206: 1325-1336.
36. Willemen MA, Jacobs MW, Schamhardt HC. In vitro transmission and attenuation of impact vibrations in the distal forelimb. Equine Vet J Suppl 1999; 30: 245–248.

37. Davies HMS, Philips CJ, Merritt JS. Chapter 2: Functional anatomy of the equine digit: determining function from structure. In: Floyd AE and Mansmann RA, eds. St Louis, MO: Saunders Elsevier, Equine Podiatry 2007; 25-41.
38. Bowker RM, Van Wulfen KK, Springer S. Macroscopic and microscopic anatomy of the ungular cartilage: a hemodynamic flow hypothesis of energy dissipation. In Proceedings. 43th AAEP 1997; 354-355.
39. Bowker RM. Chapter 29: Functional anatomy of the palmar aspect of the foot. In: Ross MW and Dyson SJ, eds. Diagnose and management of lameness in the horse. St Louis, MO: Saunders, 2011: 320-323.
40. Chateau H, Degueurce C, Denoix JM: Evaluation of three-dimensional kinematics of the distal portion of the forelimb in horses walking in a straight line. Am J Vet Res 2004; 65: 447-455.
41. Back W, Schamhardt HC, Hartman W et al. Kinematic differences between the distal portions of the forelimb and hindlimbs for horses at the trot. Am J Vet Res 1995; 56: 1522-1528.
42. Clayton HM. The effect of an acute hoof angulation on the stride kinematics of trotting horses. Equine Vet J Suppl 1990; 9: 86-90.
43. Lawson SEM, Chateau H, Pourcelot P, et al. Effect of toe and heel elevation on calculated tendon strains in the horse and the influence of the proximal interphalangeal joint. J Anat 2007; 210: 583-591.
44. Clayton HM, Willemen ML, Lanovaz JL, et al. Effects of a heel wedge in horses with superficial digital flexor tendinitis. Vet Compar Orthop Trauma 2000; 13: 1-8.
45. Wilson AM, McGuigan MP, Fouracre L, et al. The force and contact stress on the navicular bone during trot locomotion in sound horses and horses with navicular disease. Equine Vet J 2001; 33: 159–165.
46. Busche T, Turner TA, Poulos PW, et al. The effect of hoof angle on coffin, pastern and fetlock joint angles. In: Proceedings. 33th AAEP 1987; 729-738.
47. Chateau H, Degueurce C, Jerbi H et al. Three-dimensional kinematics of the equine interphalangeal joints: articular impact of asymmetric bearing. Vet Res 2002; 33: 371-382.
48. Chateau H, Degueurce C, Denoix JM. Three-dimensional kinematics of the distal forelimb in horses trotting on a treadmill and effects of elevation of heel and toe. Equine Vet J 2006; 38: 164–169.
49. Clayton HM, Sha DH, Stick JA et al. 3D kinematics of the proximal and distal interphalangeal joints of walking and trotting horses. Vet Comp Orthop Trauma 2007; 20: 1-7.
50. Riemersma DJ, van den Bogert AJ, Jansen MO, et al. Influence of shoeing on ground reaction forces and tendon strains in the forelimbs of ponies. Equine Vet J 1996; 28: 126–132.
51. Clayton, HM, Lanovaz, JL, Schamhardt, HC et al. Net joint moments and powers in the equine forelimb during the stance phase of the trot. Equine Vet J 1998; 30: 384-389.
52. Chateau H, Degueurce C, Denoix JM. Effects of 6 degree elevation of the heels on 3D kinematics of the distal portion of the forelimb in the walking horse. Equine Vet J 2004; 36: 649–654.
53. Eliashar, E, McGuigan, MP, and Wilson, AM. Relationship of foot conformation and force applied to the navicular bone of sound horses at the trot. Equine Vet J 2004; 36: 431-435.

