

Comparison of Gait Characteristics for Horses With No Shoes, With Aluminum Shoes, and With
Steel Shoes

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Abstract

Many equine athletes wear metal shoes to provide protection, support, and traction. The two most common horseshoe materials are steel and aluminum. In some equine disciplines, shoes are removed (barefoot) or changed to a lighter shoe material (aluminum) during an equestrian event to achieve perceived advantages such as more aesthetic limb flight. Shoeing has an impact on performance and health of athletic horses. Thus, the impact of shoe characteristics on performance and welfare of sport horses is coming under increased scrutiny. However, objective information regarding the effects of shoeing on gait characteristics of performance and show horses is scant and there is little scientific evidence to guide decisions about shoeing and its impact on competition fairness and animal welfare. Commonly utilized body-mounted inertial sensor systems can be used to measure symmetry of head and pelvic movement, but do not directly evaluate other gait characteristics important to subjective judging. More recently, triaxial hoof-mounted inertial sensor systems have been used to measure stride characteristics in horses. These sensors yield information about hoof orientation in all three axes and allow more detailed analysis compared to other systems. This technology could be a useful tool to measure changes in gaits of horses under various hoof shoeing conditions and yield information to help guide welfare policy. The objective of our study was to determine differences in gait characteristics pertinent to subjective judging of horses at the trot under various hoof shoeing conditions (barefoot, aluminum shoes, and steel shoes). We hypothesized that hoof shoeing conditions would not affect symmetry of head and pelvic movements as detected with body-mounted inertial sensors or mediolateral hoof deviation during swing phase, stride length, and duration of stride phases detected with hoof-mounted IMUs. We also hypothesized that lower foot-shoe weight (barefoot or aluminum shoes) would result in lower early and late swing phase hoof flight height (arc height a and arc height b, respectively) as detected with hoof-mounted IMUs. A prospective crossover design was used.

Twelve healthy, adult, client-owned horses without lameness, hoof or limb abnormalities, or positive response to hoof testers were included. The horses included multiple breeds (Quarter Horse, Thoroughbred, Warmblood, and mixed breed) and were used for several different disciplines (western, eventing, and pleasure riding). Horses were evaluated with body- and hoof-mounted inertial sensors at a trot on firm (asphalt) and soft (sand) surfaces. Evaluations were performed in the following order: with existing shoes (baseline), no shoes (barefoot), aluminum shoes and steel shoes. Hoof balance radiographs (lateromedial and dorsopalmar) were obtained at baseline, barefoot, and after each shoe change prior to data collection. All trimming and shoeing were performed by the same Certified Journeyman Farrier. Data were collected using body-mounted inertial sensors (Lameness Locator, Equinosis, Columbia, MO) and hoof-mounted triaxial inertial sensors (Hoofbeats, Werkman Black Tolbert Tolbert, Netherlands). Data collected included Q score (measure of head and pelvic asymmetry), hoof arc height and lateral deviation, stride length, and mid-stance, breakover, swing, and landing stride phase times. Data were compared among shoeing conditions and surfaces (asphalt and soft footing) and analyzed for statistical relevance. Normally distributed data was analyzed using a mixed model ANOVA. Skewed variables were analyzed using the least squares means and Tukey-Kramer to adjust for multiple comparisons. Significance was set as $P < 0.05$.

Significant differences in arc height between aluminum and steel shoes were detected. Aluminum arc height was significantly smaller in both right and left forelimbs ($P < 0.0001$) in soft ($P < 0.0001$) and hard ($P = 0.0009$) footing compared to steel shoes. Barefoot arc height was significantly smaller on soft footing in both right ($P = 0.0297$) and left ($P = 0.0006$) forelimbs compared to steel shoes. Hoof arc height was not significantly different between barefoot conditions and aluminum shoes. No significant differences in Q score, lateral deviation, stride length, and mid-stance, breakover, swing, and landing stride phase times were observed. Limitations of the study included the small sample size, and the variation in horse use and breed. Future research should focus on horses of a single breed and those that are actively competing at high level hunters where the practice of changing shoeing conditions for perceived benefit is more relevant.

The null hypothesis that there is no correlation between shoeing conditions and hoof arc can be rejected; there are significant differences in the foot arc height for horses shod with aluminum

shoes compared to steel shoes, and horses shod with steel shoes in comparison to barefoot conditions. Aluminum shoes did not change foot arc height compared with barefoot conditions and thus do not support the practice of removing aluminum shoes to compete barefoot in certain phases of competition as no significant differences in gait characteristics were observed. The significant findings of this study suggest further investigation is warranted to determine the impact this has on competition fairness and animal welfare.

Comparison of Gait Characteristics for Horses With No Shoes, With Aluminum Shoes, and With Steel Shoes

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General Audience Abstract

Equine athletes present a unique facet of competitive sport which, due to its breadth and popularity, has developed a wide scope of regulations and oversight to protect sportsmanship, fairness, and ultimately the welfare of the equine athletes who remain the center and foundation of the field. Guidelines and regulations develop out of necessity and ideally under rigorous scientific investigation.

Most equine athletes are outfitted with metal shoes, primarily fashioned from steel or aluminum, to provide support and traction to the foot. Shoeing is a widely accepted practice as routine care and maintenance for domesticated horses. Throughout history, it has been observed that the addition of horseshoes has improved the utility and longevity of the working horse. Modern scientific understanding and investigation has discovered quantifiable effects of horseshoes, and their added weight, on the gait of the horse. This has led to attempts at altering shoe characteristics to improve both the wellbeing and athletic performance of horses. One train of thought has led to the practice of removing shoes in the middle of an equine competition to alter equine gait such that it may appear more aesthetically pleasing (i.e. lower arc of flight, longer stride) to a subjective judge. At this time, not enough scientific evidence exists to provide guidelines related to the shoes and mid-competition changing of shoes on athletic horses. The following research seeks to provide quantifiable evidence that changing the shoes on a horse will have measurable changes in hoof flight and therefore, may have implications for the ethics and welfare surrounding equine athletes in a competition setting. Alterations to the limb flight of horses were measured using hoof-mounted sensors and found to be significant when comparing the gait of horses wearing no shoes, steel shoes, and aluminum shoes.

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To Dr. Santonastaso, I owe her infectious enthusiasm for equine podiatry and her insight to streamline our data collection protocols. To Dr. Trager, I am grateful for her wealth of sport horse knowledge and sports medicine perspective. To Dr. Bogers, I could not have navigated through the darkness of scientific writing, organization, and manuscript submission; this project may never have been completed without her. Similarly, my research and I would have no meaning without Dr. Werre. I am eternally grateful for his education in veterinary statistics as part of my master's degree, and for his contributions to the manuscript. He coached me to produce a data set I had not previously thought I was capable of.

Ultimately, I must dedicate this thesis to Dr. Byron, my research advisor, our principal investigator, and the mentor of a lifetime. I thank him for his contributions, not only to my masters program and research project, which are immense, but for all the training I have received from him during my surgical residency; for always making time to hear my thoughts and suggestions; for knowing when to step in and when to step back; and for endeavoring to make the large animal clinical department the best it can possibly be. I have treasured the opportunity to work with and for Dr. Byron.

Finally, I extend love and gratitude to my barn family and my real family, especially my mom, for supporting my long journey towards this achievement. And to every horse that has ever taught me something, in the saddle, in the surgery suite, and in my heart.

Attributions

The research and analysis performed in *Chapter 3: Comparison of gait characteristics for horses without shoes, with steel shoes, and with aluminum shoes* was only made possible by extensive contributions from my colleagues and committee. All contributors are also co-authors on the manuscript. The following is a brief description of their contributions.

Christopher Byron, DVM, MS, DACVS is an Associate Professor of Large Animal Surgery and the department head of Large Animal Clinical Sciences at the Virginia-Maryland College of Veterinary Medicine. Dr. Byron is responsible for conceptualization, methodology, resource procurement, review and editing of the manuscript, supervision of data collection, project administration, and funding acquisition.

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Chapter 1: Introduction

Thesis Organization

This thesis is formatted around a journal manuscript and an original research experiment as the central portion of the document. The publication is entitled “Comparison of gait characteristics for horses without shoes, with steel shoes, and with aluminum shoes” and contains its own introduction, materials and methods, results, discussion, and references. The following provides a brief overview of the research topic. The literature review is an expansion of the introduction to the manuscript and provides a summary of pertinent literature background information.

Introduction

Since the first nomads herded wild *Equus feris caballus* in Kazakhstan, Eastern Europe, and across Asia, 4400-4800 B.C.E., the history of horses has been intimately intertwined with the rise and fall of civilizations for the last 6,000 years [1]. Debbie Busby suggests in *The Horse; A Natural History*, “of all the animals to have been domesticated, the horse is the most significant to our history” [1]. Although archeological evidence cannot conclude whether horses were first used for riding or driving, domesticated horses were transitioned from food source to companion and pack animal in Kazakhstan around 3500 BCE and their use and athleticism continued to evolve from there to modern day [1].

Not long after horses were domesticated, their human masters observed horses’ need for intensive hoof care. As early as 400BCE, Roman horses were outfitted with “hipposandals” [2]. Concurrently, woven shoes made from medicinal plants were applied to horse hooves in Asia [2]. Horseshoes fashioned from metal and nailed to the sole of the hoof were introduced in the first and second centuries, perhaps first employed by the Celts [2]. Although early shoes were

made from copper, over time, and with the metamorphosis of the field of farriery, stronger metals and standardized shoes have proven to stand the test of time.

With the advent of the steam engine, automobiles, and other technologies, horses are rarely employed in the fields of transportation, agriculture or warfare in the developed world. Today, horses often represent a luxury and elite compartment of society and are primarily bred and trained for their competitive athleticism alone.

Most equine athletes wear metal shoes to provide protection against the surface, support the foot, and aid traction. Modern research on equine gait and performance has evolved with modern technology to focus on the movement of the distal limb, kinematics, and the forces acting on the hoof and ground, kinetics, to quantify characteristics of stride. Collected data has proven changes in shoe type, style and application have significant effects on kinetics and kinematics acting on the foot during exercise as well as incidence of injury and strain in the limb and foot [3] [4] [5]. This information has fuelled both equestrians and veterinary researchers to determine methods of shoeing and trimming to maximize the athletic and competitive potential of the horse.

Historic data collection methods focused on kinetics. As a result, the wealth of knowledge on the effect of shoeing on equine gait is related to phases of stride where the hoof is in contact with the ground, also known as the stance phase. However, the moments of stance phase have minimal effect on the aesthetic quality of gait. Conversely, the swing phase of stride is used to assess the quality of movement and is a function of the kinematics of the distal limb. Kinematics related to range of motion through the joints of the forelimb and vertical displacement of the horse and limb have become the focus of research and the goal of modern technology measuring characteristics of gait. Individual horses show the most variation in

expressiveness and athleticism during the swing phase of stride [6] and yet there is a void in data quantifying and evaluating the arc made by the hoof during the swing phase of stride or how it can be manipulated with horseshoes to optimize the aesthetic quality.

Inertial measuring units (IMU) are body mounted sensors coupled with computer software which present a novel approach to quantifying characteristics of gait. The HoofBeats hoof-mounted IMU system obtained for the following research can yield information about hoof orientation in all three axes (x,y,z). The software generates a more detailed analysis of the kinematics of the distal limb and produces a map of hoof flight. It was hypothesized that the HoofBeats Gait Mapping System may help explain the effect of horseshoeing practices on the characteristics of limb flight.

The impact of shoe characteristics on performance and welfare of sport horses is under increased scrutiny, especially at the upper levels of competition [7]. Equine athletes shod in either steel or aluminum shoes are having the shoes pulled between classes under the assumption that a barefoot horse will likely have a more aesthetically pleasing gait and may have an advantage over the other competitors. Regulation changes have been proposed to the United States Hunter Jumper Association (USHJA) in an effort to prevent shoeing changes during competition and classify this practice as ‘performance enhancing’ [7]. Regulation changes were rejected on the basis that there was no scientific data to support or refute any competitive advantage or welfare concerns [7]. There remains a lack of objective information regarding the effects of horseshoes on gait characteristics and performance of show horses, and no scientific evidence exists to guide decisions about the impact of shoeing on potential competition outcomes and animal welfare. The overall objective of the following literature review, original thesis, and final comments is to amass and evaluate all the relevant literature on equine gait measurement to determine the current evidence available on the effects of horse shoes on the

kinematics of the distal limb, to present original research and the significant findings on the effect of shoe material on gait characteristics quantified using hoof-mounted IMUs, and to provide a commentary on the available information, old and new, regarding the future of equine gait research and the ethics and welfare of equine athletes.

References

1. The Horse A Natural History. Busby, D. and Rutland, C., eds. 2019: Princeton University Press. Princeton, NJ.
2. Scoda, A. Historic Horseshoes and Blacksmiths. 2025 [cited 2025; Available from: <https://sandiegoarchaeology.org/historic-horseshoes/>].
3. Hill A.E.; Gardner I.A.; Carpenter T.E.; Stover S.M. Effects of injury to the suspensory apparatus, exercise, and horseshoe characteristics on the risk of lateral condylar fracture and suspensory apparatus failure in forelimbs of Thoroughbred racehorses. *Am J Vet Res*, 2004(65): p.1508-1517.
4. Singer E.; Garcia T.; Stover S. Hoof position during limb loading affects dorsoproximal bone strains on the equine proximal phalanx. *J Biomech*, 2015. 48(10): p.1930-1936.
5. Kelleher M.E.; Burns T.D.; Werre S.R.; White NA. The Immediate Effect of Routine Hoof Trimming and Shoeing on Horses' Gait. *J Equine Vet Sci*, 2021. 102: p.103633.
6. Clayton H.M.; Hoyt D.F.; Wickler S.J.; Cogger E.A.; Lanovaz J.L. Hindlimb net joint energies during swing phase as a function of trotting velocity. *Equine Veterinary Journal*, 2002. 34(S34): p.363-367.
7. Loushin, K.B.M. Shoe-pulling remains legal and more action from USHJA annual meeting, in *The Chronicle of the Horse*. 2022: <https://www.chronofhorse.com/article/shoe-pulling-remains-legal-and-more-action-from-ushja-annual-meeting>.

