EFFECT OF INDUCED HINDLIMB LENGTH DIFFERENCE ON BODY-MOUNTED INERTIAL SENSOR MEASURES OF HINDLIMB LAMENESS IN HORSES

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

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LIST OF ABBREVIATIONS

AAEP	American Associated of Equine Practitioners
BMIS	Body-mounted inertial sensor system
CT	Computed Tomography
HHD	Differences between upward movement amplitudes between left and right tuber coxae
MRI	Magnetic Resonance Imaging
P_{max}	Differences in maximum pelvic height before and after hindlimb stance between right and left halves of a stride
P_{min}	Differences in minimum pelvic height during hindlimb stance between right and left halves of a stride

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ABSTRACT

This study has investigated the effect of induced hindlimb length difference on differences in minimum and maximum pelvic heights in horses trotting in a straight line and lungeing on both hard and soft surfaces. The horses were trotted in a straight line and lunged in both directions on both hard and soft surfaces. Wilcoxon ranked sum tests were used to determine the effect of hindlimb length difference on differences in minimum (P_{min}) and maximum (P_{max}) pelvic height values. Difference in P_{min}, indicating an impact-type lameness, in the limb with the elevation, was consistently measured in both the straight line and while lungeing. Difference in P_{max}, indicating pushoff-type lameness, in the opposite, non-elevated limb, was found in the straight line but not while lungeing. A limited extended elevation trial was performed with no definitive pattern of results obtained. Statistics were not performed on this data and future study in this area is warranted.

CHAPTER 1: INTRODUCTION

a. Lameness in the horse

Equine lameness is a common veterinary medical issue resulting in a major economic impact to owners and other equine industry professionals.(1) Lameness is measured as asymmetry of movement between right and left halves of the body and can interfere with the comfort and function of the horse. A multitude of varying causes of lameness exist and diagnosis requires thorough examination and evaluation of the horse.

b. Hindlimb length difference and lameness

Hindlimb length difference can result from growth discrepancies of the hooves or long bones between the right and left limbs. These discrepancies may have been caused by injuries that are healed and no longer painful, or differences in functional demand from specialized training or repetitive movement, leading to the development of “leggedness” (“handedness” in humans).(2, 3) Such differences in limb length would not be expected to cause pain, but the resulting asymmetry may appear as lameness during evaluation.

Hindlimb length difference is visualized as an asymmetric pelvis with tuber coxae height from the ground higher on one side compared to the other. In a study of Standardbred Trotters, existing pelvic height asymmetry, found in 39 of 500 horses, was associated with poor performance, as measured by total earnings.(4) Thus, hindlimb length difference may also be associated with poor performance in horse. In human studies, leg length differences have been shown to increase the incidence of a variety of abnormalities and pathologies, including low back pain, hip osteoarthritis, sacroiliac disease, stress fractures, loosening of hip prostheses, and running injuries.(5)

In addition to the possible effects on performance, pelvic asymmetry caused by hindlimb length difference creates difficulty for the veterinary practitioner evaluating horses for hindlimb lameness, because most veterinarians observe pelvic movement when trying to detect hindlimb lameness.

c. Subjective Lameness Evaluation

Traditionally, a lameness evaluation consists of a subjective visual examination of the horse in motion. During a subjective evaluation, the clinician is attempting to determine if the horse is displaying lameness and if so, which limb(s) are involved. Visual assessment with the horse in motion is most commonly evaluated at both the walk and the trot. Occasionally, horses are evaluated at the canter. Lameness in the horse is observed as asymmetry of motion between the right and left sides of the horse's body. Horses with pre-existing hindlimb length difference may appear lame because they move asymmetrically, but the asymmetric movement may be due to the pre-existing length difference and not pain.

Following identification of the limb(s) with lameness, further assessment is needed to determine the location within the limb that is the source of the lameness. Evaluation of anatomic asymmetry, palpation of the musculoskeletal system, hoof tester application, joint flexion tests, and diagnostic anesthesia can be performed to determine the source of lameness. In hindlimb lameness special attention should be paid to evaluating asymmetry of the pelvis, usually by assessment of the height of the tuber coxae from the ground with the horse standing squarely. Once a specific area has been identified, diagnostic imaging such as radiography, ultrasonography, CT (computed tomography), or MRI (magnetic resonance imaging) is often performed in an effort to arrive at a diagnosis.

The American Association of Equine Practitioners (AAEP) has recommended a lameness scale ranging from 0 to 5 that allows veterinarians to communicate in an objective manner about lameness and document accurately in medical records. An AAEP grade of 0 designates a horse that does not have a perceptible lameness under any circumstance; grade1 designates a lameness that is difficult to observe and not consistently apparent; grade 2 designates a lameness that is difficult to observe when trotting in a straight line, but consistently observable under certain circumstances; grade 3 designates a lameness that is consistently observable at the trot under all circumstances; a grade 4 designates a lameness that is observable at the walk; and a grade of 5 designates a horse that is minimally weight bearing at rest or in motion. Unfortunately, not all horses will meet the grade criteria exactly and will fall into areas between the current grading system. This categorical, qualitative method of lameness description causes difficulty when describing and recording severity of lameness to others and within medical records.

