biomechanical considerations in equine laminitis

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Dedication

To my father, William G. Schleining, who taught me the importance of setting goals and to
my husband, Frank, who has journeyed with me
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CHAPTER 1. GENERAL INTRODUCTION

Thesis Organization

This thesis offers a contemporary review of the biomechanics involved in the disease of equine laminitis with respect to the methods of prevention and treatment. It starts with an introduction of the anatomy of the equine foot and how that anatomy serves a biomechanical purpose. The forces acting on a normal equine foot are presented with respect to different periods of the stance phase. The reaction of the internal structures of the foot to impact shocks and weightbearing is also outlined. Using the most current data, a generalized overview of laminitis follows. While each theory is briefly explained, it is beyond the scope of this thesis to compare and contrast the many different proposed etiologies for the pathophysiologic origin of laminitis. However, regardless of the inciting pathophysiologic mechanism, there is agreement that laminitis has four distinct phases which are covered in detail. Known risk factors for laminitis and identified epidemiologic trends as well as economic impact are presented. Chapter one concludes with a look at laminitis from a biomechanical perspective and how the biomechanical consequences may affect prognosis. Chapter two is a compilation of the scientific literature specifically relating to the biomechanical effects of current methods of laminitis prevention and treatment. Chapter three is organized as a scientific journal manuscript and outlines a study evaluating the center of pressure and load distribution in a population of normal horses utilizing a common, but unsubstantiated, treatment for acute laminitis. This chapter is intended for publication and will be submitted to the Journal of the American Veterinary Medical Association. Chapter four concludes the thesis and provides a summary of our current understanding of the
biomechanics of laminitis, treatment and prevention options, and direction for future studies utilizing information gained from the study described in chapter three.

**Introduction to the Normal Biomechanical Function of the Equine Foot**

The biomechanical function of the equine foot is to accept loads from the ground and musculoskeletal system and effectively absorb, transmit, and disperse those loads amongst the soft tissues and bones of the distal limb.\(^1\) Anatomically, the foot is composed of the hoof, the skin between the bulbs of the heel, and all structures within. This includes the distal interphalangeal joint, the third phalanx, the laminae, the terminal deep digital flexor tendon, the navicular bone and its associated structures (bursa and ligaments), the collateral cartilages, the digital cushion, the sole, the frog, and an extensive network of arteries and veins arising from the palmar (or plantar) digital artery and vein.\(^2,3\) At a gallop, a single forelimb can sustain substantial vertical loads up to 1.7 times the horse’s body weight. This can be upwards of 9000 N.\(^4\) Because of the extreme loads placed on the equine digit, the individual components of the foot would certainly fail if exposed to these loads alone. This makes one acutely aware of the importance of all structures in the foot working in concert to absorb and dissipate these loads. Here, special attention is given to the laminae.

The laminae are villi-like structures that functionally attach the hoof capsule to the third phalanx. There are approximately 600 primary sensitive, or dermal, laminae originating from the laminar corium which is contiguous with the periosteum covering the parietal surface of the third phalanx. These interdigitate with the insensitive, or horny, laminae of the stratum internum, the deepest layer of the hoof wall. Each of these primary laminae contains
approximately 100 secondary laminae increasing the functional surface area and overall strength of the laminar junction.\textsuperscript{3,5,6}

In the normal horse, loads encountered at the ground/hoof interface are transmitted through the hoof wall, to the laminae, the third phalanx, and finally to the bony column of the leg.\textsuperscript{7} Additionally, when the foot experiences higher loads, such as when the horse is cantering or galloping, the frog contacts the ground assisting in load dissipation. The wedge shape of the frog allows loads to be transferred to the bars and caudal hoof wall. This is then transmitted to the sole and digital cushion.\textsuperscript{3} In an \textit{in vitro} study examining the attenuation of impact shocks, it was determined that the bones and interphalangeal joints were responsible for a reduction of shock amplitude, but the laminar structures and hoof wall attenuated the frequency similar to a low pass filter.\textsuperscript{8} In contrast, an \textit{in vitro} study found that 67\% of impact vibration damping occurred at the interface between the hoof wall and the distal phalanx, i.e. the laminae.\textsuperscript{9} This finding was supported by an \textit{in vivo} study performed by Gustas \textit{et al} that concluded vertical and horizontal impact-related shocks were mostly absorbed by structures within the foot and distal limb and were negligible by the time the shocks reached the metacarpophalangeal joint.\textsuperscript{10} This establishes the importance of the laminae and structures of the distal limb in shock attenuation and load transmission.

The forces acting on a normal static foot at mid-stance are outlined in Figure 1-1. The main force is directed vertically and represents the support function of the limb. This is broken down into the force exerted on the ground by the weight of the horse countered by the ground reaction force directed upward. Also included is the tensile force exerted by the laminae on the hoof wall, tensile force of the deep digital flexor muscle via the insertion of the deep digital flexor tendon on the solar surface of the third phalanx, and the tensile force
exerted by the common (or long) digital extensor tendon on the extensor process of the third phalanx. These relationships are important when calculating joint moments and tendon forces using the method of inverse dynamics. When the foot is in static equilibrium, such as the instantaneous moment when the ground reaction force is greatest, the force of the deep digital flexor muscle on the third phalanx can be calculated by multiplying the moment arm created by the ground reaction force and the center of rotation of the distal interphalangeal joint by the magnitude of the ground reaction force.