Chapter 2: Literature Review

Anatomy and Physiology

The equine digit is a unique and specialized evolutionary adaptation able to withstand miraculous strain, store and convert immense forces of energy, and has developed a fascinating, yet sometimes fragile, form and function throughout history [1–7]. Descending from the small, three-toed *Hyracotherium*, horses have evolved to have a single, massive digit skeletally comprised of the third metacarpus and three phalanges (proximal, middle, and distal). The metacarpus, first, and second phalanges are typical long bone structures with an epiphysis, metaphysis and diaphysis with articulations at either end. The third phalanx is a specialized structure formed without a cortex or medullary cavity and instead traversed by several vascular channels funneling intricate blood supply to the digit and hoof [8]. It articulates at only one margin with both the second phalanx and distal sesamoid bone, given the name navicular bone. The navicular bone is a boat shaped structure with an articular surface contacting both the distal and second phalanx. The navicular bone also possesses an extensor surface on the palmar/plantar surface which contacts the soft tissues and plays an important role in extensor tendon function. [8]

The three distal joints of the digit are ginglymus joints, meaning they allow movement in only one plane. The middle interphalangeal joint has a minimal range of motion, while the range of motion at the distal interphalangeal joint is considerable. This joint often communicates with the navicular bursa on the flexor surface of the sesamoid bone, although there is evidence that this communication may be functional rather than physical, and flow of contrast has been observed passing into the navicular bursa from the distal interphalangeal joint, but not the other way around. [9]

There are no muscular structures surrounding the digit, thus the soft tissue coverage is reduced from that of the rest of the horse. However, the complexity of those soft tissue

structures is much greater than those covering the trunk. An extensive lattice of tendon and ligaments function to optimize the athletic ability and potential of the horse.

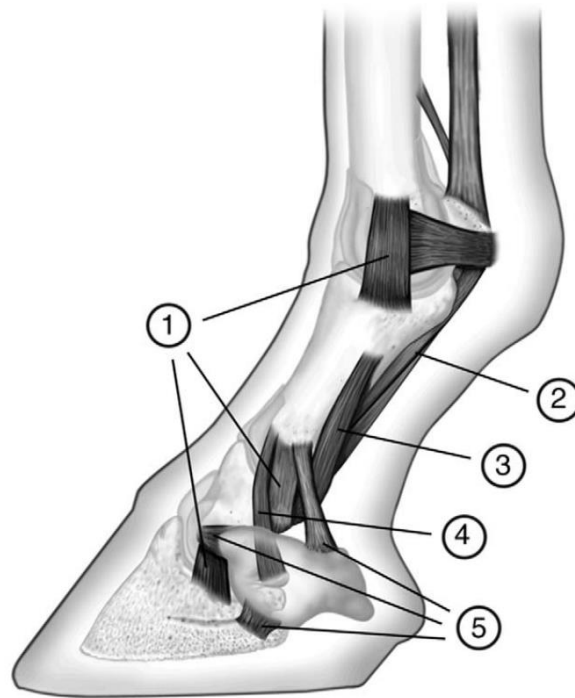


Figure 2.1 Ligaments of the digit. Ligaments of the digit: 1. collateral ligaments of the metacarpophalangeal joint and interphalangeal joints; 2. distal sesamoidean ligaments (two shown); 3. palmar ligament; 4. collateral sesamoidean ligament; 5. ligaments of the unguis [10]. Reprinted with permission from Elsevier.

Although the action and motion of the stride is controlled by extensor and flexor tendinous extensions of the related musculature at the antebrachium, which will be described later, there are also a number of tendons and ligaments responsible for stabilizing the bony structures of the foot, as well as their associated articulations. For example, collateral ligaments contribute to joint stability at all interphalangeal joints and the metacarpophalangeal joint. Straight, oblique, and cruciate sesamoidian ligaments stabilize the fetlock and proximal sesamoid bones. The distal sesamoid bone, referred to as the navicular bone, is suspended by symmetrical

abaxial suspensory ligaments and a distal impar ligament which strengthens its position and function by inserting on the distal phalanx.

The foot itself is primarily composed of the distal phalanx, the navicular bone, and the distal second phalanx, all of which are encapsulated in and suspended from the hoof. Hoof tissue is composed of deeper living and softer tissues and the outer, keratinized horn.



Figure 2.2 Image of an equine hoof cut in cross-section demonstrating the anatomy and arrangement of the distal phalanx within the hoof capsule. Photograph courtesy of Dr. Lauren Trager-Burns.

The suspensory apparatus of the distal phalanx is a complex connection between the distal phalanx and the epidermal layer of the hoof capsule. An extensive lattice of interdigitating collagen structures called lamellae connects the coffin bone to the hoof wall with the sole purpose of distributing weight bearing forces from the bones of the distal limb to the outer hoof wall and ground contacting surface [8]. An immense surface area of load dispersion is accomplished by primary and secondary lamellae and the basement membrane that connects

them.

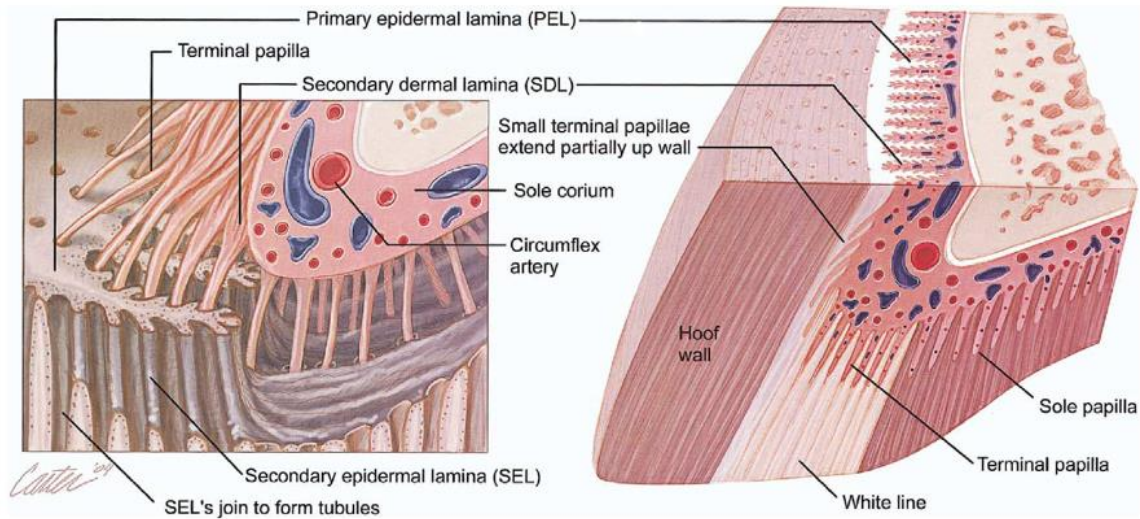


Figure 2.3 Microscopic anatomy of the distal dermal lamellae in the suspensory apparatus of the distal phalanx within the hoof. Primary and secondary lamellae are pictured to emphasize the massive surface area of contact and suspension between the distal phalanx and the hoof wall [8]. Reprinted with permission from Elsevier.

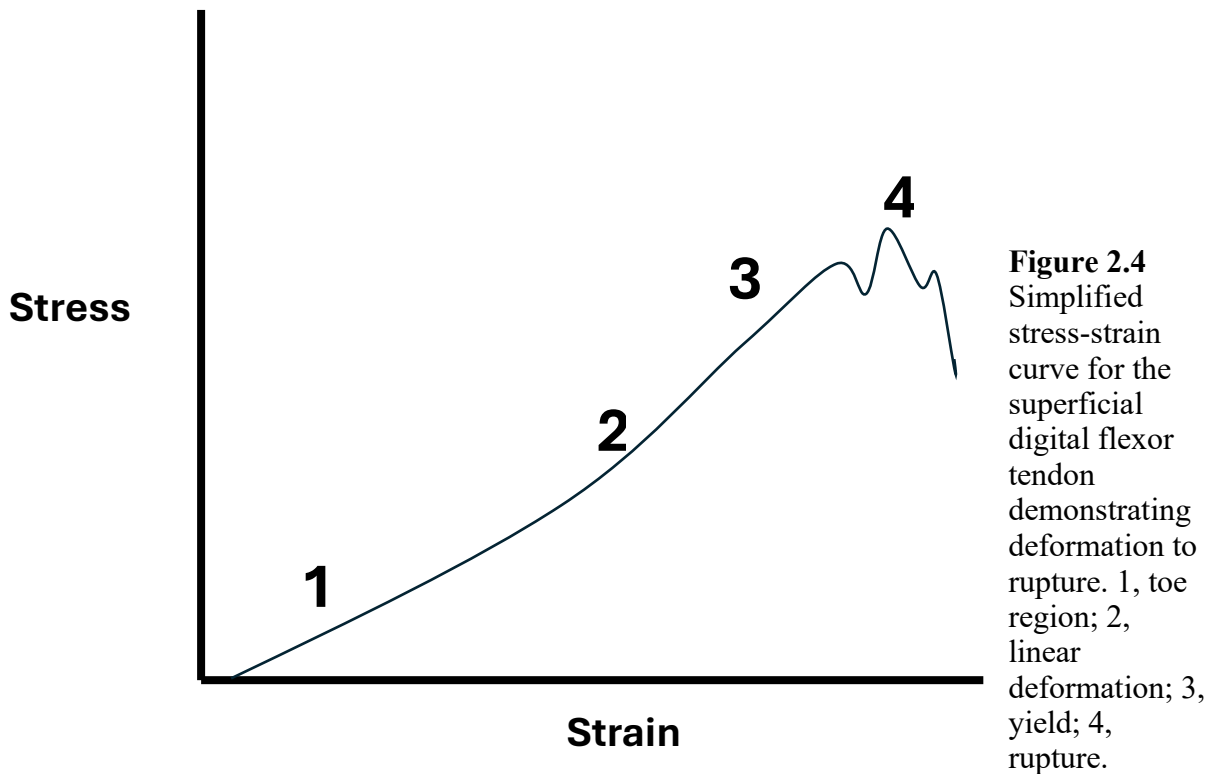
Although the foot plays an important role in the soundness of the horse, as the primary weightbearing structure, the aesthetic quality of stride is a function of the antebrachial muscles and their tendonous extensions into the distal limb. The extensor tendons on the dorsal aspect of the forelimb include the common digital extensor tendon, the lateral digital extensor tendon, and the extensor carpi radialis. The tendons work in conjunction to extend the carpus, fetlock, and interphalangeal joints. On the palmar aspect of the limb, digital flexor tendons present as more substantial structures with greater strength and function. The flexor tendons include the deep and superficial digital flexor tendons, superior and inferior check ligaments. Also located on the palmar aspect of the metacarpus is the suspensory ligament, and the sesamoidean ligaments on

the palmar aspect of the pastern, which play a vital role in distal limb stability, but not flexion of the limb.

The tendons are composed primarily of type I collagen arranged within an extracellular matrix, high in water content, resulting in a strong but elastic structure which is reinforced by crosslinking between collagen fibers [11]. Strength is important to stabilize and suspend the fetlock during weightbearing, and elasticity is vital for storing and releasing energy which ultimately reduces the energy cost of high-speed locomotion [12]

The superficial digital flexor tendon (SDFT) is located on the palmar aspect of the limb. It originates from the superficial digital flexor muscle at the musculotendinous junction in the palmar aspect of the carpus and inserts as medial and lateral branches on the proximal aspect of the second phalanx. The SDFT acts to prevent overextension of the metacarpophalangeal (fetlock) joint and stabilize the proximal interphalangeal joint. During swing phase of the stride, passive elasticity contributes to the initiation of flexion at the carpal, metacarpophalangeal, and proximal interphalangeal joints, which is continued more dramatically by active flexor muscle activity in late swing phase [12]. The elastic nature of the SDFT, and indeed other tendons, can be demonstrated by Young's Modulus which shows the linear relationship between stress and strain on the tendinous structure (see Figure 2.4) [15]. Tendon stiffness is strain-rate dependent, whereby increasing the rate of strain will shift the slope of stress-strain curve to the left, resulting in failure at lower load bearing [13]. This is clinically relevant to tendon failure exhibited by single exertional load to failure rather than cyclic loading. Interestingly, it has been found that the cross-sectional area of the SDFT is inversely related to the collagen content and strength [13]. Because of this, stiffness and elasticity of tendons is thought to be related to extra-collagenous matrix, and the efficiency of eliminating water from the structure [13]. The superior check ligament is the accessory ligament of the SDFT (AL-SDFT) and originates on the palmar

surface of the radius attaching to the SDFT distally and lies adjacent to the proximal and medial aspect of the carpal sheath [14]. The purpose of the AL-SDFT is to protect the SDFT during extension of the carpus by accepting some of the load.



The deep digital flexor tendon (DDFT) acts to limit flexion of the carpus and metacarpophalangeal joint and facilitates flexion of the proximal interphalangeal joints. It also

acts to stabilize and extend the distal interphalangeal joint. In fact, the DDFT is responsible for the initiation of propulsion at the end of stance phase [12]. Similar to the SDFT, the DDFT is relaxed in early swing phase resulting in passive flexion, which is exacerbated by engagement of the DDFT muscular components above the carpus. The inferior check ligament is the accessory ligament of the DDFT and is responsible for stabilization of the distal interphalangeal joint during stance phase.