Partly because of the inherent inexactness of such qualitative methods, the utility of subjective evaluation of lameness has been questioned. Intra-observer agreement of experts evaluating videos of horses trotting on a treadmill for determination of lameness was equivalent to what it considered a diagnostic test of moderate difficulty, but inter-observer agreement for determining limb of origin and amplitude of hindlimb lameness was unacceptably low.(6) Other studies have shown that subjective evaluation is only moderately reliable and that veterinarian bias exists when interpreting results of diagnostic anesthesia.(7-11) In a later study, agreement of evaluators on subjective evaluation of mild hindlimb lameness was determined to be poor.(11) Additionally, objective evaluation is more sensitive when compared to subjective evaluation and therefore, is able to identify more subtle asymmetries.(12) The sensitivity of the inertial sensors system was previously studied by evaluating induced lameness via a special shoe with an adjustable screw to apply sole pressure. The inertial sensor system was able to identify the limb of origin after less screw turns than three experienced equine veterinarians. (12) These findings of low expert agreement and bias in interpretation highlight the advantage of performing an objective lameness evaluation as an aid to subjective evaluation.

d. Objective Evaluation with Inertial Sensors

When using the body-mounted inertial sensors of one commercially available system developed specifically for equine lameness evaluation, vertical head and pelvic acceleration are measured. This body-mounted inertial sensor system allows vertical torso acceleration and deceleration to be measured over multiple strides on varying footing surfaces during a lameness evaluation. These measurements are converted by the system to vertical position in the local reference frame of the horse.

To evaluate hindlimb lameness, differences in minimum (P_{min}) and maximum (P_{max}) pelvic height are determined for each stride at the trot. P_{min} is the minimum pelvic height during right hind limb stance minus minimum pelvic height during left hind limb stance . P_{max} is maximum pelvic height preceding right hind limb stance minus maximum pelvic height preceding left hind limb stance (figure 1). An impact-type lameness, measured as P_{min}, occurs when there is a decreased downward force of the rear torso onto a lame hindlimb in the first half of stance (figure 2-3). This occurs due to an abbreviated fall of the pelvis to the ground during stance of the sound limb. A pushoff-type lameness, measured as P_{max}, occurs when there is a decreased upward force from a lame hindlimb in the second half of stance (figure 4-6). This results due to an abbreviated rise of the pelvis, so that it reaches a lower position relative to the ground than after stance of the sound limb.

Measurement of asymmetrical vertical movement of the pelvis used by the sensor system is a common and accepted method to detect hindlimb lameness. The pelvis falls to a minimum height during stance and rises to a maximum height after stance, twice during one stride.(11, 13-16) In horses without lameness, this rise and fall is symmetrical between right and left strides. In horses with pain during hindlimb weight-bearing, the pelvic fall, the pelvic rise, or both, are decreased for the lame compared to the non- or less-lame hindlimb, reflecting a decreased force of impact or pushoff, respectively.(13) This results in higher minimum pelvic height during stance or lower maximum pelvic height after stance of the lame limb. This model of hindlimb lameness detection and measurement assumes equivalent hindlimb length between right and left sides during pain-free weight bearing.

However, it is reasonable to assume that not all horses have symmetrical hindlimb length, even if the horse is healthy and functioning normally. Because objective measures of hindlimb lameness assume anatomical symmetry, the presence of hindlimb length difference may invalidate results obtained.

A study on the effect of a unilateral hindlimb orthotic lift on upper body movement symmetry in the trotting horse was performed by Vertz, et al. In this study, movement asymmetry was calculated from vertical displacement of poll, withers, sacrum, and left and right tuber coxae after varying size orthotic lifts were used to increase hindlimb length. Results showed increased downward movement of the entire pelvis (as measured on midline between the tubera sacral) during stance of the shorter limb (without the orthotic lift) and increased upward movement during and after stance of the longer limb (with the orthotic lift). However, the amplitude of increased downward and upward movement was less than the height of the orthotic lifts (3 – 7 mm for 15 mm lifts and 4-10 mm for 30 mm lifts).(17) On the other hand the same study showed that difference in total upward movement of the tuber coxae between the two limbs (elevated and non-elevated) was not affected by the orthotic lifts.

In this study, the effect of hindlimb length difference was only evaluated in horses trotting in a straight line on hard surfaces, which are limited conditions compared to common clinical evaluation.(17) After a search of the literature, previous research has not been published on the effect of hindlimb length difference on pelvic asymmetry measures commonly used for hindlimb lameness assessment during the lunge or on different surfaces.