Figure 1-1. Biomechanical forces of the equine digit. The weight of the horse (A) is countered by ground reaction force (B). Other forces include the tensile forces of the deep digital flexor tendon (C), the laminae (D), and the common(or long) digital extensor tendon (E). Arrows are for illustrative purposes only and are not scaled according to magnitude. Illustration courtesy of Dr. Stephanie S. Caston.
For the purposes of biomechanical analysis, gait is divided into two phases, stance and swing.\textsuperscript{2} The stance phase of gait is defined as the time period when the foot is in contact with the ground. This is further separated into three segments correlating to the movement of the hoof with respect to the surface. The first of these segments, \textit{impact} or “heel strike”, occurs when there is a rapid decrease in acceleration (deceleration) corresponding to a high rate of loading. This lasts approximately the first 30 msec of stance.\textsuperscript{2} The second, and longest, phase is \textit{support} where the entire foot contacts the ground and the load is high. The final segment is \textit{breakover} which begins when the heel leaves the ground and ends at the point of toe lift-off as the flexing moment about the distal interphalangeal joint exceeds the extending moment.\textsuperscript{2,12,13} While this phase comprises only 5\% of the total stance phase, breakover is constantly manipulated by farriers and veterinarians in an effort to elicit a biomechanical advantage for both athletic function and in disease treatment.\textsuperscript{14}

During the stance phase, the third phalanx undergoes controlled displacement within the hoof capsule.\textsuperscript{6} During impact, the third phalanx displaces toward the sole and away from the wall in response to being loaded. As the foot progresses through the support phase and enters breakover, the sole reaches maximal compression and then acts as a fulcrum for the third phalanx. Consequently, the distal aspect of the third phalanx is displaced toward the wall and the proximal aspect of the bone continues to displace toward the sole due to the compliance of the digital cushion.\textsuperscript{6}

\textbf{General Overview of Laminitis}

Laminitis, termed “founder” in its chronic form, is defined as inflammation within the laminar structures.\textsuperscript{15} The disease can be crippling, excruciatingly painful, life-threatening,
and often ends the athletic career of the horses it affects.\textsuperscript{16} Multiple etiologies for laminitis have been proposed. Current research is concentrated on three main pathways, one involving a vascular/hemodynamic mechanism, one a toxic/metabolic/enzymatic mechanism, and finally, a traumatic/mechanical process.\textsuperscript{17} It is believed that the onset of laminitis is likely multi-factorial, and therefore, it is difficult to identify a single inciting mechanism of action. Many \textit{in vitro} experiments have provided potential pathways in the development of laminitis but they are difficult to corroborate \textit{in vivo}.\textsuperscript{17} While the exact etiology of laminitis remains elusive, the stages of laminitis can be classified into four phases. These include developmental, acute, subacute, and chronic.\textsuperscript{15}

The developmental stage of laminitis is the stage which precedes clinical detection. It is estimated the duration of this stage ranges from 24 to 60 hours making the window for intervention very small.\textsuperscript{15} The next stage is acute laminitis and covers the period from the onset of clinical signs to evidence of rotation and/or distal displacement (“sinking”) of the third phalanx. If mechanical failure of the foot does not occur, the acute phase is considered over by 72 hours after the onset of clinical signs and is followed by the subacute phase.\textsuperscript{15} The subacute phase is defined as the time required by the foot to completely heal from the inflammatory insult without experiencing digital collapse. The length of this stage is variable, but can last several months during which time the laminar structures are considerably weaker than their normal state.\textsuperscript{15} The final stage is the chronic stage which is initiated by digital collapse. Digital collapse is identified by rotation and/or vertical digital displacement of the third phalanx.\textsuperscript{15}

Laminitis usually occurs in the front feet which is logical given that horses bear approximately 60\% of their weight on their front limbs.\textsuperscript{18, 19, 20} However, laminitis of all four
feet is not uncommon, nor is laminitis of a single digit when it assumes the responsibility of weightbearing subsequent to an injury or lameness of the opposing limb.¹⁸,²¹

While the exact etiology of laminitis evades us, risk factors for laminitis have been identified. Horses aged 5-7 and 13-31 years, of the female gender, and of a breed other than Quarter Horse or Thoroughbred are more likely to develop acute laminitis. For chronic laminitis, horses were at a greater risk if they were between the ages of 10-14 years or 15-38 years, were a female, and were a breed other than Thoroughbred, with ponies being 9.1 times more likely to develop chronic laminitis than Thoroughbreds.²² Conversely, in an epidemiological study there were no associations between age, breed, sex, or weight and development of acute laminitis.²³ However, when chronic laminitis was examined females and older horses were more commonly affected. An early study linked testosterone and an increased risk of laminitis with geldings having fewer incidences of laminitis versus their intact male counterparts. That study also concluded that ponies were 4.3 times more likely to develop laminitis than all other equine species.²⁴ For horses with unilateral lameness that developed laminitis of a contralateral limb, duration of lameness, but not weight, was found to be a significant risk factor. Additionally, horses that developed contralateral limb laminitis were more likely to be euthanized than their matched controls.²¹ In horses diagnosed with duodenitis/proximal jejunitis at a university hospital, those weighing more than 550kg and horses having hemorrhagic gastric reflux at the time of presentation were twice as likely to develop laminitis.²⁵ Additional predisposing factors include other gastrointestinal diseases,²³,²⁶ endotoxemia and sepsis,¹⁸,²⁷ nutritional derangements (grain overload and “grass founder”),¹⁸,²⁸ retained placenta,¹⁸,²⁸ direct digital trauma,²⁸ obesity¹⁸, and endocrinopathies.¹⁸,²⁹
Economically, laminitis has a substantial impact and has afflicted the equine population for centuries. The cost of lameness (including laminitis) in 1998 was estimated at $678 million with 110 days of lost use per lameness event. More recent data indicates that in 2007, nearly 200,000 horses were diagnosed with laminitis in the United States. According to the United States Department of Agriculture’s National Animal Health Monitoring Service, 13% of all horse facilities in the United States reported a case of laminitis on their premise within the previous 12 months. Given these economic consequences and the lack of an identified etiology despite the efforts of prominent researchers, the need for continued investigation is clear. This is supported by the United States Department of Agriculture’s priority funding of laminitis research and the inception of a laminitis fund named in honor of the 2006 Kentucky Derby winner, Barbaro, at the University of Pennsylvania’s New Bolton Center after he succumbed to laminitis in 2007.

**Biomechanical Implications of Laminitis**

In the acute phase of laminitis, the laminae undergo microscopic changes that alter their biomechanical function. The initial histopathological change observed following lameness detection is vascular endothelial cell swelling followed by erythrocyte congestion and occlusion of capillaries by 8 hours. Leukocyte migration to the perivascular tissues follows and initiates the movement of inflammatory cells into the epidermal tissues. By 24 hours, microvascular thrombi and marked edema have occurred with hemorrhage appearing in the primary dermal laminae by 72 hours. Cellular response to the ischemic injury results in cell edema, vacuolization, nuclear swelling and pyknosis. This causes a distortion of the laminae defined as an initial thinning and lengthening of the laminae followed by reduction,
flattening, and detachment of the basement membrane. The basement membrane is critical for laminar attachment and the loss of its integrity leads to destabilization of the foot resulting in mechanical breakdown. In another etiologic theory of laminitis, matrix metalloproeinases (MMP’s) are responsible for basement membrane pathology.

