GROUND REACTION FORCE AND DORSOPLANTAR BALANCE IN MOTION

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ABSTRACT

Farriers often work with injured horses and constantly seek innovative ways to assist recovery while respecting the horses' anatomy. However, despite significant differences in anatomy and biomechanics between the limbs, shoeing strategies are frequently applied to the hind limb simply because those strategies have been proven effective on the front limb.

Theoretically, modifications that change the web width of a shoe alter how Ground Reaction Force (GRF) is dispersed on the foot and leg. This research focuses on the hind limbs, using shoe web width modifications and an understanding of GRF to change how the foot interacts dorsoplantar with the ground. The aim of this study is to demonstrate that changes in shoe web width will affect the distribution of GRF, influencing the floatation and penetration of the hind foot.

This study was organized into separate parts: GRF theory and real-world application. The pilot study utilized a press device developed specifically to test theory. Digital levels were used to calculate the degree of interaction of the foot in variable footings. The primary study involved 10 horses, with a total of 320 measurements collected. Of these, 120 measurements were relevant to the hind limb and were taken in soft footing. Measurements were only taken in soft footing because the GRF modifications being applied are designed to influence GRF on deformable surfaces.

Measurements were taken with the Hoof Beat. This equipment has 4 sensors that attach to the hooves, each including a gyroscope and 2 accelerometers. The results of both studies were conclusive and ultimately supportive of the hypothesis.

DECLARATION

I hereby declare that the work within this Fellowship dissertation is my own. Any sources have been duly referenced and any illustrations or diagrams that are not mine are used with permission of the owner.

Signed by the candidate.

Word count 5,184 (includes the main body of text without the Abstract, figures, tables, Contents, References, Manufacturers and Appendices.)

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INTRODUCTION

Ground reaction force has been studied in horses by several researchers, including Dr. Hillary Clayton and Dr. Jenny Hagen. Researchers have explored how the limbs interact with the ground, but not much has been studied about how modifications on the GRF of the shoe would affect the interaction between the foot and the footing on live horses.

THE AIM & HYPOTHESIS

This thesis examined 3 situations: a control, a wide-toe suspensory shoe, and a wide euro-style bar shoe. The aim of the study was to demonstrate that flotation of different parts of the hind foot could be achieved through shoe modifications affecting the Ground Reaction Force (GRF). The hypothesis was that altering the web width or section of the shoe would change the way the foot interacted with the footing and, consequently, affect GRF distribution on that foot.

BACKGROUND

Farriers must understand key biomechanical and anatomical principles of the hind limb, particularly the reciprocal apparatus (RA), which influences their ability to affect the limb. The RA consists of the Superficial Digital Flexor tendon on the caudal aspect and the Peroneus Tertius on the cranial aspect of the hind limb. The Peroneus Tertius, located on the cranial aspect of the limb, is smaller and originates at the cranial distal femur, inserting into the dorsoproximal aspect of the 3rd metatarsal bone and the 3rd and 4th tarsal bones. The Superficial Digital Flexor tendon originates from the distal 3rd of the femur and inserts on the calcaneal process of the calcaneal bone at the tarsus (Sisson and Grossman, 1953).

The RA creates a situation in the hind limb where flexion or extension of one joint causes all joints to flex or extend. Although the metatarsophalangeal joint is less affected than the hock or stifle, it remains part of the RA. Consequently, changes to GRF and trimming strategies on the hind foot do not always produce the desired limb adjustments. Altering foot balance on the dorsoplantar plane directly impacts hind limb posture, as supported by Sharp and Tabor's study, which found that hoof balance influences hind limb orientation (Sharp and Tabor, 2022).

During the stance phase of the stride the foot exerts a force against the ground, and according to Newton's 3rd law of motion, the ground exerts a reaction force against the hoof that is equal in magnitude and acts in the opposite direction (Back and Clayton, 2013). The GRF comes from the interaction between the feet and the ground (Smith, 2020).

Ground Reaction Force (GRF) is influenced by factors such as foot balance, speed, weight, shoe presence, and footing type (Clayton, H., 2019). Adjusting the shoe's web width or adding a wedge alters how the foot interacts with the footing, affecting GRF distribution. This study examines the interaction between different shoe modifications and footing, focusing on their impact on GRF.

Balance is critical to performance. The basic trim is the most significant aspect of proper farriery (Baxter and O'Grady, 2011, p. 1186). The same evaluation techniques used for front limbs are often applied when balancing hind limbs. The problem is that the anatomy is different, and the way fronts and hinds work is different. In consequence, the way to achieve balance would be different. On the hind end, it is impossible to see the foot in the air in a weight bearing situation. This is due to the reciprocal apparatus. Since the flexion of the stifle affects the degree of flexion in the hock and fetlock of the hind limb, picking up the hind foot causes the fetlock to fold, altering how the hoof's solar surface aligns with the leg's axis. The appropriate method to evaluate balance on the hind feet is to stand in front of the leg with the foot on the ground. How the foot bears weight is the most important consideration when determining how to balance a foot (Gregory, 2011, p. 232) (Curtis, 2002, p.112). It is generally agreed that a horse is balanced when it lands flat. Regardless of the method used to achieve this, a flat landing is often considered a sign of balance. (Cody Gregory, personal communication, 18 July 2023).

Biomechanics and conformation are related to one another. The way a horse is built influences how the legs are loaded, how the horse moves and, in part, how well the horse can perform. Conformation refers to the physical appearance and outline of a horse, as dictated primarily by bone and muscle structures (Baxter and O'Grady, 2011, p. 73). Conformation has been regarded as an important indicator of performance and soundness (Back and Clayton, 2013). The effects of conformation on lameness and athletic potential have mostly been evaluated subjectively and based on anecdotal evidence or experience of the observer (Were and Denoix, 2006, cited in Equine Locomotion-Second Edition, p. 229).

Shoe attributes and selection are vital in therapeutic cases, as modifying forces around the center of pressure is a key strategy for treating lameness. The Center of Pressure (COP), defined as the point where GRF is applied beneath the solar surface of the hoof, is closely tied to GRF dynamics (Clayton and Hobbs, 2019, p. 5). Changes to a shoe's web width logically alter how GRF is distributed across the foot and limb. Understanding these concepts equips farriers with trimming and shoeing techniques to maintain soundness in healthy horses and rehabilitate lame horses.

STUDY DESIGN

This study was based on several key assumptions that supported the hypothesis. Hard surfaces were assumed to prevent the foot from sinking, meaning modifications to the web width of the horseshoe would not affect the Ground Reaction Force (GRF). In contrast, soft surfaces were expected to allow shoes with varying web widths to either sink or float, resulting in measurable variations in GRF. Specifically, increasing the web width of the toe on shoes, such as the suspensory shoe, was predicted to reduce toe sinking and increase heel sinking when the foot was on soft ground. This effect was analogous to a reverse wedge or a dorsal elevation of the hoof. Conversely, a bar shoe with a wide web on the bar, like the European-style bar shoe, was expected to keep the heels in contact with the surface while the toe "floated" on soft ground, creating a mechanical plantar wedge and elevating the heel.

The study was structured in 2 distinct phases: an "in vitro" pilot study testing GRF theory and an "in vivo" real-world application study involving live horses. The pilot study focused on isolating the effects of the shoes by eliminating the variables introduced by a live horse. A hydraulic press and a wooden foot model mounted on a steel swivel were used to replicate the load and movement of a hoof across various surfaces, ensuring results reflected the shoe's physical properties. Angle changes were measured using digital levels (see Figure 1) (Coobeast, 2021). This method was chosen over the use of a frozen foot to focus exclusively on the shoe's performance. Casting impressions taken from the press model and live horses in the primary study were found to be very similar, validating the model's accuracy in replicating hoof mechanics.

The 2nd phase, the primary study, involved 10 horses ridden in a dirt arena and on an asphalt road. This sample size was selected to generate 40 data points per shoe per gait, providing a statistical power of 83.585% at a 95% confidence level (with the power expected to exceed 80%). The power calculation was based on an ANOVA test standardized for Kruskal-Wallis (Chaparro M., 2024). Once the statistical power was established, the data was analyzed using the non-parametric Kruskal-Wallis test.

Data collection was carried out using the Hoof Beat System (see Figure 2), which consisted of 4 sensors attached to each hoof. The sensors included a gyroscope and 2 accelerometers to capture precise data, which was then processed and displayed by a software application (Werkman, C., 2024).

FIGURE 1: The wooden hind foot being readied for the press using two digital levels (see Appendix 1).

FIGURE 2: The Hoof Beat sensors on a test horse (see Appendix 1).

These 2 complementary studies allowed for the evaluation of both an ideal controlled environment and a real-world approach with live horses. Controlling variables on live horses was inherently complex and required consideration of factors such as weather and rider weight. The pilot study ultimately yielded valid, comparable data and supported the primary study by isolating the effects of the shoe without the influence of the horse.

MATERIALS & METHODS

PILOT STUDY

The initial phase of the study was conducted "in vitro" using a hydraulic press and a wooden foot model. The wooden model foot was designed with an articular joint, allowing it to move freely under pressure and simulating natural movement. The press was used to eliminate the variable of the horse, enabling the physics of the shoes to be tested independently. This approach determined the extent to which anatomy influenced the practical functionality of the shoes. This distinction was important because the relationship between horses and shoe selection was theorized to be heavily influenced by the horse's anatomy. Ultimately, 3 different shoes were tested, each secured to the model using the 3rd nail on each side of the shoe. The test shoes included an open-heel shoe as the control, a wide European-style bar shoe, and a Suspensory Shoe. The specifications for these shoes are detailed as follows.

The control shoe was a 3/4 fullered steel size 0 Kahn Forge "Certifier." This shoe had a 10 mm x 19 mm uniform section (see Figure 3).

FIGURE 3: The Khan Forge 'Certifier' was the control shoe (see Appendix 1).

The European-style bar shoe was a handmade bar shoe forged by Emilio Giannotti, AWCF. The final section dimensions were 10 mm x 19 mm, with the bar width being twice the width of the toe. The toe featured a concave inner edge to allow penetration into the footing.

FIGURE 4: The European style bar shoe used for testing (see Appendix 1).

The final shoe was an aluminum Grand Circuit Suspensory Hind Shoe. A commercial shoe of this type was used to maintain the ratios between the toe, branches, and heel. It featured a wide toe and narrow branches.

FIGURE 5: The Grand Circuit Suspensory Hind Shoe shoe used for testing (see Appendix 1).

PILOT STUDY PROCEDURE

The shoes were fixed to a hand carved wooden hind foot using a nail on each side. A swivel was placed on the center of the leg side of the wood foot and fitted on the press (see Figure 6).

FIGURE 6: The wooden hind foot with a swivel joint attached to the leg side (see Appendix 1).

All shoes were tested on 2 different footings. For each measurement, 1,043 kilograms of pressure was applied for 6 seconds, repeated 4 times per shoe. The measurements were highly consistent, so only 4 repetitions per shoe were required to ensure reliable data. The conditions were chosen to match the point of footing yield, creating footprints similar to those observed in a live arena with the same surface type (see Figure 7).

FIGURE 7: Casted footprints from the press test showing penetration depth (see Appendix 1).

The dirt footing used for the press was sourced from the same arena as the "in vivo" study, while the synthetic footing was obtained from a Kruse Cushion Ride all-weather arena (2024). Each footing was placed in a clear plastic container and reworked after each measurement to reset the test conditions.

The measurement device included 2 Coobeast digital angle gauges, each magnetically attached to a welded swivel strut. These precise tools measured angles up to 360°/4×90° and displayed values on an LED screen, automatically adjusted for accuracy. One gauge recorded dorsoplantar angle changes, while the other measured medial-lateral angle changes with the footing (Coobeast, 2021).

The "in vitro" portion of the study aimed to compare these measurements with those from the live horse study. Using the hydraulic press eliminated individual animal variables, which was essential for isolating the shoe’s effects. This approach clearly demonstrated how shoes with different GRF modifications performed under controlled pressure conditions, offering valuable insights into their mechanical behaviour.

LIVE HORSE STUDY PROCEDURE

The primary study involved live horses, with each horse fitted with all 3 shoe types. The shoes were secured using heel nails on each side, ensuring consistency by using the same nail hole for each shoe. Data was collected using the Hoof Beat System, a commercial sensor system designed to measure locomotion.