Numerous studies have shown that the horse moves differently when lungeing (moving in a circle) than when moving in a straight line. Because the torso is tilted to the inside of the circle the pelvis falls less during weight bearing of the inside hindlimb and rises less after pushoff of the outside hindlimb, the same effects seen with application of an orthotic lift in horses trotting in a straight line. Thus, lungeing with the orthotic lift applied to the inside hindlimb should be expected to magnify the effects on asymmetric rise and fall of the pelvis.(18-20)

Prior to development of body-mounted inertial sensor systems, stationary force plates were the most commonly used equipment to objectively evaluate horses for lameness. Vertical ground reaction force measures have been shown to be accurate and precise measures of lameness in horses. However, clinical use of the force plate is difficult due to expense, availability, difficulty in obtaining consistent results, and the inability of obtaining data from multiple contiguous strides. One study has evaluated the association of force plate and body-mounted inertial sensor system measures of hindlimb lameness. Inertial sensor–derived measurements of asymmetric pelvic fall was most strongly associated with a decrease in peak vertical ground reaction force, but measurements of asymmetric pelvis rise was most strongly associated with vertical impulse and transfer of vertical to horizontal force in the second half of stance.(13) Probably the most important clinical aspect of lameness is related to changes in ground reaction force during weight bearing. Body-mounted inertial sensors that measure vertical acceleration do not directly measure ground reaction force, but many studies have shown that they are reasonable proxy measurements that can be obtained from multiple contiguous strides. They offer a useful objective measurement of lameness in a clinical setting where high stride-by-stride variability is commonly seen.

e. Summary

Since lameness is a common problem in the horse, detecting lameness is an important task for equine veterinarians. Objective lameness evaluation helps practitioners avoid the pitfalls and disadvantages of simple subjective visual assessment, especially for the more difficult-to-detect hindlimb lameness. Body-mounted inertial sensors, that assess vertical movement of the pelvis to detect hindlimb lameness, are now a commonly used objective method. However, limb length discrepancies may interfere with this method of objective assessment of hindlimb lameness. Knowledge of the effect of limb length discrepancy on body-mounted inertial sensor detection and measurement of hindlimb lameness during the activities that veterinarians commonly use to assess horses for lameness will help to further develop this technique and method.

CHAPTER 2: EXPERIMENTAL PURPOSE AND HYPOTHESIS

The purpose of this study was to investigate the effect of induced hindlimb length difference on differences in minimum and maximum pelvic heights in horses trotting in a straight line and lungeing on both hard and soft surfaces. We expected that, after induction of hindlimb length difference, differences in minimum and maximum pelvic height would reflect simple differences in limb length, with higher maximum and minimum heights in the limb with increased length. This would result in a false measurement of impact type hindlimb lameness (differences in minimum pelvic height) in the limb with increased length, and of a false pushoff type hindlimb lameness (differences in maximum pelvic height) in the limb opposite the limb with increased length, under all conditions (straight/lunge, hard/soft surfaces).

CHAPTER 3: MATERIALS AND METHODS

a. Horses

Fifty horses used in an equestrian program and kept at a private university were evaluated for potential inclusion in this study. All horses were being cared for and ridden daily by disciplined equestrian trainers and college students. Medical care was monitored and directed by a resident faculty equine veterinarian specializing in equine practice with over 20 years experience evaluating lameness in horses. Screening for enrollment of the study was initiated six months prior to the anticipated start date of the study. Only horses that were not considered lame in the hindlimbs by the resident veterinarian were evaluated for enrollment.

b. Lameness Measurement Technique

Horses were instrumented with a commercially available, body-mounted inertial sensor system (BMIS) consisting of 3 devices. An accelerometer device (uni-axial, vertical accelerometer sensor) was placed on the midline of the head using a manufactured head bonnet and on the pelvic midline between the tubera sacrale with pelvic sensor pad and pelvic clip. The sensors on the head and pelvis measure vertical acceleration and convert to vertical position. The third device (uni-axial, sagittal plane gyroscope sensor) was placed on the dorsal surface of the right forelimb pastern in a pastern wrap pouch. The right forelimb sensor measures angular velocity and was used as a time index marker indicating beginning of right forelimb stance. This time index was used to determine side of lameness as positive or negative differences in maximum and minimum pelvic height. Sensors were sampled at 200 Hz and data was wirelessly transmitted via Bluetooth Class 1 product after 8-bit analog-digital conversion. A previously described moving-window, error-correcting, double-integration procedure was used to convert vertical acceleration to position.(21) The angular rate signal from the right forelimb was smoothed and peak detection was used to identify right forelimb stance. Due to the knowledge that the horses in this study were trotting, right hindlimb stance could be inferred.

In this study, only pelvic sensor measurements of hindlimb lameness were evaluated. For each stride, the minimum and maximum pelvic height differences between left and right stride halves were calculated. P_{min} measures the result of decreased downward force of the rear torso onto a lame hindlimb in the first half of stance. P_{max} measures the result of decreased upward force from a lame hindlimb in the second half of stance. By convention, positive P_{min} and P_{max} values indicate right hindlimb, and negative P_{min} and P_{max} indicate left hindlimb lameness. P_{min} measures the lameness in the first half of stance (an impact type lameness). P_{max} measures the lameness in the second half of stance (a pushoff type lameness).