During stance, the laminae withstand both tensile and shear forces. When loss of laminar attachment occurs, the third phalanx effectively moves independent of the hoof capsule and the main force acting on the bone is the tensile force of the deep digital flexor tendon. When the dorsal laminae are predominantly damaged to the point that they are no longer able to counter the force of the deep digital flexor tendon, rotational displacement about the distal interphalangeal joint occurs. In a study of ponies with naturally occurring chronic laminitis and 6°-13° of phalangeal rotation, the force exerted by the deep digital flexor tendon was significantly less than that of control ponies as calculated by the method of inverse dynamics. The force from the deep digital flexor tendon did not reach normal levels until the end of stance phase. However, when damage has occurred to the laminae circumferentially, shear forces resulting from weightbearing cause the third phalanx to displace vertically. In these situations much of the responsibility for stabilizing the third phalanx shifts to the sole and is seen as an increase in the compressive force applied by the displaced third phalanx. Clinically, this can be seen as a flat, or even convex, sole. In severe cases, the tip of the third phalanx will prolapse through the sole. A study of the laminar junction collected from two groups of horses with chronic laminitis, “treatable” and “non-treatable”, were compared to that of normal horses. In the “treatable” classification, the strength of the laminar junction was 60% of normal values. However in the horses classified
as “non-treatable”, those that had been refractory to treatment for six months, the strength of the laminar junction was only 42% of normal.\textsuperscript{42}

The prognosis is generally poor for horses that experience rotational displacement and grave for those that have distal displacement of the third phalanx.\textsuperscript{18,35,43} In one study, horses with less than 5.5° of rotation returned to athletic performance, but those with more than 11.5° of rotation did not.\textsuperscript{44} Conversely, a subsequent study revealed that radiographic assessment of rotation did not correlate with outcome and that the degree of lameness was a more accurate predictor of outcome.\textsuperscript{45} While the exact origin of pain in laminitis is not understood, it can be reasonably concluded that the degree of pain is likely proportional to the severity of laminar damage.\textsuperscript{18,43} Another predictor of outcome may be the manner and speed in which the animal responds to treatment. Because of the many factors involved in case progression (i.e. how long the patient has been experiencing laminitis prior to treatment, how many and which treatments have been attempted, etc.) a solid time frame in which recovery is expected cannot be given. Each case must be handled individually. However, cases refractory to treatment will generally have a worse outcome.\textsuperscript{18}

**Overall Goal**

Given the plethora of often conflicting empirical information regarding the treatment of laminitis, together with a lack of understanding of the cellular mechanisms that cause laminitis and the realization that there may be many different pathways resulting in the disease that work alone or in concert with one another, one objective of this masters program was to become educated in the current understanding of the disease process. However, the overall goal was to identify areas where biomechanical assessment is lacking that
consequently provide an opportunity for research and contribution of scientific evidence leading to the successful treatment of the disease.

References


CHAPTER 2. REVIEW OF LITERATURE RELEVANT TO PREVENTION AND TREATMENT

Current Therapies for Laminitis Prevention

The best manner in which to treat laminitis is to prevent it altogether. While this statement seems logical, without an accurate etiology, prevention has proven to be very difficult. Further compounding this fact is the understanding that a lone etiology likely is not adequate to describe all situations of laminitis. At this time, prevention is mainly directed at addressing known predisposing factors with the hope that it will prevent laminitis from occurring. Prevention with respect to the biomechanics of some of the most common predisposing factors will be addressed. Many of these preventative measures are also used in the treatment of acute and chronic laminitis and further exploration of the biomechanical benefits of these treatments will be addressed in the following section on laminitis treatment.

Support limb laminitis occurs in a limb that has assumed the majority of weightbearing when its opposing limb has an injury or other painful or neurologic condition precluding normal weightbearing. In this situation, clinical signs usually appear between 2 and 5 weeks following a shift in weightbearing.\(^1\) It has been shown that the weight placed on a single forelimb increases from 28% to 54% of body weight during unilateral weightbearing. This change in weightbearing causes a significant decrease in total blood flow to the foot.\(^2\) Measures should be taken to prevent contralateral laminitis because if treatment is delayed until clinical signs develop, the result can be catastrophic.\(^1,3\) The best method of prevention in this case is to address the inciting cause of the lameness to encourage normal
weightbearing of the ipsilateral limb. This is important because it has been shown that the most important risk factor in the development of support limb laminitis is the length of increased weightbearing by the contralateral limb.\textsuperscript{4} Biomechanically, prevention of support limb laminitis usually occurs in the form of measures to encourage weight loss, recruit the sole and frog to assume weightbearing responsibility, and decrease the moment arm about the distal interphalangeal joint (move the center of pressure palmarly).\textsuperscript{1} Means by which to do this include application of frog support, encouraging the horse to lie down, beveling or rolling the toe, placing the horse in soft sand, and temporary use of a full body sling.\textsuperscript{1,5}

For laminitis secondary to systemic disease (namely colitis, enteritis, endotoxemia, metritis, and generalized sepsis), prevention mainly lies in treatment and correction of the underlying disease while applying supportive treatment to the feet. Usually attention is paid to all four feet rather than just the forelimbs as whatever constitutes the triggering mechanism is likely carried to the feet by the bloodstream making it plausible that all four feet will be affected.\textsuperscript{6} Recently, the use of distal limb cryotherapy has returned promising results in the prevention of acute laminitis when used in the developmental stage.\textsuperscript{7} The mechanism by which cryotherapy is effective is not fully known, but it is hypothesized that its success can be attributed to one or both of the following: potent vasoconstriction causing the prevention of systemic trigger factors from reaching the foot and/or the induction of a hypometabolic state within the laminar cells making them more resistant to the effect of trigger factors.\textsuperscript{7,8}

Mechanical support to the foot includes recruiting the sole and frog to assist with weightbearing and decreasing the pull of the deep digital flexor tendon on the third phalanx by a number of different methods that will be discussed in the treatment section. Other pharmacologic therapies outside the scope of this thesis include anti-endotoxic, low-dose
administration of flunixin meglumine and polymixin B, non-steroidal anti-inflammatory therapy, vasodilator administration (i.e. acepromazine and nitroglycerin), anticoagulant therapy, administration of oxygen free radical scavengers (DMSO), and hemorrhheologic agents (Pentoxifylline), supportive fluid therapy, and other amino acid supplementation.\textsuperscript{9,10,11,12}

**Current Treatment of Laminitis**

Many of the therapies introduced in the section on prevention are also applicable to treatment after clinical signs have developed. While noting that pharmacologic intervention is very important, the main focus here will be placed on the biomechanical effects of different treatment regimens and the scientific evidence of their efficacy.