The Equine Gait

Defining equine gait may seem a somewhat daunting task, especially when considering the rich history of horses intertwined with man has resulted in hundreds of breeds, phenotypes, and uses of the horse[1]. The most simplified philosophy can break down equine locomotion into 4 recognized gaits that are almost always preserved across the many breeds and phenotypes; the walk, the trot, the canter, and gallop. Each gait is unique in rhythm of limb movement and foot-falls, has different energetic efficiency, and trajectories of velocity and inertia.

The walk is a four-beat gait in which all limbs move independently of each other such that swing phase, landing, stance, and breakover are not synchronized and there is no airborne component to the stride.

Trot is the most studied and most useful gait due to its symmetrical quality. This two-beat gait maximizes the function of form in the distal limb, storing energy in tendons and ligaments to both accelerate and decelerate the limb to result in efficient, and beautiful propulsion of the horse in forward motion. The first 40-60% of the swing phase of trot is characterized by activity of the extensor muscles where the energy moment is at the flexor

surface. The final 40-60% of the swing phase is dominated by flexor muscles which act to resist inertia by the limb.

Canter, a three-beat gait, is also characterized by a completely airborne phase of stride. It is, however, not symmetrical in nature and there exists a gap in research focused on quantifying characteristics of the canter. Even so, when judging a sport horse during competition, the athleticism, precision and aesthetic control of canter plays an important role in the overall evaluation of the horse and its subsequent ranking among competitors. Finally, the gait with the highest velocity, the gallop, represents a four-beat gait which employs great strength to increase the airborne phase and maximize ground coverage.

Due to the symmetrical nature of the trot, it is often the focus of gait evaluation, especially regarding lameness. As previously mentioned, the trot is a two-beat gait; each beat represents the footfall of diagonal pairs of limbs (i.e., the pair of left front and right hind, and the pair of right front and left hind). This cyclic pattern of the trot is controlled by a central rhythm generator in each limb which acts to initiate flexor muscle activity and inhibit extensor muscle activity for a set length of time [16].

An early representation of the trot phases was depicted by the Phillipson Extension Phases [16]. The depiction begins with timepoint E1, where the extension phase of trot begins at the time where the limb transitions from protraction to retraction under the influence of flexor muscle control. The limb, and also the horse, is airborne until time point E2 which is marked by first ground contact of the foot and the beginning of stance phase. It is important to note that the limb is still under flexor control as the limb is brought under the horse, and the body is propelled forward. By timepoint E3, or midstance, the limb is driving the horse forward and the fetlock

achieves maximal flexion. Timepoint F breaks ground contact at breakover and the limb is protracted into swing phase [16].

Although the overall appearance of trot is symmetrical and for the purposes of research and measurement, it is, in fact, a symmetrical gait, mathematically there exist theoretical differences between phases and limbs. There is a dissociation between right and left which occurs at breakover and favors the right side. Swing phase does not equal stance phase; the moment where swing phase duration is equal to stance phase duration in any given horse represents a theoretical threshold below which the horse must walk, and above which would break to a trot [16].

Furthermore, all legs do not have equal stance duration or stride length, despite the overall stride length and duration of stride remaining equal. This can be explained by the distance of the origin of the limb related to the weight of the animal which is carried 60% on the forelimbs and 40% on the hindlimbs in the average horse [16]. For reference, the origin of the forelimb is the scapula, and the hindlimb is the point of the hip. This is described by the following equation:

$$F'_H = aW + hF_D / a+b$$

$$F_s = bW - hF_D / a+b$$

$$FD = 0.6W$$

Where F'_H represents the force exerted by the hindlimbs and is equal to the relationship of the weight of the horse (W), the distance (h) from the center of mass, the ratio of forelimb contribution (a) and hindlimb contribution (b). Similarly, F_s represents the force exerted by the forelimbs. When the forelimbs are unloaded, the weight supported by the forelimbs (FD) is equal to 60% of the weight of the horse (W) [16].

Furthermore, the mathematical theoretical explanation of trot can be further complicated by the understanding of quadrupedal forward motion. For example, each time the hoof contacts the ground, forces act both on the limb and on the ground; these are ground reaction forces (GRF). The result is an upward force as well as a horizontal force on the forelimbs and can be described as a driving force, acting to move the horse forward. The driving force also results in torque around the center of mass leading to lifting off at the forelimbs and depression on the hindlimbs. As a result, the front hooves rise and break ground contact while the hind end falls and prolongs the ground contact. The overall effect is further exacerbated by the net restraining action of the forelimbs which exceeds the net propelling action, the result of which is a reduction in inertia in the limb when the fore foot contacts the ground [16]. It is this very reason that horseshoes are designed to take as much weight off the forelimbs and minimize braking forces.

The focus of this research is aimed at quantifying characteristics of swing phase of stride, primarily arc height and limb flight. While the overall appearance of and symmetry of gait is a highly interdependent collaboration between all four limbs and every phase of stride, the aesthetic quality of stride can be attributed primarily to the fluid movement of the airborne swing phase of the limb [17, 18].

Subjective Components of Gait Evaluation

The evaluation of the gait can be divided into two processes of thought; first as an evaluation of soundness, whereby assessment by a veterinarian trained in the appropriate locomotion of an equid can make determinations regarding the motion through the limbs, preferential utilization of musculature and form, but most importantly the symmetry of gait primarily from the position of medical wellness and welfare. The second process is most often performed by the lay-person,

breeders, trainers and equestrians and focuses on the aesthetic quality of the gait. It is often stated, “the horse is poetry in motion” and the powerful yet graceful movement of the horse has captivated men, women, and children across time. Historically, the most aesthetically pleasing horses have been coveted by royalty as a symbol of prestige, and it is understood in the horse community that this extends beyond the stationary form and incorporates the athletic ability of the horse in motion. In modern day, when the horse is no longer required for agriculture, transport, or daily life, this infatuation with the movement of the horse is manifested by the sport horse, or equine athlete. Today, the equine world revolves around competition, during which horses are judged subjectively on their ability to perform and horses with a more athletic, pleasing, and fluid gait are exalted above others. This is primarily true in disciplines such as dressage, western pleasure, and hunter/jumpers.

As such, there is a divide in the way horses are evaluated for soundness and the way they are evaluated for athleticism or aesthetics. Both will be discussed here to provide context for the ways both judgments converge to evaluate the apparent performance of the equine athlete.

As mentioned, subjective evaluation of gait by a veterinarian is primarily associated with symmetry of gait. The American Association of Equine Practitioners (AAEP) has developed a grading system which subjectively evaluates lameness at the trot [19]. Clinically, and in research, lameness is characterized as a loss in symmetry of gait, and thus the trot has become the center of this evaluation. The equine veterinarian is trained to evaluate changes to the symmetry of the trot, identifying the specific limb, or limbs, affecting changes to symmetry. This training can also extend to identifying changes to the motion of the limb swing, landing, stance, or breakover that alerts them to specific pathologies affecting the digit. In this way, the veterinarian is able to provide specialized and specific diagnostics and care to the horse in order to relieve pain, optimize locomotion, and improve athleticism of the horse. Such diagnostics and

treatments, other than involving the trimming and shoeing of the horse, are beyond the scope of this thesis and will not be discussed. A difference in symmetry of movement ranging from >7mm to >14.5mm in forelimb lameness and >4 to >7.5mm in hindlimb lameness has been reported as a clinical threshold for lameness [20]. Human observation of gait asymmetry compared with sensor-based system measurement found a threshold of observation by the human eye to be a difference in symmetry >25% [21]. Many such veterinarians have developed and perfected objective classifications for the subjective gait evaluation. The aforementioned American Association of Equine Practitioners (AAEP) Lameness Scale [19] classifies the level of asymmetry in gait as follows:

Grade 0: The horse is sound

Grade 1: Lameness is difficult to observe or inconsistent regardless of circumstances

Grade 2: Lameness is difficult to observe on a straight line, but is consistent on a circle, incline or hard surface

Grade 3: Lameness is consistently observed at a trot under all circumstances

Grade 4: Lameness is observed at the walk

Grade 5: Lameness results in minimal or non-weightbearing, or inability to move

Others have developed similar and more intricate systems of assessing asymmetry in gait and lameness. For example, Auer et al. developed a musculoskeletal pain scale designed for use by veterinarians and lay-people alike which found the new scoring system to differ significantly between horses that needed veterinary intervention and those that did not [22]. Furthermore, they found good interobserver repeatability between expert and lay scoring, significant correlation with lameness, and good predictive validity for long-term health outcomes [19, 22]

Regardless, in terms of evaluating the art and athleticism of the equine gait, these systems are very simplified.

In contrast, the competition world is, perhaps sometimes optimistically, but especially at the highest levels, composed of equine athletes possessing a near perfect symmetry of gait and thus are judged on the aesthetic and even artistic qualities of each horse's performance. There are qualities which are deemed most beautiful by the community at large, and by the judges employed at each competition ring and whose job it is to rank the competitors and their horses based on performance. Much like veterinarians, these judges are usually experienced competitors and horse people themselves who have undergone training to study the regulations and expectations of each discipline of riding. There are specific qualities of gait that are revered as more aesthetically pleasing and horses possessing these qualities are more likely to perform better and catch the judge's eye subjectively [18, 23-27].

Regardless, subjective evaluation of the equine gait is reliant on the training, experience, and inherent skill of the observer. When 131 mature horses were evaluated for lameness by a group of experienced clinicians, researchers found those clinicians agreed on the lame limb 76.6% of the time when the horse was trotted on a straight line. When the entire lameness evaluation was performed (including circles, changes in footing, flexions), this number decreased to 72.9% [19]. Furthermore, when the lameness was assigned a score greater than 1.5 on the AAEP Lameness Scale, clinicians agreed 93.1% of the time. If the lameness score was less than or equal to 1.5, the agreement dropped to 61.9% [19]. That study found that agreement between clinicians was slightly higher for forelimbs than for hindlimbs. If the clinicians in the study were asked to determine if the entire horse was lame and which leg was the worse limb, clinicians only agreed 51.6% of the time [19, 28, 29]. When considering the purpose of the subjective lameness evaluation is to identify asymmetry of gait, specifically the trot, one must question the

ability of the human eye to perceive such a thing. Prior to 2009, no study had determined the ability of the human eye to detect asymmetry in moving objects. Subsequently, Parkes and colleagues determined the threshold for detection of asymmetry in movement was a 25% difference in amplitude between two objects [21]. Specifically, their study challenged two groups, one experienced veterinarians and the other inexperienced lay-people, to observe a computer simulation of markers meant to represent the tuber coxae of horses. Patterns of asymmetry were extrapolated from lame horses, imperceptibly lame horses, and a sin wave predicting artificial data. The most interesting results from this research found that there was no difference in the ability to detect asymmetry between experienced and non-experienced observers when presented with the artificial simulations. Conversely, experienced observers were significantly better at detecting asymmetry than non-experienced observers when they were presented with simulations based on lame horse data [21]. This suggests that there exists an expertise in interpretation of equine gait beyond detection of asymmetry and inspires researchers to pursue quantification of gait characteristics that make the equine athlete unique and aesthetic and emphasize the need to understand gait characteristics as they relate to equine performance beyond the simple quantifications of symmetry.

With intensified interest to improve detection and quantification of asymmetry as it pertains to lameness, body-mounted sensors comprised of accelerometers and gyroscopes (measuring changes in acceleration and angular velocity, respectively) have been modified from aerospace and automotive stabilization systems to objectively analyze and quantify characteristics in the gait of horses [28–31].

The most common body-mounted inertial sensor system, the Equinosis Lameness Locator is composed of two accelerometers mounted on the horse at the top of the head and over the sacrum, and a gyroscope attached to the dorsum of the right front pastern. The system

quantifies asymmetry as a function of changes to minimum and maximum head and pelvic height [29]. The Lameness Locator was developed and first evaluated in 2011 by Keegan et al [28]. Their research found inertial measuring systems of this configuration to have sufficient repeatability at the trot on a straight line for both forelimbs and hind limbs and became the gateway for further investigation into clinical use [28]. When comparing the Lameness Locator to subjective evaluations performed by experienced veterinarians and with the quantitative evaluations of force plate measurements in a carpal chip model of lameness, subjective evaluation was still better at identifying the lame limb (54% of lame horses) than force plates (40% of lame horses); however, the inertial sensor system was superior, capable of identifying 60% of the horses as lame [32]. In an induced lameness model, where a screw can be tightened to the sole of a foot via specialized shoe, the Lameness Locator was able to identify the lameness with fewer turns of the screw than visual observation by veterinarians [29]. The software identified the lame limb before the veterinarian 58.8% of the time, and at the same time as the veterinarian 33.3% of the time [29], demonstrating the inherent ability of the inertial sensors to detect characteristics of gait before the magnitude is detectable by the human eye.

Findings of a study performed by Keegan et al. in 2013 comparing subjective lameness evaluation and evaluation with an inertial sensor system found that those methods were significantly correlated but did not have strong agreement [33]. Subjective evaluators agreed on the category of lameness in the forelimb 58.8% of the time and 54.7% of the time in the hindlimbs [33]. The investigators concluded that inertial sensor systems could be used to improve interpretation of a lameness evaluation but would not be able to replace the subjective evaluation by a trained professional [33]. Overall, the findings of research on gait highlight the need for quantifying characteristics of gait to remove bias and improve repeatability and precision.

Technology for Objective Gait Evaluation

Modern technology has integrated into most industries and day-to-day activities. Equine medicine and gait evaluation is no exception. This extends beyond what is capable with subjective evaluation with the human eye and has even broken into the world of Artificial Intelligence (AI) where an AI marker-less tracking system has been developed and compared with the current gold standards of IMU and visual lameness evaluation [34]. Although AI systems still require intensive quality assurance research, it follows the historical progression of gait evaluation technology to be well established in the future.