Amplitude of hindlimb lameness when trotting in a straight line was considered mild if the absolute value of P_{min} or P_{max} was greater than 3 mm but less than 6 mm, mild-to-moderate if greater than 6 mm but less than 9 mm, moderate if greater than 9 mm but less than 12 mm, and moderate-to-severe if greater than 12 mm. Strength of evidence of lameness was assessed based on consistency of measurement of P_{min} and P_{max} over all strides selected for analysis. Strength of evidence of lameness when trotting in a straight line was considered weak if the standard deviation of P_{min} and P_{max} was greater than 100%, moderate if the standard deviation was between 50 – 100%, and strong if the standard deviation was < 50%, of the mean. Both amplitude and strength of evidence of lameness group values were determined from previous evaluations with the inertial sensor system and were set in accordance with typical clinical evaluation subsets. Categorical amplitude and strength of evidence of lameness when trotting in a straight line was used only for selection of subjects for study. No horses were selected for the study that measured with more than weak evidence of mild hindlimb lameness.

A random number generator was used to determine if the control (before induction of hindlimb length asymmetry) or treatment (after induction of hindlimb length asymmetry) trials were collected first. The subsequent trials, treatment if the control was collected first, or control if treatment was collected first, were performed the following day. Prior to collection, horses were lightly walked or lunged for 5-10 minutes. Hindlimb lameness was measured before and after induction of hindlimb length asymmetry during a straight-line trot and lungeing in both directions on both hard (dirt) and soft (sand/fiber) surfaces. For straight line trot trials, the horse was trotted back and forth for about 90 meters, twice. This resulted in the collection of data for at least 25 strides. For lungeing trials, data was collected for about 1 minute. This resulted in the collection of data for at least 40 strides.

In previous studies, the design of the sensors, method of wireless transmission, method of stride selection, and choice of hindlimb lameness measures have been described and validated.(14, 21)

c. Induction of hindlimb length difference

The Easyboot Glue-On shoe (EasyCare, Inc. Tucson, AZ, US), with a ground surface thickness of 12.5 mm, was used to induce hindlimb length difference. The side of hindlimb length elevation was selected via a random number generator. Each horse was properly fitted with the correct size Easyboot Glue-On shoe by performing manufacturer recommended measurements illustrated in figure 7. The shoe was secured to the hind foot using Elastikon® 3-inch elastic tape (figure 3). Nothing was applied to the other hindlimb. In three horses, the elevation was left in place for 4 days and additional evaluations were performed daily

To estimate the amount of pelvic asymmetry caused by induced hindlimb length differences, pelvic height from the ground was measured on both the left and right sides, before and after induction of hindlimb length difference. This was measured as the vertical distance from the ground to the tuber coaxe using a tape measure with units of +/- 0.1 cm.(4) During the measurement, all horses were properly positioned and assessed to be standing square and bearing weight equally on both hindlimbs on the same flat and level surface by the same investigator (JP). Any horses with pelvic asymmetry greater than 6 mm before induction of hindlimb length difference were not selected for the study.

d. Statistical Analysis

Differences in P_{min} and P_{max} before and after induced hindlimb length difference were investigated for each of the lameness trial types (straight line, lunge left, lunge right; hard, soft). P_{min} and P_{max} results for most trial types were not normally distributed. Differences in P_{min} and P_{max} were evaluated for all trials with the non-parametric ANOVA equivalent (Friedman's test). Multiple comparisons of individual trial types before and after treatment were evaluated with the Wilcoxon Signed-Rank Test. Significance level was set at $p<0.05$.

CHAPTER 4: RESULTS

a. Animals

Sixteen adult (mean age = 15.8 years, range 8-25 years) horses (4 Warmbloods, 4 Thoroughbred/Thoroughbred crosses, 3 Quarter Horses, 3 Arabian/Arabian crosses, and 1 Morgan; 10 geldings, 6 mares), out of the 50 screened horses were included in the study. Six of the horses performed as hunter/jumpers, 6 were western performance horses, and 4 performed as dressage horses. All excluded horses measured with more than weak evidence of mild hindlimb lameness. None of the horses were excluded for pre-existing pelvic asymmetry.

b. Induction of Hindlimb Length Difference

The elevation was applied to the left hindlimb in 10 horses and the right hindlimb in 6 horses. In all horses, the height from ground to tuber coxae increased (approximately 50 mm) in the elevated limb and was unchanged in the non-elevated limb.

c. Effect on Inertial Sensor Lameness Measures for Single Collection

Differences in P_{min} were statistically significant during both straight line trials (soft and hard) with elevation placed on either hindlimb (left and right). Additionally, differences in P_{min} were significant during the following lungeing trials: left hindlimb elevation trotting to left on soft surface and trotting to right on hard and soft surface; right hindlimb elevation trotting to left on hard and soft surface and trotting to right on soft surface. Notably, no significant difference in P_{min} was obtained with a left hindlimb elevation lungeing to the left on a hard surface or with a right hindlimb elevation lungeing to the right on a hard surface.