As outlined previously, the main goals of laminitis treatment are to remove the inciting cause, minimize pain and suffering, prevent or minimize permanent damage to the laminae, and prevent or reduce the amount of mechanical collapse. Various pharmacologic, biomechanical, and surgical mechanisms are used to achieve these goals.\textsuperscript{3,12} Addressing the inciting cause usually involves medical support and management, is dependent on the predisposing factor, and will not be covered here. The minimization of pain and suffering also has a pharmacologic basis, but efforts to manage the biomechanical deficiencies of laminitis usually have an effect on the patient’s comfort level as well.

Attempts to minimize permanent damage to the laminae come in many forms. It is generally accepted that recruiting the sole and/or frog to disperse the load placed on the dorsal hoof wall is desirable. The importance of this practice is emphasized by a study in which the load exerted on the front limbs of horses experiencing acute laminitis was not
different than that experienced prior to induction of laminitis via carbohydrate overload. Load was not different until after phalangeal displacement had occurred.\textsuperscript{13} However, the mechanism by which this is accomplished is not as straightforward. There is much anecdotal evidence to support the use of different methods, but scientific proof of efficacy for many treatments is lacking. External methods of frog support are believed to add stability and support to the third phalanx by decreasing pressure normally placed on the wall and laminae. This may thereby decrease pain and, in theory, prevent rotational displacement of the third phalanx. Caution should be advised because too much rigid support may be counterproductive, further compromising blood flow to the sole via compression.\textsuperscript{12} There are numerous methods of applying external frog support described in the literature. One is the temporary application of roll gauze to the frog with tape. While certain texts advocate its placement over the entire frog,\textsuperscript{12,14} others recommend placing it only on the caudal third of the frog\textsuperscript{3} and the gauze characteristics are not addressed (porosity, size of roll, duration of placement, etc.). A commercial frog support, the Lily Pad®, is available for use as an emergency aid and is marketed as being able to “offer the painful foot a resilient cushion support as well as protection, slight heel elevation and the benefit of slightly reduced breakover.”\textsuperscript{15} However, no scientific data is available to substantiate these claims. A study on the effect of Lily Pads® on the level of pain in horses with naturally occurring chronic laminitis concluded that their application did not decrease pain level. Additionally, horses were more comfortable following removal of the pad.\textsuperscript{16} The use of Styrofoam® placed on the bottom of the foot is another method used to provide frog, and in addition, sole support. Commercial foam pads are marketed as part of the Equine Digital Support System (EDSS) or can easily be made by cutting out supports from a sheet of industrial insulation sheeting.
Many authors reference the use of Styrofoam® in the developmental and acute stages of laminitis, but consistency among application methods is lacking. Additionally, while each author explains the purported benefits of Styrofoam®, no scientific evidence is presented.

More expensive, aggressive support in the form of special shoeing provides an additional option for sole and/or frog support. One of the more familiar shoes for treatment of laminitis is the heart bar shoe and it is available in adjustable and non-adjustable forms. The construction of the heart bar shoe includes a triangle-shaped plate forged onto the caudal aspect of the shoe that connects the heels and extends over the dimensions of the frog. It has followings of both loyal fans and devoted enemies likely due to the fact that the shoe in one person’s hands appears to be successful, while in another it is disastrous. When used improperly, the heart bar shoe can cause further damage to the frog and digital cushion, compromising healthy structures and increasing patient discomfort. Biomechanically, the heart bar is believed to decrease the strain on the laminar structures by providing additional weightbearing surface area to the foot, decrease the pressure placed on the solar plexus by the third phalanx thereby aiding digital perfusion, and prevent rotational displacement of the third phalanx. While there are several references for construction and application of a heart bar shoe, little scientific evidence is available to document the biomechanical benefit of such. One study reviewed the ability of the heart bar to reduce the amount of pain in chronically affected laminitic horses. It concluded that after 7 days, there was no improvement in the level of pain following placement of a heart bar shoe. On the other hand, when scintigraphy was used to assess digital perfusion, a significant increase in dorsal laminar perfusion was seen 12 weeks after application of a heart bar-egg bar shoe.
Additionally, horses were significantly less lame by 6 weeks following shoe placement. A notable drawback of that paper, however, is the lack of a control group, and it cannot be concluded that these horses progressed any differently than horses who did not have heart bar-egg bar shoes. No other concrete evidence to substantiate the biomechanical claims of the benefits of the heart bar shoe are published.

A reverse shoe with an adjustable frog support plate was evaluated \textit{in vitro} using normal cadaver limbs. Pressure applied to the frog just less than that causing patient discomfort as assessed prior to euthanasia significantly decreased total hoof wall weightbearing and caused palmar movement of the third phalanx up to loads of 1300N. Other methods of support utilizing various shoeing techniques include filling the shoe with a range of commercial epoxy formulations to recruit weight bearing from the sole and frog. However, the only study examining the benefits of a filler used a polyurethane-filled standard keg shoe applied to normal horses. The pressure exerted on the sole was not significantly different from a shoe without polyurethane until the horse was exposed to a deformable surface. This study has implications for the use of fillers in laminitic horses as it emphasizes the importance of the surface the horse is housed on during recovery and rehabilitation.

