Ground Reaction Force in Application

Cody Gregory A.W.C.F.

Submitted in partial fulfillment of the requirements for the award of Fellowship of the Worshipful Company of Farriers

Acknowledgements

Thank you to every person who has ever shared anything with me. I am who I am today because of the past experiences and knowledge that people have poured into me.

Chris Gregory F.W.C.F.

Without the example he set, this would undoubtedly not be happening now. His unwavering faith and encouragement have given me the strength to pursue dreams like this.

Emilio Giannotti A.W.C.F.

This man started the conversation that set everything in motion. Additionally, his kindness in embarking on this adventure with me has been invaluable.

Jonathan Nunn F.W.C.F.

He began helping me years ago through our endless days talking about shoeing while kindly letting me ride along with him. His shared insights and knowledge have been invaluable for this thesis.

Rachel Herrington C.F.

Her ability to create spreadsheets and crunch data made this possible. Additionally, the numerous rubber-ducky conversations that helped me identify missing factors in the equation made her indispensable throughout this process.

Renate Weller and Thilo Pfau

During their busiest time, they took the time to advise on statistics, demonstrating an exceptional willingness to help. Their humility and kindness will forever be remembered.

My Family

How can anyone adequately express the gratitude owed to this incredible group of people?

Abstract

This study investigates the principles of Ground Reaction Force (GRF) as applied to horseshoe design and its effect on the dynamic balance of the foot and limb. Utilizing both in vitro and in vivo studies, the research compares the impact of GRF-based shoe designs against traditional wedge methods across various surfaces. The in vitro pilot study involved machined shoes tested under controlled conditions, while the in vivo study involved ten live horses, resulting in 320 unique measurements with the Hoof Beat (HB). The results indicate that shoes with web-width disparity can achieve similar or greater effects than a 3.0° lateral wedge, with the position of the wide branch being a critical factor in the shoe's ability to influence GRF. Additionally, as speed increases, the granular flow dynamics change in a way that makes GRF more effective. These findings highlight the complex interactions between shoe design, placement, and movement speed in optimizing performance and balance in horses.

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.

Contents

Word count 4,723 (includes the main body of text without the Abstract, figures, tables, Contents, References, Manufacturers and Appendices.)

Introduction

This was a collaborative thesis with Emilio Giannotti A.W.C.F. that started in October of 2022. This took a team of people to complete. To list a brief scope of the team, we had farriers, veterinarians, a machinist, a tech wiz, researchers, and statisticians and many others. Just for the primary study, measuring and entering the data resulted in over 8,320 individual data points and took approximately 1,032 work hours to complete. Analyzation of this data took an innumerable number of hours. The following information is organized in a specific order to ensure clarity and gain maximum benefit from the results.

Background

Ground Reaction Force theorem, as it pertains to horseshoe design and its effect on the dynamic balance of the foot and limb, has been discussed and is supported by anecdotal evidence. However, very little research has been done, utilizing GRF principles, to support shoe performance in differing surfaces.

Knowledge of GRF principles can play a very important role in everyday work. Newton's third law describes GRF; for every action there is an equal and opposite reaction (Smith, 2020). The foot in motion as it lands is the action, and the opposing reaction is the ground itself. When a horse is standing, the weight will equal the GRF. As the body moves, the GRF will increase due to the increase in acceleration, as dictated by Newton's Second Law; Force = Mass x Acceleration (Physics LibreTexts, 2024). For example: a 1200 lbs (544 kg) horse standing with all limbs loaded, will have 60% of total body weight distributed between the front feet (Gregory, 2011). Consequently, the GRF will equal 360 lbs (163 kg) per front foot. If that same horse is galloping at approximately 29 mph, this will exert 2300 lbs of GRF on a single front foot during midstance. (see Appendix B.1).

It is important to mention the distribution of the weight will not be just the weight bearing surface area of the shoe divided by the GRF. If this was true, a shoe with web width disparity would have more weight on the branch that has more surface area. Instead, there will be a certain amount of weight per branch. Here are some theoretical examples for the purpose of explanation. Please note that the results have been rounded for simplicity.

Example 1 (see Figure 1); 2300 lbs (1043 kg) of GRF distributed on a control shoe that has 8.22 in^2 surface area, equates to 280 pounds per square inch (PSI), resulting in 1150 lbs (521 kg) being applied to each branch.

FIGURE 1: *A control shoe showing perfectly even load distribution (see Appendix A.1).*

Example 2 (see Figure 2)**;** A lateral extension that has 10.07 in^2 of surface area equates to 228 PSI. This shoe has a surface area distribution of 4.11 in^2 on the medial branch and 5.96 in^2 on the lateral branch. If the weight was not distributed per branch of the foot, but equally over the shoe, the lateral side of the foot would bear 1358 lbs (615 kg); the medial would bear 937 lbs (425 kg) In that scenario, I would expect the medial side that has less GRF to float.

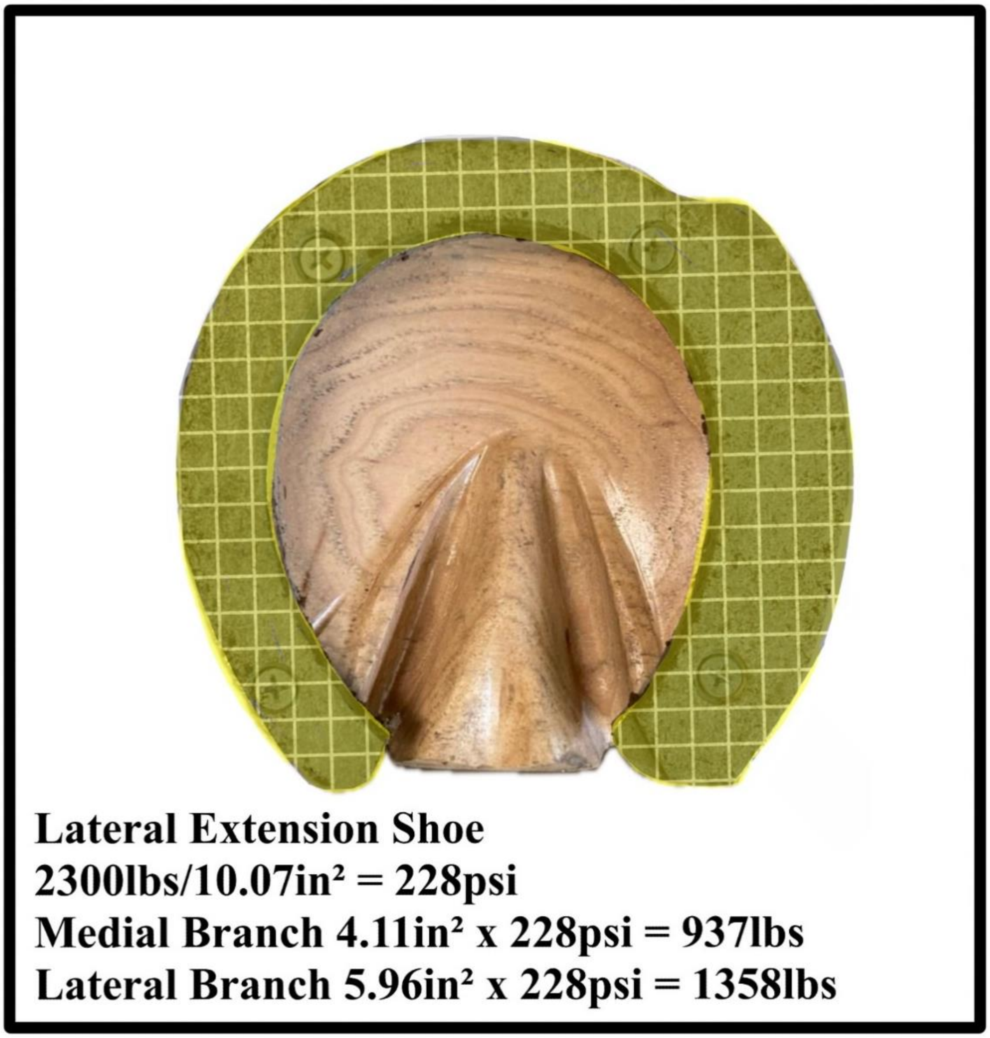


FIGURE 2: *An example of load distribution on a lateral extension shoe without considering GRF (see Appendix A.1).*

Example 3 (see Figure 3); With the previous examples in mind, the calculation is performed using 1150 lbs (521 kg) per side and divided by the surface area of that branch, so that the lateral side of the shoe bears 193 PSI and the medial side bears 280 PSI. When evaluating the GRF in this scenario, it is logical for the lateral branch to float and the medial branch to sink deeper into the medium.

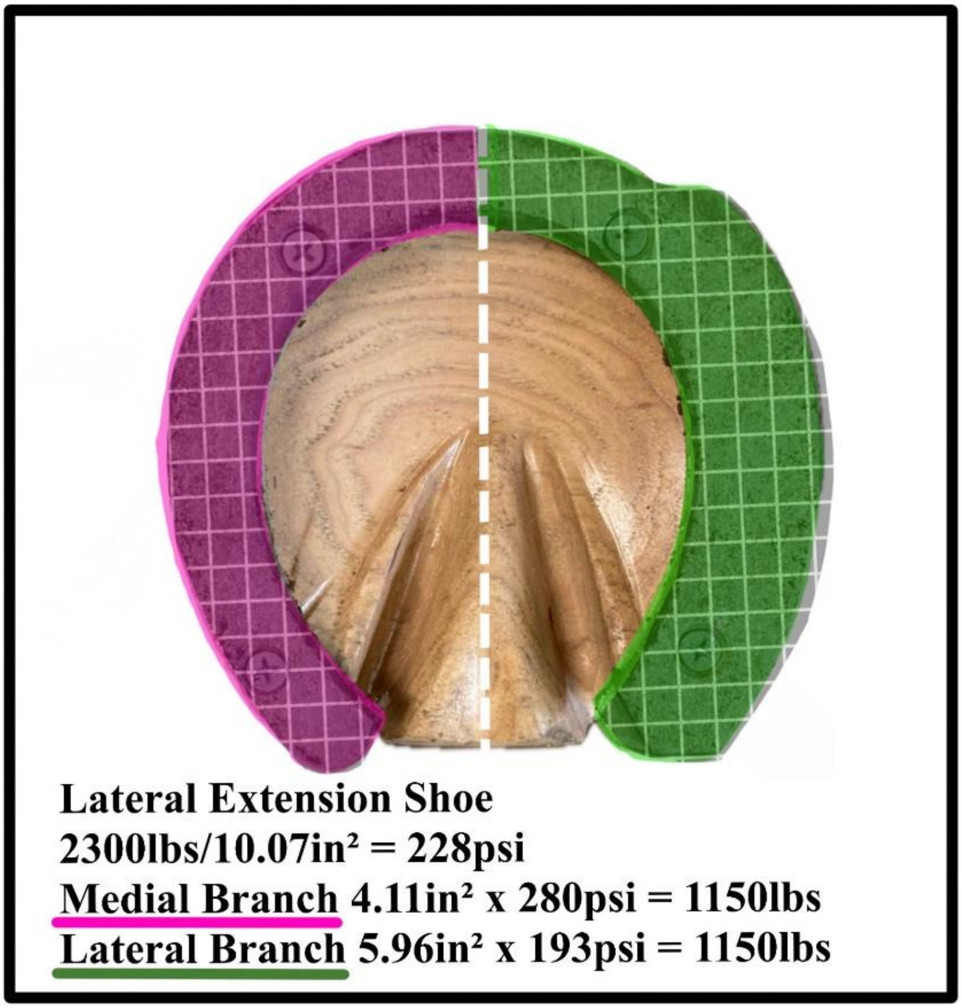


FIGURE 3: *A lateral extension shoe showing a more realistic example of load distribution (see Appendix A.1).*

Without the knowledge of GRF, a shoe applied to balance a horse may not have the expected result, especially when considering all surfaces. This is important because the meticulous attention given to achieving the desired balance in a stationary foot may not accurately reflect the balance in motion due to GRF. From working with experienced farriers, a tolerance of 0.0625” (1.5 mm) is a common standard that is held in everyday work. That converts to 0.716° on a 5.0” wide foot (see Appendix B.2). It is not the point of this theses to define balance, but to give a perspective that will allow for intended balance to be applied in a functional way. If

GRF isn't considered, the shoe applied could change the dynamic balance by degrees. That amount would be well outside the accepted range that was intended in a static situation.

Objective

The aim of this thesis is to determine how shoes with web width disparity would react in real-world environments to the horse's foot. This knowledge will educate discussions and broaden the perspectives regarding the importance of web width and shoe placement in everyday shoeing. It will also illustrate how some practices used for balancing a foot are faulty without considering GRF.

Significance

The results of these studies will provide evidence of how some shoes and GRF will affect the intended balance. It is impossible to shoe a horse for every medium and every step that it takes, but as farriers our goal is always to do the best for the horse in as many situations as possible. Without this consideration, we might not achieve the desired results or accomplish our objectives as intended.

Hypothesis

The hypothesis; web width disparities, using GRF theory principles, will be able to create medial-lateral differences in soft mediums.

Methods & Materials

Shoe System

For both studies, shoes were manufactured that would be able to prove the relationships between GRF, web width disparity, and placement of the shoe. The shoes selected for this thesis were the shoes that deal with changing medial-lateral balance on front feet. In the interest of science and precision, the shoes needed to be the same shape, have a known amount of web width differences, and be applied in the exact same place on the foot. To achieve this the shoe specifications are as follows:

Shoe Manufacturing

All test shoes were precisely machined in a CNC mill (Cody Gregory LLC, 2022). This means that when a manufactured shoe indicates that it has 0.6" (15.2 mm) added to the inside of the lateral branch, it will be 0.6" (15.2 mm) wider than the inside branch + /- 0.01" (0.254 mm). All the shoes had four holes that were countersunk to allow them to be attached to a base shoe. The test shoes had a locating pin machined into the foot side of the shoe.

Shoe Material

All shoes were made from aluminum, excluding the locating pins on the Lateral Wedge. There was a 0.7 oz (19 g) difference between the lightest and heaviest shoe. When bolted together the heaviest shoe weighed 6.5 oz (187 g).

Test Shoe Selection

Six test shoes were created: one control shoe, three shoes for medial lateral changes and three shoes for dorsal palmar. Only the first four are the subject of this thesis. The specifications of the test shoes are listed below and will be referred to by name moving forward (see Figure 4).

FIGURE 4*: The original six test shoes, only four are the subject of this thesis (see Appendix A.1).*

Base Shoe

The base shoe had locating holes and four tapped holes to receive the different test shoes that were applied. This was done to make sure the shoe was placed in the same position every time. The base shoe had Hanton System ™ clips welded to it that allowed it to be glued on [Broadline Farrier Solutions, 2022]. By using this method, the base and test shoes were less than 0.375” (10 mm) thick from the surface of the foot. This made the implementation comparable to a normal shoeing protocol. This shoe was used for both the pilot and primary studies (see Figure 5).

FIGURE 5: *The Base Shoe with Hanton System ™ clips welded on and ready for application (see Appendix A.1).*

Control Shoe

This shoe has a 0.70” (17.8 mm) web width that is consistent. The idea was to create a shoe with a similar profile to that of a normal shoeing protocol. This shoe was used for both the pilot and primary studies (see Figure 6).