Early quantified data was collected by measuring ground reactive forces acting on the hoof when it contacts the ground. Force plates were widely considered the standard for measurements of gait. The platforms, measuring ground reactive forces, were embedded into the ground at research facilities and under treadmills to allow data collection as horses were led across them. Financial restrictions limit the length and location of force plates. Other setbacks encountered using force plates, such as limiting data collection to a straight line and limited number of strides over a single-footing type, lead researchers to develop other methods of measurement. Force plates were adjusted to fit into shoes and collect data on horses under more conditions, under saddle, and on different footing. In 2008, Chateau et al demonstrated a dynamometric horseshoe composed of four piezoelectric sensors between two aluminum plates was suitable for detecting ground reactive forces on several different footings under several conditions; this subsequently increased the scope of research possible compared with traditional force plates. That study reported a root mean square error of 1.3% in normal direction, and 3.1% in transversal direction for this type of force plate [35].

Despite more specific kinetic data compiled with shoe mounted force plates, there remained gaps in the knowledge regarding actual kinematics without the ability to directly evaluate gait characteristics of the distal limb, such as limb arc and flight. These gait characteristics may be important to subjective judging outcomes during competitions.

In order to more directly measure the kinematics of the distal limb, optical motion capture (OMC) software was developed. To calculate indirect measures of distal limb kinematics, available software will process data collected from video footage of horses wearing reflective sensors on predetermined anatomic landmarks of the limb. Data obtained using OMC has also been used to determine and quantify lameness. Hardeman et al. found a positive correlation between subjective lameness grading using the AAEP Lameness Scale and quantitative measures of asymmetry using optoelectric motion capture software, supporting the value of subjective lameness evaluation by trained veterinarians [36]. They found good agreement between intra- and inter-veterinarian evaluation of the lame limb; however, the data also indicated that agreement on grade of lameness was poor [36]. Research utilizing video motion capture, has also supported the ways in which inertial measuring systems can be more accurate in detecting small differences versus human visual observation. Although there are correlations between motion capture evaluation of asymmetry and visual assessment, small but significant differences (on the order of millimeters) measured by motion capture led researchers to conclude that quantification of lameness via that technology improve the overall evaluation of gait [36]. That study suggests implementing quantified measuring systems would reduce bias and improve diagnostic quality, especially when evaluating results of diagnostic analgesia in lame horses. In addition to growing the available data on equine gait symmetry, OMC has also been used to define the kinematics of the distal limb. Using OMC to quantify kinematics of horses on a water treadmill, investigators confirmed that changing the forces acting on the equine

distal limb in motion (such as a horse walking in water) has been shown to affect the kinematics of the limb, including maximum angle of joints [37].

Hoof mounted inertial measuring units (IMU) were engineered from automotive and aerospace positioning systems. IMUs have proven superior in quantifying gait characteristics important to aesthetic evaluation, including swing phase of stride and the duration of landing, stance, and breakover. IMUs provide superior quantification because triaxial measurement quantifies changes in acceleration and angular velocity, and can determine the position of the limb as it moves thereby producing a map of limb flight. Recently, triaxial hoof-mounted inertial sensor systems have been shown to be highly accurate for measurement of distal limb stride characteristics in horses [29–31, 33]. These sensors produce quantifications of stride length, landing duration, mid-stance duration, breakover duration, vectors of inertia, and produce a dynamic map of the flight taken by the hoof during swing phase.

A study performed by Hagen et al. evaluated and validated the use of hoof-mounted inertial measuring units for quantifying gait characteristics against the previous standard, optoelectric video capture [31]. Their study confirmed high agreement between optoelectric monitoring and hoof-mounted IMUs for the parameters swing, landing duration (LandD), midstance duration (MidD), and breakover duration (BoD). Interestingly, they found IMU have weaker agreement for higher speed parameters (LandD, BoD, which ultimately affect MidD) due to higher accuracy with IMU measurements compared to more subjective optoelectric measurements. This discrepancy is magnified when the horse travels on soft and penetrable footing that hides and delays the moment of heel off, or breakover, from the video capture and visual observation [31]. Pagliara et al. were able to validate IMU measurement of fetlock kinematics by comparing data to the optoelectric motion capture data and finding temporal agreement in 97.33% of cases [30]

Hagen et al. concluded that measurement with hoof-mounted IMUs yields improved precision and accuracy [31]. In addition, the ease of application and data acquisition coupled with built-in software analysis make this system a superior technology for measuring the influence of different orthopedic treatments, shoeing, or training on gait quality of horses [31]. Hoof mounted sensors are considered the standard for detecting landing as determined by first hoof contact with the ground, mid stance, and breakover as determined by toe-off [31, 38]. It was found that when placing the IMU more proximal on the limb, even to just the pastern region, mean errors in measurement were between 1 and 6 ms [38]. That same study found this error was most profound during the stance phase of stride across all tested surfaces (asphalt, grass, and sand), measuring 0.1% to 1.16% of a stride cycle [38]. Ultimately, the validity of hoof-mounted inertial measuring units combined with the ability of the accompanying software to produce a three- dimensional map of limb flight would present the means for quantifying and categorizing the characteristics of equine gait that are related to swing phase and allow comparisons for different experimental conditions, such as shoeing.

Shoeing the Horse

For centuries, humans have increased the longevity and functional capacity of our equine companions by applying metal shoes to the weight bearing surface of the hoof. This functions to support and protect the hoof. Throughout history, the understanding of equine locomotion and the way it can be manipulated and optimized using hoof trimming and shoes has continued to broaden. The influence of shoeing and trimming on locomotion has been the subject of study by blacksmiths, veterinarians, farriers, trainers and riders.

Today, there is an immense volume of literature demonstrating the complex physics, kinetics, and kinematics of the equine digit and how trimming and shoeing can affect the forces acting on and exhibited by the limb. The potential energy stored and expended by the elastic nature of the distal limb tendons acts much like a trebuchet (catapult) apparatus. The potential energy of the counterweight is transferred and converted into motion in the arm of the catapult. The range, accuracy and movement of the associated projectiles can be determined by altering the loading and positioning of the counterweight. Thus, increasing the elastic potential energy of the distal limb by adding weight in the form of a horseshoe or weighted boot will result in greater kinetic energy during motion [39]. Furthermore, adding weight to the distal limb in the form of a shoe increases the inertia of the digit and results in a decrease in ability to resist changes in velocity, which is most apparent during swing phase of stride [40]. This concept that may be manipulated to improve aesthetic quality of gait.

As early as 1997, researchers were able to prove the effects of normal shoeing on the quality of trot, building on previous research which confirmed alterations to the concussive force of loading the limb such that horses with shoes had alterations to concussive dampening mechanisms as determined using force plates and OMC [41]. Subsequent research sought to expand mechanisms of data collection and the methods of evaluating all aspects of the equine trot stride.

When considering the function of the distal limb tendons to store and release energy within the elastic collagen structure, it is easy to understand the mechanisms by which routine hoof trimming and shoeing by a farrier can exploit the counterweight phenomenon to alter the inertia of the limb. When evaluating kinematic and kinetic data of the distal forelimb as a function of shoeing, researchers found an increased weight of the shod foot correlated with an increase in inertia of the distal limb during swing phase of the stride [42]. When relative stance

phase duration, relative swing phase retraction, and maximum extension of the trot are measured, the animation of the trot can be evaluated. Results of this research found no significant effect of shoes on GRF during stance phase, supporting the measurement of kinematic data as superior to kinetics when evaluating for the characteristics of gait pertinent to gait animation [42].

Using OMC, it has been proven that the flexor and extensor muscles of forelimbs shod with metal shoes generate more energy during early and late swing phase, respectively [43]. Similarly, when metal shoes are applied to hind limb hooves, it is associated with an increase in maximum angle of the tarsocrural (hock) joint and a lower AAEP Lameness grade when compared to the same horses without shoes [44]. The weight of the shoes increases inertia of the hoof and distal limb during early swing phase and increases momentum in late swing phase, which necessitates greater energy to overcome [43].

When routine hoof trimming and shoeing are performed by a farrier, it results in significant changes to hoof angle and coronary band height but does not result in changes to medial-to-lateral balance when evaluated on a normal shoeing cycle of 4-6 weeks [5]. Similarly, farrier intervention does not result in significant changes to symmetry of gait as measured by body-mounted sensors [5].

A study by Kelleher et al. was performed on non-lame horses to simulate a routine farrier appointment which included shoe removal, trimming, and shoe placement. Data were collected at two time points: prior to shoe removal (Time 1) and immediately following trimming and shoe placement (Time 2). The study determined a difference of minimum and maximum head movement was correlated with heel length between Time 1 and Time 2. While heel length was significantly different between Time 1 and Time 2, minimum and maximum head movement was

not significantly different between those times, suggesting, but not supporting, that changes in heel length may affect forelimb metrics [5].

Similarly, the difference in maximum pelvic height was correlated with length of dorsal hoof wall, heel overhang, and heel length in the forelimbs [5]. This conformational change would lead to less left hind push off after trimming between trial Time 1 and Time 2. Similarly, a difference in minimum pelvic height was associated with heel length and hoof angle in the forelimbs, suggesting trimming and shoeing had effects on the stance phase of stride [5]. Another study found that when tungsten road nails are applied to the left hindlimb, but not the right, data collected by an objective lameness locator recorded small increases in load bearing and push off of the left hindlimb compared to the right; this suggested both an increase in traction by such shoes and changes in the kinetics of limb and gait characteristics [45].

Hoof mounted IMUs have been shown to improve the accuracy and precision when measuring the most sensitive characteristics of stride [31]. Moments that mark the hoof's first contact with the ground (landing) and final moments of toe contact (breakover) at the beginning and ending of ground contact, respectively, are of great interest from the perspective of interventional farriery. Horseshoes have been developed to improve the comfort of horses with pathology of the foot, such as navicular syndrome. Specialized shoes for specific pathologies are designed to manipulate physics to change the kinetics and kinematics at the level of the foot to improve comfort. One such way is to ease (or reduce) the forces at breakover. Hoof-mounted IMUs have been used to quantify the way different shoes typically used for navicular disease or easing breakover would objectively affect the breakover duration (BoD). Changing hoof angle does affect the gait, mainly BoD [40], which is shortened with more acute hoof angles. The angle of the foot can be increased by trimming, but also by the addition of a wedged pad to the

sole and shoe apparatus to ease forces of the DDFT on the navicular bone by increasing the angle of the DIPJ [40].

The 2021 Hagen et al. study used hoof-mounted IMUs to investigate various shoe conditions for changes in BoD; they compared the BoD of horses with a 5° wedge pad, plain steel shoes, rolled-toe shoes, and palmarly placed quarter clipped shoes [31]. Results of the study concluded that trimming had no significant effect on BoD [31]. However, as previously hypothesized, heel elevation resulted in a significant decrease in BoD [31]. Not surprisingly, plain steel shoes significantly increased the BoD at the walk, but not at the trot. If the steel shoe was given a rolled toe or placed palmarly on the hoof, the increase in BoD observed at the walk in plain steel shoes was eliminated; however, none of these changes were observed at the trot, likely due to the higher velocity and changes in locomotion at that gait [31]. This data is in accordance with an early piece of research comparing plain steel, rocker-toe, rolled-toe and square-toe shoes, which concluded that modifying the toe of a shoe did not significantly reduce the breakover duration when compared to plain steel shoes with a normal toe [46].

When evaluating the effect of shoeing on moment arm across the distal interphalangeal joint (DIP), and thus forces on the deep digital flexor tendon and navicular bone, it was found that breakover duration was not significantly reduced by shoes specially designed to aid in breakover (i.e. Natural Balance shoes and shoes with quarter clips set back at the white line) compared to the standard of toe clip shoes [47]. However, the moment arm around the DIP was significantly reduced during breakover by Natural Balance Shoes and shoes with quarter clips when compared to toe clip shoes [47]. These data were collected using force plates and motion capture, which would have resulted in reduced accuracy when identifying true parameters of breakover and breakover duration.

If hoof-mounted IMUs are used to measure the effect of shoes on breakover duration, a significant effect of shoes on breakover duration may be found. Although trimming does not affect breakover duration, adding a plain steel shoe significantly increases the breakover duration at the walk, which could be eliminated to baseline by rolling the toe or placing the shoe more palmar on the hoof [40]. The greatest effect on breakover can be established by adding a 5 degree wedge to the heel, which significantly decreases breakover duration [40]. Hagen et al. were able to conclude that the high resolution of a hoof-mounted inertial measuring system would be superior to accurately evaluate breakover duration, especially in the context of determining the effects of horseshoes on hoof related gait characteristics [31].

A study using biplanar radiographs and finite element analysis (FEA) established that a stainless steel shoe could increase distal limb mechanical loading of a Thoroughbred racehorses at the walk by demonstrating changes to the extension and flexion of the distal interphalangeal (DIP) joint and proximal interphalangeal (PIP) joint throughout midstance [48]. More specifically, application of a stainless-steel shoe will shift ground reactive forces at midstance in addition to affecting the rotation angles of the DIP and PIP joint; increasing PIP extension and decreasing DIP extension in the shod condition when compared with the unshod condition [48]. These findings add to those supporting the clinical application of shoeing to reduce the forces acting on the digit and thus the navicular bone when treating horses with navicular disease. However, as previously mentioned, these changes are not replicated when the horse accelerates to a trot from a walk and thus this information has minimal applicability to an active equine athlete.

Other research exists to demonstrate the effects of horseshoes on the limb proximal to the foot. For example, application of an egg-bar shoe increases peak strain on the suspensory ligament, while simultaneously decreasing peak strain on the deep digital flexor tendon [49].