Another avenue used to minimize damage to the dorsal laminae includes the manipulation of breakover. It is a common belief that decreasing breakover, or decreasing the amount of time from heel-off to toe-off, provides a biomechanical advantage by decreasing the strain on the dorsal laminae through manipulation of the moment about the distal interphalangeal joint. There are many ways by which farriers and clinicians attempt to do this. One of these methods is by “rolling the toe”. This is easily accomplished by using a
hoof rasp to decrease the amount of toe contacting the ground or by placing a shoe with a roll at the toe (i.e. a “rolled toe” or “rocker toe” shoe). Many times this is done concurrently with squaring the toe. However, several studies have refuted the claim that squaring or rolling the toe actually decreases breakover. The first of these compared characteristics of breakover in horses shod with rocker toe, rolled toe, and square toe shoes with standard steel shoes. No difference in breakover was detected. In a similar study comparing rocker toe shoes with standard shoes in non-lame horses using both motion capture and force platform data, no difference was found in the length of breakover. While yet another study was in agreement with the duration of breakover being unchanged, a rolled toe shoe improved the characteristics of the unrollment pattern and decreased the peak loading of the distal limb during breakover leading to the conclusion that a rolled toe was, in fact, favorable. An evidence-based article addressing the question of whether or not rolled or squared toes affected the rate of breakover concluded that there was no scientific evidence to support the claim of improved breakover. Shoes with a squared toe, such as the Natural Balance shoe, also have self-purported claims of improving breakover. However, despite decreasing the moment arm when compared to toe-clip shoes, both Natural Balance and quarter-clip shoes failed to improve the peak moment about the distal interphalangeal joint countering the claim of the ability of those shoes to ease breakover.

Raising the heels is another reported method of protecting the damaged dorsal laminae from mechanical collapse, and is advocated by many authors. This is believed to decrease the stress on the laminae by decreasing the tensile stress placed on the third phalanx by the deep digital flexor tendon. An 18º heel wedge was reportedly successful in the majority of 29 cases in which it had been used on the basis of improvement
in the level of the horse’s comfort, but no biomechanical assessment was included. In a study utilizing a computer generated, model-based system based on kinematic and computed tomography data, peak strain in the deep digital flexor tendon was significantly decreased with a 6° heel elevation. A toe elevation resulted in a significant increase in peak strain of the deep digital flexor tendon. Other publications have documented an increase in the flexion angle of the distal interphalangeal joint with heel elevation and subsequently concluded a likely decrease in the strain of the deep digital flexor tendon, but no direct measurements of strain occurred. Another study using a finite element model of the equine hoof under a simulated 5° heel wedge resulted in decreased stresses within the hoof capsule. Finally, use of a hoof cast incorporating a 15-20° heel wedge was found to decrease strain by 59% on the dorsal hoof wall, but increase strain on the lateral hoof wall by 34%, using rosette strain gauges instrumented on cadaver specimens.

Surgical techniques have been employed as a salvage effort in severe cases of laminitis to prevent further rotational displacement of the third phalanx. This effectively removes the stress applied by the deep digital flexor tendon by performing a deep digital flexor tenotomy at mid-metacarpus or at the level of the pastern. Tenotomy of the accessory ligament of the deep digital flexor tendon has also been documented as an alternative to transection of the deep digital flexor tendon, but is not recommended due to the fact that it actually increases the peak load of the deep digital flexor tendon at certain stance times. The procedure of deep digital flexor tenotomy is usually reserved as a “last ditch” effort to prevent further rotational displacement of the third phalanx and is reserved for cases which are either refractory to other treatments or display a rapid progression of rotation. While the biomechanical effects have not been specifically studied, it is reasonable to expect
that by removing the pull of the deep digital flexor tendon, the stress placed on the damaged laminae is decreased. In one retrospective study following the procedure mid-pastern, 85% of horses returned to comfort in the follow up period.\textsuperscript{41} Similarly, a study of 35 cases showed that 77% of horses subjected to a tenotomy at the mid-metacarpus survived greater than 6 months, and 59% were still alive after 2 years. Obel grade lameness, degree of third phalangeal rotation, and horse body weight had no effect on outcome.\textsuperscript{40} Conversely, another study found that while pain relief followed the surgical procedure in the short term, only 30% of horses were alive at 6 months following surgery and that it may not alter outcome.\textsuperscript{42}

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CHAPTER 3. THE CENTER OF PRESSURE AND LOAD DISTRIBUTION IN THE FOREFEET OF NORMAL HORSES

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Abstract

Objective – To evaluate the ability of pads created from industrial foam insulation sheeting to redistribute loads placed on normal weight bearing structures of the foot and shift the location of the center of pressure palmarly. The overall goal was to assess the ability of foam pads to decrease the load on the laminar structures with the long-term goal of providing an evidence-based approach to treatment of acute laminitis.

Design - Self-controlled study with repeated measurements

Animals – 25 sound mature horses

Procedures – Both right and left forefeet from each horse were included in the study. Center of pressure data and solar load distribution patterns were recorded during a five second trial using a commercial pressure measurement system prior to placement of foam sole support. These measurements were repeated at 0, 6, 12, 24, and 48 hours after placement. Total
contact surface area, contact pressure, peak contact pressure, and center of force positions were then compared using a linear mixed model with repeated measurements.

**Results** – Total contact surface area was increased significantly at all time points while contact pressure and peak contact pressure were significantly decreased at all time points following application of foam sole supports. Immediately following application of sole support, the position of the center of pressure was significantly moved anteriorly. However, for the remaining time periods, there was a trend of palmar movement of the center of pressure and by 48 hours the center of pressure was significantly positioned more palmarly than prior to application of the foam supports.

**Conclusions and Clinical Relevance** - The results of this study support the use of foam sole supports as an effective, economical, and immediate treatment for acute laminitis.

**Introduction**

In the normal horse, sensitive lamina on the dorsal surface of the third phalanx interdigitate with the insensitive lamina on the deep surface of the hoof wall effectively attaching the third phalanx (coffin bone) to the hoof capsule. Laminitis has afflicted the equine population for centuries and continues to be a significant contributor to equine morbidity. In a recent study, 13% of all equine facilities in the United States reported a case of laminitis on their premise within the previous 12 months. The American Horse Council reports that nearly 200,000 animals per year are affected with laminitis. The disease can be crippling, life-threatening, elicit signs of severe pain, and often ends the athletic career of affected horses. Although difficult to accurately quantify, the ramifications of lameness and
laminitis on the horse industry are substantial. The economic cost of lameness in 1998 was estimated at $678 million with 110 days of lost use per lameness event.\(^7\)