FIGURE 6: *The Control shoe (see Appendix A.1).*

Lateral Wedge

This shoe is a 3.0° lateral wedge. It has the same web width and shape as the Control Shoe, eliminating any GRF difference between the two shoes. This shoe was used for both the pilot and primary studies (see Figure 7).

FIGURE 7: *The Lateral Wedge shoe (see Appendix A.1).*

Lateral Add 0.6”

This shoe has an additional 0.6” (15.2 mm) width added to the inside edge of the lateral branch of the shoe. This shoe was used for both the pilot and primary studies (see Figure 8).

FIGURE 8: *The Lateral Add 0.6” shoe (see Appendix A.1).*

Lateral Extension

This shoe that has 0.3” (7.6 mm) of additional width, in comparison to the inside/medial branch, added to the outside lateral edge of the shoe. This shoe was used for both the pilot and primary studies (see Figure 9).

FIGURE 9: *The Lateral Extension shoe (see Appendix A.1).*

'In Vitro' Pilot Study

A test foot was carved out of wood with a swivel placed in the center on the leg side. The Base Shoe was glued to the wooden foot (see Figure 10). A strut was welded in place for a digital level [Coobeast, 2021]. This was placed in a hydraulic press. Under the foot was a container that held the medium (see Figure 11).

FIGURE 10: *The wooden foot with the Base Shoe applied (see Appendix A.1).*

FIGURE 11: *The wooden foot in a hydraulic press (see Appendix A.1).*

Two different mediums were used. The first was dirt from the arena used in the primary study and the second an all-weather synthetic footing (Kruse Cushion Ride, 2024). After each measurement, the footing was worked to keep it in the same condition for every test.

To gather the data, a pressure of 2,300 lbs was applied to the foot for six seconds. These conditions were chosen because they corresponded to the point at which the mediums yielded, creating footprints similar to those observed in a moving horse (see Figure 12). Using 2300 lbs is comparable to the front foot of a 1200 lb horse in motion at approximately 29 mph (see Appendix A.1). Four measurements per shoe and surface were taken.

FIGURE 12: *An example of the casting method used to demonstrate shoe penetration depth (see Appendix A.1).*

'In Vivo' Data Collection

The tests were carried out on horses using Hoof Beat for measurements (see Appendix A.2). The Hoof Beat sensors use accelerometers and gyroscopes to collect raw data (Back and Clayton, 2013). Its software converts this data into visual representations. The Hoof Map was the portion of the application where the data was sourced and transcribed (see Figure 13).

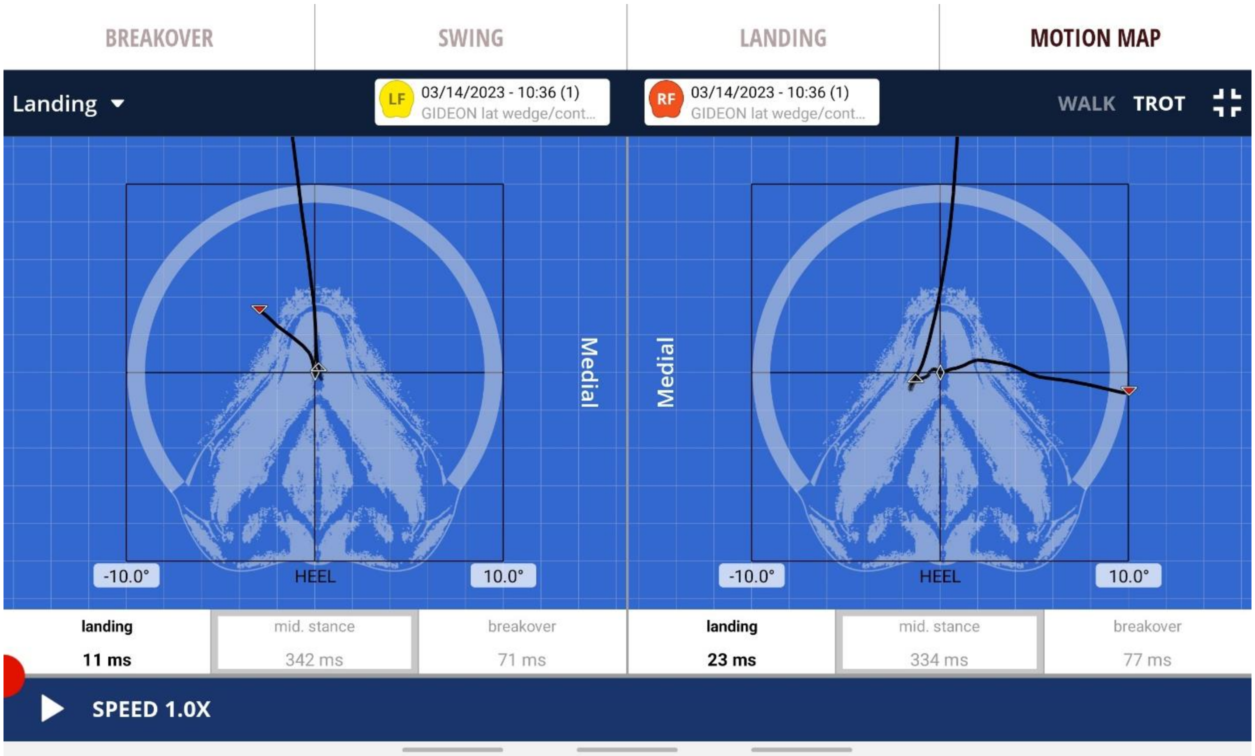


FIGURE 13: *Example of the Hoof Beat Motion Map of a front foot (see Appendix A.2).*

The X-axis, horizontal, reflects mediolateral degrees of change, while the Y-axis, vertical, represents dorsopalmar degrees of change (see Figure 14). A delta is a Greek letter that is used in mathematics to represent the change in a variable, it is also used to represent the difference between two numbers (Day, 1981; Morgan, 1970). The data collected represents the X-axis delta from landing to breakover coordinates in the Motion Map. This delta was appropriately named L/B Delta X.

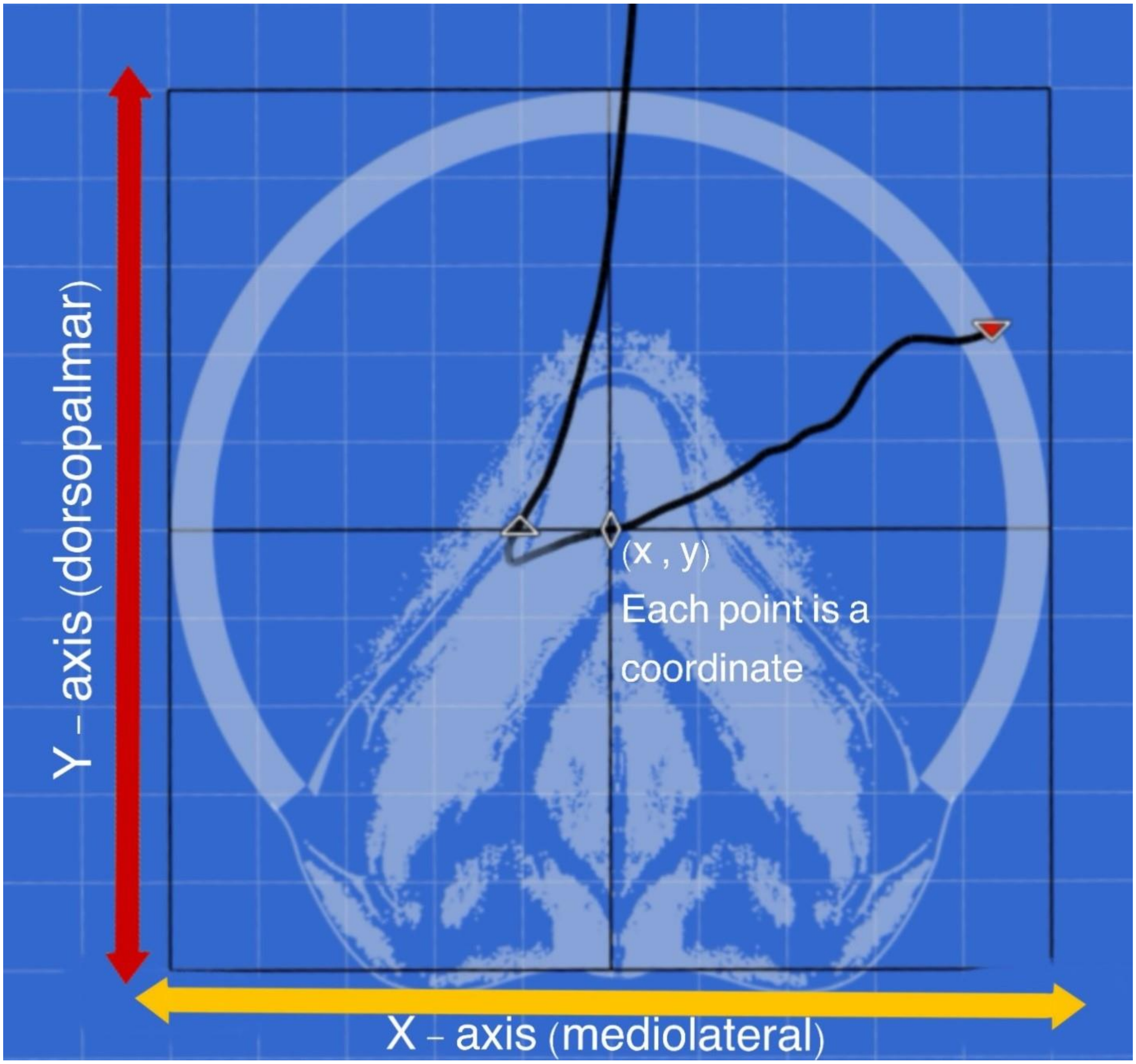


FIGURE 14: *The Motion Map uses the Cartesian coordinate system. Landing coordinates are represented in the graph by a red downward pointing isosceles triangle, while the breakover is represented by an upward pointing isosceles triangle. Diamond is coordinate (0,0) (see Appendix A.2).*

Once L/B Delta X was collected, another delta was taken from the test shoe vs control on the same surface and gait and each individual foot. The second delta, called Net Delta X, will be the data that is represented (see Table 1). All near feet data was inversed to make the near and off feet comparable (Hagen, 2021).

TABLE 1: *A table showing an example of the measurements on a single horse, foot, gait, and surface (see Appendix A.1).*

Shoe	**Foot**	**Gait**	**Surface**	**Landing X**	**Landing Y**	**Breakover X**	**Breakover Y**	**Delta X**	**Delta Y**	**Net Delta X**
Control	Near Front	Walk	Soft	3.8	10.3	0	0.5	3.8	9.8	0
Lateral Wedge	Near Front	Walk	Soft	3.8	16	-1.1	1.7	4.9	14.3	1.1
Lateral Add 0.6”	Near Front	Walk	Soft	3.7	10	-0.8	1.3	4.5	8.7	0.7
Lateral Extension	Near Front	Walk	Soft	3.1	13.6	-1.3	0.4	4.4	13.2	0.6

A total of 320 measurements were taken across ten horses that had similar foot size (5.0” W X 5.25” L), reasonable comparability, and were assessed free of lameness by a veterinarian (Giannotti, 2022). 160 of those measurements were used for this thesis. The horses were ages 5 through 21 with an average age of 10. They were all quarter horses chosen for temperament and accessibility.

All feet were prepared and trimmed by either Cody Gregory, A.W.C.F or Emilio Giannotti, A.W.C.F, using their trained eye as the protocol to determine appropriate balance. Balance was evaluated to the long axis by a minimum of two team members. The Base Shoe was glued in place using Hanton Clips ™ (Broadline Farrier Supply, 2022) and Hoof Life ™ acrylic glue (Victory Racing Plate Co., 2022) (see Figure 15). All the horses were ridden by the same person to keep the weight, tack, riding style, and speed the horse traveled the same.

FIGURE 15: *The shoeing system in action; the Base Shoe glued on with a Lateral Wedge and Hoof Beat applied (see Appendix A.1).*

Procedure

The horses were walked and trotted on two surfaces (see Figure 16). For the soft medium, an arena that was freshly dragged prior to data collection was used. Before each run the bottom of the feet were sprayed with Pam, a nonstick cooking spray, to reduce dirt compacting in them (see Figure 17) (ConAgra Foods, 2024).

FIGURE 16: *All shoes were tested in a worked dirt arena and on asphalt (see Appendix A.1).*

FIGURE 17: *(Left) This photo is post-measurement; the Pam prevents dirt from sticking in the shoe. (Right) A new test shoe being applied to the base shoe (see Appendix A.1).*

The hard surface was an asphalt road. Each run was 180 feet (54 meters) long to get the minimum strides required by the HB (Hoof Beat Systems, 2022). This process was repeated with all test shoes.

To test the hypothesis some specific comparisons needed to be made. Applying a shoe with a known amount of wedge on a hard surface creates a comparison between the lateral wedge and the control. This gives a baseline for hypothesized success with the shoes that have features intended to manipulate GRF.

In summary, the comparisons and expected results are as follows; the Lateral Extension and Lateral Add 0.6” in soft surface will mimic the Lateral Wedge on hard surface.

Preliminary Pilot Study Results & Conclusion

'In Vitro' Pilot Study

The pilot study conducted in the press supports the hypothesis about GRF and its behavior in different mediums. Here are some of the outcomes followed by the supporting evidence. It is important to mention that the Net Delta X measurement, used in the 'in vivo' study, represents the difference between a test shoe and control shoe. This measurement is applicable to this study as well since it also creates a comparable dataset between the two studies. All the numbers represented here are the Net Delta X from the pilot study (see Appendix B.3).