Conversely, peak strain is reduced on the suspensory ligament when a 7° heel wedge is applied, while simultaneously increasing the peak strain on the deep digital flexor tendon and the inferior check ligament [49]. Relocating the 7° wedge to the toe was shown to increase peak tension on the inferior check ligament [49]. All changes in peak tension were correlated with changes in torque at the distal interphalangeal joint as calculated by ground reactive forces on a force plate [49]. It is reasonable to conclude from these changes in peak tension and force that would be translated into more kinetic energy of the distal limb, that shoes would increase the motion and animation of the limb as it is in the swing phase of stride.

Kinematics Associated with Gait Quality

Although insufficient data exists for the USHJA to impose regulations on the practice of pulling shoes mid-competition, it is not uncharacteristic for regulating bodies to take a stance on which practices are accepted or outlawed within their realm of jurisdiction. One such regulating body is the International Association of Icelandic Horses. Like hunter horses, subjective judging of Icelandic horses is related to gait characteristics. Such characteristics as height of forelimb action are outlined by the International Federation of Icelandic Horses competition guidelines and is scored higher by judges. Similarly, in the discipline of Icelandic horse competition, techniques in hoof care and shoeing have become standardized to improve the gait characteristics important to subjective judging. Unlike the hunters, Icelandic horse governing bodies have recognized these practices and implemented shoe checking procedures at competitions to ensure ethical conduct for all competitors and oversight of height and length of hooves and weighted boots intended to increase the arc height of the limbs, a quality of the trot and tolt which receives a higher point reward. Data obtained using force plates, OMC, and body mounted IMUs

concluded that when Icelandic horses were shod in the manner suspected of enhancing performance (tall hooves, long toe, and heavier competition shoe and packing) the gait quality was improved when compared with a standardized, more natural hoof trim and shoe. The data proved gait quality was improved as perceived according to standards set by the International Federation of Icelandic Horse competition by demonstrating a lower SR, longer SL, and higher limb protraction (arc height) without any significant changes to gait symmetry at both trot and tolt [26]. The kinematic data were compared to the overall subjective judging scores. With the support of kinematic data, performance enhancing alterations to the feet of competitive Icelandic horses have been identified and regulated by the appropriate overseeing bodies to improve the welfare of the equine athletes and improve the ethics of such competitions.

The judgements of horses competing under USHJA regulations are based on a different system than the Icelandic horses, however. Because significant data on animation of stride can be extrapolated using body and hoof- mounted IMUs and OMC, it could be determined whether mid-competition changes in horseshoes performed in hunter horses is affecting the swing phase of stride.

Research on non-Icelandic, non-gaited horses exists to support extrapolation of kinematic data measurements of gait characteristics to the aesthetic quality of horses in motion. When comparing kinematic data collected using motion capture video software in two-year-old warmbloods trotting on a treadmill to gait evaluation performed by subjective judging on a predetermined scale, it was proven that stride duration, scapula rotation, and fetlock extension were highly correlated with the aesthetic quality of the gait [17]. This research was able to link stride duration with 'length of trot' and fetlock extension with 'suppleness'. Quantification of length of trot and suppleness provides data on two defining characteristics of gait. It is proposed

that greater fetlock extension results in greater shock absorption and thus smoothness of movement [17].

Furthermore, it is proposed by Hobbs in their review of research on dressage horse performance, that when the trot is more ‘bouncy’ (as achieved when swing phase is longer than stance phase) and the swing phase achieves a greater elevation, the gait is preferred by subjective dressage judges [50]. In fact, dressage scores after subjective evaluation during competition show direct correlation to vertical displacement as measured by body-mounted inertial measurement units [18]. Other research comparing subjective scores of high level dressage riders shows a direct correlation between score and stride frequency, where slower frequency will result in a better score [25]. Unfortunately, the research presented in the current literature is limited to body mounted inertial sensors and does not provide direct kinematic data on the flight path of the limb.

Inter-rater reliability of judges is poor despite descriptive linear scoring systems and highlights the need for quantified measurements when comparing gait characteristics [51]. Similarly, when linear scoring is compared to a 100-point scale to determine the tendency of warmblood mares to be predisposed to dressage or jumping, there is not sufficient significant differences between the subjective methods of evaluation [24]. This study concluded that more objective forms of evaluating such qualities of movement and conformation are necessary [24].

Measuring Parameters of Performance and the Future of Research

The use of kinematic and kinetic parameters to predict performance has been used in the equine industry before. A model comparing performance parameters of Olympic level dressage riders and horse performance was able to predict which kinematic variables would likely affect the

overall performance and scoring of the horse during a dressage test [25]. The results of research comparing the subjective scoring of vaulting horses to inertial measurements of the trunk found predictable correlation between these two data sets. Higher subjective scores awarded by the judge were correlated with a canter that was more elevated, had greater propulsion, and good regularity of beats as measured by a body mounted inertial sensor at the sternum [23].

Subjective evaluation, and indeed aesthetic appreciation, of the equine gait is primarily associated with the swing phase of stride and which is demonstrated by longer forelimb retraction in higher scoring horses [52]. There was significantly greater flexion at the elbow and carpus in horses scoring higher by trained subjective judges in the beginning of swing phase [52]. Even still, the current literature is limited in its ability to define direct measurements of limb flight. Ground reactive forces are limited to kinetic measures of stance phase which do not provide insight to the characteristics of stride more pertinent to subjective judging. Similarly, body mounted inertial units are limited to measures of symmetry and do not provide direct measures of distal limb kinematics at the level of the foot. While OMC can detect and report on the high detail parameters of landing, breakover and swing phase, the software must report an indirect calculated measurement of kinematics. Ultimately, it has been shown that hoof-mounted inertial measuring units with the ability to detect spatial parameters of limb flight in three axes is more accurate in measuring kinematics of the distal limb for both ground contact and swing phases of stride [31]. Likewise, the effects of horseshoes on the swing phase of stride are limited by the previously available methods of measurement. Further research using hoof-mounted IMUs is needed to measure the direct effects on kinematics of the various shoeing conditions used in the hunter equestrian discipline. These findings could be used to determine any changes to limb flight that would support effects on the scoring performed by subjective judges.

References

1. The Horse A Natural History. Busby, D. and Rutland, C., eds. 2019: Princeton University Press. Princeton, NJ.
2. Scoda, A. Historic Horseshoes and Blacksmiths. 2025 [cited 2025; Available from: <https://sandiegoarchaeology.org/historic-horseshoes/>].
3. Hill A.E.; Gardner I.A.; Carpenter T.E.; Stover S.M. Effects of injury to the suspensory apparatus, exercise, and horseshoe characteristics on the risk of lateral condylar fracture and suspensory apparatus failure in forelimbs of Thoroughbred racehorses. *Am J Vet Res*, 2004(65): 1508-1517.
4. Singer E.; Garcia T.; Stover S. Hoof position during limb loading affects dorsoproximal bone strains on the equine proximal phalanx. *J Biomech*, 2015. 48(10): 1930-1936.
5. Kelleher M.E.; Burns T.D.; Werre S.R.; White NA. The Immediate Effect of Routine Hoof Trimming and Shoeing on Horses' Gait. *J Equine Vet Sci*, 2021. 102: 103633.
6. Clayton H.M.; Hoyt D.F.; Wickler S.J.; Cogger E.A.; Lanovaz J.L. Hindlimb net joint energies during swing phase as a function of trotting velocity. *Equine Veterinary Journal*, 2002. 34(S34): 363-367.
7. Loushin, K.B.M. Shoe-pulling remains legal and more action from USHJA annual meeting, in *The Chronicle of the Horse*. 2022: <https://www.chronofhorse.com/article/shoe-pulling-remains-legal-and-more-action-from-ushja-annual-meeting>.
8. Gerard, M.P. Anatomy and Physiology of the Equine Foot. *Vet Clin North Am Equine Pract*, 2021. 37(3): 529-548.
9. Hontoir, F.; Rejas, E.; Falticeanu A.; Nisolle, J.F.; Simon, V.; Nicaise, N.; Clegg, P.D.; Vandeweerd, J.M.E. Communication between the distal interphalangeal joint and the navicular bursa in the horse at Computed Tomography Arthrography. *Anat Histol Embryo*, 2019. 56(5): 842-857.
10. Parks, A. Form and function of the equine digit. *Vet Clin North Am Equine Pract*, 2003. 19(2): 285-307.
11. Thorpe, C.T.; Clegg, P.D.; Birch, H.L. A review of tendon injury: why is the equine superficial digital flexor tendon most at risk? *Equine Vet J*, 2010. 42(2): 174-180.
12. Denoix, J.M. Functional anatomy of tendons and ligaments in the distal limbs (manus and pes). *Vet Clin North Am Equine Pract*, 1994. 10(2): 273-322.
13. Dowling, B.A. and Dart, A.J. Mechanical and functional properties of the equine superficial digital flexor tendon. *Vet J*, 2005. 170(2): 184-192.

14. Southwood, L.L.; Stashak, T.S.; Kainer, R.A.; Wrigley, R.H. Desmotomy of the accessory ligament of the superficial digital flexor tendon in the horse with use of a tenoscopic approach to the carpal sheath. *Vet Surg*, 1999. 28(2): 99-105.
15. Goodship, A.E., H.L. Birch, and A.M. Wilson, The pathobiology and repair of tendon and ligament injury. *J Biomech*, 1994. 10(2): 323-349.
16. Leach, D.H.; Rose, R.J.; Snow, D.H. Equine exercise physiology. *Equine Vet J Supplement*; 9. 1990, Newmarket, Suffolk: Equine Veterinary Journal.
17. Back, W.; Barneveld, A.; Bruin, G.;Schamhardt, H.C.; Hartman, W. Kinematic detection of superior gait quality in young trotting warmbloods. *Vet Q*, 1994. 16 Suppl 2: p.S91-96.
18. Biau, S. and Barrey, E. Relationships between stride characteristics and scores in dressage tests. *Pferdeheilkunde Equine Medicine*, 2004. 20(2): 140-144.
19. Keegan, K.G., Dent, E.V.; Wilson, D.A.; Janicek, J.; Kramer, J.; Lacarrubba, A.;Walsh, D.M. Repeatability of subjective evaluation of lameness in horses. *Equine Vet J*, 2010. 42(2): 92-97.
20. Pfau, T.; Sepulveda, M.F.; McCarthy, R.; Cheetham, L.; Forbes, B.; Rhodin, M. Comparison of visual lameness scores to gait asymmetry in racing Thoroughbreds during trot in-hand. *Equine Vet Educ*, 2020. 32(4): 191-198.
21. Parkes, R.S.V.; Weller, R.; Groth, A.M.; May, S.; Pfau, T. Evidence of the development of 'domain-restricted' expertise in the recognition of asymmetric motion characteristics of hindlimb lameness in the horse. *Equine Vet J*, 2009. 41(2): 112-117.
22. Auer, U.; Kelemen, K.; Vogl, C.; von Ritgen, S.; Haddad, R.; Borda, L.T.; Babmaier, C.; Breteler, J.; Jenner, F. Development, refinement, and validation of an equine musculoskeletal pain scale. *Front Pain Res (Lausanne)*, 2023. 4: 1292299.
23. Hobbs, S.J.; St George, L.; Reed, J.; Stockley, R.; Thetford, C.; Sinclair, J.; Williams, J.; Nankervis, K.; Clayton, H.M. A scoping review of determinants of performance in dressage. *Peer J*, 2020, 8: e9022.
24. Borowska, A. and Lewczuk, D. Comparison of conformation and movement characteristics in dressage and jumping sport warmblood mares based on point evaluation and linear scoring system. *Animals (Basel)*, 2023. 13(19): 3101.
25. Hobbs, S.J.; Braganca, F.M.S.; Rhodin, M.; Hernlund, E.; Peterson, M.; Clayton, H.M. Evaluating overall performance in high-level dressage horse-rider combinations by comparing measurements from inertial sensors with general impression scores awarded by judges. *Animals (Basel)*, 2023. 13(15): 2496.

26. Waldern, N.M.; Wiestnew, T.; Ramseier, L.C.; Amport, C.; Weishaupt, M.A. Effects of shoeing on limb movement and ground reaction forces in Icelandic horses at walk, tolt and trot. *Vet J*, 2013. 198 Suppl 1: e103-8.
27. Cruz, A.M.; Vidondo, B.; Ramseyer, A.A.; Maninchedda, U.E. Effect of trotting speed on kinematic variables measured by use of extremity-mounted inertial measurement units in nonlame horses performing controlled treadmill exercise. *AJVR*, 2018. 79(2): 211-218.
28. Keegan, K.G.; Kramer, J.; Yonezawa, Y.; Maki, H.; Pai, P.F.; Dent, E.V.; Kellerman, T.E.; Wilson, D.A.; Reed, S.K. Assessment of repeatability of a wireless, inertial sensor-based lameness evaluation system for horses. *Am J Vet Res*, 2011(72): 1158-1163.
29. McCracken, M.J.; Kramer, J.; Keegan, K.G.; Lopes, M.; Wilson, D.A.; Reed, S.K.; LaCarrubba, A.; Rasch, M. Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation. *Equine Vet J*, 2012. 44(6): 652-6.
30. Pagliara, E.; Marenchino, M.; Antenucci, L.; Costantini, M.; Zoppi, G.; Giacobini, M.D.L.; Bullone, M.; Riccio, B.; Bertuglia, A. Fetlock joint angle pattern and range of motion quantification using two synchronized wearable inertial sensors per limb in sound horses and horses with single limb naturally occurring lameness. *Vet Sci*, 2022. 9(9):456.
31. Hagen, J.; Jung, F.T.; Brouwer, J.; Bos, R. Detection of equine hoof motion by using a hoof-mounted inertial measurement unit sensor in comparison to examinations with an optoelectronic technique - a pilot study. *J Equine Vet Sci*, 2021. 101: 103454.
32. Donnell, J.R.; Frisbie, D.D.; King, M.R.; Goodrich, L.R.; Haussler, K.K. Comparison of subjective lameness evaluation, force platforms and an inertial-sensor system to identify mild lameness in an equine osteoarthritis model. *Vet J*, 2015. 206(2): 136-42.
33. Keegan, K.G.; Wilson, D.A.; Kramer, J.; Reed, S.K.; Yonezawa, Y.; Maki, H.; Pai, P.F.; Lopes, M.A. Comparison of a body-mounted inertial sensor system-based method with subjective evaluation for detection of lameness in horses. *Am J Vet Res*, 2013(74): 17-24.
34. Calle-Gonzalez, N.; Lo Fuedo, C.M.; Ferucci, F.; Requena, F.; Stucchi, L.; Munoz, A. Objective assessment of equine locomotor symmetry using an inertial sensor system and artificial intelligence: a comparative study. *Animals (Basel)*, 2024. 14(6): 921.
35. Chateau, H.; Robin, D.; Simonelli, T.; Pacquet, L.; Pourcelot, P.; Falala, S.; Denoix, J.M.; Crevier-Denoix, N. Design and validation of a dynamometric horseshoe for the measurement of three-dimensional ground reaction force on a moving horse. *J Biomech*, 2009. 42(3): 336-40.
36. Hardeman, A.M.; Egenvall, A.; Braganca, F.M.S.; Swagemakers, J.H.; Koene, M.H.W.; Roepstorff, L.; van Weeren, R.; Bystrom, A. Visual lameness assessment in comparison to quantitative gait analysis data in horses. *Equine Vet J*, 2022. 54(6): 1076-1085.