The Hoof Beat System included sensors equipped with accelerometers and gyroscopes. Accelerometers measured motion changes, specifically the foot's acceleration in different directions, while gyroscopes recorded the hoof's orientation and rotational movement during each stride. These sensors were secured to the hooves using durable hook-and-loop fasteners. Data collected by the sensors was processed using software developed by Werkman Horseshoes Company, which graphed the information to measure changes in foot dynamics. A key feature of the software, the Motion Map, graphically represented the interaction between the foot and the footing, displaying data in degrees. To ensure valid measurements, the horse completed at least 20 strides at each gait and on each surface. The software analyzed the data and provided median values for timing and angles during different phases of the stride (Hoof Beat System, 2019). The Hoof Beat System was chosen for this study due to its availability and practicality in real-world field settings.

American Quarter Horses were chosen for the study to ensure consistency in gait, foot size, and disposition. The horses ranged in age from 5 to 21 years, with an average age of 10 years. All measurements were conducted at Heartland Horseshoeing School in Lamar, Missouri. To minimize variables, the same rider and tack were used for all trials. Each horse walked and trotted on both hard and soft surfaces with each shoe type applied. However, only measurements on soft footing were deemed relevant, as the shoe modifications did not affect performance on hard surfaces. The sample included 10 horses, yielding n=40 data points per shoe and gait.

The arena used for the study was worked and dragged with a tractor to provide fresh footing for each measurement. It was reconditioned after each horse was ridden to ensure every measurement was taken on an undisturbed path. The trimming and balancing of the horses' hind feet followed the criteria outlined by Chris Gregory (Gregory, 2011, p. 232). Medio-lateral balance was assessed by standing in front of the tarsus and observing the plumb line from the stifle joint, while dorso-plantar balance was evaluated from the horse’s side (Hood, 2006, p. 7). Shoes were replaced after every 4 measurements, and data was downloaded to the Hoof Beat software on a tablet after each measurement.

Each horse was required to take at least 20 steps at both the walk and the trot to ensure valid measurements, as per the Hoof Beat System requirements (Hoof Beat System, 2019). The measurements always began with the horse standing still to ensure consistency in data collection.

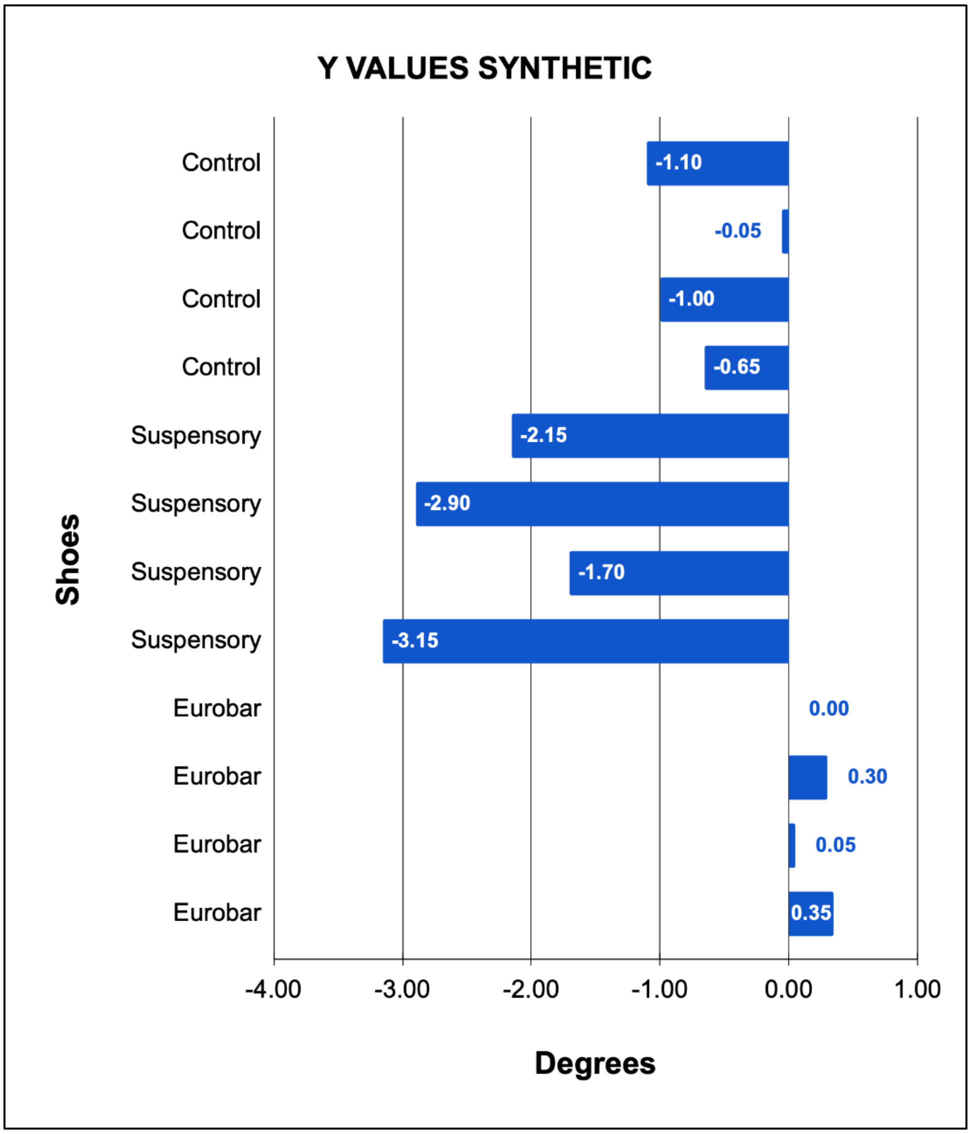
DATA ANALYSIS AND RESULTS

For both parts of the study, the same operators collected the data. The data was manually extracted from the Hoof Beat System and checked by 2 people by hand for accuracy. It was then digitally transcribed to Google Sheets by a 3rd person for further analysis (Google LLC, 2024).

After the data was entered into Google Sheets for processing and analysis, the left and right legs were treated as equivalent for measurement purposes. Previous studies have shown that the left and right legs are comparable in terms of biomechanical measurements (Hagen, 2021). A total of 10 horses were measured, with each horse assessed twice for each of the three shoe types—control (open heel), European-style bar shoe, and Suspensory shoe—at both the trot and the walk. This resulted in 60 measurements in total for each gate. Since the left and right legs were considered the same, this provided 120 data points for each gait, leading to a sample size of N=40 for each shoe type on each surface at each gait. With N=40, the dataset was considered to have sufficient statistical power for reliable statistical evaluation. (Chaparro M., 2024).

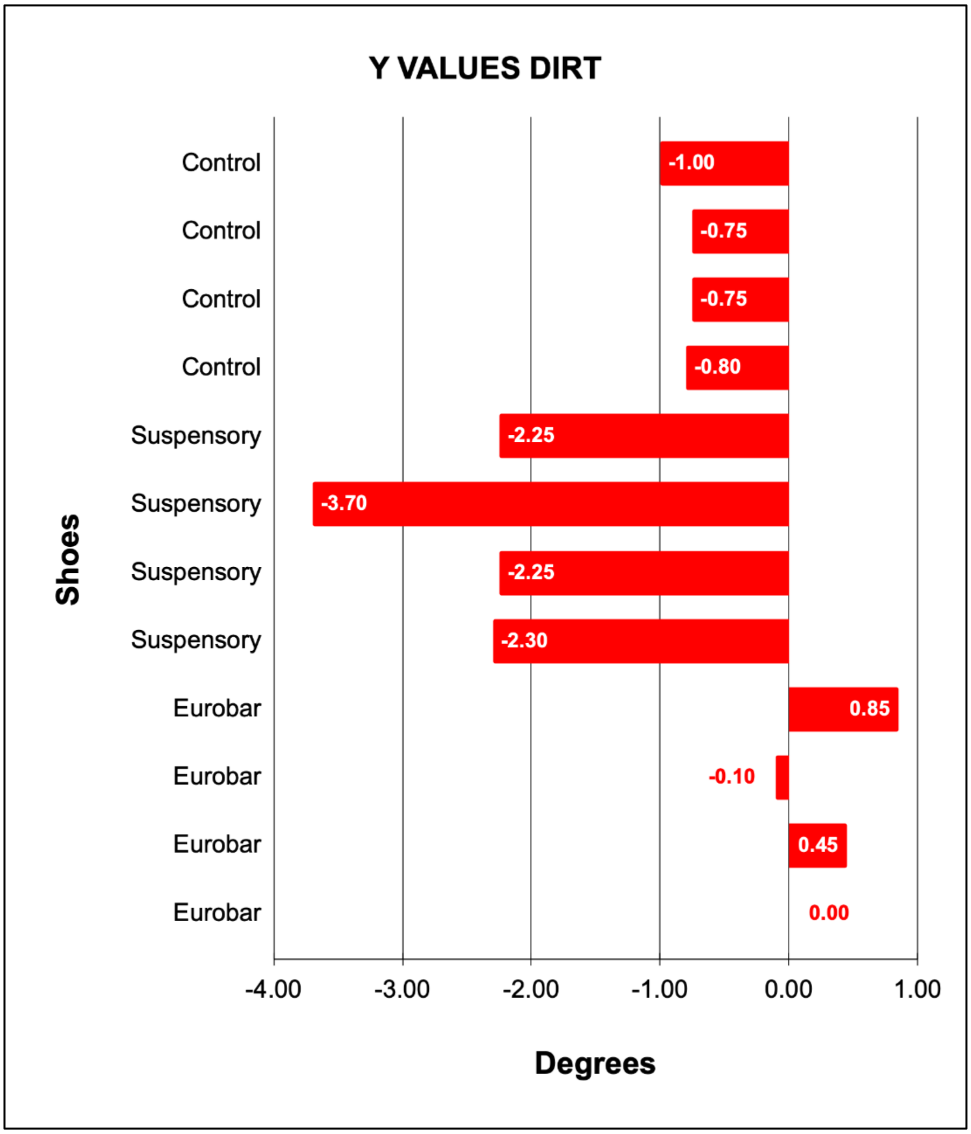
The pilot study provided a reference to test the physics of GRF on different mediums without the additional variable of the horse. Negative values, in the context of graphs, refer to the amount of heel sinkage on the dorsoplantar axis. Positive values reflect degrees of heel floatation. Rephrased, the negative values represent plantar penetration, while the positive values show toe sinkage.

Refer to Graph 1 for synthetic footing comparisons from the pilot study. The suspensory shoe demonstrated greater plantar sinkage on synthetic footing compared to the control shoe. In contrast, the euro-bar shoe exhibited no plantar sinkage, instead "floating" on the surface under load. The mean plantar sinkage values were -0.7° for the control shoe and -2.475° for the suspensory shoe, while the euro-bar shoe showed 0.175° of dorsal sinkage.



Graph 1: *A graph illustrating pilot study dorsoplantar values for synthetic footing. Negative numbers refer to heel sinkage, positive to toe sinkage (see Appendix 1).*

Refer to Graph 2 for press result comparisons on dirt arena footing. The suspensory shoe demonstrated significantly greater plantar sinkage than the control shoe, while the euro-bar shoe exhibited no plantar sinkage and slightly increased dorsal sinkage. The mean plantar sinkage values were -0.825° for the control shoe and -2.625° for the suspensory shoe, with the euro-bar shoe showing a mean dorsal sinkage of 0.3°.



Graph 2: *A graph illustrating pilot study values for dirt footing. Negative numbers refer to heel sinkage, positive to toe sinkage (see Appendix 1).*

Summarily, the press data supports the hypothesis; altering the web width of the shoe or section changes the way that the foot interacts with the footing, directly affecting GRF distribution on that foot.

In synthetic footing, the suspensory shoe averaged 1.7° of heel sinkage, relative to the control, and an average of 1.8° in the arena footing. Comparatively, the euro-bar gained an average 0.875° of heel floatation in synthetic footing, and an average of 1.125° in dirt. The difference in degrees demonstrates how the modification of the GRF on the shoes works compared to the control or normal shoe.

In the primary study, the sample size was n=40 for each shoe, surface, and gait. Derived from a total of 240 measurements (walk and trot), each horse provided 24 hind shoe measurements. Each horse underwent 2 measurements per shoe for each gait, considering the left and right sides as equal. The surface tested was the same dirt arena footing as the pilot study. For data final collection, 3 critical data points were transcribed from the Motion Map of the Hoof Beat. The original data consisted of X and Y coordinates, where X represents degrees of change towards medial or lateral, and Y represents degrees of change dorsal or plantar. The data points were specifically taken from the landing phase to the beginning of breakover in the stride. During data analysis, it was noted that 2 data points for the control group and 2 for the Suspensory LBy were missing. This was due to an error during field data collection. These missing points were considered part of the accepted margin of error, and the analysis proceeded without including these data points.