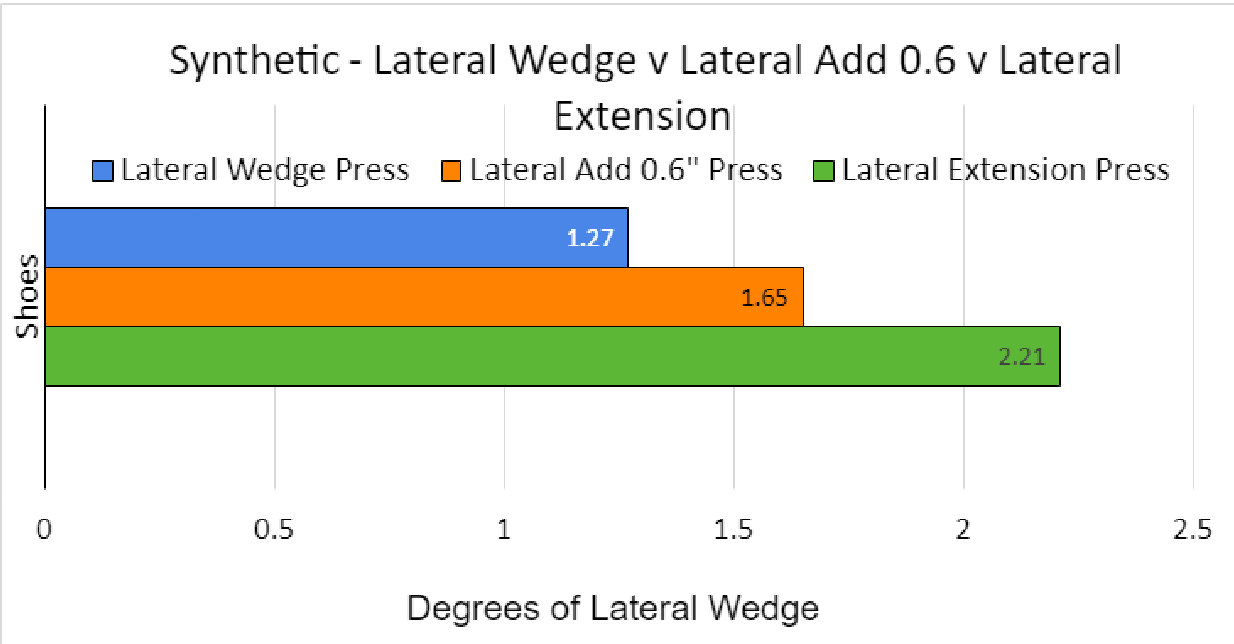
Web-width disparity in a horseshoe can achieve similar results to using a wedge, depending on the width and location of the added material relative to the center of the shoe. A lateral wedge was consistently created using web-width disparity with GRF principles (see Table 2). The total wedge achieved was comparable to or greater than a 3.0° wedge in the same medium.

TABLE 2: *A table representing the averaged results of each test in the Pilot Study, the Control average was subtracted from these totals for clarity giving us the Net Delta X. Note that the 3.0° Lateral Wedge never actually achieves 3.0° of wedge in either medium (see Appendix A.1).*

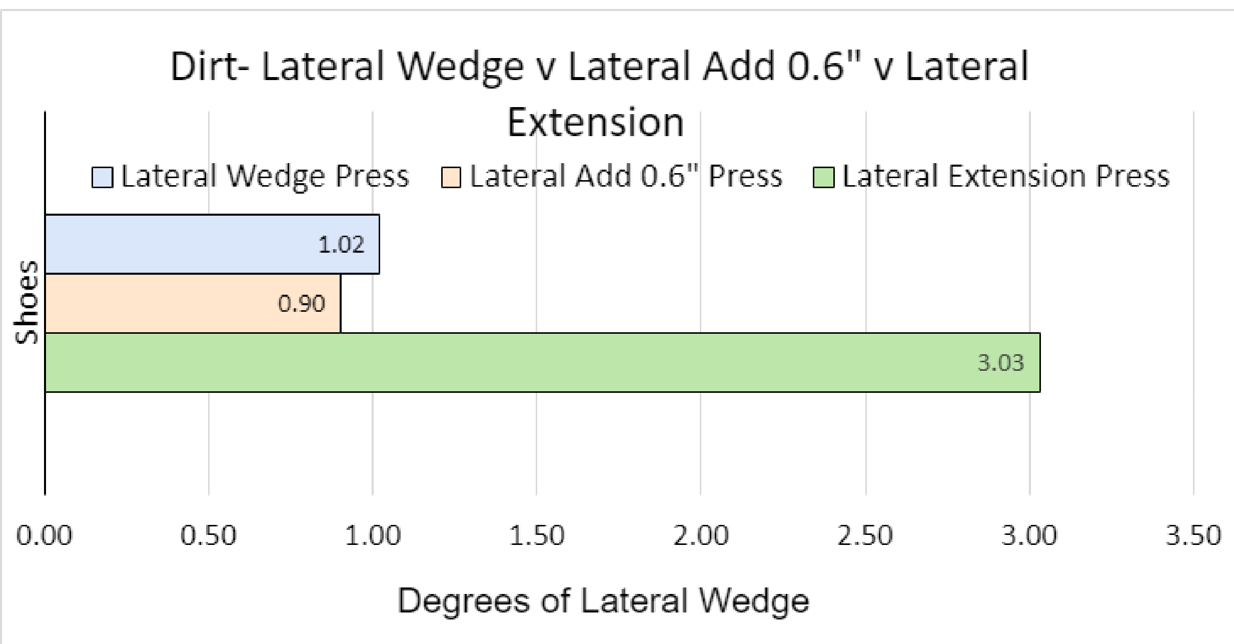
PILOT STUDY - DEGREES OF LATERAL WEDGE

SHOE	DIRT	SYNTHETIC
Lateral Wedge	1.02	1.27
Lateral Add 0.6"	0.90	1.65
Lateral Extension	3.03	2.21

There were measurable differences in how each medium responded to GRF. The synthetic medium created a more consistent amount of wedge between the three shoes when compared to the arena dirt medium (see Graph 1, 2). The dirt medium produced the best results when the shoe was made with the added material as an extension rather than added to the inside edge of the branch. The Lateral Extension produced 3.03° of wedge versus the Lateral Add 0.6" only producing 1.02° of wedge in dirt (see Graph 2)



GRAPH 1: *All pilot study shoes results in synthetic (see Appendix A.1).*

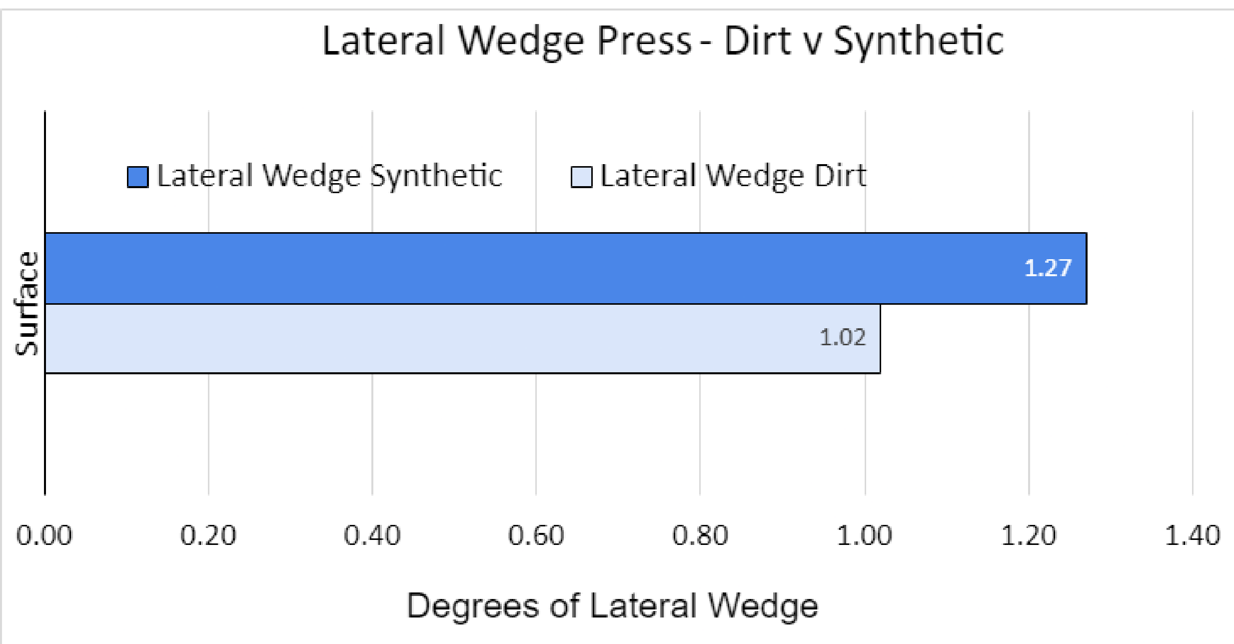


GRAPH 2: *All pilot study shoes results in dirt (see Appendix A.1).*

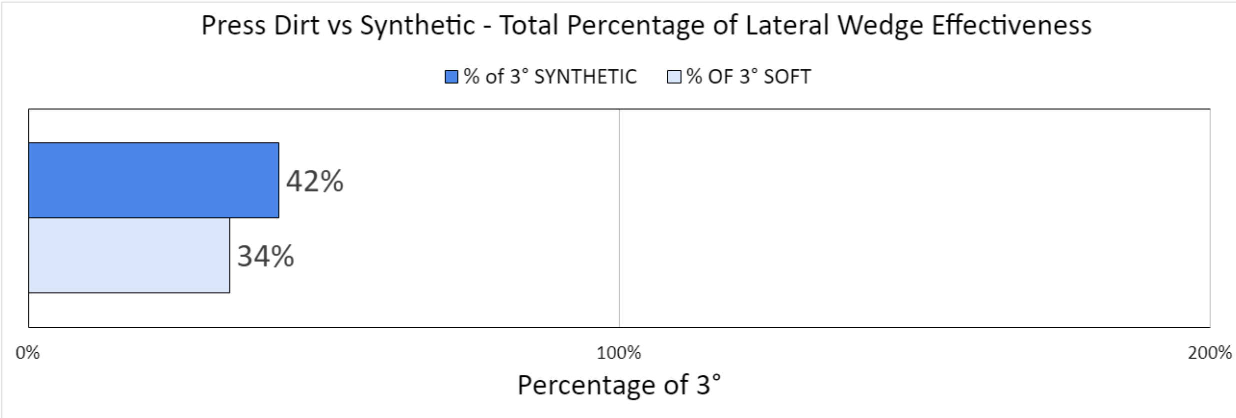
In both mediums, the location of the added material to the branch had a significant influence on results. The Lateral Extension created the most exacerbated wedge in both mediums even though it had 1 in^2 less material than the Lateral Add 0.6” on the lateral branch. The Lateral Extension was able to consistently produce a marked amount more wedge than the 3.0° wedge shoe. The key specific results are as follows.

Lateral Wedge

The Lateral Wedge produced 1.27° of wedge in the synthetic and 1.02° of wedge in the dirt (see Graph 3). This shoe had the same section, shape, and position as the Control Shoe. It should be noted that without considering GRF when applying a wedge, the 3.0° of wedge were reduced by 58% on the synthetic medium, and 66% on the dirt; resulting in a total wedge reduction average of 62% across both mediums (see Graph 4).



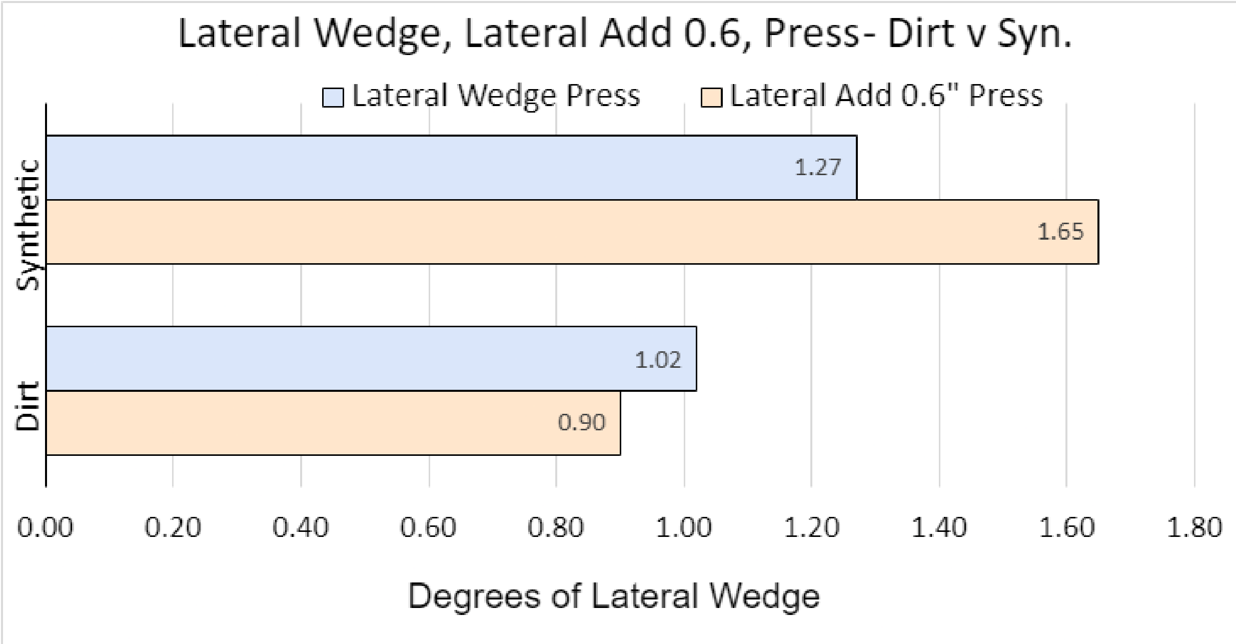
GRAPH 3: *The 3.0° Lateral Wedge was never able to produce 3.0° of wedge in soft mediums (see Appendix A.1).*



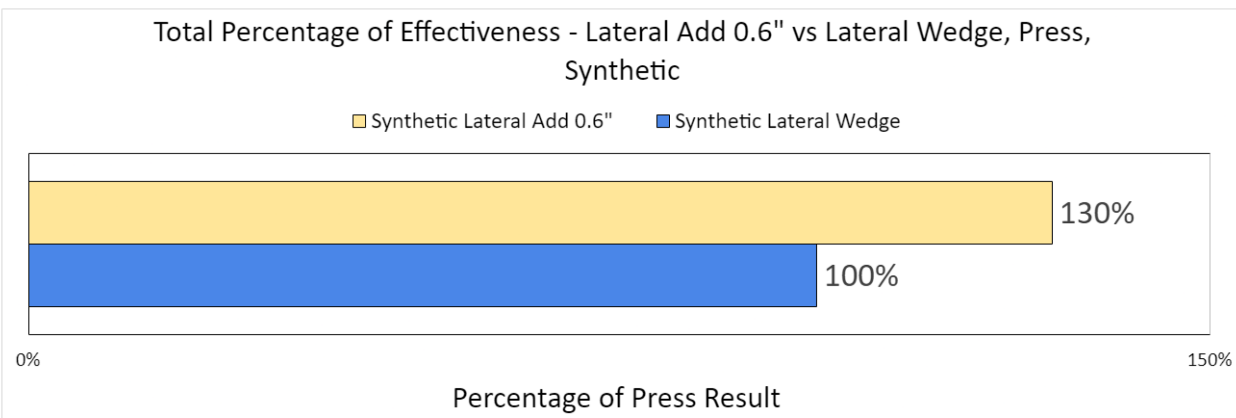
GRAPH 4: *The Lateral Wedge in synthetic was 8% more effective than in dirt, but still fell short of 3° of wedge. (see Appendix A.1).*

Lateral Add 0.6”

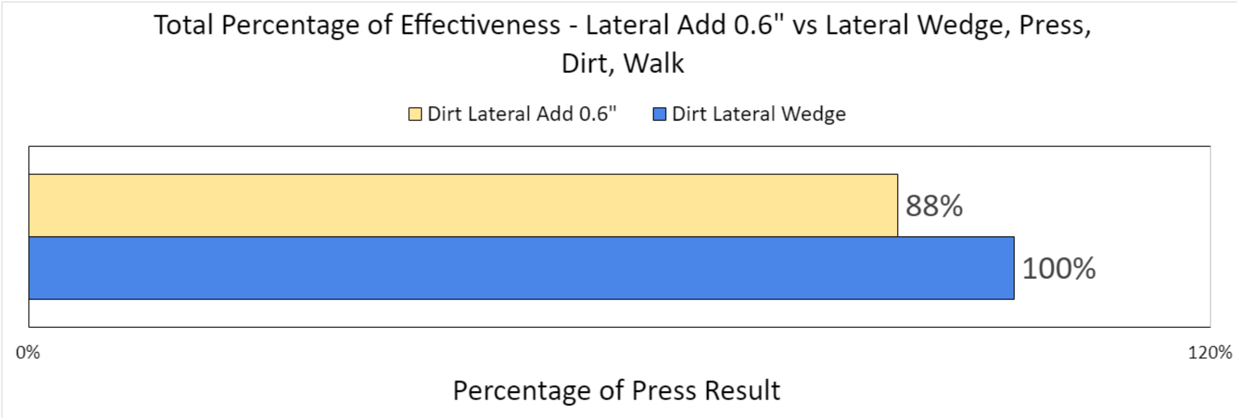
The Lateral Add 0.6" created a 1.65° wedge in synthetic and a 0.90° wedge in dirt based on GRF principles (see Graph 5). In synthetic, this resulted in 129% of wedge compared to the Lateral Wedge results in the same surface (see Graph 6). In dirt, it is achieving 88% of what the Lateral Wedge achieved in the same surface (see Graph 7).