37. Nankervis, K.J.; Tranquille, C.A.; Chojnacka, K.; Tacey, J.B.; Deckers, I.; Newton, J.R.; Murray, R.C. Effect of speed and water depth on limb and back kinematics in Thoroughbred horses walking on a water treadmill. *Vet J*, 2023. 300-302: 106033.
38. Briggs, E.V. and Mazza, C. Automatic methods of hoof-on and -off detection in horses using wearable inertial sensors during walk and trot on asphalt, sand and grass. *PLoS One*, 2021. 16(7): e0254813.
39. Merriam, J.G., The role and importance of farriery in equine veterinary practice. *Vet Clin North Am Equine Pract*, 2003. 19(2): 273-83.
40. Hagen, J.; Bos, R.; Brower, J.; Lux, S.; Jung, F.T. Influence of trimming, hoof angle and shoeing on breakover duration in sound horses examined with hoof-mounted inertial sensors. *Vet Rec*, 2021. 189(4): e450.
41. Roepstorff, L.; Johnston, C.; Drevemo, S. The effect of shoeing on kinetics and kinematics during the stance phase. *Equine Vet J Suppl*, 1999(30): 279-85.
42. Willemen, M.A.; Savelberg, H.H.C.M.S.; Bameveld A. The improvement of the gait quality of sound trotting warmblood horses by normal shoeing and its effect on the load on the lower forelimb. *Livestock Production Science*, 1997. 52: 145-153.
43. Singleton, W.H.; Clayton, H.M.; Lanovaz, J.L.; Prades, M. Effects of shoeing on forelimb swing phase kinetics of trotting horses. *Vet Comp Orthop Traumatol*, 2003(16): 16-20.
44. Panos, K.E.; Morgan, K.; Gately, R.; Wilkinson, J.; Uden, A.; Reed, S.A. Short communication: changes in gait after 12 wk of shoeing in previously barefoot horses. *J Anim Sci*, 2023. 101:skac374.
45. Day, P.; Collins, L.; Horan, K.; Weller, R.; Pfau, T. The effect of tungsten road nails on upper body movement asymmetry in horses trotting on tarmac. *J Equine Vet Sci*, 2020. 90: 103000.
46. Clayton, H.M.; Sigafoos, R.; Curle, R.D. Effect of three shoe types on the duration of breakover in sound trotting horses. *J Equine Vet Sci*, 1991. 11(2): 129-132.
47. Eliashar, E.; McGuigan, M.P.; Rogers, K.A.; Wilson, A.M. A comparison of three horseshoeing styles on the kinetics of breakover in sound horses. *Equine Vet J*, 2002. 34(2): 184-90.
48. Panagiotopoulou, O.; Rankin, J.W.; Gatesy, S.M.; Hutchinson, J.R. A preliminary case study of the effect of shoe-wearing on the biomechanics of a horse's foot. *PeerJ*, 2016. 4: e2164.
49. Riemersma, D.J.; van den Bogert, A.J.; Jansen, M.O.; Schamhardt, H.C. Influence of shoeing on ground reaction forces and tendon strains in the forelimbs of ponies. *Equine Vet J*, 1996. 28(2): 126-32.

50. Hobbs, S.J.; St George, L.; Reed, J.; Stockley, R.; Thetford, C.; Sinclair, J.; Williams, J.; Nankervis, K.; Clayton, H.M. A scoping review of determinants of performance in dressage. *Peer J*, 2020, 8: e9022.

51. Gmel, A.I.; Gmel, G.; von Niederhausern, R.; Weishaupt, M.A.; Neuditschko, M. Should we agree to disagree? An evaluation of the inter-rater reliability of gait quality traits in Franches-Montagnes stallions. *J Equine Vet Sci*, 2020. 88: 102932.

52. Holstrom, M.; Fredrickson, I.; Drevemo, S. Biokinematic differences between riding horses judged as good and poor at the trot. *EVJ*, 1994. Supple 17: 51-56.

Chapter 3: Comparison of Gait Characteristics for Horses With No Shoes, With Aluminum

Shoes, and With Steel Shoes

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Animals

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Abstract

Objective information regarding the effects of shoeing on gait characteristics of performance horses is scant. Such information is relevant to competition regulation and animal welfare. The objective of this study was to determine differences in gait characteristics for horses under various shoeing conditions (barefoot, aluminum, steel). We hypothesized the various conditions

would not affect symmetry of head and pelvic movements but would affect hoof arc height, stride length, and duration of stride swing, stance, and breakover times. Twelve healthy, adult, client-owned horses without musculoskeletal abnormalities or lameness were included in a prospective crossover study design. Horses were evaluated with body- and hoof-mounted inertial sensors at a trot on firm and soft surfaces under barefoot, aluminum shoe and steel shoe conditions. Data collected included Q score, hoof arc height and lateral deviation, stride length, and mid-stance, breakover, swing, and landing stride phase times. Data were compared among shoeing conditions and surfaces. Significant differences in arc height were detected between aluminum and steel shoes in right and left forelimbs ($P<0.0001$) and remained consistent on soft footing ($P<0.0001$) and asphalt ($P=0.0009$). Differences in hoof arc height were also significant between barefoot and steel shoes on soft footing in right ($P=0.0297$) and left ($P=0.0006$) forefeet. Limitations included the small sample size. The significant differences in hoof arc height of horses shod with steel shoes versus aluminum or barefoot conditions have potential implications on competition regulation and animal welfare. Further investigation is warranted to determine the impact this has on competition fairness and animal welfare.

1. Introduction

Many equine athletes wear metal shoes to provide protection against surfaces, support the foot, and aid traction. Steel has traditionally been chosen for its durability, availability, and low cost. However, aluminum can be used to manufacture a lighter shoe construct which is thought to have desirable effects on gait aesthetics [1]. In some equine disciplines, steel shoes are removed (barefoot) or changed to a lighter shoe material (e.g., aluminum) during an equestrian event to achieve perceived advantages such as more aesthetic limb flight during certain aspects of the

competition; heavier shoes may be left in place to improve traction and support during other portions of a competition [2]. Existing evidence has demonstrated the impact of horseshoes on the performance and health of athletic horses [1,3–6]. Results of these studies have shown that changes in shoe type, style, and application have significant effects on kinetics and kinematics of horses during exercise as well as incidence of injury and strain in the limb and foot. Huguet et al [1] found a significant effect of aluminum versus steel shoes on minimum carpal angle and maximum hoof height measurement in horses at the trot but no effects on other gait characteristics such as stride length. Other investigators have found that shoeing and surface affect duration of stride breakover [7]. Swing phase of stride is typically used to assess aesthetic aspects of movement and horses show the most variation in expressiveness and athleticism during this stride phase, which is an important component of subjective judging [8]. Studies to-date do not provide detailed information on flight of the hoof during the swing phase of the stride. This study aims to fill gaps in knowledge and understanding of the effect of shoeing practices on the flight of the hoof.

Body-mounted sensors comprised of accelerometers and gyroscopes (measuring changes in acceleration and angular velocity, respectively) have been modified from aerospace and automotive stabilization systems to objectively analyze and quantify characteristics in the gait of horses [9]. The most common body-mounted inertial sensor systems measure gait symmetry using head and pelvic movement [10]. A key limitation to body-mounted systems is that they do not directly evaluate gait characteristics of the distal limb, such as limb arc and flight. These gait characteristics may be important to subjective judging outcomes during competitions. Limb-mounted inertial measurement unit systems (IMUs) are accurate, as determined by comparison with optical motion capture systems [11]. Recently, triaxial hoof-mounted inertial sensor systems have been shown to be highly accurate for measurement of distal limb stride characteristics in

horses [12–14]. These sensors yield information about hoof orientation in all three axes and allow more detailed analysis of movements of the distal limb. This technology is a useful tool to measure and quantify changes in the gait characteristics of horses, especially when under various hoof shoeing conditions. Such methods are useful for examination of the effects of horseshoeing practices and may provide more detailed information regarding characteristics of hoof movement than methods used in prior studies.

The impact of shoe characteristics on performance and welfare of sport horses is under increased scrutiny, especially at the upper levels of competition. For example, regulation changes have been proposed to the United States Hunter Jumper Association (USHJA) to ban changes in shoeing during competition. These regulation changes were recently rejected because there exists scant scientific data to support or refute concerns [2]. There remains a lack of enough objective information regarding the effects of horseshoes on certain aspects of the gait, particularly swing phase characteristics such as hoof arc height. This information may be relevant to regulating bodies considering changes in rules for competitions. The objective of this study was to compare objectively measured gait characteristics in horses for various hoof shoeing conditions (barefoot, aluminum shoes, and steel shoes) using hoof-mounted IMUs. We hypothesized that hoof shoeing conditions would not affect symmetry of head and pelvic movements as detected with body-mounted inertial sensors or mediolateral hoof deviation during swing phase, stride length, and duration of stride phases detected with hoof-mounted IMUs. We also hypothesized that lower foot-shoe weight (barefoot or aluminum shoes) would result in lower early and late swing phase hoof flight height (arc height a and arc height b, respectively) as detected with hoof-mounted IMUs.

2. Materials and Methods

2.1 Animals

Based on power analysis determining population size for statistical significance ($\alpha = 0.05$; power = 0.80), 12 healthy, client-owned horses without lameness, hoof or limb abnormalities were recruited for the study. Protocols were approved by the Virginia Tech Institutional Animal Care and Use Committee (protocol 22-127). Horses included 9 American Quarter Horses and 3 Thoroughbreds. The mean weight of horses was 479.9 kg (range, 431.4 kg to 535.5 kg). The horses were used for several different disciplines (western pleasure, eventing, and pleasure riding) and were all in active training and use.

2.2 Procedures

A physical examination was performed prior to initiation of the experiments for all 12 horses. Hoof testers were applied to all four feet at the toe margins, lateral bars, across the frog, and across the heels. Hoof balance radiographs (lateromedial and dorsopalmar projections) were obtained of the front feet prior to the removal of the horses' own shoes. Horses were trotted in hand on a straight line over asphalt and evaluated by the same observer (CB) to ensure they did not have lameness prior to inclusion. Horses were to be excluded if they had a history of laminitis or performance-limiting orthopedic disease, were sensitive to hoof testers, had received nonsteroidal anti-inflammatory drugs within the prior 7 days, or had an AAEP Lameness Grade greater or equal to 1/5. No abnormalities were detected during physical examination, hoof tester application, lameness assessment, or radiography; therefore, no horses were excluded.

Horses were fitted with a single axis accelerometer fastened to the most dorsal aspect of the poll using a specialized neoprene cap attached to the halter, a second single axis accelerometer fastened to the skin on midline between the tuber sacrale, and a single axis gyroscope attached to the dorsal aspect of the right front pastern in a specialized neoprene boot (Lameness Locator,

Equinosis Inc., Columbia, MO). A hoof-mounted inertial measurement unit (IMU; HoofBeats Gait Mapping System, Werkman Black, Netherlands) was applied to the dorsal aspect of the hoof wall on each forefoot using adhesive and Velcro for repeatability of subsequent placement (Figure 1). Each IMU was placed approximately 1 cm distal to the coronary band on midline of both forelimbs. Data were collected while the horses were trotted in hand on a straight line over asphalt and soft footing (mortar sand over #10 stonedust base). Data were collected for horses before interventions of shoe removal and trimming (baseline) and under three experimental conditions in the following order: barefoot, aluminum shoes (Kerckhaert Aluminum Comfort, Kerckhaert Royal Horseshoes, Netherlands), and steel shoes (Kerckhaert Steel Comfort, Kerckhaert Royal Horseshoes, Netherlands). All trimming and shoeing was performed by the same farrier (TB). Shoes were weighed prior to application; mean \pm SD weights were 172.9 ± 19.3 grams for aluminum shoes and 372.9 ± 31.6 grams for steel shoes. Data were collected immediately after shoeing changes. Under each condition, the horses were trotted in hand on a straight line over asphalt followed by soft footing; each trial was performed in triplicate for each condition and surface. Hoof balance radiographs (0° lateromedial and 0° dorsopalmar projections) were obtained to confirm appropriate hoof balance and confirm that no major subjective changes to hoof balance had occurred during shoe placement.