Using the Motion Map the following points were transcribed. Point 1 “Landing Point”; the 1st point of hoof loading after contact with the ground. Point 2, also referred to as “Point Z”; the furthest point the foot rotates plantarly. Point 3 “Breakover Point”; the transition of the stance phase into the break over phase (see Figure 7).

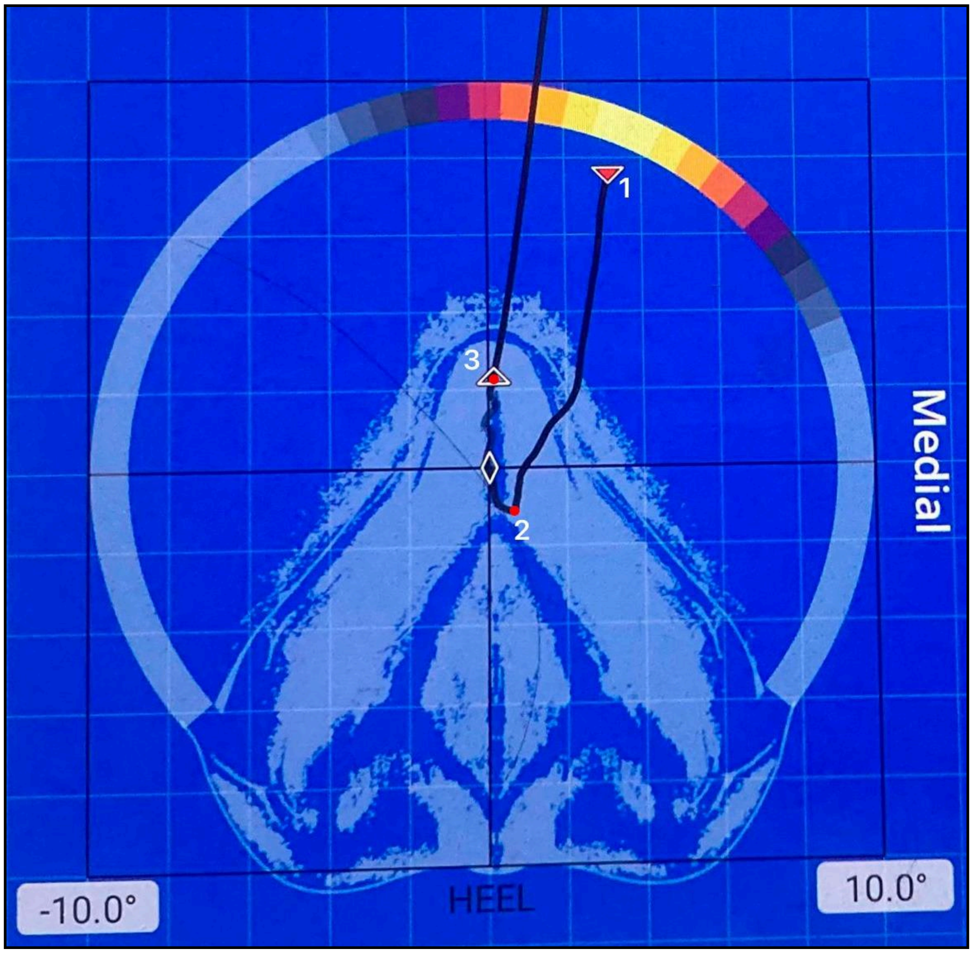


FIGURE 7: *A screenshot of the Motion Map on the Hoof Beat.*
The numbered points are referenced in the paragraph below (see Appendix 2).

Next, it's important to understand how the data is distributed. Data can be classified as either parametric or nonparametric. Parametric data follows a normal distribution, often represented as a bell curve (called a Gaussian curve), where the mean and median tend to be identical (Chaparro M., 2024). Nonparametric data, on the other hand, does not follow a normal distribution, and in these cases, the mean and median are different. Nonparametric data is often encountered in studies involving animals, as variability is expected due to the differences in movement between individual animals. Nonparametric data is less affected by outliers—extreme values that would otherwise skew the results in parametric data.

For this study, the Kruskal-Wallis test was applied to the data. This test is specifically designed for nonparametric data and was recommended by the professional statistician overseeing the project, Dr. Mauro Chaparro. The Kruskal-Wallis test helps determine whether there are significant differences between the groups being studied. After performing the Kruskal-Wallis test, the next step is to evaluate the null hypothesis. The null hypothesis suggests that there is no difference between the groups being compared. For the null hypothesis to hold, the data must show 95% confidence, meaning that 95% of the results should be similar across the datasets. If the p-value from the test is greater than 0.05, it indicates no significant change compared to the control group. If the p-value is below 0.05, this suggests a statistically significant difference between the groups, indicating that the null hypothesis does not hold.

When the p-value is less than 0.05, the post Hoc Dunn test is applied. This test is used to further analyze the data and identify where significant differences lie between the groups. It helps pinpoint specific pairs of datasets that differ from one another, providing more detailed insights into which variables are driving the observed differences. The lower the p-value, the greater the evidence that a meaningful difference exists between the groups being compared, supporting the hypothesis that the shoe types or other experimental conditions influenced the results.

While evaluating the following tables, it is important to remember that any results below the threshold p-value of 0.05 show a statistically significant change from the behavior of the control shoe.

In scholarly contexts, delta (Δ) typically represents a difference or change in a specific variable. For example, in mathematics and science, it often signifies the change in a quantity, such as Δy for a change in the variable “y” (Day, 1981; Morgan, 1970).

The landing phase of a hind foot begins when the foot first contacts the ground, which is measured by the Hoofbeat system as the initial point of deceleration. Following this, the foot enters the stance phase, during which the heels sink into the ground. As the horse propels itself forward, the foot rotates dorsally, and the toe sinks into the medium just before the breakover phase begins. In this context, the deltas represent the movement of the foot upon ground contact, capturing the changes in both position and rotation throughout the landing and stance phases.

Delta LBy specifically measures the plantar sinking of the heels after landing. It is calculated as the difference between the 1st point of contact and the deepest point the foot sinks into the ground. This delta reflects the extent to which the heel penetrates the surface under the horse's weight during the stance phase.

Delta Z captures the dorsal rotation of the foot before breakover starts. It measures the rotation of the foot around its dorsal axis, which occurs after the heel sinks but before the hoof leaves the ground during the breakover phase.

Table 1: *The results for the Kruskal Wallis Test for soft ground, walk and trot (see Appendix 1).*

DELTA	TROT	WALK
ΔLBy	p - value = 0.0007236	p – value = 0.002
ΔZ	p – value = 0,001398	p – value < 0.0001

Table 2: *Results for the post Hoc Dunn Test for soft ground, trot (see Appendix 1).*

TROT COMPARISON	Δ L β γ	Δ Z
Control vs Euro-bar	0.004	0.005
Control vs Suspensory	1	1
Euro-bar vs Suspensory	0.002	0.005

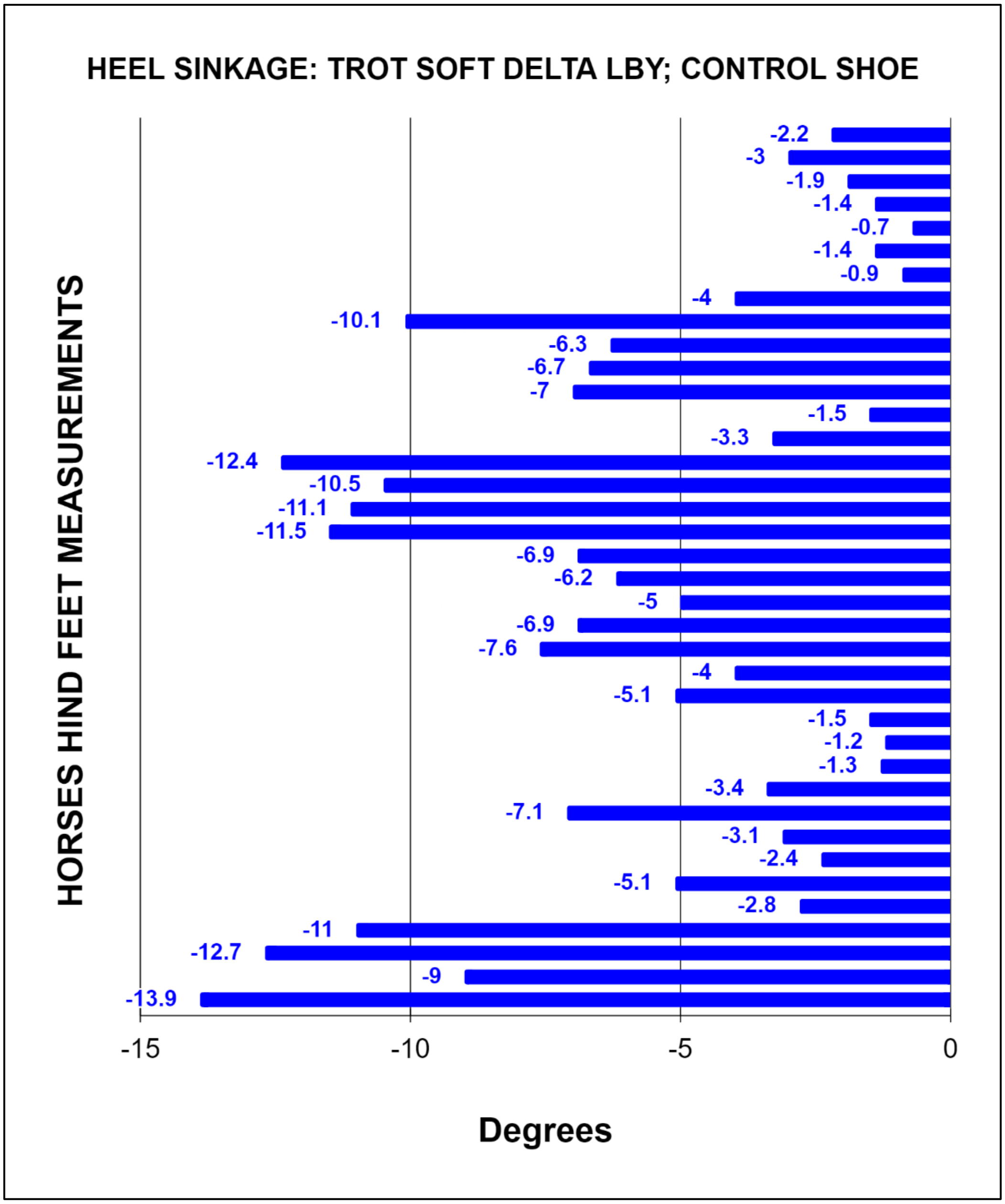
Table 3: *Results for the post Hoc Dunn Test for soft ground, walk (see Appendix 1).*

WALK COMPARISON	Δ L β γ	Δ Z
Control vs Euro-bar	0.01	> 0.0001
Control vs Suspensory	1	1
Euro-bar vs Suspensory	0.0005	> 0.0001