GRAPH 5: *Lateral Add 0.6" in dirt vs synthetic medium (see Appendix A.1).*



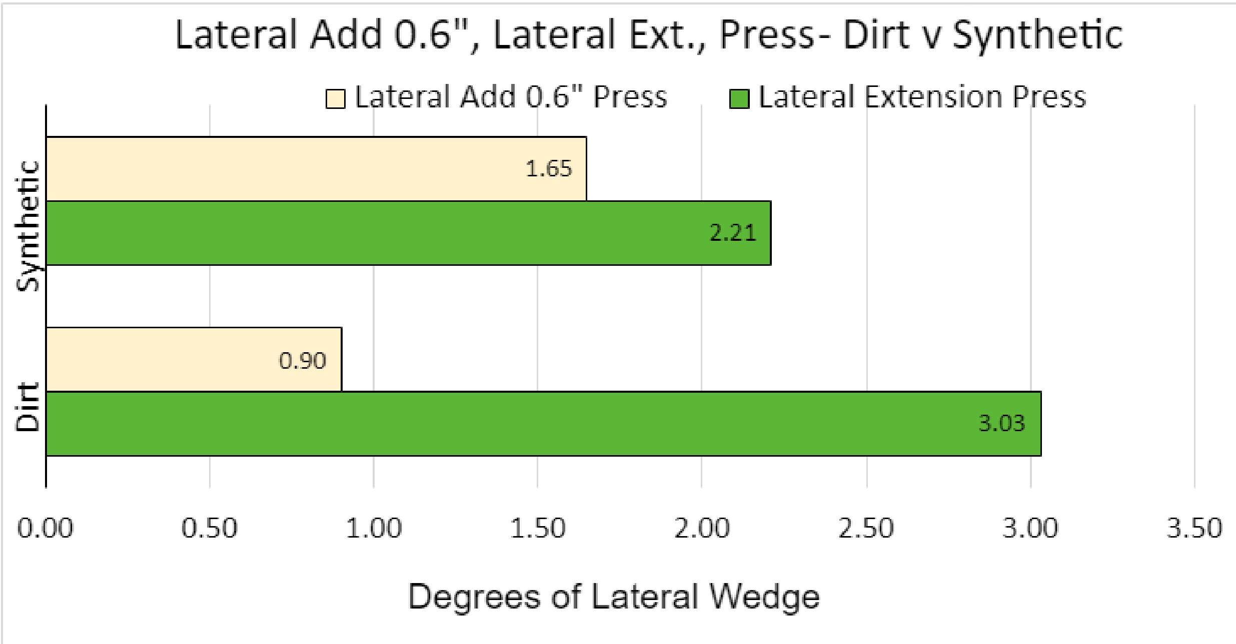
GRAPH 6: *The Lateral Add 0.6" performed better than the Lateral Wedge in synthetic. (see Appendix A.1).*



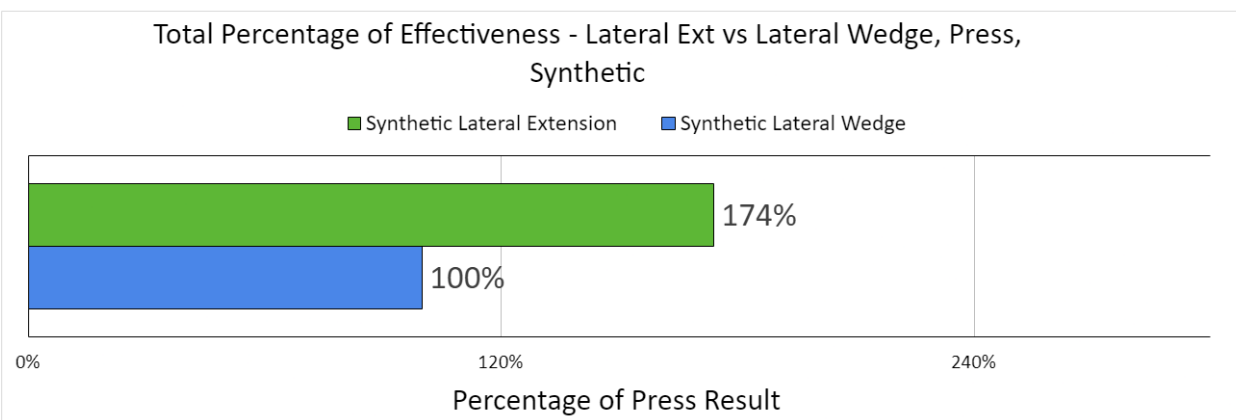
GRAPH 7: *The Lateral Wedge showed more favorable results than the Lateral Add 0.6" in dirt. (see Appendix A.1).*

Lateral Extension

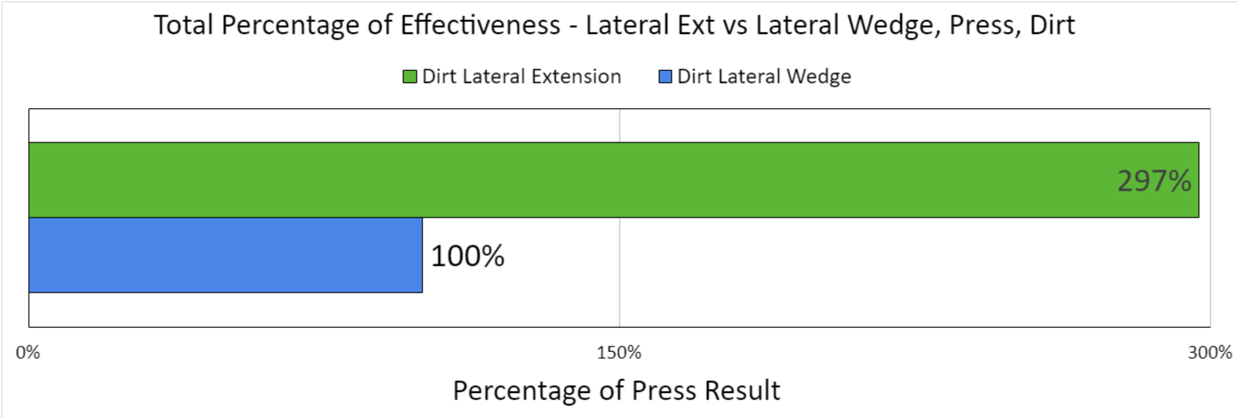
Regarding the Lateral Extension, having the width on the outside of the shoe made it the most effective at GRF manipulation. The shoe was able to produce 2.21° of wedge in the synthetic medium, and 3.03 ° of wedge in dirt (see Graph 8). In the synthetic medium, this shoe produced 174% of wedge that the Lateral Wedge achieved on the same surface (see Graph 9). In dirt, this shoe generated 297% of the wedge effect compared to the Lateral Wedge on the same surface (see Graph 10).



GRAPH 8: *The Lateral Extension yielded better results than the Lateral Add 0.6" in dirt, highlighting the importance of web width placement on the shoe. (see Appendix A.1).*



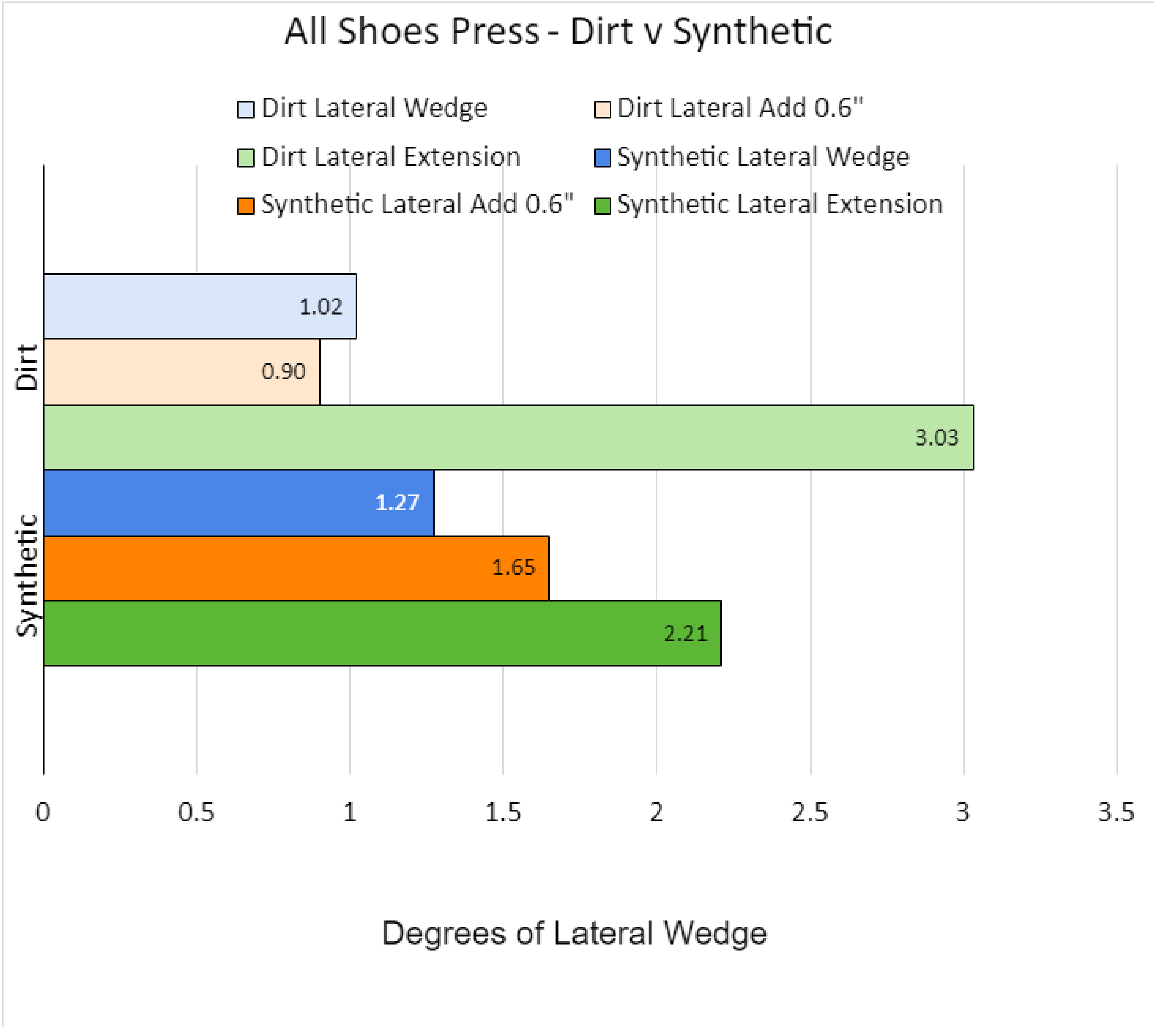
GRAPH 9: *The Lateral Extension was more effective than the Lateral Wedge in synthetic. (see Appendix A.1).*



GRAPH 10: *The Lateral Extension proved more successful than the Lateral Wedge in dirt. (see Appendix A.1).*

'In Vitro' Pilot Study Conclusion

From this study, it is evident that GRF shoe modifications produce the hypothesized results under ideal conditions. When a wedge shoe is applied without considering GRF, there is a substantial reduction in the applied angle. A shoe with an additional 0.6" (15.2 mm) on the inside edge of a branch has a similar effect to a 3.0° wedge in the soft mediums used in this study. Additional width added to the outside of the shoe maximizes the effects of shoe modifications that influence GRF (see Graph 11).



GRAPH 11: *Primary study results summary of all shoes on both surfaces (see Appendix A.1).*

Primary Study Statistics

The statistics showed that the Lateral Wedge on hard surfaces had statistical significance when comparing all variables (IBM Corp., 2021) (see Appendix C.2). However, applying horseshoeing and statistics to a moving horse is very challenging. For instance, this study involved 20 feet from ten horses equaling a sample size of n=20. To achieve 95% statistical confidence, 19 feet would need to perform identically. The inclusion of variables such as a moving horse and arena surface affects the statistical results. Table 3 shows that the Lateral Add 0.6” had the desired effect on at least seven of the ten horses, while the Lateral Extension produced the intended outcome on eight of the ten horses. This consistency, while outside statistical relevance, indicates functional reliability.

TABLE 3: *A table representing how often the shoes performed as expected across all 10 horses. While this is below the 95% confidence recognized by statistics, it does show a reliable pattern.*

BOOLEAN VALUES - HOW OFTEN DID THE SHOES CREATE A LATERAL WEDGE?

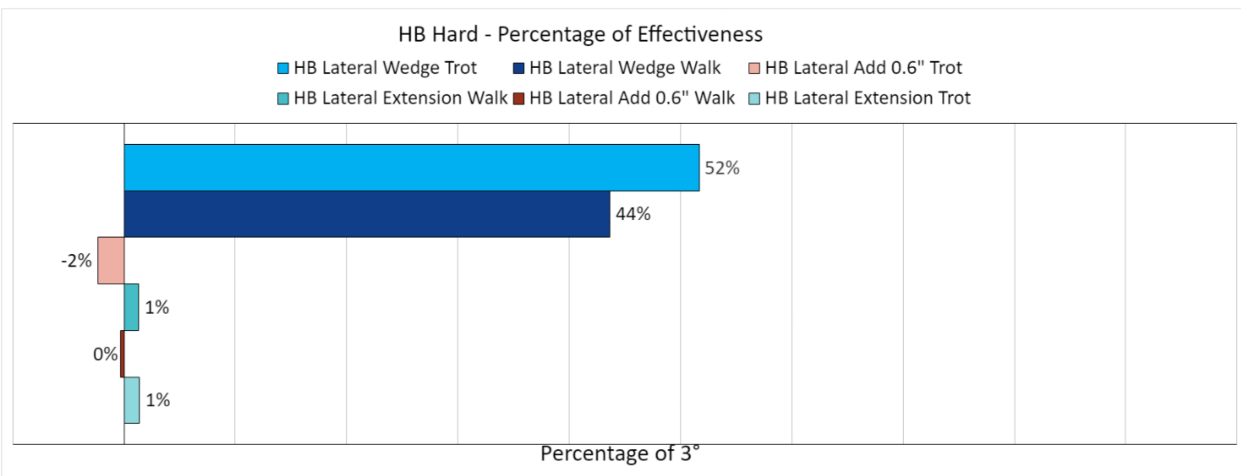
TEST & SHOE ACROSS 10 HORSES	YES	NO
Lateral Add 0.6” Walk Soft	8	2
Lateral Add 0.6” Trot Soft	7	3
Lateral Extension Walk Soft	8	2
Lateral Extension Trot Soft	8	2

After observing the consistency of Table 3, it was decided to use the averaged data. After averaging all relative data points with each other, the data revealed the patterns seen from the in vitro pilot study. This pattern is also visible in the Motion Map. The hard measurement data shows that all flat shoes, such as the Control Shoe, the Lateral Extension, and the Lateral Add 0.6", responded +/- 0.07% the difference, supporting the decision to use the averages (see Table 4, Graph 11). All the data represented here will be the averaged angles and the Net Delta X on each horse at the same gait and surface (see Appendix B.3).