Differences in P_{max} were statistically significant during straight line trotting trial with left hindlimb elevation on a hard surface and right hindlimb elevation on a soft surface. In addition, difference in P_{max} was significant with left hindlimb elevation lungeing to the left on a hard surface. No other trials had significant findings for this parameter.

Results with and without limb elevation are summarized in Tables 1-2 for P_{min} and in Tables 3-4 for P_{max}. Representative trial results from a single horse are displayed in Figures 11 – 16. The most consistent effect in hindlimb lameness measurement was a change in P_{min} after hindlimb elevation. Under most circumstances P_{min} changed significantly when elevation was placed on a hindlimb. Change in P_{max} was less consistent and found only in 2 straight line trials and 1 lungeing trial.

P_{min} became more negative when the elevation was placed on the left hindlimb and more positive when placed on the right hindlimb for all straight-line conditions (hard and soft surfaces) and for most lunge conditions. The exception (P_{min} not significantly different) for lungeing trials was when the elevation was placed on the limb to the inside of the lungeing circle on a hard surface.

In contrast to P_{min}, during straight line trotting, P_{max} became more positive when the elevation was placed on the left hindlimb and more negative when placed on the right hindlimb. This increase was significant when the shoe was placed on the left hindlimb only when trotting on hard surface and when placed on the right hindlimb only when trotting on a soft surface. Except for one lungeing trial type (lunge left, hard surface, left hind elevation), P_{max} was not significantly changed after hindlimb elevation during lungeing.

d. Induced hindlimb length difference over four days duration

Due to the finding of no definitive pattern of results, statistical evaluation was not performed. Results for P_{min} are summarized in Tables 5-7 and results for P_{max} are summarized in Tables 8-10.

CHAPTER 5: DISCUSSION

This study investigated the effect of induced hindlimb length difference by hoof elevation, and the associated induction of pelvic asymmetry, on hindlimb lameness evaluation in horses. Limb-specific lameness, indicated as differences in minimum and maximum pelvic heights, was observed when the horse was trotting in a straight line and while lungeing on both hard and soft surfaces. Difference in minimum pelvic height during the stance phase, indicating an impact-type lameness, was consistently measured in the limb with the elevation in both the straight line and lungeing trials. Difference in maximum pelvic height, indicating pushoff-type lameness in the opposite, non-elevated limb, was found less consistently.

P_{min} became more negative when elevation was applied to the left hindlimb, and more positive when applied to the right hindlimb, in the straight line and while lungeing, compared to values without elevation. These results are in agreement with a previous study of horses trotting in a straight line by Vertz et al.(17) However, for both this study and ours, the magnitude of the changes in P_{min} were less than the height of the elevation applied to the hindlimb. This implies some compensation by the horse with greater pelvic fall and downward vertical force, or greater pelvic rotation in the frontal plane toward the shorter, non-elevated hindlimb, during the stance phase of the elevated limb. P_{max} became more positive when elevation was applied to the left hindlimb and more negative when applied in the right hindlimb, but only in some straight line conditions and in one lungeing trial (LH elevation, lunge left, hard ground) type. In another study, the effects of hindlimb elevation on Pmax were similar but more consistent (i.e. more negative for right hind elevation and more positive for left hindlimb elevation), creating a pushoff-type hindlimb lameness on the limb opposite the elevation. However, the magnitude of that effect was less than that found with P_{min} and also less than expected with the amount of limb length elevation created.(17) This implies that the horse may be compensating by increasing pushoff force and vertical rise of the pelvis on the non-elevated, short limb.

As expected, during the lunge, P_{min} also became more negative when the elevation was placed on the left and more positive when placed on the right hindlimb, but on hard ground, when the elevation was on the inside limb, the change in P_{min} was not significant. This was an unexpected finding. In many studies it has been shown that, when horses are lunged, the torso is tilted to the inside of the circle and the pelvis falls less during weight bearing of the inside hindlimb. This results in a more negative P_{min} lungeing to the left and a more positive P_{min} lungeing to the right.(18-20) If the effect of limb elevation and torso tilt to the inside of the circle were simply additive, then an even greater effect of limb elevation on P_{min} would be expected at the lunge compared to straight line trot. It is possible that tilting the torso toward the inside of the circle while lungeing on hard ground with the inside limb elevated is awkward to the horse, inducing the horse to avoid torso tilt and lunge with a more upright body position. This would allow greater downward pelvic movement during stance. Soft footing (in this case sand) may have allowed the horse to lunge more comfortably with a typical pelvic tilt to the inside of the circle.