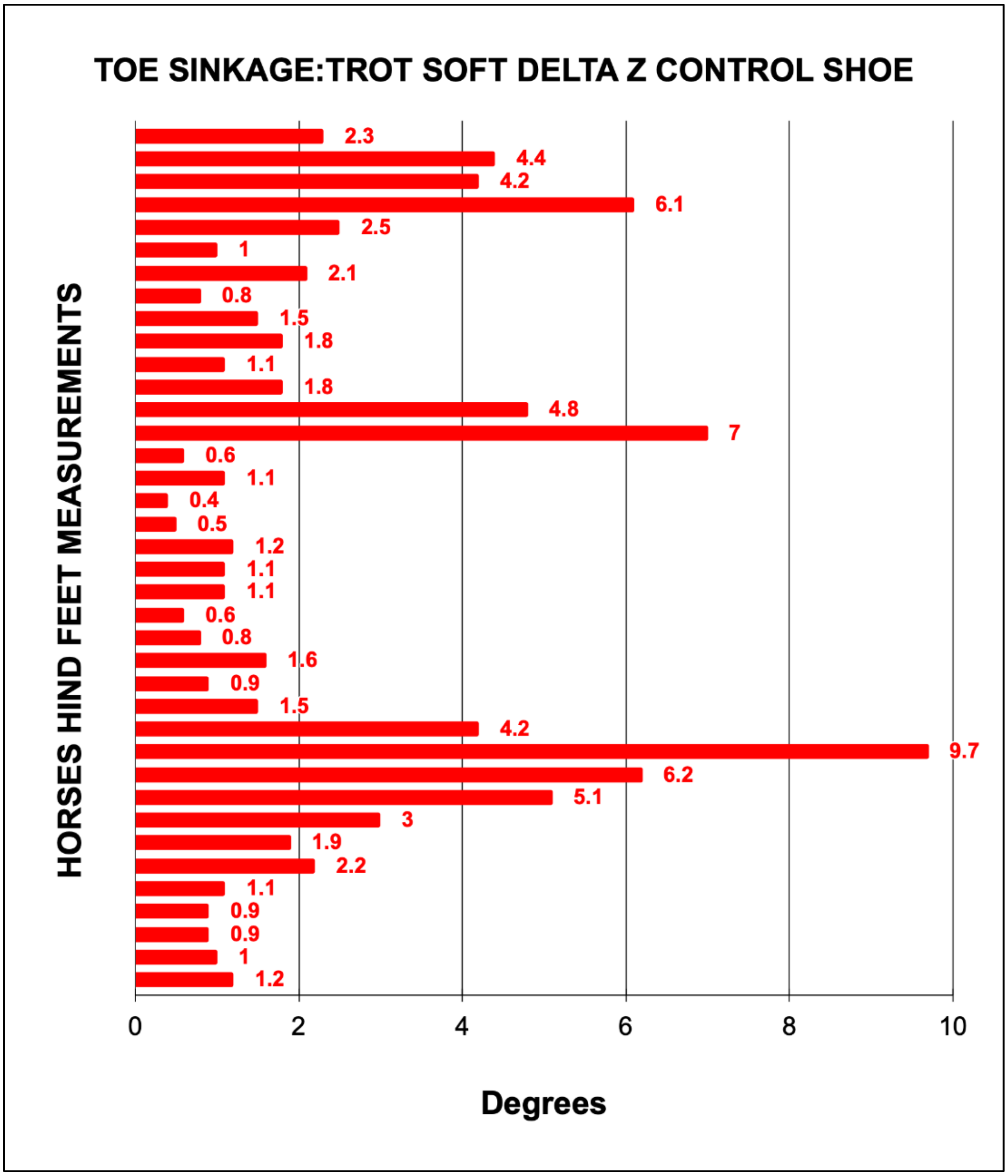
With these results, it can be inferred that the control and suspensory shoes are statistically similar. However, the euro bar shoe exhibits a statistical divergence that is present in both gaits.

TROT COMPARISONS

Graphics 3 and 4 illustrate the behavior of the control shoe at the trot on live horses. The blue bars indicate the heel sinkage, Delta LBy, after the initial point of loading, while the red bars represent the dorsal movement, Delta Z, of the foot before the breakover begins.

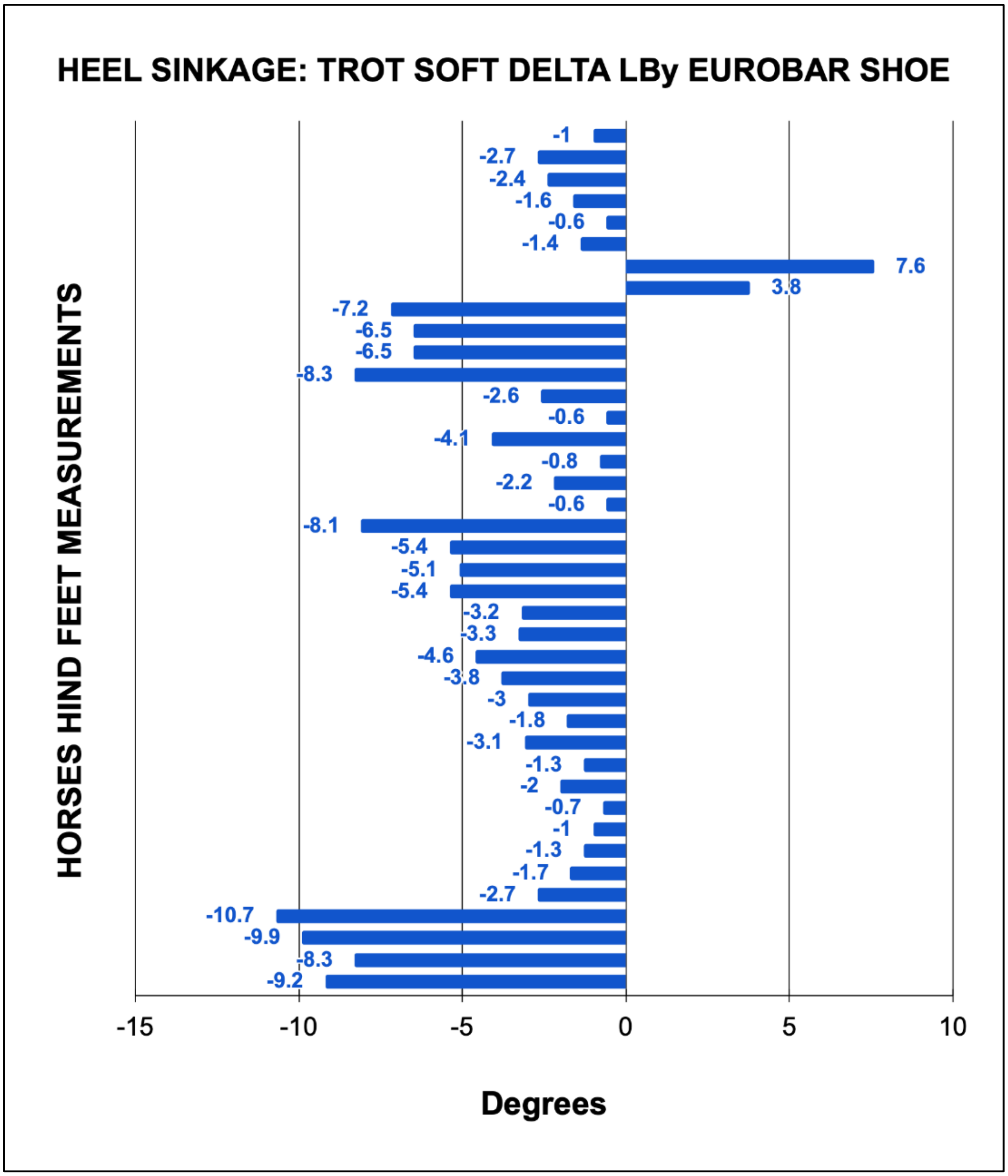


Graph 3: *Heel sinkage measurements of the control shoes across all feet on all horses (see Appendix 1).*

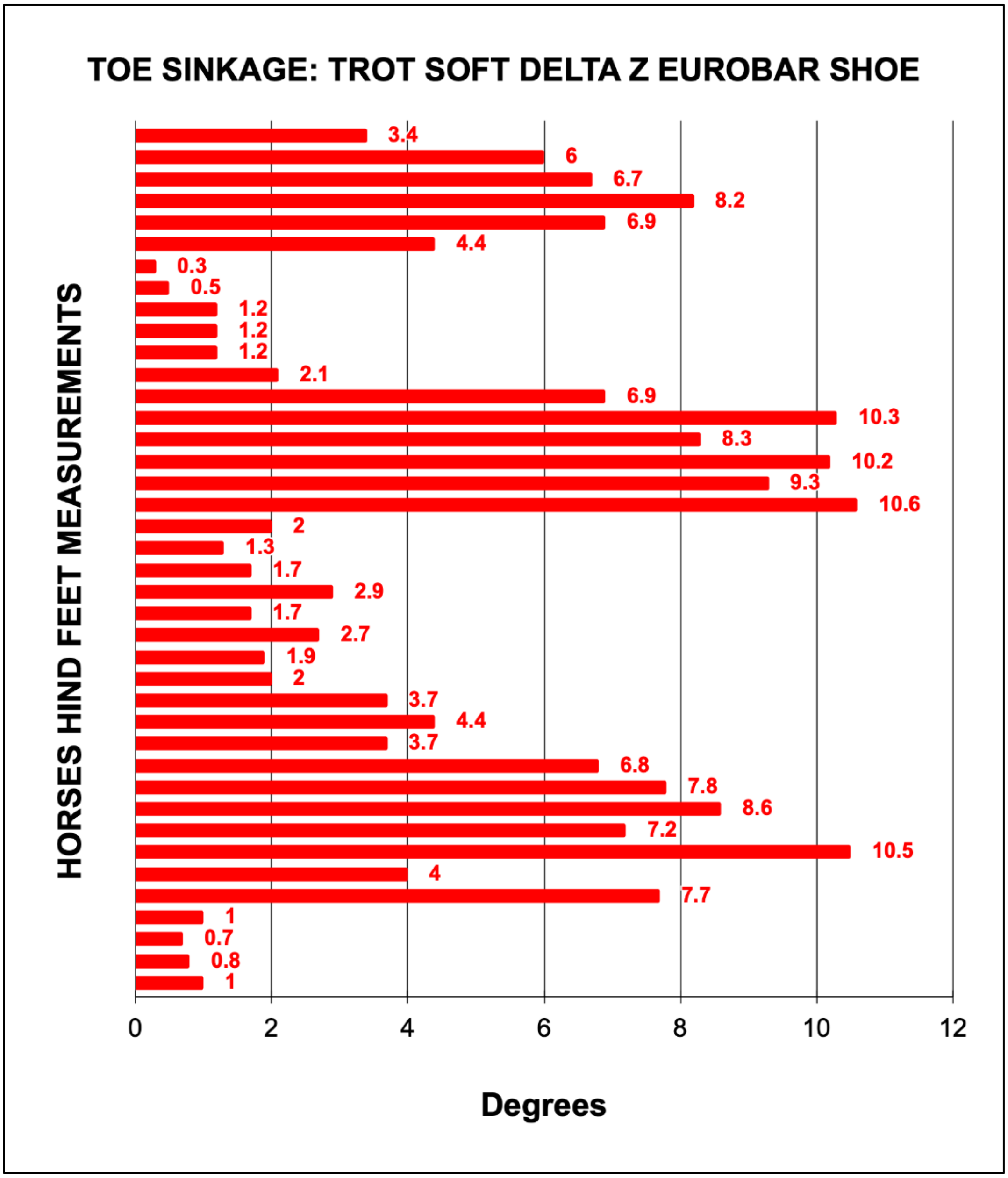


Graph 4: *Toe sinkage measurements of the control shoes across all feet on all horses. (see Appendix 1).*

Graphics 5 and 6 illustrate the euro-bar shoe's action, showing 2.25° less plantar sinkage at the trot compared to the control shoe. The Delta LBy indicates significant dorsal sinkage at the toe. On average, the euro-bar shoe provides 1.89° more heel flotation than the control shoe across all horses.

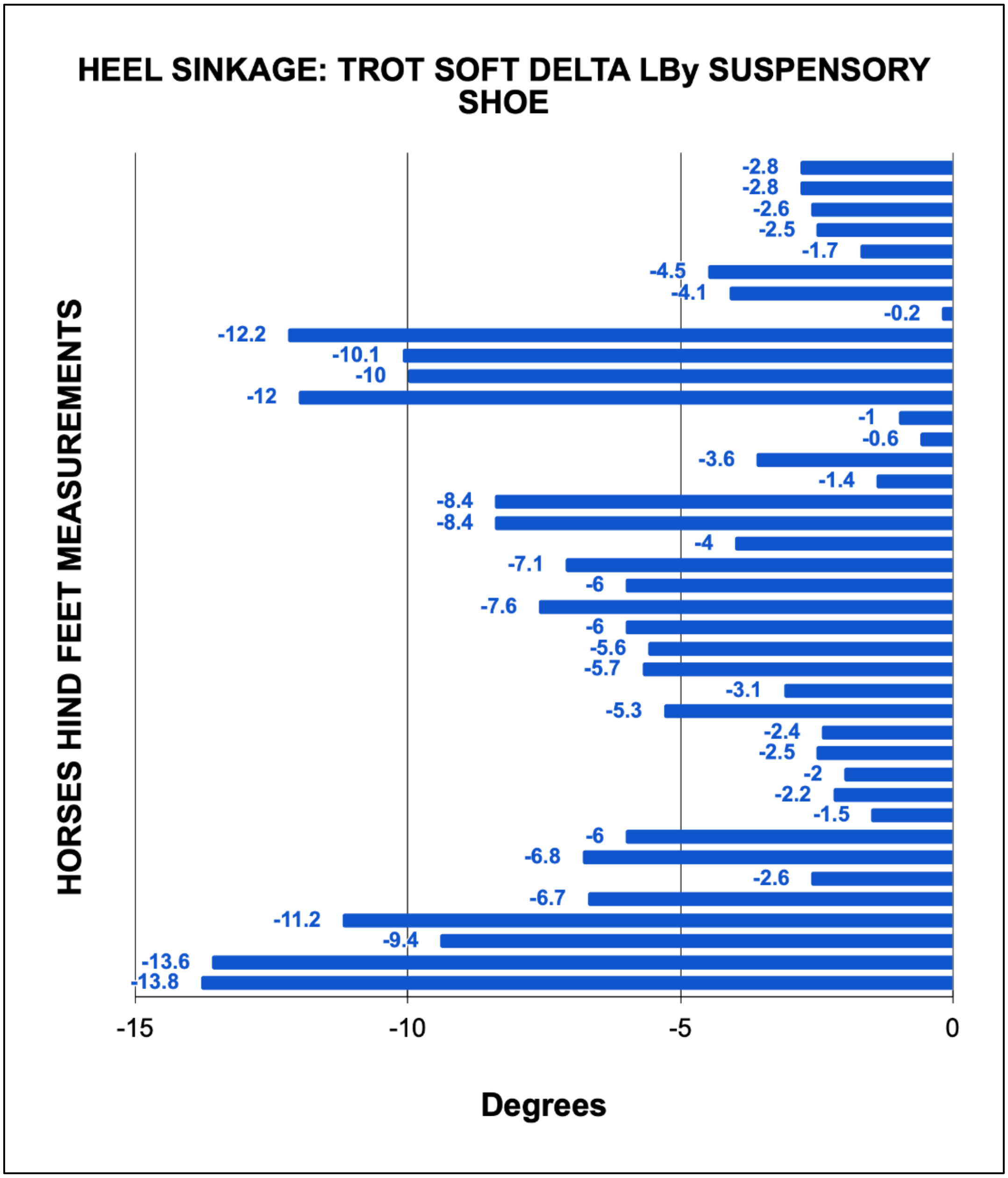


Graph 5: *Heel sinkage measurements of the euro-bar shoes across all feet on all horses (see Appendix 1).*