TABLE 4: *A table representing the averaged results of each test in both studies. The synthetic medium press measurements have been omitted (see Appendix A.1).*

AVERAGES - DEGREES OF LATERAL WEDGE ACHIEVED

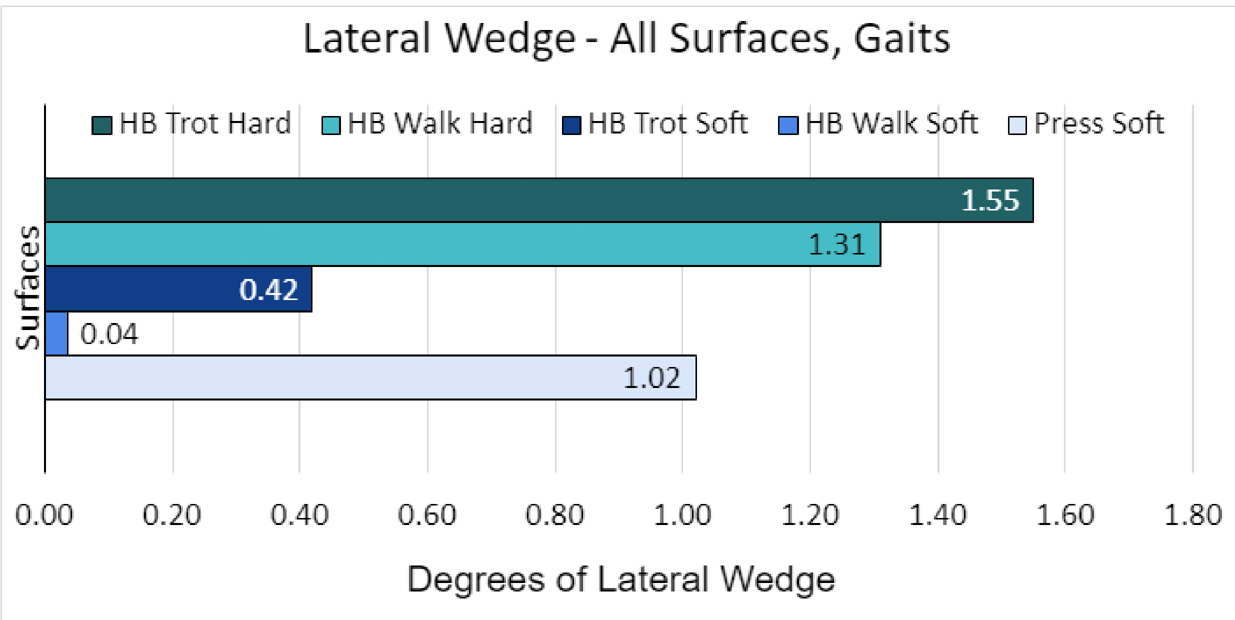
TEST & SHOE	SOFT	HARD
Press Lateral Wedge	1.02	N/A
Press Lateral Add 0.6”	0.90	N/A
Press Lateral Extension	3.03	N/A
HB Lateral Wedge Walk	0.04	1.31
HB Lateral Add 0.6” Walk	0.21	-0.01
HB Lateral Extension Walk	0.54	0.04
HB Lateral Wedge Trot	0.42	1.55
HB Lateral Add 0.6” Trot	0.28	-0.07
HB Lateral Extension Trot	0.92	0.04



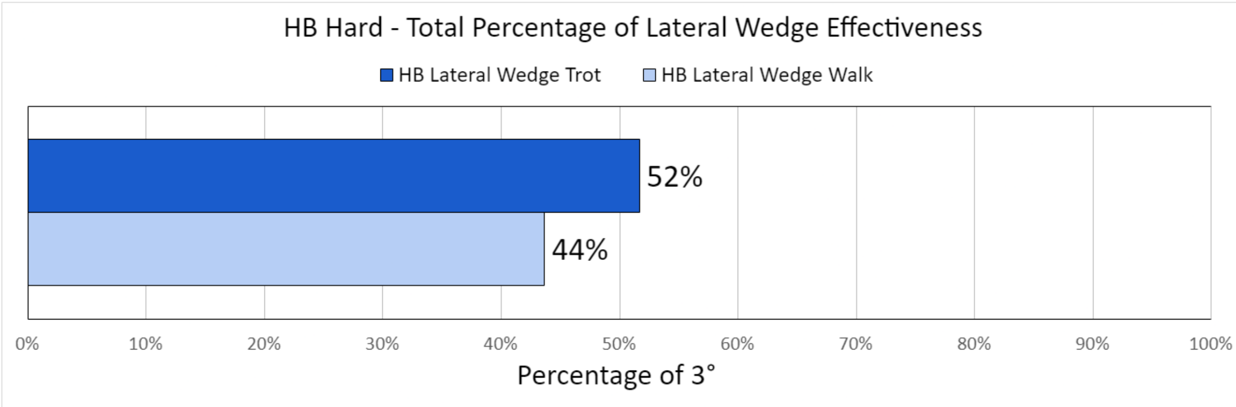
GRAPH 11: *A graph showing the effectiveness of all shoes, at achieving 3° of wedge on hard surface. The only shoe that makes any realistic change is the Lateral Wedge, as expected, all other shoes had 1% or less of lateral wedge. For exact values please reference (see Appendix A.1, C.1).*

Lateral Wedge

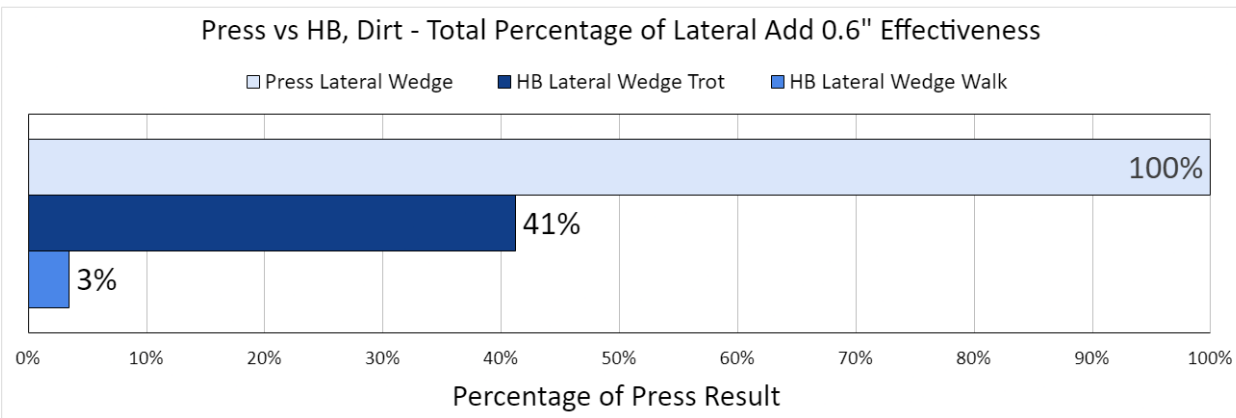
On a hard surface, this shoe showed a 1.31° lateral wedge at a walk and a 1.55° lateral wedge at a trot. These consistent measurements indicate an average of 48% reduction from the expected 3.0° wedge that was applied. However, on a soft surface, this shoe produced a 0.03° lateral wedge at a walk. This result of only 0.03° is a great example of how applying a wedge shoe without GRF consideration can have no effect to dynamic balance (see Graph 12). At a trot on the soft surface, the shoe showed a 0.42° lateral wedge making it 41% as effective as the in vitro results. (see Graph 13, 14).



GRAPH 12: *The lateral wedge shoe on all surfaces at all gaits, including press values.*



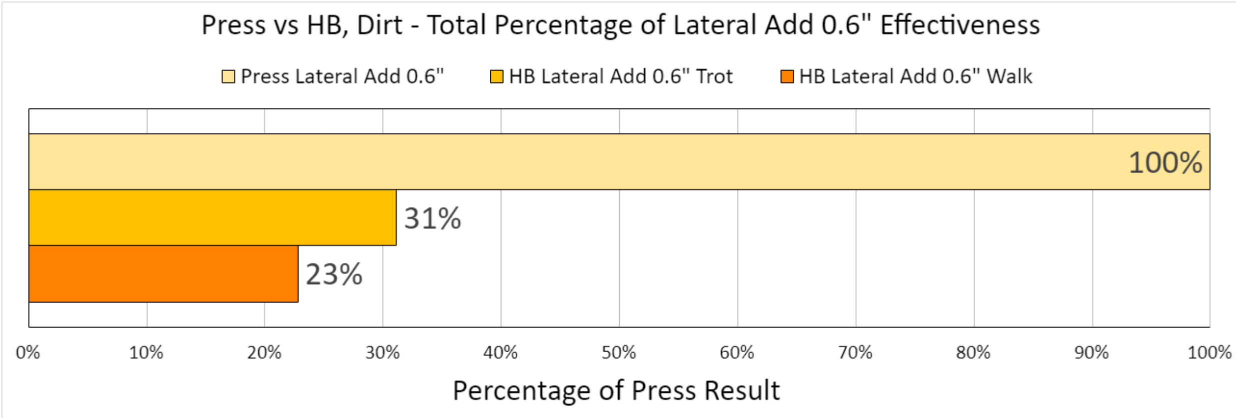
GRAPH 13: *A graph showing the effectiveness of the Lateral Wedge at achieving 3° of wedge on hard surface at a walk. (see Appendix A.1).*



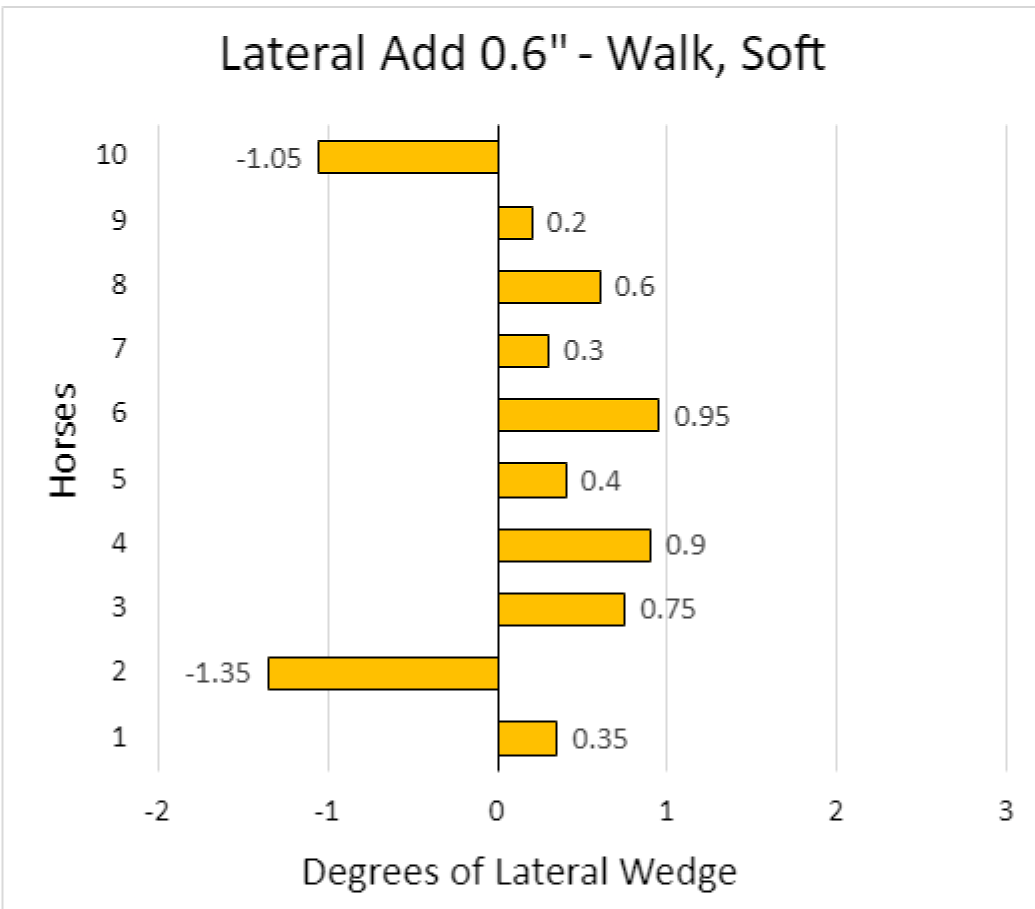
GRAPH 14: *A graph showing the effective percentage of the Lateral Wedge in vitro results to the HB in vivo results. (see Appendix A.1).*

Lateral Add 0.6”

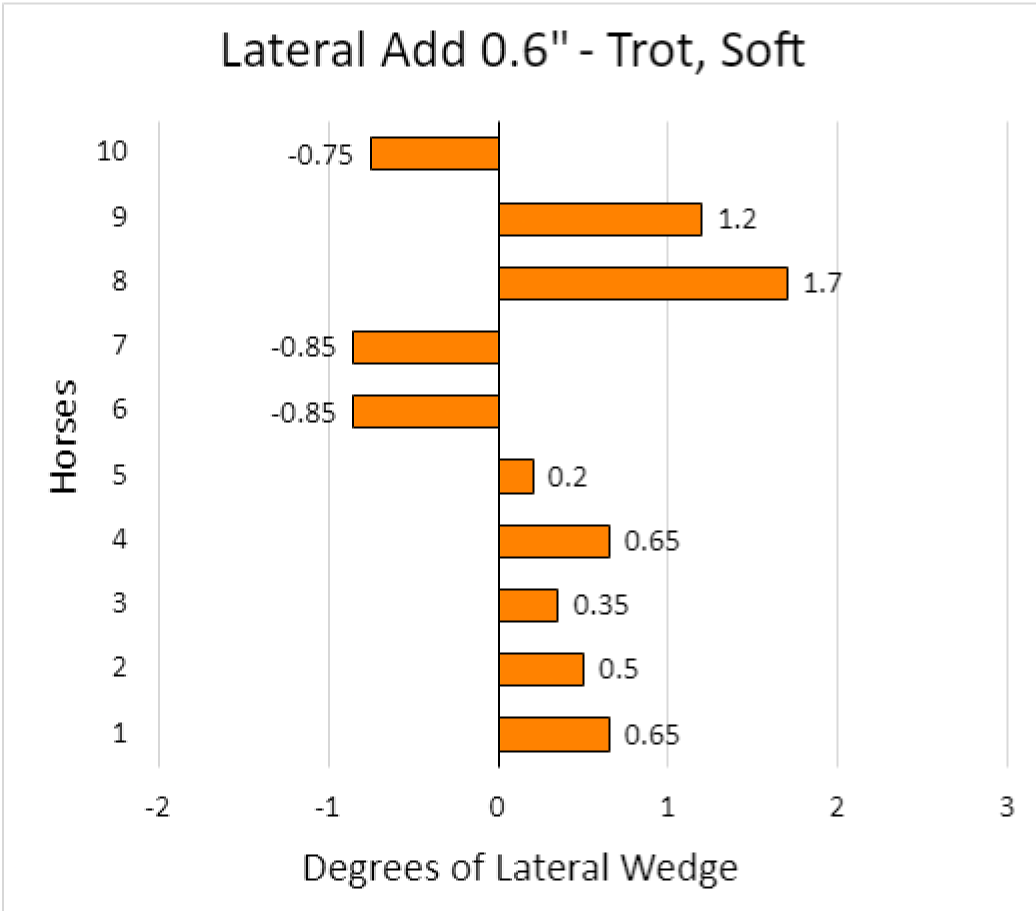
This shoe at a walk produced 0.21° of lateral wedge and 0.28° of lateral wedge at a trot. Compared to the pilot study's result of 0.90° from the same shoe and surface this equates to 23% effective at a walk and 31% effective at a trot (see Graph 15). This shoe created a lateral wedge 80% of the time at the walk and 70% at the trot (Graphs 16, 17).