Multiple etiologies for laminitis have been proposed and can be categorized into three mechanistic processes: 1) Those involving a vascular/hemodynamic mechanism; 2) a toxic/metabolic/enzymatic mechanism, and 3) a traumatic/mechanical process.\(^8\) It is believed that the onset of laminitis is likely multi-factorial, and therefore, it is difficult to identify a single mechanism of action. Many \textit{in vitro} experiments have provided insight to potential pathways for the development of laminitis but they are difficult to confirm \textit{in vivo}.\(^8\) While the exact etiology of laminitis remains elusive, the stages of laminitis can be classified into four phases. These include developmental, acute, subacute, and chronic.\(^2\)

Treatment is dependant on the phase of laminitis. Acute laminitis should be considered an emergency as the opportunity for possible successful intervention is relatively short at 72 hours.\(^2,9\) Early recognition and institution of treatment may potentially prevent or minimize displacement of the coffin bone and change the course of the disease.\(^9\) Horses with radiographic signs of displacement of the third phalanx have a guarded prognosis for return to athletic soundness and even survival.\(^6\) There is considerable controversy regarding the best way to approach and treat laminitis in the acute phase.\(^10\) Many treatments have been proposed and are generally based on empirical evidence, clinician/farrier preference, and past successes. Often one treatment is attempted, and when that treatment fails to elicit an improvement, another is tried. Treatment of acute laminitis can be a frustrating obstacle for owners, farriers, and veterinarians alike. It is not possible to predict which cases will have catastrophic outcomes and which ones will improve with little intervention.\(^11\) At this time,
the goals of treatment of acute laminitis are mainly supportive – relieve pain, halt or slow progression of the disease, and enhance recovery.\textsuperscript{12}

Recent interest in utilizing an evidence-based approach to medicine highlights the need for high-quality studies to substantiate these treatments.\textsuperscript{13} Current treatments for laminitis include stall confinement, shoe removal, bedding the horse in sand or deep shavings, application of a supportive synthetic material to the sole to redistribute weight bearing over a larger surface, beveling the toe to decrease breakover, hoof wall resection, hoof wall grooving, and a number of different methods to elevate the heel.\textsuperscript{12} Additionally, administration of nitroglycerin with or without an endothelin receptor antagonist,\textsuperscript{14,15} therapeutic shoes and hoof casts\textsuperscript{9,16}, frog supports\textsuperscript{17}, vasodilator (i.e. Isoxsuprine and acepromazine) therapy\textsuperscript{18,19}, and prolonged limb cryotherapy\textsuperscript{20,21} have been utilized. Non-steroidal anti-inflammatory medications, hemorrheologic agents (i.e. Pentoxifylline) and dimethylsulfoxide (DMSO) have also been advocated.\textsuperscript{19,22}

This study evaluates the effect of the application of industrial foam insulation sheeting ("blue foam") to the sole of the foot. The popular belief is that the support offered by the foam redistributes the weight of the horse from mainly being borne by the hoof wall to include the entire bottom of the foot.\textsuperscript{10,17} This would then decrease primary weight bearing on the hoof wall and laminar structures and redistribute weight to the sole and frog. In addition, it may provide support to the digital cushion and tissues between the coffin bone and the sole. To this effect, prevention of laminar separation may be possible.

The purpose of this study was to evaluate the ability of foam sole supports to increase the weight bearing surface area of the foot, decrease contact pressure, move the center of pressure palmarly thereby decreasing the load exerted by the deep digital flexor tendon, and
validate its use as an effective means of minimizing load on the laminar structures with the long-term goal of providing an evidence-based approach to treatment of acute laminitis of the foot. We hypothesized that the weight bearing surface area in the forefeet of horses would be increased, the contact pressure decreased, and the center of pressure would be moved palmarly with placement of commercial blue foam.

**Materials and Methods**

Twenty five healthy, mature horses (mean age 11 years, range 3-25; mean weight 493kg, range 311-667) were used in this study. There were 10 Quarter Horses, 3 Paints, 2 Thoroughbreds, 2 Arabians, 2 Appaloosas, 2 Friesian crossbreds, 1 Haflinger, 1 Morgan, 1 Thoroughbred crossbred, and 1 Arabian crossbred. Each horse was required to have a history of regular foot care, currently be barefoot, and have had no previous history of laminitis. Prior to inclusion in the study each horse was determined to be healthy based on a normal physical examination including attitude, rectal temperature, pulse rate, respiratory rate, and digital pulses and be free of lameness. Physical inspection of each foot was used to identify and exclude horses with divergent growth rings, prolapsed soles, and defects at the coronary band. Radiographs were obtained of each front foot to confirm absence of previous laminitis (i.e. displacement of the third phalanx, third phalanx remodeling, etc.). Horses were housed in individual stalls with wood shaving bedding over rubber mats, allowed free access to water, and fed a grass/alfalfa mix hay twice daily. Daily monitoring of general attitude, feed intake, water intake, urination and defecation was performed. This study was approved by Iowa State University’s Institutional Animal Care and Use Committee.

*Study Design*
Due to the need for equal weightbearing on both front feet during each condition of the study it was necessary to employ a block design. Each front limb of all horses was subjected to two test conditions and served as its own control. In the first (control) condition each forefoot was thoroughly cleaned with a hoof pick and wire brush and positioned on a high-resolution pressure mat on a smooth, level, concrete surface. Each horse was allowed time to stand calmly and evenly. Care was taken to ensure each horse was standing squarely. Center of pressure data and solar load distribution patterns were then recorded during a five second trial at a sampling frequency of 100 Hz. If the horse moved during the sampling time, that trial was terminated and a new trial initiated. Following data collection of the control condition, a foam sole support was placed on each front foot initiating the treatment condition. The horse was then allowed to briefly bear weight on each foam support prior to positioning each foot again on the pressure mat for data collection at time 0. The horse was returned to its stall and data collection repeated at time points 6, 12, 24, and 48 hours. Calibration of the pressure mat occurred prior to data collection at each time period.