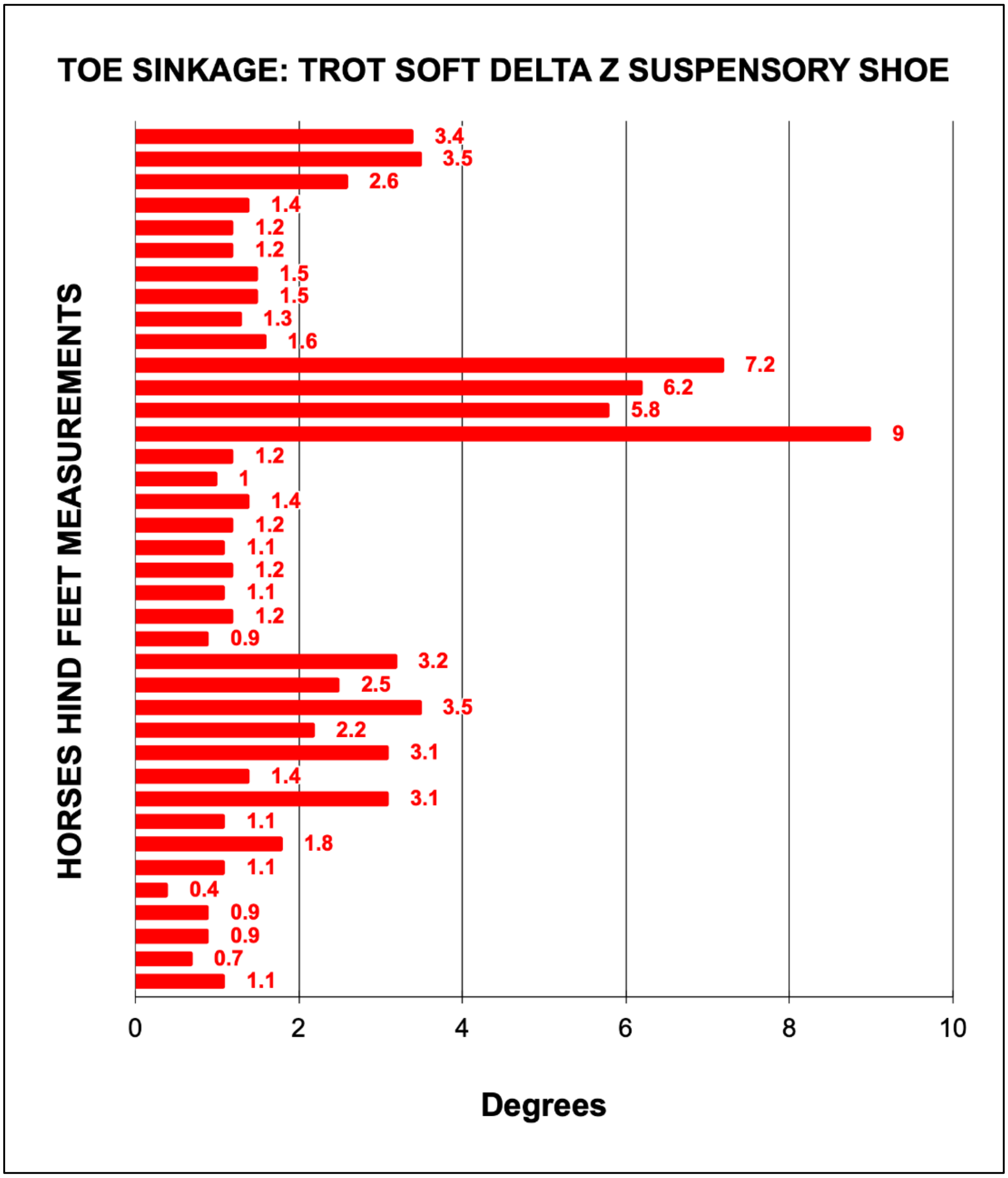


Graph 6: *Toe sinkage measurements of the euro-bar shoes across all feet on all horses (see Appendix 1).*

Graphics 7 and 8 show the performance of the suspensory shoe, which differs minimally from the control. On average, it has 0.08° less heel sinkage and 0.11° less toe sinkage than the control.



Graph 7: *Heel sinkage measurements of the suspensory shoes across all feet on all horses (see Appendix 1).*



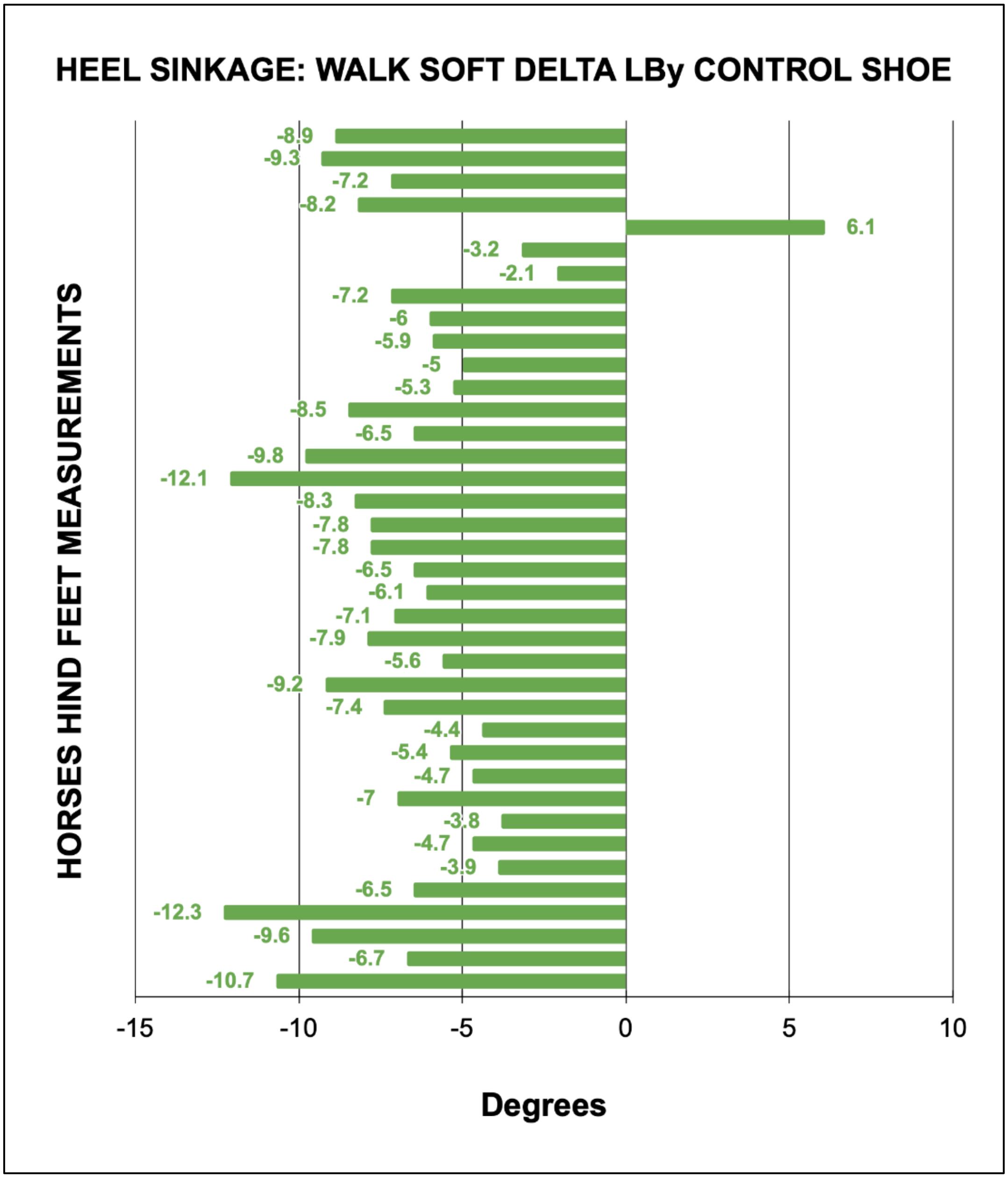
Graph 8: *Toe sinkage measurements of the suspensory shoes across all feet on all horses (see Appendix 1).*

After evaluating the mean values, the control and suspensory shoes show insignificant variance: -5.58° for the control versus -5.5° for the suspensory shoe on Delta LBy. A minimum difference of 0.5° was required to be considered significant (Chaparro

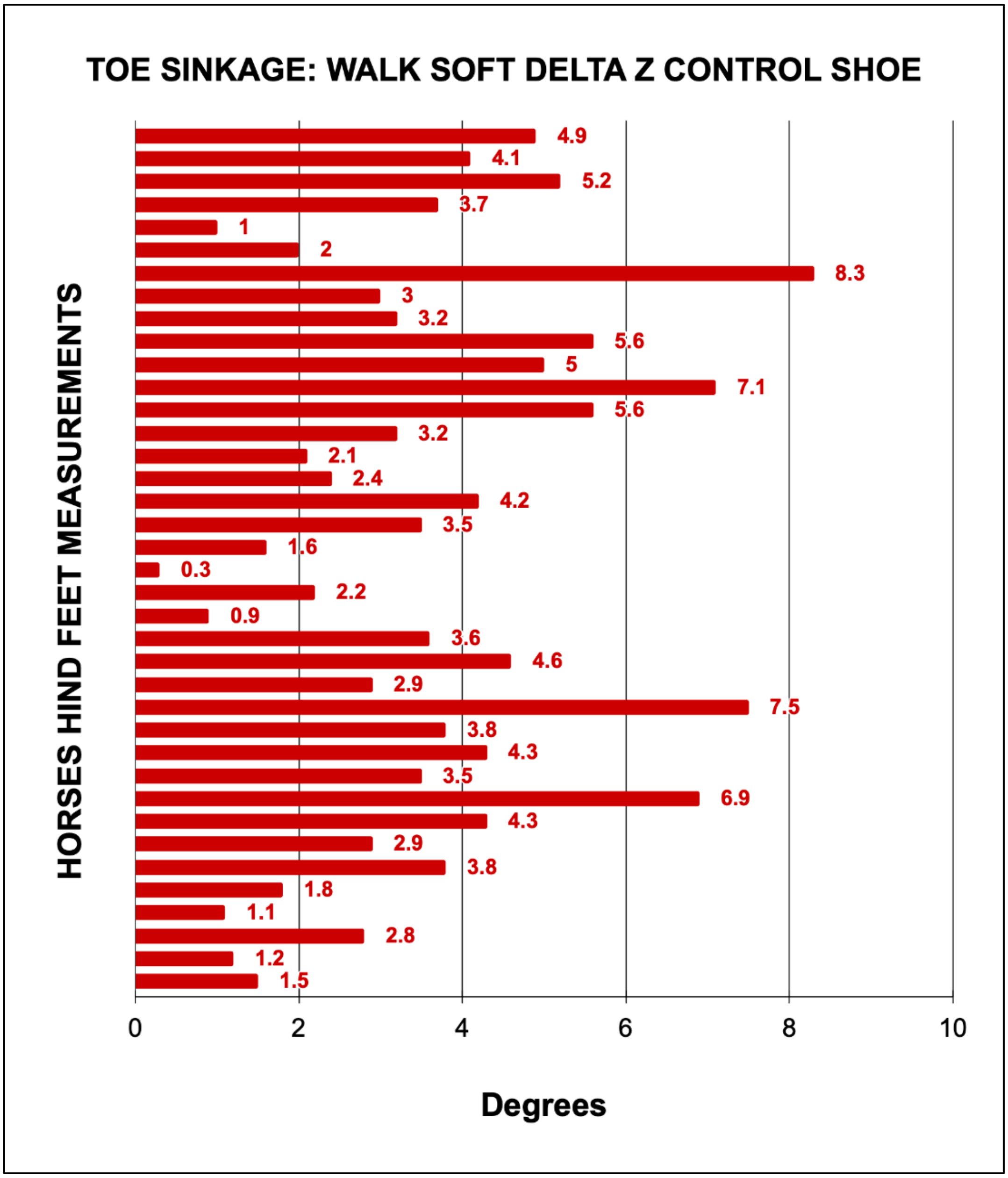
M., 2024). For Delta Z, the control measured 2.37° and the suspensory 2.23°, differing from the press results where the suspensory shoe's GRF modification performed as expected under straightforward pressure. The euro-bar shoe, with a median of -2.7° for Delta LBy and 3.7° for Delta Z, aligns with the press results, demonstrating its ability to float the heels and prevent plantar rotation after ground contact.