GRAPH 15*: A graph showing the effective percentage of the Lateral Add 0.6" in vitro results to the HB in vivo results. (see Appendix A.1).*



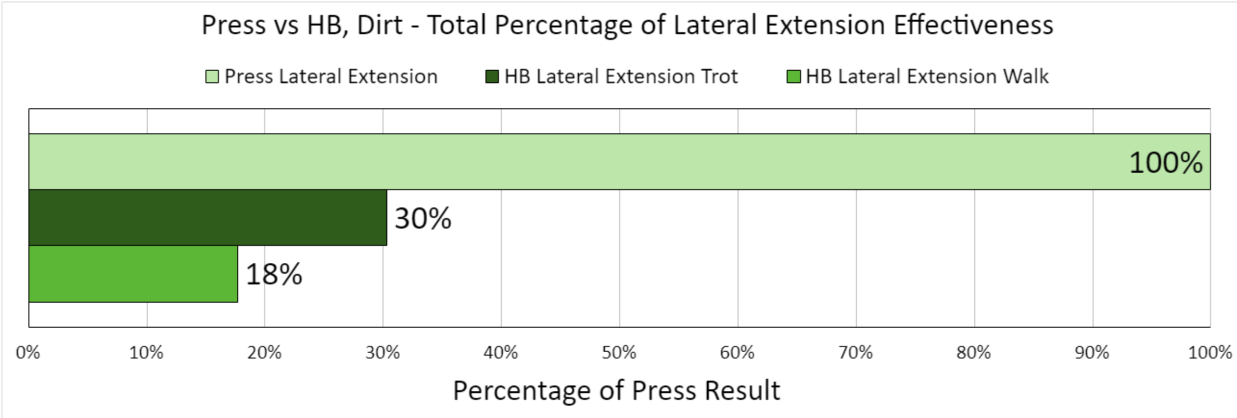
GRAPH 16: *The Lateral Add 0.6", at a walk, on arena surface with averaged left and right feet. This graph shows the success of the shoe on 8 out of 10 horses (see Appendix A.1).*



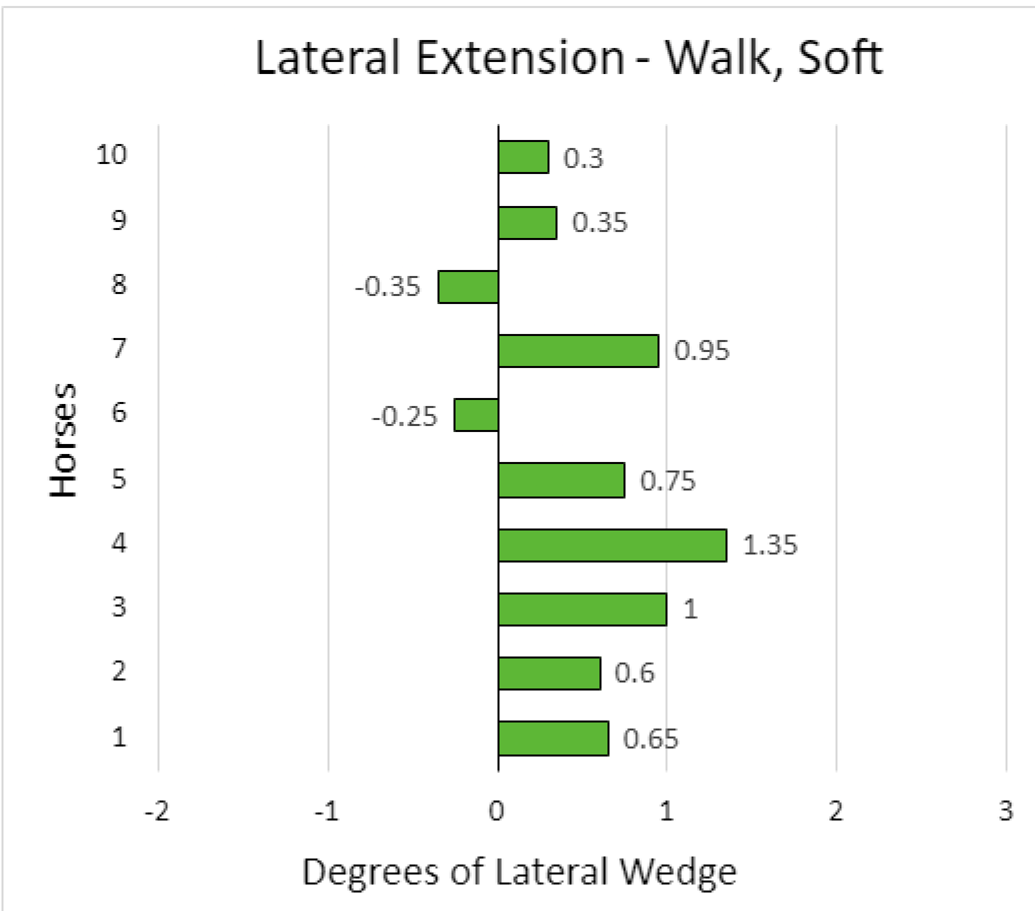
GRAPH 17: *Lateral Add 0.6” Trot on arena surface with averaged left and right feet. This graph shows the success of the shoe on 7 out of 10 horses (see Appendix A.1).*

Lateral Extension

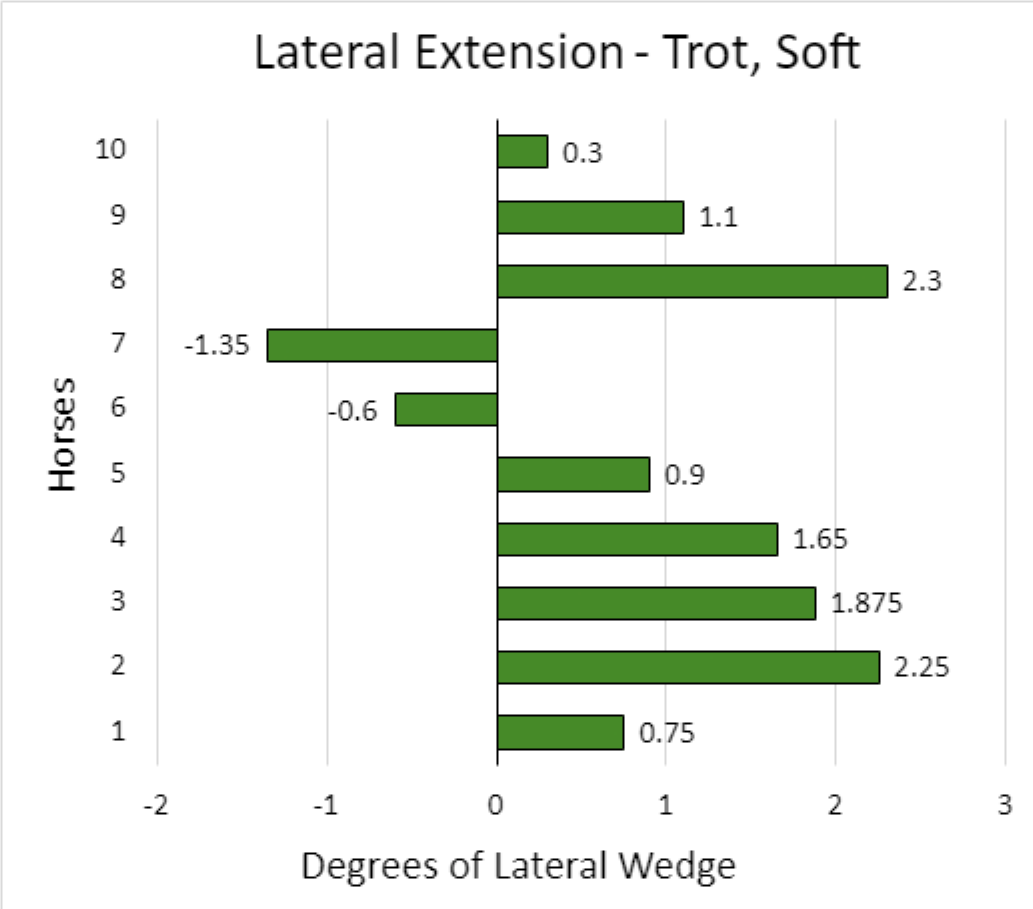
This shoe was the most effective in both studies. At a walk on soft surfaces, it added 0.54° of lateral wedge, achieving 18% of the in vitro study results. At a trot on soft surfaces, the shoe produced 0.92° of lateral wedge, achieving 30% of the in vitro results on the same medium (see Graph 18) This shoe successfully created a lateral wedge 80% of the time at both gates (see Graph 19, 20).



GRAPH 18: *A graph showing the effective percentage of the Lateral Extension in vitro results to the HB in vivo results. (see Appendix A.1).*



GRAPH 19: *The Lateral Extension, at a walk, on arena surface with averaged left and right feet. This graph shows the success of the shoe on 8 out of 10 horses (see Appendix A.1).*

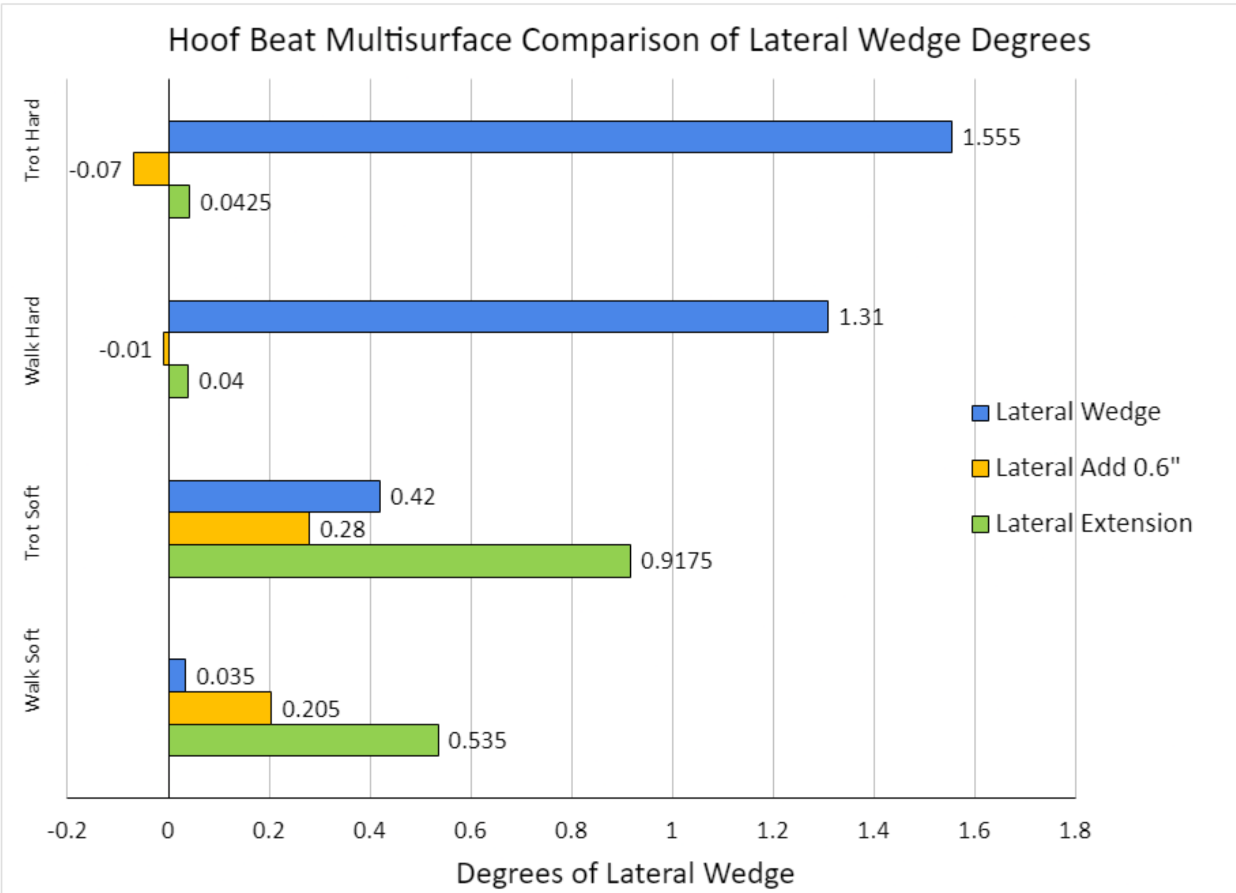


GRAPH 20: *Lateral Extension, at a trot, on arena surface with averaged left and right feet. This graph shows the success of the shoe on 8 out of 10 horses (see Appendix A.1).*

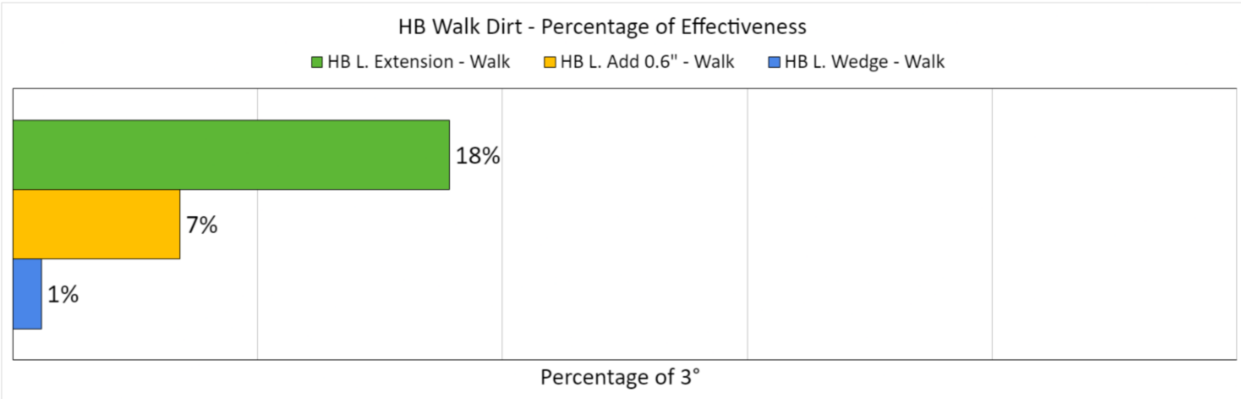
In Summary

To summarize; with a lateral wedge on a hard surface, only half of the expected 3.0° wedge was recorded (see Graph 12). The lateral wedge's effect in soft conditions on dirt was significantly less pronounced compared to the in vitro study. Specifically, at a walk, the lateral wedge produced only 3% of the effect observed in the in vitro study, while at a trot, it produced 44% of the in vitro effect (refer to Graph 13). The Lateral Add 0.6" in soft conditions at a walk and trot it produced less than half a degree of wedge (see Table 4). Among the shoes designed to use GRF principles to affect medial-lateral balance, the Lateral Extension was the most impactful (see Graph 21).