Figure 3.1 Image of a hoof-mounted inertial measuring unit affixed to the midline on the dorsal aspect of the hoof wall approximately 1 cm distal to the coronary band.

2.3 Measures of outcome

Data were collected using the hoof-mounted inertial sensors including hoof arc height at two points of limb flight (arc height a [early swing phase] and arc height b [late swing phase]; Figure 2), mediolateral deviation of the hoof flight, stride length, and the time of each phase of stride (landing, midstance, breakover, and swing phases). Two arc height measurements (arc height a and arc height b) identified by the inertial sensor system result from the biphasic path of hoof flight during the swing phase of the stride. In early stance phase, the hoof attains an initial maximum height (arc height a) followed by a period of decreasing height. A second peak in arc

height (arc height b) occurs in late swing phase before the initiation of stance phase, when the hoof contacts the ground. Data collected using body-mounted sensors (Lameness Locator) included measures of head and pelvis asymmetry (Q score).



Figure 3.2. Example gait map for hoof flight at the trot of left (LF, yellow tracing) and right (RF, red tracing) forelimbs. Two distinct maximum hoof heights are indicated as the maximum arc height during early swing phase (arc height a; fuschia arrows) and maximum arc height during late swing phase (arc height b; cyan arrows) immediately prior to landing.

2.4 Statistical Analysis

A median reading from the 3 trials (technical replicates) was used for downstream analyses. Distribution properties of the data were assessed using normal probability plots. Normally distributed outcomes (stride length and the time of each phase [landing, midstance, breakover, and swing] of stride) were summarized as mean (standard deviation). Non-Gaussian outcomes (hoof arc height at two points of limb flight [arc height a and arc height b], Q score, and mediolateral hoof arc deviation) were summarized as least squares means (standard error). Effects of Shoeing (baseline vs barefoot vs aluminum vs steel) and footing (A [asphalt] vs SF

[soft footing]) on outcomes were assessed using mixed model ANOVA for normally distributed data or linear generalized estimating equations for non-Gaussian data. All models specified horse identification as the subject of repetition. Where appropriate, P-values were adjusted for multiple comparisons using Tukey’s procedure. Statistical significance was set to 0.05. All analyses were performed using SAS version 9.4 (Cary, NC, USA).

3. Results

3.1 Hoof arc height

The least squares means and standard error arc height a and arc height b for left and right forelimbs under all conditions (baseline, barefoot, aluminum shoes, and steel shoes) and surfaces (asphalt and soft footing) are reported in Table 1.

Table 3.1. Least squares means and standard errors for hoof height from the ground at early swing phase maximum (arc height a) and late swing phase maximum (arc height b) for 12 horses before intervention (baseline) and under barefoot, aluminum shoe, and steel shoe conditions. Data are presented for horses trotting on asphalt (A) and soft footing (SF).

Limb	Variable	Footing	Shoeing	Least Squares	
				Means (cm)	SE
	Arc height				
Left forelimb	a	A	Baseline	14.00	0.54
			Barefoot	13.38	0.73
			Aluminum	12.88	0.40
			Steel	14.42	0.46

		SF	Baseline	15.00	0.46
			Barefoot	13.38	0.69
			Aluminum	14.75	0.52
			Steel	15.92	0.50
	Arc height				
	b	A	Baseline	12.08	0.30
			Barefoot	12.38	0.35
			Aluminum	12.04	0.27
			Steel	11.67	0.21
		SF	Baseline	13.83	0.44
			Barefoot	14.13	0.44
			Aluminum	14.42	0.48
			Steel	13.71	0.42
Right	Arc height				
forelimb	a	A	Baseline	14.29	0.74
			Barefoot	13.42	0.73
			Aluminum	12.88	0.49

		Steel	14.42	0.61
	SF	Baseline	14.71	0.45
		Barefoot	13.92	0.75
		Aluminum	14.54	0.50
		Steel	15.75	0.49
Arc height				
b	A	Baseline	12.25	0.27
		Barefoot	12.88	0.39
		Aluminum	11.92	0.25
		Steel	11.67	0.22
	SF	Baseline	13.75	0.48
		Barefoot	14.08	0.43
		Aluminum	14.25	0.46
		Steel	13.63	0.40

3.1.1 Arc height a

Overall comparisons adjusted for data on all surfaces (asphalt and soft footing) indicated arc height a for left and right forelimbs was significantly ($p < 0.001$) lower for aluminum shoes versus steel shoes. For horses trotting on asphalt, left and right forelimb arc height a was

significantly ($p < 0.001$) lower for aluminum shoes versus steel shoes. Likewise, for horses trotting on soft footing, left and right forelimb arc height a was significantly ($p < 0.001$) lower for aluminum shoes versus steel shoes. On soft footing, arc height a was also lower for barefoot conditions versus steel shoes in left ($p < 0.001$) and right ($p = 0.03$) limbs. In addition, for horses trotting on asphalt, right forelimb arc height a was significantly ($p = 0.03$) lower for aluminum shoes versus initial (baseline) conditions.

3.1.2 Arc height b

For all surfaces, left forelimb arc height b was significantly ($p = 0.005$) greater for aluminum versus steel shoes. Right forelimb arc height b for all surfaces was significantly ($p = 0.007$) greater for barefoot conditions than baseline conditions. For both left ($p = 0.005$) and right ($p = 0.002$) forelimbs on all surfaces, arc height b was significantly greater for barefoot conditions versus steel shoes. Left ($p = 0.04$) and right ($p < 0.001$) forelimb arc height b was significantly greater for barefoot than steel shoes on asphalt. Left ($p < 0.001$) and right ($p = 0.02$) forelimb arc height b was significantly greater for aluminum than steel shoes on soft footing. Additional significant comparisons for right forelimb arc height b on asphalt included aluminum greater than barefoot ($p < 0.001$), barefoot greater than baseline ($p = 0.003$), and baseline greater than steel ($p = 0.04$).

3.2 Stride length

The mean and standard deviation stride length under all conditions (baseline, barefoot, aluminum shoes, and steel shoes) and surfaces (asphalt and soft footing) are reported in Table 2. No significant differences were found for comparisons of shoeing conditions on each surface.

Table 3.2. Means and standard deviations for stride length in 12 horses before intervention (baseline) and under barefoot, aluminum shoe, and steel shoe conditions. Data are presented for horses trotting on asphalt (A) and soft footing (SF).

Footing	Shoeing	Mean (cm)	SD
A	Baseline	208.67	20.40
	Barefoot	206.58	28.22
	Aluminum	208.13	20.71
	Steel	204.25	21.89
SF	Baseline	212.63	14.68
	Barefoot	215.58	20.93
	Aluminum	217.29	18.04
	Steel	214.42	14.58

3.3 Q score

The least squares means and standard error Q score for left and right forelimbs under all conditions (baseline, barefoot, aluminum shoes, and steel shoes) and surfaces (asphalt and soft footing) are reported in Table 3. No significant differences were found for comparisons of shoeing conditions on each surface.

Table 3.3. Least squares means and standard errors for Q score in 12 horses before intervention (baseline) and under barefoot, aluminum shoe, and steel shoe conditions. Data are presented for horses trotting on asphalt (A) and soft footing (SF).

		Least Squares	
Footing	Shoeing	Means	SE
A	Baseline	10.10	2.21
	Barefoot	13.73	2.26
	Aluminum	11.63	2.23
	Steel	11.55	2.34
SF	Baseline	11.10	1.49
	Barefoot	9.72	0.95
	Aluminum	12.18	2.68
	Steel	9.42	2.20

3.4 Mediolateral deviation of the hoof and time of each stride phase

The least squares means and standard error mediolateral hoof deviation in swing phase of the stride for left and right forelimbs under all conditions (baseline, barefoot, aluminum shoes, and steel shoes) and surfaces (asphalt and soft footing) are reported in Table 4. No significant differences were found for comparisons of mediolateral hoof deviation.

The mean and standard deviation duration of phases of the stride (landing, midstance, breakover, and swing) for left and right forelimbs under all conditions (baseline, barefoot, aluminum shoes,

and steel shoes) and surfaces (asphalt and soft footing) are reported in Table 5. No significant differences were found for comparisons of stride phase time among shoeing conditions for each surface.

Table 3.4. Least squares means and standard errors for mediolateral hoof deviation during the swing phase of the stride of left and right forelimbs in 12 horses before intervention (baseline) and under barefoot, aluminum shoe, and steel shoe conditions. Data are presented for horses trotting on asphalt (A) and soft footing (SF).

Limb	Footing	Shoeing	Least Squares	
			Means (cm)	SE
Left forelimb	A	Baseline	4.96	0.89
		Barefoot	6.08	0.89
		Aluminum	4.88	0.61
		Steel	4.58	0.63
	SF	Baseline	4.04	0.55
		Barefoot	4.00	0.61
		Aluminum	3.88	0.52
		Steel	3.83	0.51
Right forelimb	A	Baseline	4.71	1.04
		Barefoot	6.29	1.08

		Aluminum	5.17	0.73
		Steel	4.67	0.86
	SF	Baseline	3.38	0.53
		Barefoot	3.92	0.78
		Aluminum	3.88	0.76
		Steel	3.54	0.59

Table 3.5. Means and standard deviations for durations of each phase of the stride (landing, midstance, breakover, and swing) for left and right forelimbs in 12 horses before intervention (baseline) and under barefoot, aluminum shoe, and steel shoe conditions. Data are presented for horses trotting on asphalt (A) and soft footing (SF).

Stride					
Phase	Limb	Footing	Shoeing	Mean (ms)	SD
Landing	Left forelimb	A	Baseline	13.7	3.8
			Barefoot	13.4	5.1
			Aluminum	12.3	1.7
			Steel	15.2	2.1
		SF	Baseline	71.8	15.5
			Barefoot	66.0	15.0
			Aluminum	76.2	20.2
			Steel	68.7	18.3

	Right				
	forelimb	A	Baseline	15.0	3.8
			Barefoot	12.9	4.3
			Aluminum	14.1	2.7
			Steel	15.7	2.4
		SF	Baseline	67.7	12.3
			Barefoot	68.4	20.0
			Aluminum	70.2	19.8
			Steel	66.8	19.3
	Midstance				
e	Left forelimb	A	Baseline	245.6	32.5
			Barefoot	258.9	39.6
			Aluminum	256.5	34.8
			Steel	262.2	35.7
		SF	Baseline	223.7	26.0
			Barefoot	229.3	26.9
			Aluminum	228.8	28.3

			Aluminum	59.7	12.9
			Steel	64.1	13.7
		Right			
	forelimb	A	Baseline	70.0	12.0
			Barefoot	73.3	16.8
			Aluminum	72.1	9.5
			Steel	76.6	12.2
		SF	Baseline	62.3	11.8
			Barefoot	59.0	12.3
			Aluminum	58.0	12.3
			Steel	63.0	11.6
Swing	Left forelimb	A	Baseline	369.3	24.8
			Barefoot	361.6	24.8
			Aluminum	372.0	24.8
			Steel	372.9	26.0
		SF	Baseline	375.1	24.2

		Barefoot	375.9	24.7	
		Aluminum	375.2	25.8	
		Steel	379.3	26.1	
	Right				
	forelimb	A	Baseline	373.3	26.2
			Barefoot	366.0	23.6
			Aluminum	375.6	25.7
			Steel	376.7	27.4
		SF	Baseline	384.5	19.4
			Barefoot	382.4	27.1
			Aluminum	382.3	29.6
			Steel	385.8	26.3

4. Discussion

The purpose of this study was to quantify effects of three different shoeing conditions (barefoot, aluminum shoes, and steel shoes) on hoof flight and stride characteristics of horses using hoof-mounted inertial measurement units (IMUs). Such effects may influence subjective judging and could impact competition outcomes. We hypothesized that hoof shoeing conditions would not affect symmetry of head and pelvic movements as detected with body-mounted inertial sensors

(Q score), or mediolateral hoof deviation during swing phase, stride length, and duration of stride phases as detected with hoof-mounted IMUs. These hypotheses were supported by findings of the study; results indicated shoeing conditions did not significantly change gait symmetry or those measured gait characteristics. We also hypothesized that lower shoeing weights (barefoot or aluminum shoes) would result in lower hoof flight height (hoof arc height a, hoof arc height b) compared with horses wearing steel shoes. Overall, the hypothesis was supported for hoof arc height a. Lighter foot conditions (barefoot and aluminum shoes) generally resulted in lower maximal hoof arc heights during early swing phase (arc height a). However, lighter foot conditions generally resulted in higher hoof arc heights during late swing phase (arc height b); therefore, this hypothesis was not supported. Findings were overall consistent for horses trotting on firm (asphalt) or soft footing.