WALK COMPARISONS

Graphics 9 and 10 show the behavior of the control shoe during the walk. Graph 9 indicates the normal plantar sinkage of the foot after the initial point of loading, while Graph 10 represents the dorsal rotation of the foot before the breakover phase.

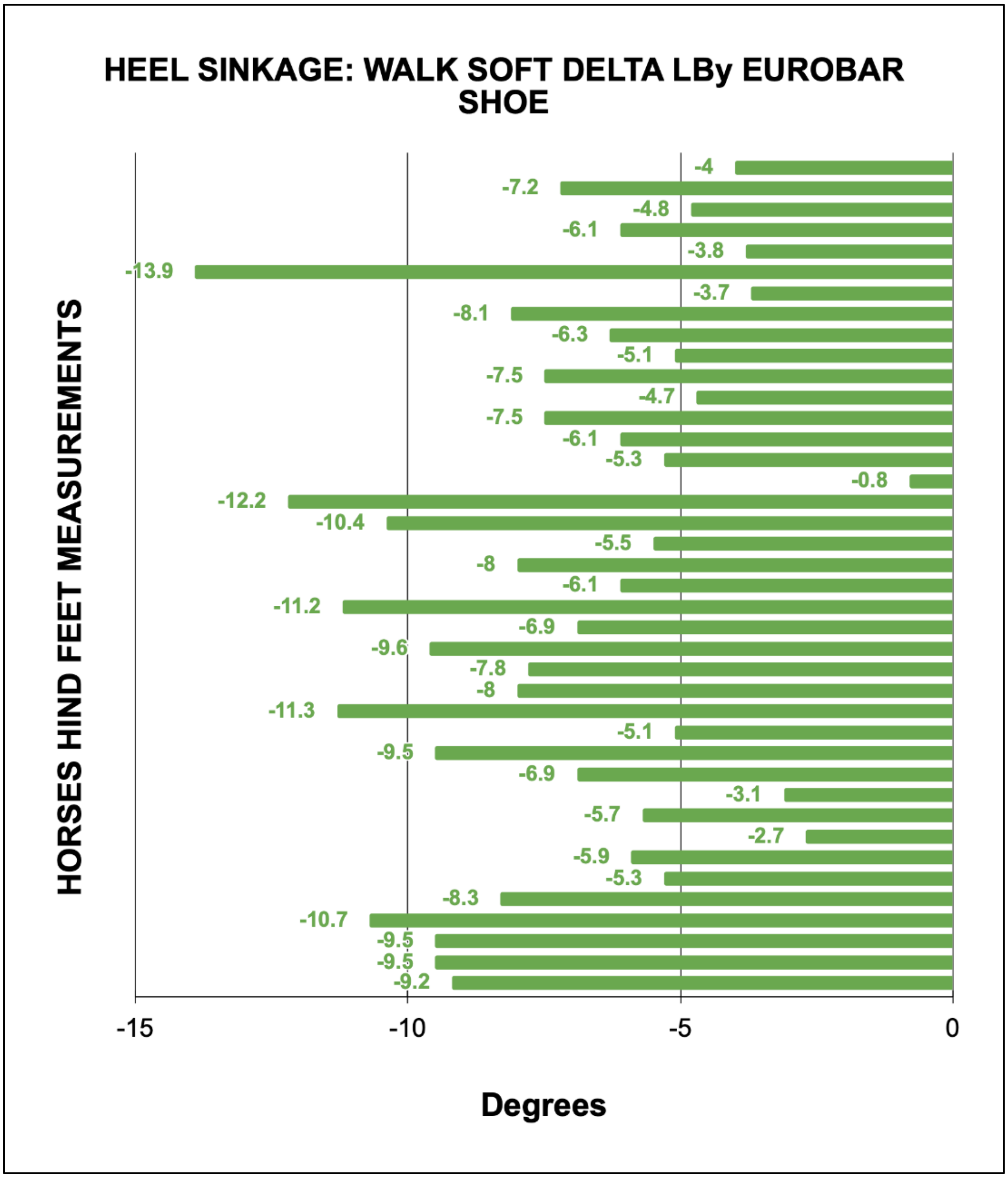


Graph 9: *Heel sinkage measurements of the control shoes across all feet on all horses (see Appendix 1).*

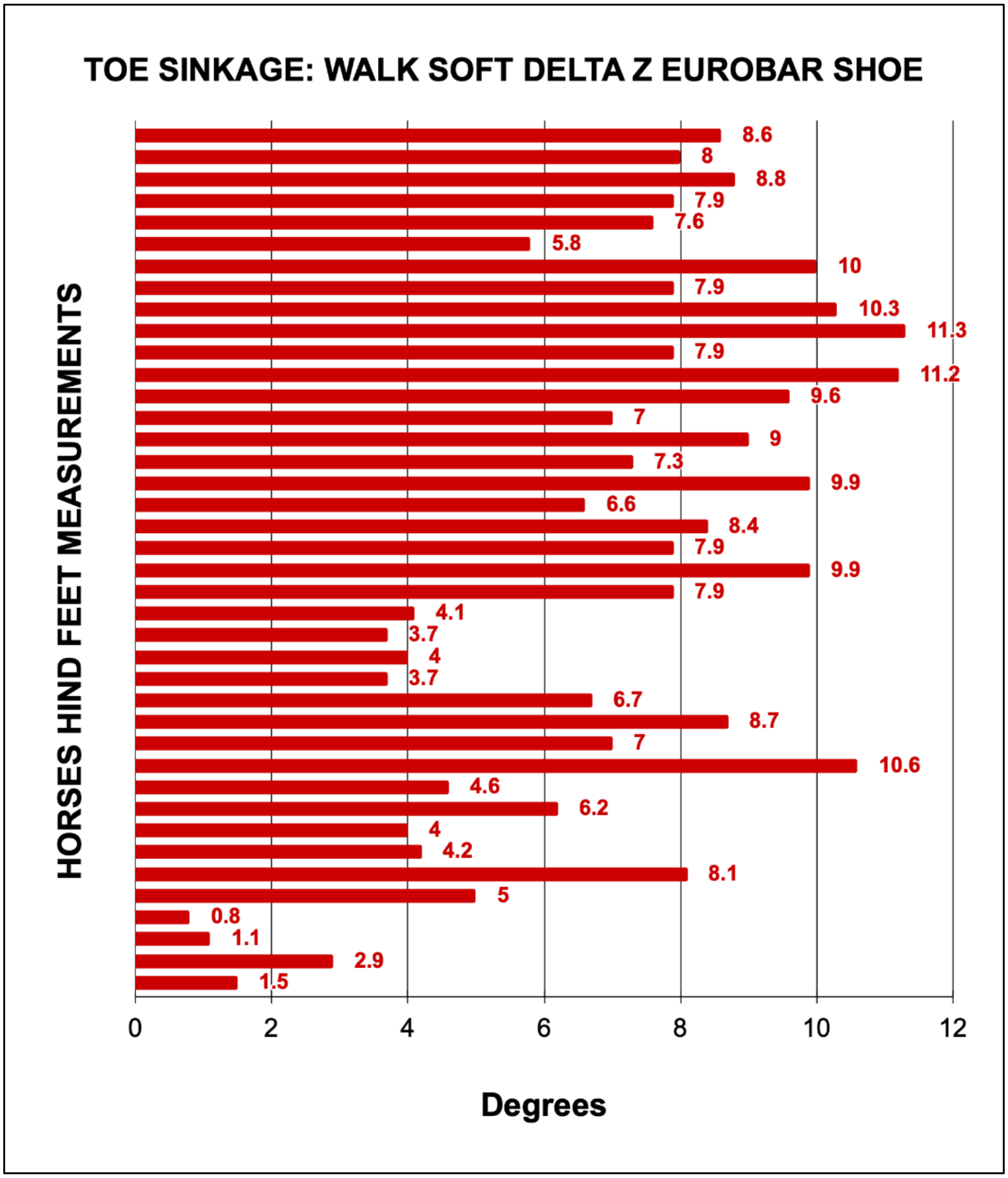


Graph 10: *Toe sinkage measurements of the control shoes across all feet on all horses (see Appendix 1).*

Graphics 11 and 12 depict the euro-bar shoe's behavior at the walk. Graphic 11 shows that its plantar sinkage is similar to the control, averaging 0.55° deeper. However, the dorsal sinkage at the heels averages 3.25° higher compared to the control.

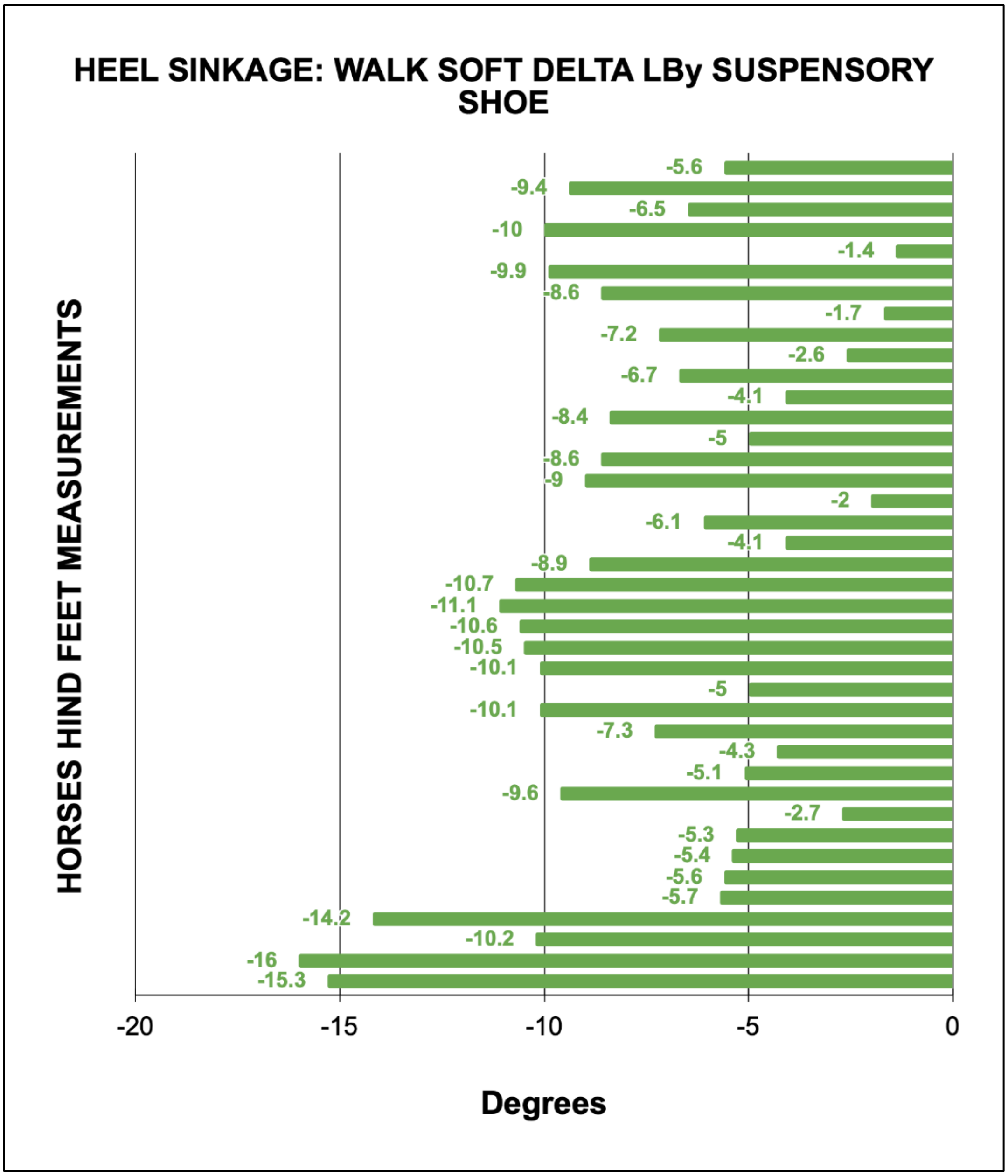


Graph 11: *Heel sinkage measurements of the euro-bar shoes across all feet on all horses (see Appendix 1).*