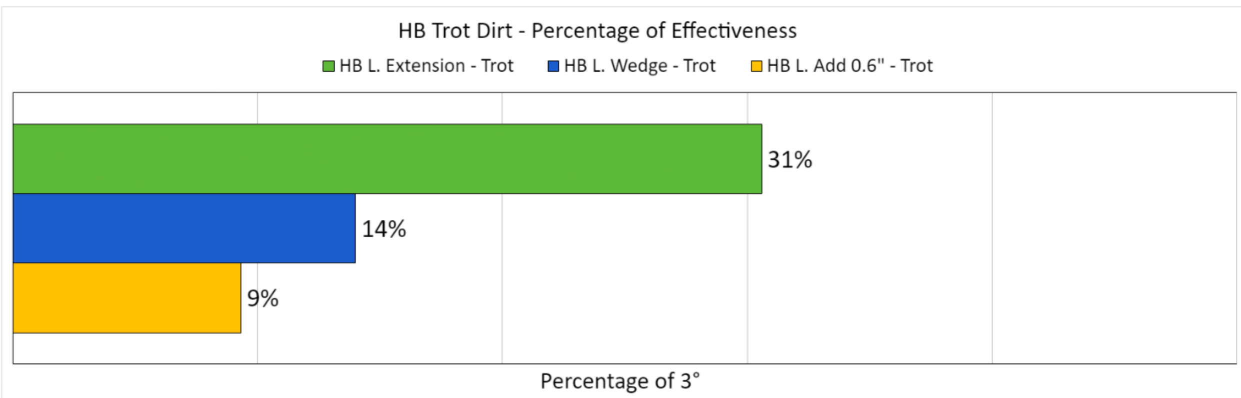
Overall, all shoes showed a significant reduction in wedge on live horses (see Graph 13, 15, 18). GRF is more potent as speed increases (Graphs 22, 23).



GRAPH 21: *Graph illustrating the comparisons between average Net Delta X measurements on the Hoof Beat across both surfaces (see Appendix A.1).*



GRAPH 22: *A graph showing the effectiveness of all shoes, at achieving 3° of wedge in dirt at the walk. (see Appendix A.1).*



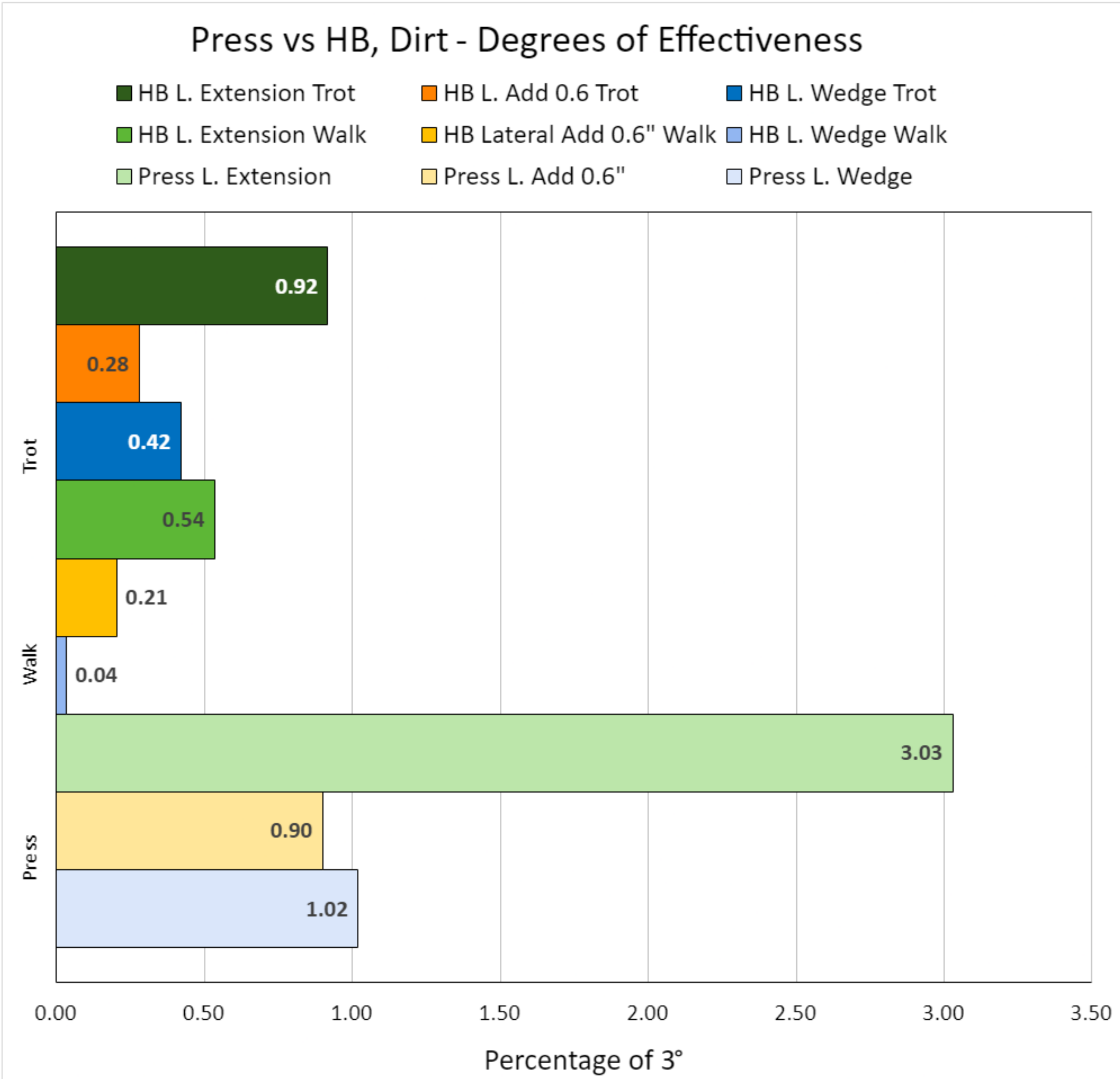
GRAPH 23: *A graph showing the effectiveness of all shoes, at achieving 3° of wedge in dirt at the trot. (see Appendix A.1).*

Discussion

The relationship between horse, surface, and GRF is complex. However, the results of these studies indicate that shoes designed using GRF principles for medial lateral angle change are effective. If GRF isn't considered, there can be severe, unexpected effects on the intended shoeing protocol. The clear results from the in vitro study provide a baseline for understanding how GRF works under test conditions. When comparing the HB data to the in vitro study results, several observations were made that enhance our understanding of using GRF in a practical way.

A notable finding is the significant reduction in the effectiveness of shoes that create a lateral wedge on a moving horse. As living animals, horses introduce their own variables, which can diminish the impact of these shoe modifications. Their natural movement patterns, proprioception, individual biomechanical differences, and preferred ways of moving can interfere with the intended outcomes. Speed also affects the efficacy of these modifications, as different gaits and velocities influence their interaction with the horse's movement and GRF. Additionally, anatomical factors like ginglymus joints and collateral ligaments provide more stability than the metal ball joint used in the press study, further reducing the modifications' effectiveness. However, the aim of this thesis was not to isolate all variables of a living horse, but to test the effect of shoes using GRF to create medial lateral angle changes.

For discussing adaptation, the 3.0° lateral wedge is the most illustrative shoe. Using this shoe on a hard surface eliminated any GRF penetration. In this test, the applied lateral wedge was reduced by up to 52%. Without adaptation, the applied 3.0° wedge should have measured as 3.0° of wedge, instead of 1.55° at a trot and 1.31° at a walk. This was also confirmed on a soft surface with the same lateral wedge. Because this shoe had no difference in web width to affect GRF, the horse was able to counteract the lateral wedge, reducing it to less than 0.1° at a walk and less than 0.5° at a trot (see Table 4). The increased effectiveness with speed indicates that adaptation is not the only factor in the reduction from the in vitro study; otherwise, there would not be a difference between the walk and trot (see Graph 24) (see Appendix A.1).



GRAPH 24: *All shoes, all gaits, and press results on dirt surface. Showing the increased effectiveness at a trot vs walk.*

As observed, there is a difference between gaits, with the trot showing the greatest effectiveness. The Lateral Add 0.6” had the smallest variance of 0.08° but was still more effective at the trot. This can be explained by the fact that as speed increases, granular materials stiffen and harden, displaying higher resistance to deformation due to granular flow dynamics (JMD Kinesitherapic Range, 2022). At higher speeds, grains of sand resist shearing or movement, like how water becomes resistant and can behave like a hard surface at high velocities (Omidvar et al., 2015). The response of the lateral wedge in dirt at a trot compared to a walk clearly demonstrates this concept.

Granular flow dynamics also explain the effectiveness of shoes using GRF principles. Consider a shoe like the Lateral Extension, which has a wider branch entering the medium. The dirt under the wide branch has more granules to move or displace. As speed increases, these granules become more resistant to movement, keeping the branch from sinking as much. Conversely, a narrow branch acts like a cutting tool, allowing the medium to move around it, reducing floatation and increasing sinkage on the narrow branch.

Another result requiring explanation is the high degree of effectiveness of the Lateral Extension in soft conditions. For this, comparing the center of rotation and the center of the shoe is important. The center of rotation is defined as the point on P2 around which the coffin bone rotates (Berger, 2017, p. 4). Typically, the center of rotation is discussed in terms of the dorsal-palmar flexion of the distal interphalangeal joint (DIP), a two-dimensional view. However, there is also a medial-lateral component to the center of rotation. Since the DIP is a hinge/ginglymus joint, the medial-lateral point will be close to the median line of this joint. The position of the center of rotation on the medial-lateral axis will correlate with the weight per branch discussed in the introduction.

There is also a point that represents the center of the shoe when viewed from the ground surface (see Figure 18). Adding material to the outside edge of the shoe or fitting it outside the foot's perimeter creates a longer moment arm relative to the center of rotation. This also shifts the center of the shoe towards the added width. In these studies, even a small shift of 0.125" (3.1 mm) with the Lateral Extension showed a significant difference. This was the primary purpose for including the Lateral Add 0.6" shoe in the study.

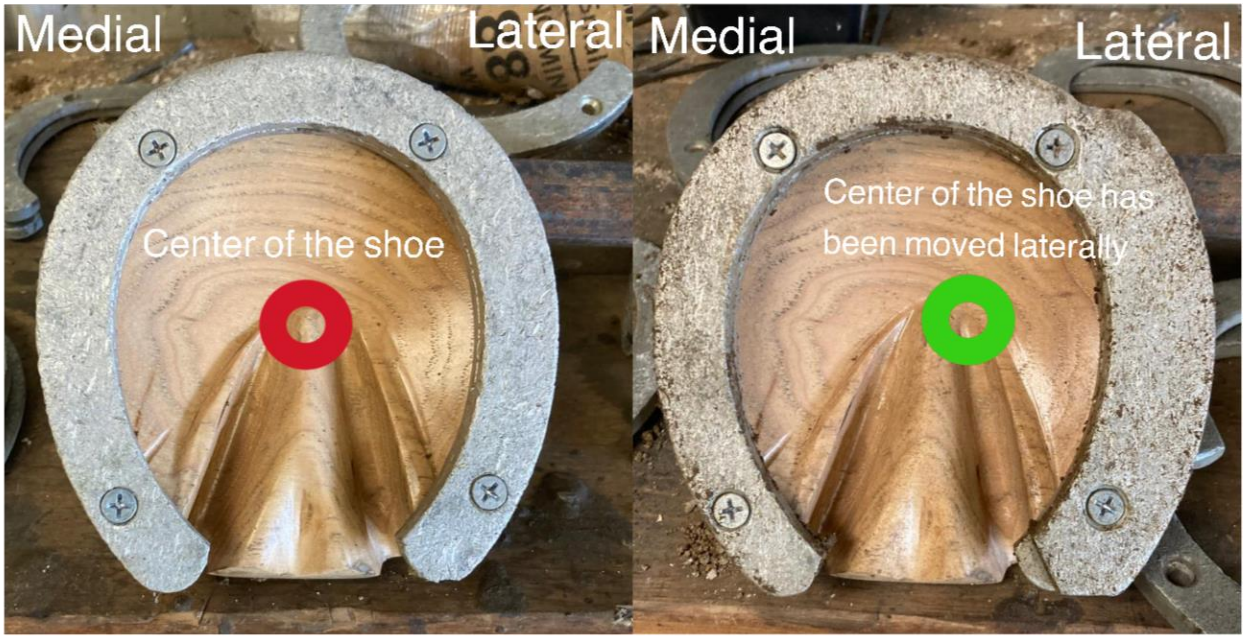


FIGURE 18: *A lateral extension moves the center of the shoe to the lateral side (see Appendix A.1).*

For a shoe to effectively use GRF principles, one of the biggest factors in its success at changing angles is the position of the center of the shoe relative to the center of rotation. This is evidenced by comparing the Lateral Extension with the Lateral Add 0.6". The Lateral Extension had 1 square inch less surface area than the Lateral Add 0.6" shoe. If the surface area of the lateral branch were the most significant factor, the Lateral Add 0.6" shoe would have created the greatest lateral wedge. However, since the Lateral Extension produced the most lateral wedge, it demonstrates that the position of the center of the shoe relative to the center of rotation is a more critical factor in a shoe utilizing GRF principles.

This thesis focused on medial-lateral angle changes, but it is anticipated that manipulating the center of the shoe dorsally or palmarly relative to the center of rotation will also affect the dorsal-palmar axis.