The results of this study may have implications for both the clinical approach to shoeing horses and the regulations surrounding sportsmanship, and potentially welfare, of equine athletes during competition. Because maximum early swing phase hoof height (arc height a) was higher and late swing phase hoof height (arc height b) was lower when horses wore steel shoes versus when they were barefoot or wearing aluminum shoes, the difference between these two arc heights is greater for horses wearing steel shoes. Conversely, horses without shoes (barefoot) or wearing aluminum shoes generally have a smaller early- to late-swing phase hoof arc height difference; this could be detected and subjectively interpreted differently by an observer (judge). This change to the shape or appearance of the biphasic hoof flight during swing phase of the stride is a novel finding, and may have observable effects on aesthetic qualities of gait [8]. Research into human observation of gait asymmetry compared with sensor-based system measurement data found a threshold of observation by the human eye to be a difference in symmetry of >25% [15]. The measured differences in least square means of hoof arc height between shoeing conditions of

this study range from 0.7 to 2.5 cm, a magnitude that might be detectable by an observer, and thus affect the aesthetic quality to a degree that could be differentiated by a trained professional (such as a competition judge). This is further supported by the findings of a study using distal limb IMU measurements of limb flight to identify phenotype of Italian horses used for dressage or draft work [16]. The researchers in that study compared the perceived limb flight and gait quality of trained equine judges to the data collected from an IMU sensor-based system and concluded that sensor data could accurately predict the evaluation of gait quality by the judges and demonstrated the potential use of the technology as an assessment of performance. Such information may be useful for regulating bodies seeking greater availability of subjective data regarding effects of shoeing changes on movement of horses [2]. These results also support the findings from a study performed by Huguet et al. which found a significant overall 2.5 cm decrease in maximum hoof height of horses shod in aluminum shoes compared to steel, without effects on stride length or other measured gait variables [1]; that study was conducted using video analysis and did not evaluate the biphasic nature of hoof flight during swing phase of the stride. These findings also agree with another study in which doubling the weight of shoes increased the arc of the swing phase in horses [17]. This phenomenon is explained and supported by the “trebuchet apparatus” which explains the physics of potential energy converted to motion when a counterweight is added to a construct. Other authors determined that alterations in swing phase characteristics are attributable to differences in shoe weight, but not configuration of shoes [18].

Results of this study indicated that, while hoof arc height was influenced by shoeing, other measures of gait and symmetry of movement were not affected. Measures of head and pelvis asymmetry (Q score) collected using body-mounted sensors were not significantly different among shoeing condition groups. This finding agrees with results of another study in which no

statistical difference in total head height and pelvis movements were found before or after farrier intervention [6]. Our results and those of that other study indicate trimming and shoeing with various materials do not have an immediate effect on gait symmetry of horses. Also, other than hoof arc height, no other measured variables of gait (stride length, mediolateral hoof deviation during swing phase, or time of stride phases) were significantly different among shoeing conditions groups, similar to findings of other authors [1]. These results suggest that, for experimental conditions in this study, the effects of shoe material and weight are primarily limited to the shape and height of hoof arc height during the swing phase of the stride.

Data acquired before farrier intervention (baseline data) were used as a measure of gait characteristics prior to intervention. Although not the primary aim of the study, it is interesting to note that baseline data were generally similar to data for steel shoe conditions. We attributed this similarity to the fact that enrolled horses wore steel shoes.

The hoof-mounted IMU system used in this study allowed detailed measurement of several variables of gait at the trot. Another study [12] in which this same system was used compared measurements of phases of stride (landing, breakover, stance, and swing) acquired with hoof-mounted IMUs to data measured with optoelectric video capture (which had been considered the gold standard method). Results of that study indicated excellent agreement between data acquired using those two modalities, and the authors determined higher accuracy of the hoof-mounted IMU system [12]. This is a convenient and accurate objective method to measure characteristics of hoof flight during phases of the stride and allowed detailed comparison among shoeing condition groups in the present study. Future research using hoof mounted IMUs could expand on this data to help guide veterinarians and farriers in improving therapeutic shoeing for horses with diseases of the foot and distal limb.

Limitations of this study include the low sample size ($n = 12$) of horses. Although a power analysis was used to determine the population size, additional comparisons may have had statistically significant differences if a larger population had been used. Also, horses enrolled in this study were in training for disciplines of western pleasure and eventing. The practice of removing shoes mid-competition is currently adopted by the hunter discipline, and discussion of the fairness and ethics of this practice has been brought before the USHJA [2]. Unfortunately, the authors did not have access to a large population of horses engaged in that discipline for recruitment in this study. Extrapolation of these results for horses in other disciplines should be made cautiously.

To mimic the custom in competition hunters of removing aluminum shoes for the flat portion of the competition we chose to perform the conditions in the same order (aluminum, barefoot, then steel). In addition, since horses enrolled in the study typically wore steel shoes because of owner preference, this experimental order allowed horses to be discharged from the study wearing their typical shoe without additional resetting. All horses were trotted on asphalt first, and secondly soft footing. This lack of randomization in the study could have affected the results if horses became more fatigued throughout the day. Additionally, it is possible the horses were able to adjust to the weight of a new shoeing condition over asphalt which may have altered their gait over soft footing. However, results for baseline conditions, which were overall similar to those for steel shoeing conditions, suggest that shoeing was the primary variable affecting the measured gait variables. Further studies should incorporate randomization to strongly corroborate the data from the current study.

The hoof-mounted IMUs used in this study are lightweight, easy to apply, and data acquisition is straightforward. In future studies, this system could be applied and used in simulated competition settings for horses undergoing changes of shoeing conditions between event types, which is

commonplace in some disciplines. Additionally, such data could be compared to subjective judging scores to determine correlations between hoof flight and aesthetic preferences of judges. Although other authors have determined that objective measurements may be useful for fitness-to-compete judgements [19,20], few studies have been conducted comparing objective analysis metrics of horse gait to subjective aesthetic judging outcomes [16]. Additional studies investigating such comparisons would enable determination of the possible effects of shoeing conditions on show performance and identification of the advantages of shoeing changes during competition. Further studies could also be performed to determine effects of shoeing condition changes on horse welfare, particularly hoof health and related lameness.

5. Conclusions

In conclusion, results of this study identified alterations in hoof flight (hoof arc height) when the conditions were changed from barefoot to aluminum to steel shoes. The data shows a significant increase in overall arc height a (early swing phase arc height) in the heavier shoe conditions (steel) compared to lighter shoe conditions (barefoot or aluminum shoes), regardless of the footing type. In addition, horses typically had lower arc height b (late swing phase arc height) when wearing heavier steel shoes. Therefore, horses wearing heavier shoes had a greater difference between these portions of the swing phase of the stride, which could be interpreted by subjective judges differently than the hoof flight path for lighter (barefoot and aluminum) shoeing conditions. Further studies are warranted to investigate comparisons between subjective judging outcomes and objectively measured hoof flight characteristics. Results of this study may be relevant to professional organizations determining regulations for competition. Further

research should be performed to confirm these findings for horses performing in specific disciplines, especially hunter/jumpers.

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Conflict of Interest: The authors declare no conflicts of interest.

References

1. Huguet, E.E.; Duberstein, K.J. Effects of steel and aluminum shoes on forelimb kinematics in stock-type horses as measured at the trot. *J. Equine Vet. Sci.* 2012, 32, 262–267.
2. Loushin, K.; Bailey, M. Shoe-pulling remains legal and more action from USHJA annual meeting. *The Chronicle of the Horse*, 2021. <https://www.chronofhorse.com/article/shoe-pulling-remains-legal-and-more-action-from-ushja-annual-meeting> Last accessed February 23, 2022.
3. Singer, E.; Garcia, T.; Stover, S. Hoof position during limb loading affects dorsoproximal bone strains on the equine proximal phalanx. *J. Biomech.*, 2015, 48, 1930–1936.
4. Hill, A.E.; Gardner, I.A.; Carpenter, T.E.; Stover, S. Effects of injury to the suspensory apparatus, exercise, and horseshoe characteristics on the risk of lateral condylar fracture and suspensory apparatus failure in forelimbs of Thoroughbred racehorses. *Am. J. Vet. Res.*, 2004, 65, 1508–1517.
5. Amitrano, F.N.; Gutierrez-Nibeyro, S.D.; Schaeffer, D.J. Effect of hoof boots and toe-extension shoes on the forelimb kinetics of horses during walking. *Am. J. Vet. Res.*, 2016, 77, 527–533.
6. Kelleher, M.E.; Burns, T.D.; Werre, S.R.; White, N.A., 2nd. The immediate effect of routine hoof trimming and shoeing on horses' gait. *J. Equine Vet. Sci.*, 2021, 102, 103633.
7. Horan, K.; Coburn, J.; Kourdache, K.; Day, P.; Harborne, D.; Brinkley, L.; Carnall, H.; Hammond, L.; Peterson, M.; Millard, S.; Pfau, T. Influence of speed, ground surface and shoeing condition on hoof breakover duration in galloping Thoroughbred racehorses. *Animals*, 2021, 11, 2588.
8. Clayton, H.M. *The Dynamic Horse: A Biomechanical Guide to Equine Movement and Performance*. Clayton, H.M., ed. Sport Horse Publications: Mason, MI, USA, 2004.

9. Keegan, K.G.; Kramer, J.; Yonezawa, Y.; Maki, H.; Pai, F.; Dent, E.; Kellerman, T.E.; Wilson, D.A.; Reed, S.K. Assessment of repeatability of a wireless, inertial sensor-based lameness evaluation system for horses. *Am. J. Vet. Res.*, 2011, 1158–1163.
10. McCracken, M.J.; Kramer, J.; Keegan, K.G.; Lopes, M.; Wilson, D.A.; Reed, S.K.; LaCarrubba, A.; Rasch, M. Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation. *Equine Vet J.*, 2012, 44, 652–656.
11. Pagliara, E.; Marenchino, M.; Antenucci, L.; Costantini, M.; Zoppi, G.; Giacobini, M.D.L.; Bullone, M.; Riccio, B.; Bertuglia, A. Fetlock joint angle pattern and range of motion quantification using two synchronized wearable inertial sensors per limb in sound horses and horses with single limb naturally occurring lameness. *Vet. Sci.*, 2022, 9, 456.
12. Hagen, J.; Jung, F.T.; Brouwer, J.; Bos, R. Detection of equine hoof motion by using a hoof-mounted inertial measurement unit sensor in comparison to examinations with an optoelectronic technique - A pilot study. *J. Equine Vet. Sci.*, 2021, 101, 103454.
13. Hagen, J.; Bos, R.; Brouwer, J.; Lux, S.; Jung, F.T. Influence of trimming, hoof angle and shoeing on breakover duration in sound horses examined with hoof-mounted inertial sensors. *Vet. Rec.*, 2021, 189, e450.
14. Crecan, C.M.; Pestean, C.P. Inertial sensor technologies-Their role in equine gait analysis, a review. *Sensors (Basel)*, 2023, 23, 6301.
15. Parkes, R.S.; Weller, R.; Groth, A.M.; May, S.; Pfau, T. Evidence of the development of 'domain-restricted' expertise in the recognition of asymmetric motion characteristics of hindlimb lameness in the horse. *Equine Vet. J.*, 2009, 41, 112–117.

16. Asti, V.; Ablondi, M.; Molle, A.; Zanotti, A.; Vasini, M.; Sabbioni, A. Inertial measurement unit technology for gait detection: a comprehensive evaluation of gait traits in two Italian horse breeds. *Front. Vet. Sci.*, 2024, 11, 1459553.
17. Balch, O.K.; Clayton, H.M.; Lanovaz, J.L. Weight- and length-induced changes in limb kinematics in trotting horses. In Proceedings of the Annual Convention American Association of Equine Practitioners, Denver, CO, USA, 1996, 42, 218–219.
18. Singleton, W.H.; Clayton, H.M.; Lanovaz, J.L.; Prades, M. Effects of shoeing on forelimb swing phase kinetics of trotting horses. *Vet. Comp. Orthop. Traumatol.*, 2003, 16, 16-20.
19. Serra Bragança, F.M.; Brommer H.; van den Belt A.J.M.; Maree J.T.M.; van Weeren P.R.; Sloet van Oldruitenborgh-Oosterbaan M.M. Subjective and objective evaluations of horses for fit-to-compete or unfit-to-compete judgement. *Vet. J.*, 2020, 257:105454.
20. de Chiara, M.; Montano, C.; De Matteis, A.; Guidi, L.; Buono, F.; Auletta, L.; Del Prete, C.; Pasolini, M.P.; Agreement between subjective gait assessment and markerless video gait-analysis in endurance horses. *Equine Vet. J.*, 2025. doi: 10.1111/evj.14516.

Chapter 4: Final Comments

This thesis investigated the effects of changing horseshoe conditions on the swing phase of stride characteristics in healthy, sound horses by using hoof-mounted inertial measuring units and a gait mapping system to observe for changes in hoof and limb flight. The intent was to provide quantifiable data on the changes to limb flight and characterize the function of manipulating limb flight using horseshoes in a competition setting.

The experiment was designed to replicate the common practice of changing shoe characteristics between classes in an equine competition in order to achieve a more aesthetically pleasing limb flight. The theory behind this practice is that a more aesthetic limb flight would result in higher scoring by a subjective judge, however no data exists to determine the efficacy of the practice, nor to provide an insight into the ethics of such a perceived advantage within a competition.

The shoeing conditions were chosen for inclusion based on the most common practice seen in equine competition. Steel and aluminum are the most common materials used for horseshoes in equine athletes; aluminum representing a lighter option. These metal shoes were compared to a barefoot condition because the practice that has come under scrutiny involves horses shod in either steel or aluminum shoes are having their horseshoes pulled between classes under the assumption that a barefoot horse would likely have a more aesthetically pleasing gait and may have an advantage over the other competitors in the class.

The shoeing conditions were compared over asphalt to provide a firm, repeatable surface for observation and comparison; and compared over soft footing to replicate the show ring conditions.

Data obtained from the experiment demonstrated a direct correlation between horse shoeing condition and maximum arc height at both point a and b as measured by the inertial measuring units mounted on the dorsal hoof wall. The findings confirmed previous kinematic data that lighter weight, such as aluminum or barefoot, would result in a lower overall hoof flight due to changes in inertia. The study also demonstrated that lighter weight conditions would result in a greater arc height at point b, which would likely result in a more showy or aesthetic quality to swing phase. No changes were observed in symmetry of gait.

In conclusion, the current available literature in combination with the data collected from the experiment could be used to demonstrate the ways swing phase of stride can be manipulated using different shoeing conditions to improve the artistic quality of the stride. It presents the question of ethical concern over the current practice of pulling shoes mid-competition to achieve an advantage over competitors and could pressure governing bodies to revisit regulations regarding horseshoes in competitive equine athletes.