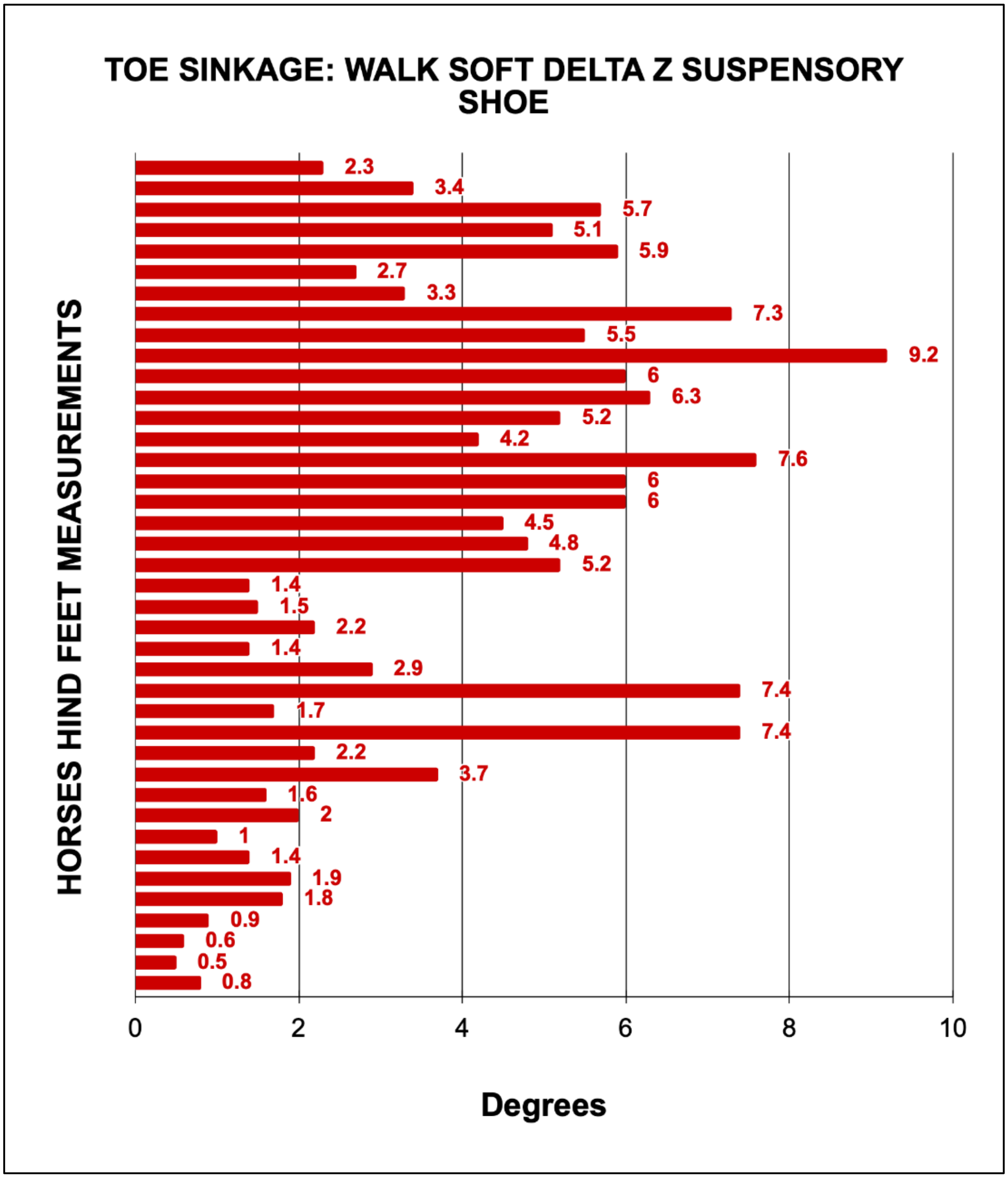


Graph 12: *Toe sinkage measurements of the eurobar shoes across all feet on all horses (see Appendix 1).*

Graphics 13 and 14 show that at the walk, the suspensory shoe averages 0.88° more heel sinkage than the control, with a nearly identical dorsal rotation, differing by only 0.19°. The mean values for the walk reveal an LBy of –6.64° for the control and –7.52° for the suspensory shoe, reflecting a 0.88° shift toward heel sinkage with the suspensory shoe. Delta Z shows a minimal difference of 0.18°, with 3.57° for the control and 3.75° for the suspensory shoe.



Graph 13: *Heel sinkage measurements of the suspensory shoes across all feet on all horses (see Appendix 1).*

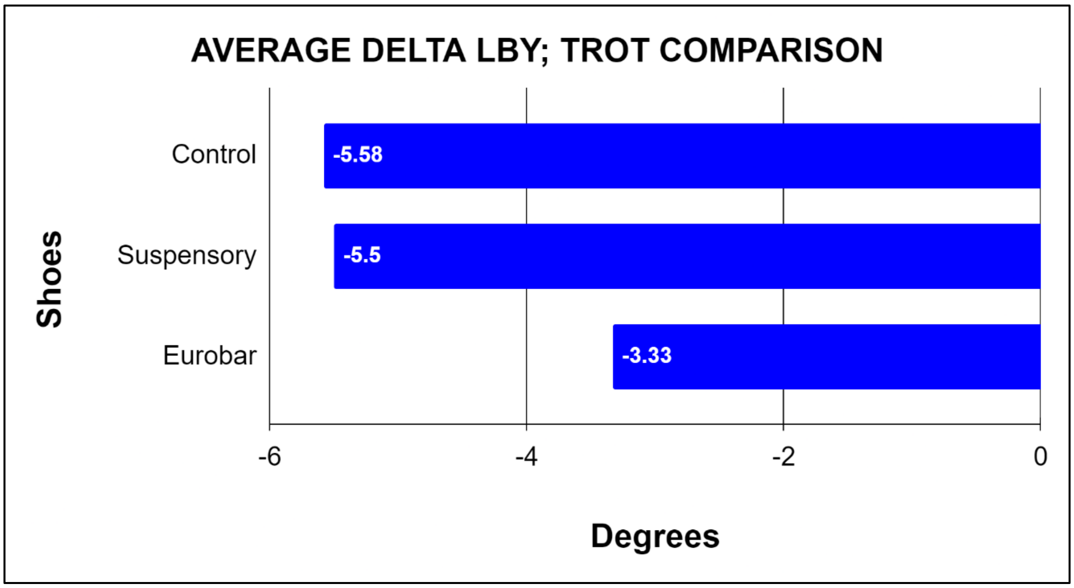


Graph 14: *Toe sinkage measurements of the suspensory shoes across all feet on all horses (see Appendix 1).*

OVERVIEW: AVERAGE DELTA VALUES COMPARISON

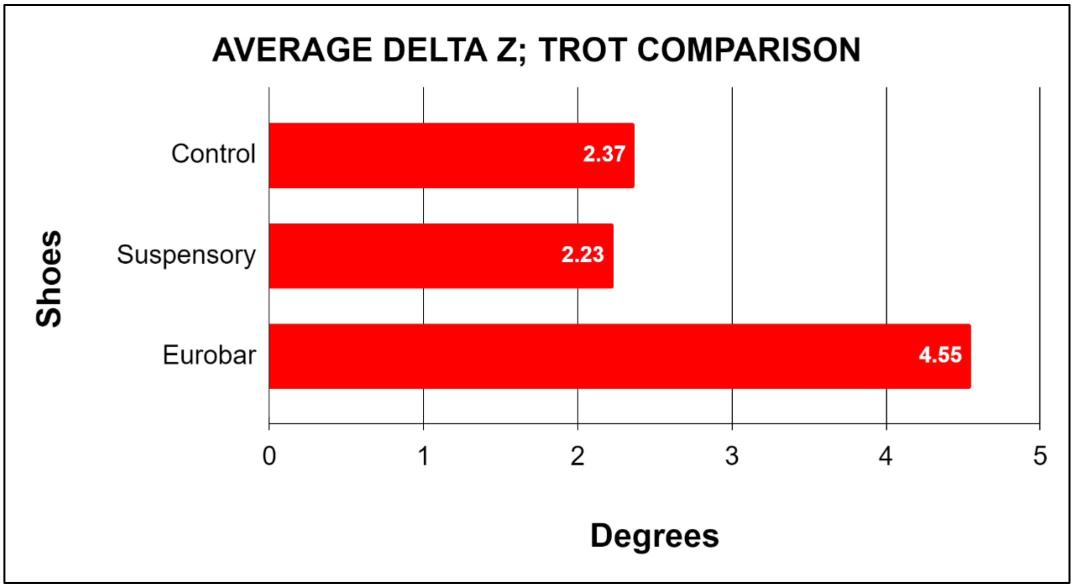
The average delta values for each shoe type were analyzed and compared, offering a clearer visual representation of the study's findings. This approach provided a better understanding of each shoe's overall performance and behavior under various conditions. The comparative analysis revealed significant trends and differences in the mechanical properties and effects of each shoe design, enabling a more comprehensive evaluation of their impact on the horses. The visual representation of these averages emphasized key variations, supporting the conclusions with robust data.

In summary, the euro-bar shoe diminishes heel sinkage on the footing during plantar rotation after initial loading, with no difference observed between the other two shoes (see Graph 15).



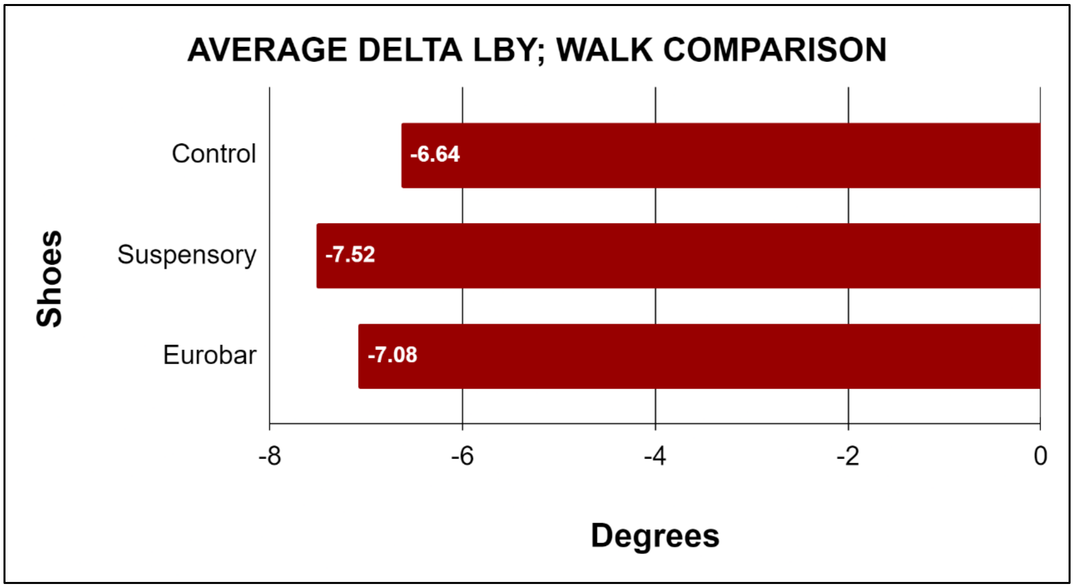
Graph 15: *Average heel sinkage measurements of all shoes across all horses, trot (see Appendix 1).*

The euro-bar shoe demonstrates a significant difference in dorsal rotation compared to the other shoes, indicating that the GRF modification significantly affects foot and footing interaction. Specifically, it shows a 2° difference compared to the suspensory shoe and 1.89° compared to the control (see Graph 16).