Conclusion

Shoes utilizing GRF principles, via web width disparity, have proven effective in manipulating medial-lateral balance on arena surfaces. Ignoring GRF means a shoe applied to change balance will not function as intended. As speed increases, the disparity in web width has a more pronounced effect on the GRF. This means that at higher speeds, variations in the width of the shoe's web can significantly change angle. Consequently, precise adjustments in web width become increasingly critical in maintaining balance and performance at faster gaits, as even minor differences can lead to substantial changes. Moreover, the position of the shoe's center relative to the center of rotation, and how GRF principles affect foot balance, should be considered for every shod foot.

Limitations

The HB measuring equipment posed a significant limitation as it provided only one measurement for all the strides, representing the median data for all strides, and the data retrieval process introduced potential human error. Evaluating moving horses using statistical methods is challenging due to their inherent complexity, variability, and adaptability. Each horse has unique biomechanical traits, conformation, training levels, age, experience, size, and proprioception, all of which influence results. Modern measurement technology has limitations, especially when processing data with high variability. Additionally, statistical assumptions like normality and homogeneity are often violated in biological studies. The dynamic nature of movement and the interaction of multiple variables further complicate analysis. Therefore, while statistics provide valuable insights, practical farrier work must account for these limitations and focus on realistic, real-world applications.

Future studies

These studies yielded significant results but do not fully encompass the knowledge on this subject. Future studies would benefit greatly from tracking the foot in three dimensions.

Equally important would be testing how the position of the center of rotation and manipulating the center of the shoe along the dorsal-palmar axis, by fitting longer or setting the toe of the shoe back, are affected by GRF in soft mediums. A small set of data has already been collected for this purpose.

REFERENCES

Back, W., and Clayton, H. (2013). *Equine Locomotion*. 2nd ed. USA: Saunders Ltd. Chapter 2, pp. 41-42, 50-51; Chapter 7, pp. 130-131, 137-142; Chapter 8, pp. 150-165, 176-179.

Berger, H. (2017). Use of external landmarks as reference points for the location of internal structures within the hoof capsule. *Theses for the FWCF*. Available at: www.wcf.org.uk, FWCF Theses (Accessed: 16 May, 2023).

Clayton, H. M., and Hobbs, S. J. (2019). Ground Reaction Forces: The Sine Qua Non of Legged Locomotion. *Journal of Equine Veterinary Science*, 76, pp. 25-35. DOI: 10.1016/j.jevs.2019.02.022. Available at: http://clock.uclan.ac.uk/28665/ (Accessed: 25 October, 2023).

Day, J.H. (1981). *Estuarine Ecology – with Particular Reference to Southern Africa*. Rotterdam: A.A. Balkema.

Giannotti, E. (2022). *Veterinarian who performed lameness evaluation on test subjects*. Veterinarian, A.W.C.F.

Physics LibreTexts. (2024). 5.4: Newton's Second Law. Available at: https://phys.libretexts.org/Bookshelves/Classical_Mechanics/Book%3A_Physics_(Boundless)/5%3A_Laws_of_Motion/5.4%3A_Newton's_Second_Law (Accessed: 16 July 2024).

Gregory, C. (2011). *Gregory's Textbook of Farriery*. USA: Walsworth Publishing for Heartland Horseshoeing School. Chapter 12, pp. 135-138, 145-150; Chapter 23, pp. 230-232.

Google LLC. (2024) *Google Sheets*. Available at: https://www.google.com/sheets/about/ (Accessed: December 14, 2022). Used for initial data collection.

Hagen, J., Bos, R., Brouwer, J., and Lux, F.T. (2021). Influence of trimming, hoof angle and shoeing on breakover duration in sound horses examined with hoof-mounted inertial sensors. *Veterinary Record*, 2021, e450. Available at: https://doi.org/10.1002/vetr.450 (Accessed: 14 November, 2023).

Hagen, J. (2021). What is Mediolateral Balance? Scientific research offers insight in the context of everyday hoof care. *American Farriers Journal*. Published in December 2021.

Hoof Beat Systems. (2022). *User Manual*. Page 10.

IBM Corp. (2021). *IBM SPSS Statistics for Windows, Version 27.0*. Armonk, NY: IBM Corp.

JMD Kinesitherapic Range (2022). ASYMETRIX JMD Hind Shoe designed by Professor Jean-Marie Denoix, DVM, PhD, Normandy, France. Available at: http://www.michel-vaillant.com (Accessed: 16 July 2024).

Morgan, J.P. (1970). Depositional Processes and Products in the Deltaic Environment. *Society of Economic Paleontologists & Mineralogists Special Publication*, Vol. 15, pp. 31–47. Tulsa.

Navarra, K. (2020). How Hind End Geometry Improves Performance and Balance. *American Farriers Journal*. Posted on May 10, 2020. Available at: www.americanfarriers.com/articles/11787 (Accessed: 18 April, 2024).

Omidvar, M., Malioche, J.D., Chen, Z., & Iskander, M. (2015). Visualizing kinematics of dynamic penetration in granular media using transparent soils. *Geotech Test J*, 38(18). Available at: https://doi.org/10.1520/GTJ20140206 (Accessed: 16 July 2024).

Reilly PT, van Eps A, Stefanosvski D, Pfau T. (2023). The influence of different horseshoes and ground substrates on mid-stance hoof orientation at the walk. *Equine Vet Journal.* https://doi.org/10.1111/evj.13990

RStudio Team. (2022) *RStudio: Integrated Development Environment for R*. RStudio, PBC, Boston, MA. Available at: https://www.rstudio.com (Accessed: 6 May, 2024).

Smith, G. E. (2020). 'The Third Law in Newton's Mechanics', *The British Journal for the History of Science*, 4(1), pp. 35-45. Available at: https://www.cambridge.org/core/journals/british-journal-for-the-history-of-science/article/abs/third-law-in-newtons-mechanics/C3AB403A04CD4B0F7995CE24C4685BC9 (Accessed: 16 July 2024).

MANUFACTURERS

Coobeast (2021) *Digital Angle Finder Magnetic, Rechargeable Digital Angle Gauge*. Available at: https://www.amazon.com/Coobeast-Rechargeable-Protractor-Measuring-Woodworking/dp/B0CCTZCNVH/ref=sr_1_8?sr=8-8 (Accessed: December 2022).

ConAgra Foods. (2024). *Pam Cooking Spray*. Available at: https://www.pamcookingspray.com (Accessed: 1 December, 2022).

Kruse Cushion Ride, superior equestrian surfaces. *Synthetic footing.*

Website: www.kruscushionride.com.

Email: email@krusecushionride.com

Telephone: 317-337-1950

Fax: 317-337-1951

The VICTORY Racing Plate Company. *Hoof Life Acrylic Glue.*

Address: 1200 Rosedale Avenue Baltimore, Maryland 21237 USA

Website: https://victoryracingplate.com/pages/contact-us

Email: info@victoryracingplate.com

Telephone: +1-410-391-6600, +1-800-872-7528

Fax: +1-410-687-4132

Kahn Forge, Inc. (1999). *Steel Hind 'Certifier'.*

Address: 1061 N Shepard St, Ste A, Anaheim, CA 92806; USA

Website: www.kahnforge.com.

Email: info@kahnforge.com

Telephone: +1-714-779-2581, 657-230-9800

Hoof Beat System, by Christel Werkman

Address: Hoofdstraat 53, 9356 AV Tolbert

Website: www.hoofbeat.nl

Email: support@hoofbeat.nl

Telephone: 0031-50-721022

Broadline Farrier Solutions. *Hanton Tabs.*

Website: https://broadlinefarriersolutions.com/

Email: torri@broadlinefs.com

Telephone: +1-502–321-6619

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.3 Permission from Renate Weller and Thilo Pfau

Permission was granted by Renate Weller and Thilo Pfau to use their contributions. (July 21, 2024).

Appendix B: Mathematical Formulas

B.1 Calculating Ground Force Reaction Static, Dynamic

Given Information

Total weight of the horse: 1200 lbs

Weight distribution on front feet: 60%

Only one front foot bearing weight at a time

Speed: 29 mph

Impact time (Δt): 0.25 seconds

Gravity (g): 9.81 m/s^2

Conversion factors:

Pounds to kilograms: 0.453592

MPH to MPS: 0.44704

Newtons to pounds-force: 0.224809

Step 1: Convert Weight to Kilograms

Formula:

$$m_{\text{kg}} = m_{\text{lbs}} \times 0.453592$$

Calculate for one front foot:

$$m_{\text{front}} = \frac{1200 \times 0.60}{2} \times 0.453592$$

Step 2: Calculate Static GRF Due to Gravity

Formula: g (acceleration due to gravity) = 9.81 m/s²

$$F_{gravity} = m \times g$$

Apply for the front foot:

$$F_{\text{front, static}} = m_{\text{front}} \times 9.81$$

Step 3: Convert Speed from MPH to MPS

Formula:

$$V_{\text{mps}} = V_{\text{mph}} \times 0.44704$$

Convert 29 mph:

$$V_{29\,mph} = 29 \times 0.44704$$

Step 4: Calculate Dynamic GRF

Assume an impact time, Δt of 0.25 seconds (typical for a running horse).

Formula:

$$F_{\text{dynamic}} = \frac{m \times V_{\text{mps}}}{\Delta t}$$

Apply for the front foot:

$$F_{front,\,dynamic} = \frac{m_{front} \times V_{29\,mph}}{0.25}$$

Step 5: Calculate Total Force on the Front Foot

Formula:

$$F_{total} = F_{static} + F_{dynamic}$$

Apply:

$$F_{front,\,total} = F_{front,\,static} + F_{front,\,dynamic}$$

Step 6: Convert Force from Newtons to Pounds-Force (Optional)

Conversion factor: 1 Newton = 0.224809 lbs-force

Formula:

$$F_{\text{lbf}} = F_{\text{N}} \times 0.224809$$

Convert total force if needed for practical applications.

B.2 Calculating Degrees over a 5” Wide Foot

Given Information

Tolerance: *0.0625* inches (or *1.5* mm).

Width of the foot: *5.0* inches.

We will use the relationship between the arc length, radius, and angle.

Steps to Solve

Step 1: Understanding the Relationship

Use the formula: $\theta = \frac{s}{r}$

Where:

θ is the angle in radians,

s is the arc length (tolerance),

r is the radius (width of the foot).

Step 2: Plugging in the Values

Given:

s = 0.0625 inchess

r = 5.0

We solve for θ

$$\theta = \frac{0.0625}{5.0}$$

$$\theta = 0.0125\, radians$$

Step 3: Converting Radians to Degrees

Convert the angle from radians to degrees using the conversion factor $\frac{180}{\pi}$:

$$\theta\ in\ \deg = \theta\ in\, radians \times \frac{180}{\pi}$$

$$\theta\ in\ \deg = 0.0125 \times \frac{180}{\pi}$$

$$\theta\ in\ \deg \approx 0.716°$$

B.3 Calculating Net Delta X

Example: calculating the Net Delta X for a particular test shoe.

[Horse #1] Delta X Test Shoe - [Horse #1] Delta X Control = [Horse #1] Net Delta X

Appendix C: Statistics & Graphs

C.1 Percentage & Degree Data Tables

Percentage Data

TEST & SHOE	% VS SELF PRESS SOFT	% OF 3 SOFT	% OF 3 HARD	% of 3 SYNTHETIC	% VS PRESS WEDGE	% VS HB SOFT WEDGE
Press Lateral Wedge	100%	34%	N/A	42%	100%%	100%
Press Lateral Add 0.6”	100%	30%	N/A	55%	100%%	88%
Press Lateral Extension	100%	101%	N/A	74%	100%%	297%
HB Lateral Wedge Walk	3%	1%	44%	N/A	3%	100%
HB Lateral Add 0.6” Walk	23%	7%	0%	N/A	20%	586%
HB Lateral Extension Walk	18%	18%	1%	N/A	52%	1529%
HB Lateral Wedge Trot	41%	14%	52%	N/A	41%	100%
HB Lateral Add 0.6” Trot	31%	9%	-2%	N/A	27%	67%
HB Lateral Extension Trot	30%	31%	1%	N/A	90%	218%

Degree Data, Net Delta X

TEST & SHOE	*DEGREES SOFT*	*DEGREES HARD*	*DEGREES SYNTHETIC*
Press Lateral Wedge	1.02	N/A	1.27
Press Lateral Add 0.6”	0.90	N/A	1.65
Press Lateral Extension	3.03	N/A	2.21
HB Lateral Wedge Walk	0.04	1.31	N/A
HB Lateral Add 0.6” Walk	0.21	-0.01	N/A
HB Lateral Extension Walk	0.54	0.04	N/A
HB Lateral Wedge Trot	0.42	1.55	N/A
HB Lateral Add 0.6” Trot	0.28	-0.07	N/A
HB Lateral Extension Trot	0.92	0.04	N/A

C.2 Statistical Analysis, the data was analyzed using IBM SPSS Statistics for Windows, Version 27.0 (IBM Corp., 2021). All statistics were run using the following parameters with a sample size of N20:

> A mixed linear model was implemented with 'horse' and 'foot within horse' as random factors and 'shoe', 'gait' and 'surface' and their two-way interactions as fixed factors and Delta X as outcome parameter. Two-way interactions with p-values above 0.1 were removed and a final model was run. The only two-way interaction remaining in the final model was shoe*surface. The level of significance was set to $P<0.05$ and a Bonferroni correction was implemented for multiple pairwise comparisons (for ‘shoe’ effects).

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	228	21.703	<.001
Gait	1	228	.891	.346
Surface	1	228	.157	.692
Shoe	2	228	5.158	.006
Gait * Surface	1	228	.310	.578
Gait * Shoe	2	228	.232	.793
Surface * Shoe	2	228	9.547	<.001
Gait * Surface * Shoe	2	228	.036	.965

a. Dependent Variable: NetDelta.

8. Gait * Surface * Shoe[a]

Gait	Surface	Shoe	Mean	Std. Error	df	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Walk	Soft	CG Lateral Wedge	.035	.324	228	-.604	.674
		CG Lateral Add .6"	.205	.324	228	-.434	.844
		CG Lateral Extension	.535	.324	228	-.104	1.174
	Hard	CG Lateral Wedge	1.310	.324	228	.671	1.949
		CG Lateral Add .6"	-.010	.324	228	-.649	.629
		CG Lateral Extension	.010	.324	228	-.629	.649
Trot	Soft	CG Lateral Wedge	.420	.324	228	-.219	1.059
		CG Lateral Add .6"	.280	.324	228	-.359	.919
		CG Lateral Extension	.917	.324	228	.279	1.556
	Hard	CG Lateral Wedge	1.555	.324	228	.916	2.194
		CG Lateral Add .6"	-.070	.324	228	-.709	.569
		CG Lateral Extension	.043	.324	228	-.596	.681

a. Dependent Variable: NetDelta.

7. Surface * Shoe[a]

Surface	Shoe	Mean	Std. Error	df	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Soft	CG Lateral Wedge	.227	.229	228	-.224	.679
	CG Lateral Add .6"	.242	.229	228	-.209	.694
	CG Lateral Extension	.726	.229	228	.275	1.178
Hard	CG Lateral Wedge	1.432	.229	228	.981	1.884
	CG Lateral Add .6"	-.040	.229	228	-.492	.412
	CG Lateral Extension	.026	.229	228	-.425	.478

a. Dependent Variable: NetDelta.