P_{max} was not significantly different at the lunge whether the elevation was on the outside or inside hindlimb on either soft or hard ground. When the horse is lungeing on hard ground, the amount of pelvic rise after pushoff of the inside hindlimb is typically less than that of the outside hindlimb. Therefore, on hard ground, if the effects of lunge direction and elevation are additive, one would expect the strongest effect when the elevation is placed on the outside hindlimb. When the horse is lungeing on soft ground, the amount of pelvic rise after pushoff of the outside hindlimb is typically less than that of the inside hindlimb. Therefore, on soft ground, if the effects of lunge direction and elevation are additive, one would expect the strongest effect when elevation is placed on the inside hindlimb. In both situations, the horse may be compensating by pushing off harder, so the pelvis rises more than expected, on the limb without the elevation, effectively cancelling out these effects.

P_{min} is a measure of minimum pelvic height during right hindlimb stance minus minimum pelvic height during left hindlimb stance. One hindlimb is contacting the ground, bearing weight, and the other is flexed and swinging forward, with the pelvis tilted towards it (the swinging leg). Therefore, direct effects due to limb length difference and pelvic tilt should be expected. On the other hand, P_{max} is a measure of maximum pelvic height before right hindlimb stance minus maximum pelvic height before left hindlimb stance, when the horse is airborne with neither hindlimb touching the ground, and when the pelvic orientation is parallel to the ground (i.e. not rotated). Direct effects of simple limb length differences or pelvic rotations should be minimal and are less expected.

Results of this study should be considered when objective measurement of vertical pelvic movement asymmetry is used to assess hindlimb lameness, as it may be subject to error if there is a pre-existing reason for asymmetric pelvic height, like differences in hindlimb length. Specifically, if the nature of hindlimb lameness is primarily lack of pushoff, i.e. with significant amplitude of P_{max}, the cause is not likely due to a pre-existing asymmetry, but to actual differences in pushoff force between the hindlimbs. However, if the nature of the hindlimb lameness is primarily lack of impact, i.e. with significant amplitude of P_{min}, at least part of the cause may be due to a pre-existing hindlimb length difference.

When using inertial sensors to measure hindlimb lameness, one should check for pre-existing hindlimb length differences and pelvic asymmetry if the measured hindlimb lameness is of a purely impact nature. This may be done by carefully standing the horse squarely on both hindlimbs and observing the distance from the ground to the tuber coxae from the rear. Large amplitudes of pre-existing hindlimb length difference or vertical pelvic asymmetry should be taken into consideration when assessing P_{min}. If the impact lameness is on the side of the higher hemi-pelvis, the true lameness may be less than measured. If the impact lameness is on the side of the lower hemi-pelvis, the true lameness due to pain may be higher than measured. Therefore, horses with pronounced pelvic asymmetry, may give the impression of a more severe lameness than actual on the side of the higher hemi-pelvis, and of a less severe lameness than actual on the side of the lower hemi-pelvis.

In human studies, the effects of limb length discrepancy on ground reaction forces are inconsistent, with some indicating increased impact force on the shorter limb.(22, 23) However, because humans are biped plantigrades and horses are quadruped unguligrades, and because most human studies have been conducted at the walk, direct comparisons of results to this study are difficult.

When 3 horses were evaluated with elevation in place for four days, P_{min} and P_{max} results varied by day and no consistent result was found. With such a small sample size only a strong and consistent effect could have been found. Also, the relatively short duration of continuous hindlimb length elevation (four days) may not have been long enough to cause significant adaptation or injurious long-term effects from the hindlimb length difference. During this portion of the study, the horses were confined to a stall to prevent misalignment or dislodgement of the elevation. Future studies with an increased sample size and increased duration of elevation are warranted to further evaluate long term effects of hindlimb length asymmetry.

Although assessment of long-term effects was not possible in this study, studies suggest that the long-term effect of compensation for limb length differences and pelvic asymmetry may be detrimental to the horse. Standardbred Trotters with hindquarter asymmetry had poorer racing performance than those without hindquarter asymmetry.(4) In human studies, leg length differences have been shown to increase the incidence of a variety of abnormalities and pathologies, including low back pain, hip osteoarthritis, sacroiliac disease, stress fractures, loosening of hip prostheses, and running injuries.(5) Whether these detrimental long term effects are directly due to the asymmetry or to the compensatory efforts to adjust for this asymmetry are unknown.

a. Limitations and Future Study

The sample size of this study was relatively small so small effects on P_{min} and P_{max} may not have been detected for some of the conditions studied. Due to concern of deleterious effects from induced hindlimb length difference on overall health and performance of the equestrian program horses in active riding use, we could not study the long-term effect of hindlimb length difference. It is possible that the effects that we did measure or the apparent compensation for induced hindlimb length asymmetry would wane or worsen over time. If possible, this should be studied further.

b. Conclusions

This study has investigated the effect of induced hindlimb length difference on differences in minimum and maximum pelvic height measurements of hindlimb lameness in horses trotting in a straight line and lungeing on both hard and soft surfaces. P_{min}, the measure of impact-type hindlimb lameness, was most consistently affected, increasing on the side of elevation. P_{max}, the measure of pushoff-type hindlimb lameness, was not consistently affected.