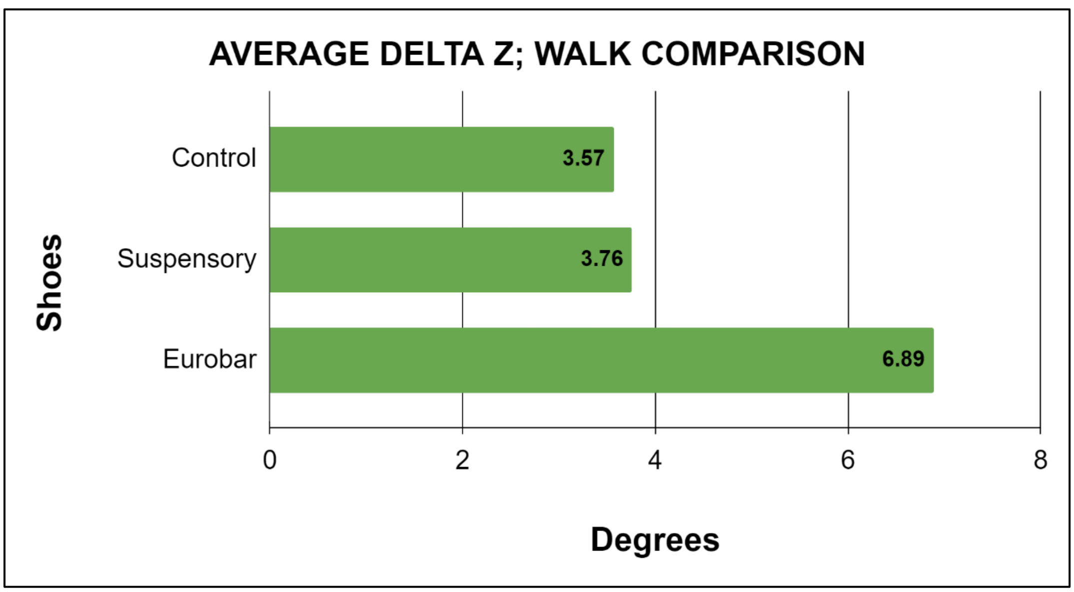
Graph 16: *Average toe sinkage measurements of all shoes across all horses, trot (see Appendix 1).*

At a walk, the GRF modification reacts differently compared to its performance at the trot. The suspensory shoe shows 0.88° more heel sinkage, consistent with theoretical predictions, while the euro-bar shoe does not perform as expected in this context (see Graph 17).



Graph 17: *Average heel sinkage measurements of all shoes across all horses, walk (see Appendix 1).*

The dorsal rotation at the walk mirrors the trend observed at the trot, with the euro-bar shoe exhibiting 3.25° more rotation than the control. As before, no difference is observed between the suspensory and control shoes (see Graph 18).



Graph 18: *Average toe sinkage measurements of all shoes across all horses, walk (see Appendix 1).*

DISCUSSION

The study focused on hind limbs due to frequent veterinary requests to apply suspensory shoe modifications for suspensory ligament injuries. Originally designed for front limbs, these shoes lack sufficient data regarding their effectiveness on hind limbs, raising questions about their suitability due to distinct anatomical and biomechanical differences. Theoretical principles suggest that widening the shoe at the toe should create flotation on the ground based on GRF principles, causing the foot to function at a mechanically broken-back axis. Conversely, a wider heel surface or bar shoe would produce the opposite effect. Whether validated or disproven on hind limbs, these principles could guide therapeutic applications or adjustments to unload specific anatomical structures.

While these principles are well-documented for thoracic limbs—where lowering the foot angle shifts the load from the suspensory ligament to the deep digital flexor tendon, and raising the angle reduces stress on the deep flexor tendon while transferring it to the superficial flexor tendon and suspensory ligament—the application to hind limbs is less straightforward. The hind limb's reliance on the reciprocal apparatus (RA), which coordinates flexion and extension across the hock, stifle, and fetlock, complicates this process. In contrast, altering the foot angle in the hind limb changes the limb's overall position relative to the horse’s body, raising questions about whether these modifications achieve the desired effects (Sharp Y., 2022).

The "in vitro" pilot study suggested that these modifications would function as intended, but the primary study on live horses revealed discrepancies. No significant differences were observed between the suspensory and control shoes, and in some cases, the control shoe's heels sank more than those of the suspensory shoe. This discrepancy may be linked to the metatarsophalangeal joint's dependence on the RA, which limits its range of motion through the interdependence of the hock and stifle.

The euro-bar shoe, however, demonstrated a consistent ability to float the heels, preventing the plantar rotation typically observed after ground contact. It also promoted deeper toe sinkage, resulting in a steeper angle before breakover. Despite these promising results, individual variation among horses was significant, with some adapting immediately to the shoeing changes. This variation underscores the complexity of GRF modifications, and their differing effects based on individual biomechanics.

CONCLUSION

The study's primary findings suggest that the euro-bar shoe successfully modifies GRF on hind feet, reducing heel sinkage after initial loading and increasing dorsal rotation. The wider toe of the suspensory shoe, however, shows no significant difference compared to the open heel shoe in live horses, although it responded positively in press tests. This observation supports the theory that the physics governing the front and hind feet differ, likely due to the reciprocal apparatus (RA) and the varying biomechanical functions of the hind limbs.

In the "in vitro" pilot study, the shoes performed as expected without the complexities of live horse interaction. However, when applied to live horses, responses varied significantly, with some horses adapting immediately to the shoe changes. Horses naturally adjust their hoof placement to maintain their natural gait, ensuring efficiency and comfort (Clayton et al., 2013). An example of this concept is depicted by Figures 8 and 9. The euro-bar shoe was particularly effective in reducing heel sinkage on soft surfaces, with 2.25° less sinkage at the trot and 2.18° more dorsal rotation compared to the control shoe, primarily due to the bar. Both the pilot and primary studies confirmed the euro-bar shoe's effectiveness.

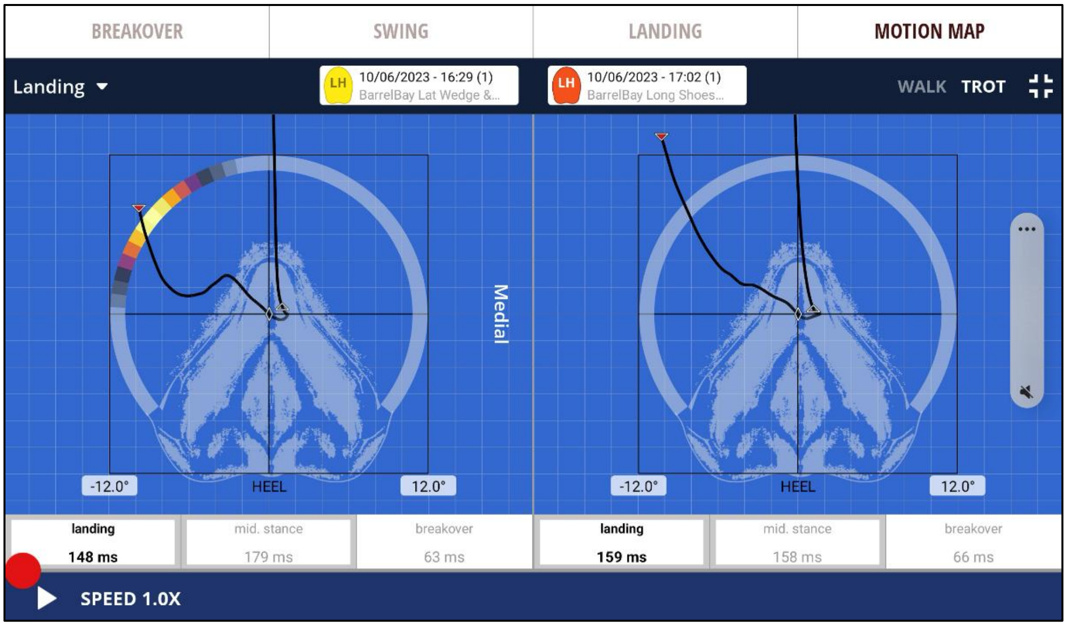


FIGURE 8: *An example of a horse adapting to different shoes using the Motion Map for comparison. Euro-bar on the left and Suspensory on the right; the results are the same (see Appendix 2).*

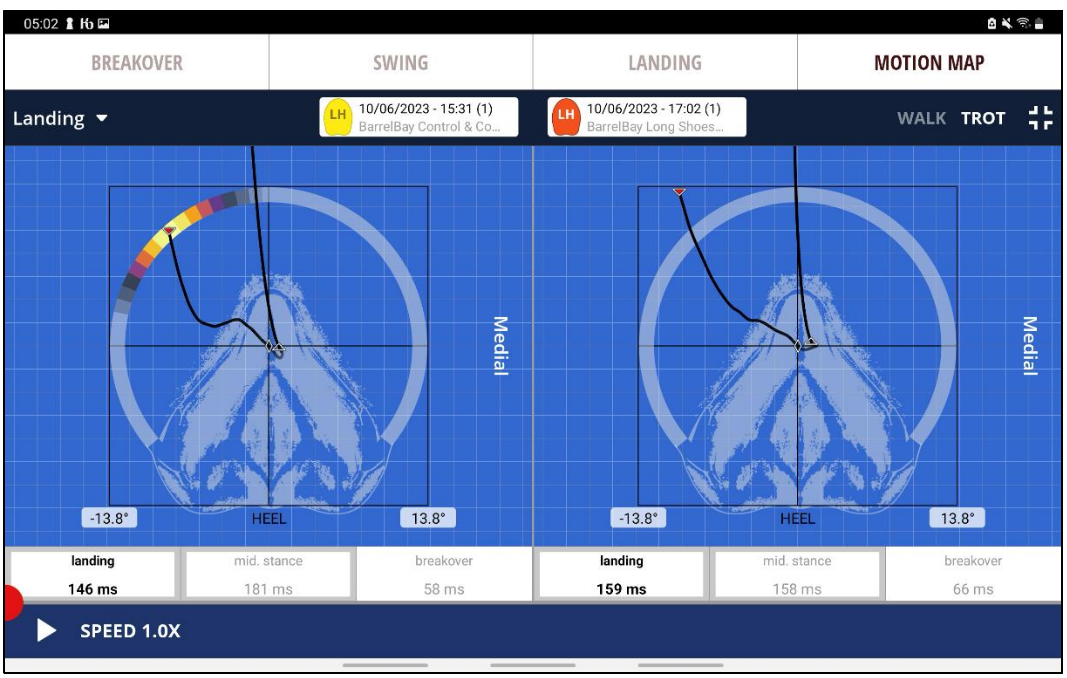


FIGURE 9: *This is the same horse as Figure 8. Euro-bar on the left and Suspensory on the right; once again the results are the same (see Appendix 2).*

The results demonstrate the importance of modifying GRF via the heels using bar shoes, which reduce plantar sinkage and enhance dorsal rotation. However, GRF modifications at the toe showed no significant difference compared to an open-heel shoe. Further research is needed to explore how horses of different sizes respond to these modifications and to measure tension on various anatomical structures during movement, providing insight into which structures in the hind limb are unloaded or overloaded.

LIMITATIONS

Every study has inherent limitations, design flaws, and a defined scope, which must be acknowledged for transparency and to guide future research. One key limitation of this study was the technology used. While the Hoof Beat System provided valid data, its proprietary software processed data in ways that could not be independently verified, requiring trust in its ability to filter out anomalies. Additionally, the system's handling of data, though effective, lacked clarity due to the private nature of its algorithms, and human interpretation played a critical role in analyzing the results. The choice of the Hoof Beat System was driven by the need for a practical, field-ready tool, as laboratory equipment was unsuitable for testing in real-world conditions. Another limitation was the study's inability to isolate the material differences between the shoes tested, as the steel European-style bar shoe and the aluminum Suspensory Shoe were evaluated without accounting for material or production differences. Future studies could address how these factors impact performance, as well as explore the long-term effects of the shoes over a full shoeing cycle and their impact on the front versus hind limbs, offering a more comprehensive understanding of their performance. Additionally, testing these shoes in a wider variety of mediums would be beneficial.

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APPENDIX

APPENDIX A: PERMISSIONS

A.1 Permission from Rachel Herrington C.F.

Permission was granted by R. Herrington of Herrington Forge & Farriery LLC to use the photographs, tables, and graphs she created or edited (R. Herrington, personal communication, December 2022).

A.2 Permission from Christel Werkman

Permission was granted by C. Werkman of Hoof Beat Systems to use data and snapshots from proprietary software (C. Werkman, personal communication, 1 July 2024).

A.2 Permission from Conrad Trow

Permission was granted by Conrad Trow of Grand Circuit by personal communication to use the suspensory shoe for this study.