*Sole Supports*

Each foot was placed on a section of 3.8cm (1.5 inch) thick industrial foam closed cell insulation sheeting to obtain an outline of the hoof. The foot was then removed and the foam cut to match the perimeter of the hoof. A foot bandage to secure the foam to the sole was created from approximately 35cm strips of duct tape placed perpendicularly to each other until it was roughly 1.5 times the diameter of the foam cutout. The foam cutout was then placed on the center of the duct tape and positioned in contact with the sole of the foot. The duct tape was then folded proximally to provide adherence to the hoof wall securing the foam. Wraps of tape circumferentially around the hoof wall were then used to further secure
the duct tape. A layer of elastic tape was used proximally to prevent shavings from interfering with the duct tape. (Figure 1) If the horse did not bear weight squarely on the foam support as determined by visual inspection, (i.e. the support slipped during initial weight bearing) a new foam cutout was created and replaced.

**Solar Load Distribution and Center of Pressure Measurements**

A high-resolution commercial pressure measuring system connected to a computer was used to record pressure distribution patterns for each foot. The thin-film (0.18mm) tactile pressure mat sensor is composed of 8448 evenly distributed individual pressure sensing elements arranged in rows and columns across the sensor surface with a spatial resolution of 3.9 sensing elements per cm$^2$. The dimension of each sensing element is 0.508 cm x 0.508 cm with each element separated by 0.508 cm. A custom software package calculated the total contact surface area, total contact pressure, and peak contact pressure for each frame of data. Center of pressure was output as x and y coordinates on the pressure mat grid. A consistent coordinate system was created with the horizontal x-axis defined by a line connecting the heels. This was done for the purpose of standardizing the center of pressure location allowing for accurate comparison. The axis origin was located at the medial heel of the right foot and lateral heel of the left foot. From the data obtained, the initial x and y coordinates for the center of pressure were determined by the investigators (JAS and TRD) and converted to the standard coordinate system ($x'$ and $y'$) using the following formulas. The Greek symbol $\alpha$ denotes the calculated angle of rotation. (Figure 2)

$$x' = x\cos\alpha + y\sin\alpha$$

$$y' = -x\sin\alpha + y\cos\alpha$$
Center of pressure was defined as the mathematical location of the point of action of the ground reaction force on the foot. The standardized y coordinate was used as the response in statistical analysis. Contact pressure was defined as the total pressure encountered by the loaded sensing elements. Peak contact pressure was defined as the pressure of the single sensing element experiencing the largest amount of load. Total contact surface area was defined as the surface area of all loaded sensing elements.

**Statistical Analysis**

For each response, data were analyzed using a linear mixed model with repeated measurements. Treatment and Time (nested within Treatment) were considered as fixed effects, while Horse and its interactions with the fixed effects were considered as random effects. Foot was the subject of repeated measurements. Three structures were considered for the covariance matrix of the repeated measurements from the same subject: variance components, compound symmetry and unstructured. Akaike's information criterion (AIC) was used as a goodness-of-fit statistic for model selection: The covariance structure with the smallest AIC was chosen for the report. Analysis was performed using the MIXED procedure in SAS software. F-tests with Kenward and Roger adjustment to degrees of freedom were applied for significance of the fixed effects. If a fixed effect was found to be significant, post-hoc Tukey's t-tests were applied for pairwise comparisons between group means. Statistical significance was set at a level of 0.05.

**Results**

The foam sole supports were well tolerated by all horses and all supports remained in place during the study interval. For total surface contact area, contact pressure, and center of pressure location, the unstructured covariance matrix structure gave the best fit to data. For
peak contact pressure, a variance component covariance structure gave the best fit. For total surface contact area, both Treatment and Time were found to be significant. Using Tukey’s adjustment for multiple comparisons, all pairwise differences between time periods (control, 0, 6, 12, 24, 48) were significant. (Figure 2) For contact pressure, both Treatment and Time were found to be significant. Using Tukey’s adjustment for multiple comparisons, differences between the control time and all other times were significant and differences between time 0 and all other times were significant. (Figure 3) For peak contact pressure both Treatment and Time were found to be significant. Using Tukey’s adjustment for multiple comparisons, differences between the control time and all other times (0, 6, 12, 24, and 48) were significant and differences between time 0 and all other times (6, 12, 24, 48) were significant. (Figure 4) For center of pressure location Time was found to be significant. At times 0 and 6, the center of pressure was significantly shifted anteriorly from the control location with a subsequent trend of palmar movement after time 0. By 48 hours a significant shift of center of pressure in the palmar direction from the control location was detected. (Figure 5)

**Discussion**

The results of this study indicate the use of foam sole support increases the weight bearing surface contact area, decreases total contact pressure, decreases peak contact pressure, and shifts the center of pressure to the palmar aspect of the foot for at least 48 hours. Recruitment of a larger surface area on the sole of the foot reduces the weight bearing demand on the hoof wall and laminae. While the importance of recruiting the sole and frog to distribute the load placed on the foot during episodes of developmental and acute laminitis is recognized by the majority of practitioners and farriers, the means by which to do so are
not as straightforward. This is supported by the myriad of home-made and commercially available products with varying degrees of evidence that weight bearing is altered. Foam supports have been advocated by many practicing veterinarians and farriers, but scientific evidence for its use has previously been unavailable.

Our study shows that total surface contact area is significantly increased up to 48 hours after placement of foam sole supports. However, it is important to note that while there was still a significant increase in surface area at 48 hours over the control condition, after time 0 there was a significant decrease in surface area at each time point compared to the previous time point likely due the conformability of the closed-cell industrial foam. Twelve hours after sole support placement 10 of 50 (20%) feet already had dimensions of varying size that were devoid of any weight bearing in the areas of the sole and frog that had previously borne weight. At 24 hours, 23 of 50 (46%) showed similar characteristics and by 48 hours this number increased to 42 of 50 (84%). By the end of the study 16 of the 50 foam sole supports (32%) were worn through exposing the toe of the foot. The authors recognize that this study was performed in normal ambulatory horses, some of whom spent considerable time walking about their stalls, and this may have been a contributory factor in foam wear. Yet, if practitioners are faced with an acutely laminitic horse that is reluctant to lay down and spends most of its time standing, the results of this study would be expected to apply.

In a study evaluating the effect of a polyurethane filled standard steel shoe on pressure distribution in normal feet, there was no difference in pressure distribution pattern or mean pressure between horses with standard shoes and those with polyurethane filled shoes when horses were on a non-deformable, concrete surface. Significance was found in both of
these variables, however, when horses stood on a deformable surface.\textsuperscript{27} Our horses were housed on concrete floors covered with rubber mats and wood shavings which may have had an effect on how the foam was compressed. The shavings could allow for further compression of the foam against the concave sole and frog. Consequently, when the horse is removed from the shavings, the concavity remains. During data collection the horses stood on the pressure mat on a level concrete surface without shavings between the mat and the foot. This could explain the areas devoid of weightbearing observed at 12, 24, and 48 hours.