Manufacturer's Details

[a]Lameness Locator, Equinosis LLC, Columbia, MO, USA

ILLUSTRATIONS

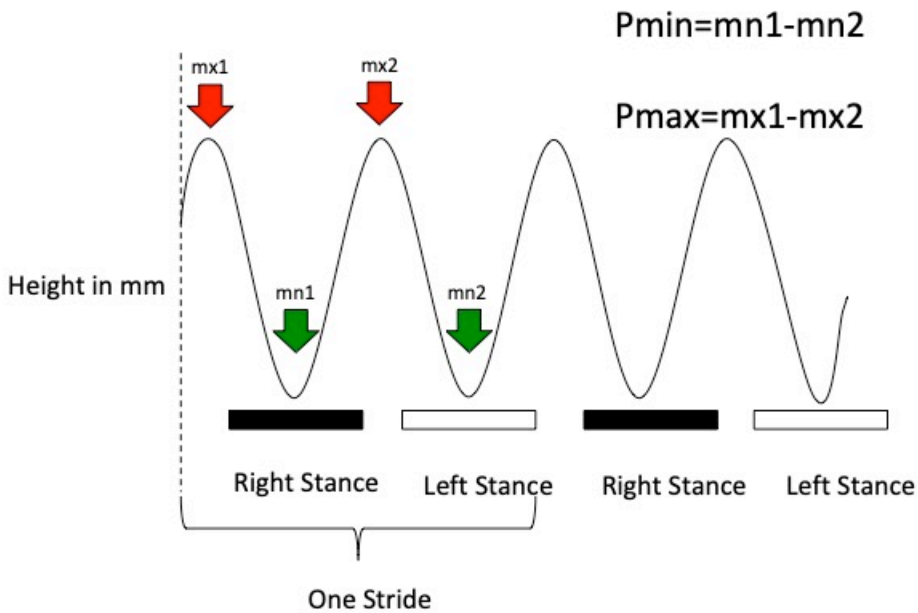

Figure 1. Schematic of pelvic height trajectory pattern of a normal horse. The solid black bars indicate estimates of right hindlimb stance and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

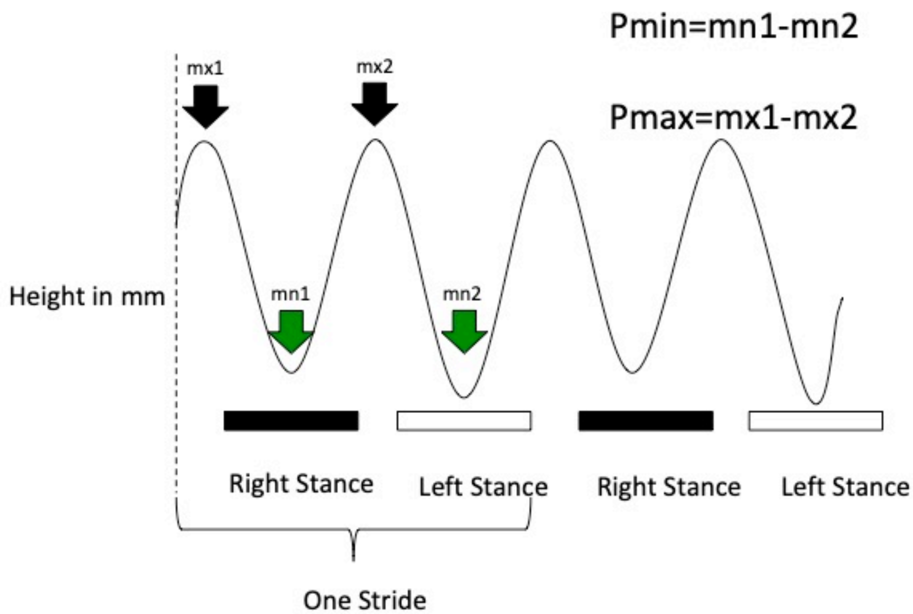

Figure 2. Schematic of pelvic height trajectory pattern of a right hindlimb impact lameness. The solid black bars indicate estimates of right hindlimb stance and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