54. Hagen J, Kojah K, and Geiger M et al. Immediate effects of tan artificial change in hoof angulation on the dorsal metacarpophalangeal joint angle and cross- sectional areas of both flexor tendons. Vet Rec 2018; 182(24): 692.
55. Hagen J, Kojah K, and Geiger M. Correlations between the equine metacarpophalangeal joint angulation and toe conformation in statics. Open Vet J 2018; 8(1): 96-103.
56. Hagen J, Hüppler M, Geiger SM, et al. Modifying the height of horseshoes: Effects of wedge shoes, studs and rocker shoes on the phalangeal alignment, pressure distribution and hoof-ground contact during motion. J Equine Vet Sci 2017; 53: 8-18.
57. Hüppler M, Häfner F, Geiger S, et al. Modifying the Surface of Horseshoes. Effects of Eggbar, Heartbar, Open Toe, and Wide Toe Shoes on the Phalangeal Alignment, Pressure Distribution, and the Footing Pattern. J Equine Vet Sci 2016; 37: 86-97.
58. Dyhre-Poulsen P, Smedegaard HH, Roed J, Korsgaard E. Equine hoof function investigated by pressure transducers inside the hoof and accelerometers mounted on the first phalanx. *Equine Vet J* 1994; **26**(5): 362-366.
59. Halsberghe BT. Effect of two months whole body vibration on hoof growth rate in the horse: a pilot study. Res Vet Sci 2018; 119: 37-42.
60. Curtis S. Factors affecting hoof horn growth and quality. In: Curtis S. ed. Corrective Farriery: a textbook of remedial horseshoeing, Volume II. Newmarket: Newmarket Farrier Consultancy, 2006; 419-422.
61. Frackowiak H and Komosa M. The dynamics of hoof growth of the primitive Konik horses (Equus caballus gmelini Ant.) in an annual cycle. Biol Rhythm Res 2006; 37(3): 223-232.
62. Reilly JD, Cottrell DF, Martin RJ, et al. Effect of supplementary dietary biotin on hoof growth and hoof growth rate in ponies: a controlled trial. Equine Vet J Suppl 1998; 26: 51-77.
63. Curtis S, Martin J, Hobbs S. Hoof renewal time from birth of Thoroughbred foals. Vet J 2014; 201(1):116-17.
64. Huntington P and Pollitt C. Nutrition and the equine foot. In: Pagan JD, ed. Advances in equine nutrition III. Nottingham: Nottingham university press, 2005; 23-36.
65. Glade MJ and Salzman RA. Effects of toe angle on hoof growth and contraction in the horse. J Equine Vet Sci 1985; 5(1): 45-50.
66. Butler KD, Hintz HF. Effect of level of food intake and gelatin supplementation on growth and quality of hoofs in ponies. J Amin Sci 1977; 44: 257-261.
67. Lockard AJ and Reinertson EL. Stimulation of equine hoof growth using a counter-irritant. Iowa state university veterinarian 1986; 48(2): 99-101.
68. Pollitt CC. An autoradiographic study of equine hoof growth. Equine Vet. J 1990; 22(5): 366-368.
69. Bowker R.M. The growth and adaptive capabilities of the hoof wall and sole: functional changes in response to stress. In: Proceedings. 49th AAEP 2003; 146- 168.
70. Moleman, M, van Heel, MCV, van Weeren, PR, et al. Hoof growth between two shoeing sessions leads to a substantial increase of the moment about the distal, but not the proximal, interphalangeal joint. Equine Vet J 2006; 38: 170-174.
71. Lesniak K, Williams J, Kuznik K, et al. Does a 4-6 week shoeing interval promote optimal foot balance in the working equine? Animals, 2017, 7(29): 1-14.
72. van Heel MC, Barneveld A, van Weeren PR, et al. Dynamic pressure measurements for the detailed study of hoof balance: the effect of trimming. Equine Vet J 2004; 36: 778–782.

73. Panagiotopoulou O, Rankin JW, Gatesy SM, et al. A preliminary case study of the effect of shoe-wearing on the biomechanics of a horse's foot. PeerJ 2016; DOI 10.7717/peerj.2164
74. Benoit P, Barrey E, Regnault JC, et al. Comparison of the damping effect of different shoeing by the measurement of hoof acceleration. Acta Anat 1993; 146: 109–113.
75. Back W, van Schie M, Pol J. Synthetic shoes attenuate hoof impact in the trotting warmblood horse. Equine Comp Exerc Physiol 2006; 3(3): 143-151.
76. Wright IM, Douglas J. Biomechanical considerations in the treatment of navicular disease. Vet Rec 1993; 133: 109–114.
77. Viitanen M, Bird J, Smith R, et al. Biochemical characterisation of navicular hyaline cartilage, navicular fibrocartilage and the deep digital flexor tendon in horses with navicular disease. Res Vet Sci 2003; 75: 113–120.
78. Crevier-Denoix N, Roosen C, Dardillat C, et al. Effects of heel and toe elevation upon the digital joint angles in the standing horse. Equine Vet J Suppl 2001; 33: 74–78.
79. Bushe T, Turner TA, Poulos PW, et al. The effect of hoof angle on coffin, pastern and fetlock joint angles. In: Proceedings. 33th AAEP 1987; 729–738.
80. Degueurce C, Chateau H, Jerbi H, et al. Three-dimensional kinematics of the proximal interphalangeal joint: effects of raising the heels or the toe. Equine Vet J Suppl 2001; 33: 79–83.
81. Chateau H, Degueurce C, Jerbi H, et al. Normal three-dimensional behaviour of the metacarpophalangeal joint and the effect of uneven foot bearing. Equine Vet J Suppl 2001;33:84–8.
82. Willemen MA, Savelberg HH, Barneveld A. The effect of orthopaedic shoeing on the force exerted by the deep digital flexor tendon on the navicular bone in horses. Equine Vet J 1999; 31: 25–30.
83. Wilson AM, Seelig TJ, Shield RA, et al. The effect of foot imbalance on point of force application in the horse. Equine Vet J 1998; 30: 540–545.
84. Lochner FK, Milne DW, Mills EJ, et al. In vivo and in vitro measurement of tendon strain in the horse. Am J Vet Res 1980; 41(12): 1929–1937.
85. Kobluk CN, Snesrud M, Bloom D et al. An equine cadaver limb model to measure energy and displacement characteristics of protective boots and bandages. Equine Nutrition and Physiology Society 1997; 197-198.
86. Crawford WH, Vanderby Jr. R, Neirby D, et al. The energy absorption capacity of equine support bandages. Part I: comparison between bandages placed in various configurations and tensions. Vet Comp Ortho Trauma 1990; 1: 2-9.
87. Crawford WH, Vanderby Jr. R, Neirby D, et al. The energy absorption capacity of equine support bandages. Part II: Comparison between bandages placed in various configurations and tensions. Vet Comp Ortho Trauma 1990; 1: 10-17.
88. Brunsting J, Dumoulin M, Oosterlinck M, et al. Can the hoof be shod without limiting the heel movement? A comparative study between barefoot, shoeing with conventional shoes and a split-toe shoe. Vet J 2019; 246: 7-11.
89. Oosterlinck M, Dumoulin M, Van de Water E et al. Biomechanische aspecten met betrekking tot hoefbeslag bij paarden (Biomechanical aspects of farriery in horses). Vlaams Diergen Tijds 2017; 86: 256-265.