As the weight of the horse molded the foam to the contours of the foot, the contact pressure steadily and significantly decreased until 6 hours after application. Since pressure is a measurement of force over area this result was not unexpected. However, after 6 hours, there was no further significant decrease in contact pressure. Likewise, the peak contact pressure decreased significantly following application of the supports and remained significantly decreased from the control condition throughout the study. But when compared to the peak pressure immediately following foam placement (Time 0), the peak pressures at the remaining time periods were significantly increased.

In the front feet, the center of pressure at mid-stance is usually located in the cranial medial quarter of the foot.\textsuperscript{30,31,32} However, center of pressure (also termed ‘center of force’) is dependent on leg and foot conformation, the manner in which the horse is standing over its body mass, position of the foot in the stance phase, and shoeing and trimming methods.\textsuperscript{27,30,32,33,34,35} For these reasons, special care was taken to ensure horses were standing squarely and comfortably before recording any data. A palmar shift in the center of pressure decreases the moment arm acting at the distal interphalangeal joint, thereby decreasing the stress on the third phalanx from the deep digital flexor tendon.\textsuperscript{36} This is an
important concept in the acute phase of laminitis where minimizing the pull of the deep digital flexor tendon may be desirable. The significant anterior movement of the center of pressure at the time of foam placement was not expected. The center of pressure did not return to the control location until between 12 and 24 hours and was not significantly shifted palmarly until 48 hours after wear. It is not likely that the foam cutout was physically weaker at the toe as it is uniformly constructed and the anterior movement was not isolated to just a few horses. It could be explained as a reaction to an unfamiliar weight bearing surface and exposure to a new situation by the horses as a change in their stance. The clinical significance of this finding, however, would indicate that it would be desirable to maintain a foam support for at least 48 hours to benefit from a palmar shift in center of pressure.

The method of treatment of acute laminitis is a controversial topic. Even consensus on the appropriate use of foam supports is not established. Some practitioners advocate the use of two layers of foam rather than one. Some replace the support altogether at 24 hours. Agreement on the appropriate thickness of the foam is not recognized. According to our data, foam supports provide a significant increase in weightbearing surface area and a significant decrease in contact pressure for 48 hours and a significant palmar movement of the center of pressure between 24 and 48 hours. While recognizing the use of normal horses as being a limitation of this study, the scientific evidence presented here suggests the use of foam sole supports as described holds promise in the treatment of early laminitis. Using the results of this study, further investigation into this economical and effective treatment can continue. Additionally, further studies of this treatment in a population of acutely laminitic horses are indicated.
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Figure 2-1. Foam pads immediately following placement. Each horse was allowed time to stand calmly and evenly. Care was taken to ensure each horse was standing squarely and looking straight ahead during data collection.

Figure 2-2. A consistent coordinate system was created with the horizontal x-axis defined by a line connecting the heels. This was done for the purpose of standardizing the center of pressure location allowing for accurate comparison. The axis origin was located at the medial heel of the right foot and lateral heel of the left foot. From the data obtained, the initial x and y coordinates for the center of pressure were determined by the investigators (JAS and TRD) and converted to the standard coordinate system (x′ and y′). α denotes the calculated angle of rotation.
Figure 2-3. Mean ± SD of total surface contact area over time. Significant differences between all time periods were detected. a-f Different letters indicate a significant (p<0.05) difference between time points.
Figure 2-4. Mean ± SD total contact pressure over time. A significant difference between the control time and all other times and a significant difference between time 0 and all other times were detected. \(^{a\,c}\) Different letters indicate a significant \((p<0.05)\) difference between time points.
Figure 2-5. Mean ± SD of peak contact pressure over time. Significant differences between the control time and all other times and significant differences between time 0 and all other times were detected. Different letters indicate a significant (p<0.05) difference between time points.
Figure 2-6. Mean ± SD of the least squares means of the position of the center of pressure on the dorsal-palmar axis of the foot over time. Significant differences between the control condition and time 0 and between control and 48 hours were detected. Time points not having a common letter are significantly (p<0.05) different.
CHAPTER 4. General Conclusion

General Discussion

There is a general paucity in the scientific evidence for many current treatments for laminitis. Our documentation of the benefit of foam sole supports fills only a small void, but provides an important stepping stone for further assessment of approaches to treatment. We know that a major factor in phalangeal displacement begins with disruption of the basement membrane of the laminae. Pharmacologic intervention will likely take precedence in preventing displacement at this level. Before that can occur, however, a distinct etiologic mechanism must be identified. In the meantime, a biomechanical approach to treatment and prevention will be important. It is conceivable that more than one approach may be more beneficial than one alone. Raising the heels to decrease load from the deep digital flexor tendon while providing solar support appears promising. Additionally, recruiting the sole and/or frog to bear weight and decrease load on the hoof wall and laminae seems rational in the short developmental and acute phases.

Direction of Future Studies

Our study assessing a foam sole support requires validation in clinical cases and is the next logical step in continuation of the work presented. Specific questions that need to be addressed include how to best minimize the force of the deep digital flexor tendon on the third phalanx and how to best manage the foot to achieve less force on the laminae while still
providing an owner with a reasonable outcome. While the obvious need for identification of the pathologic mechanism responsible for laminitis is inherent, biomechanical assessment of current treatment strategies is equally important. Providing scientific evidence to both support and refute laminitis treatments serves to unite practitioners and farriers with the ultimate goal of benefiting the horse. Future studies should focus on improving our understanding of the biomechanical consequences of laminitis, so accurate assessment of treatment can follow. Additionally, research should identify the effect of different treatment mechanisms on the forces acting on the laminar junction. Development of strain gauges that can be inserted through the hoof wall in a minimally-invasive manner to accurately detect strain at the laminar junction could provide important information about the effect of different treatment mechanisms. The potential of finite element modeling in predicting loads under simulated conditions lends promise as an alternative to inducing laminitis in normal horses. However, current models of the horse foot will require refinement before being able to use them accurately.\(^{3,4}\)

References