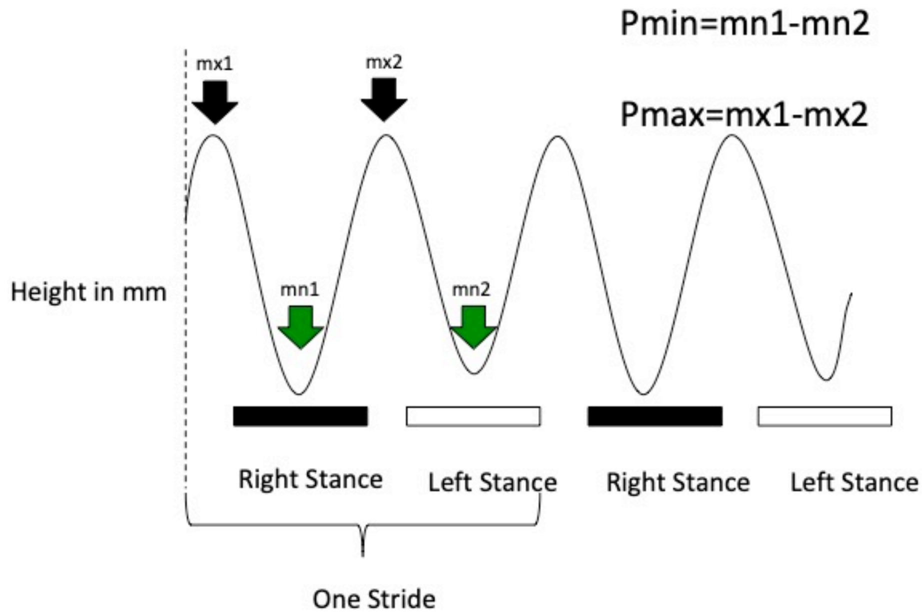

Figure 3. Schematic of pelvic height trajectory pattern of left hindlimb impact lameness. The solid black bars indicate estimates of right hindlimb stance and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

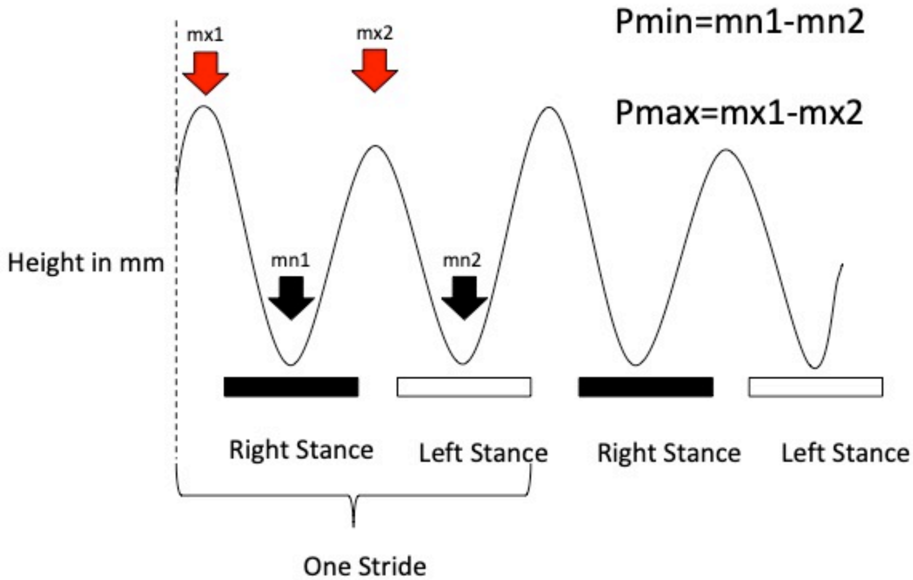

Figure 4. Schematic of pelvic height trajectory pattern of a right hindlimb pushoff lameness. The solid black bars indicate estimates of right hindlimb stance, and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

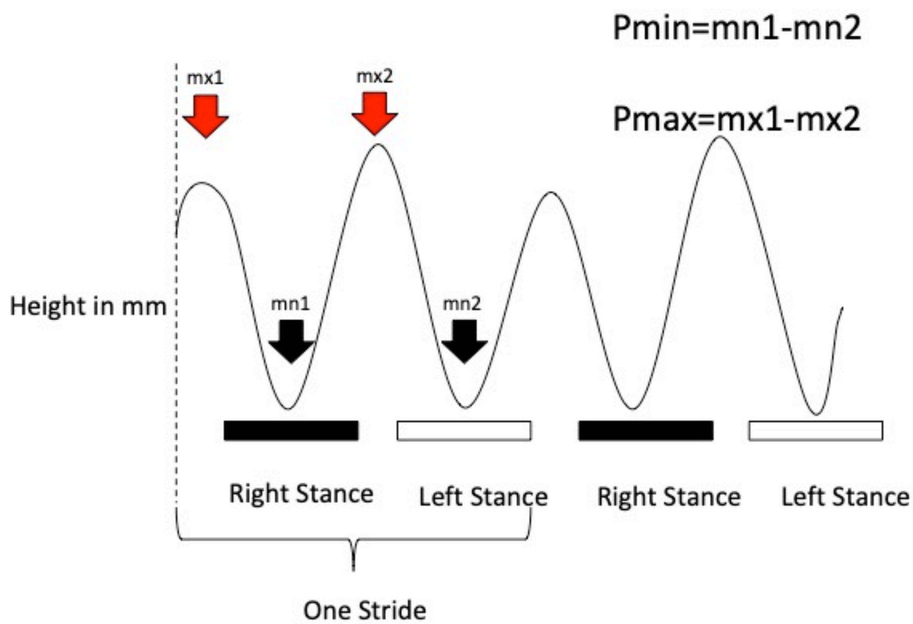

Figure 5. Schematic of pelvic height trajectory pattern of a left hindlimb pushoff lameness. The solid black bars indicate estimates of right hindlimb stance, and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

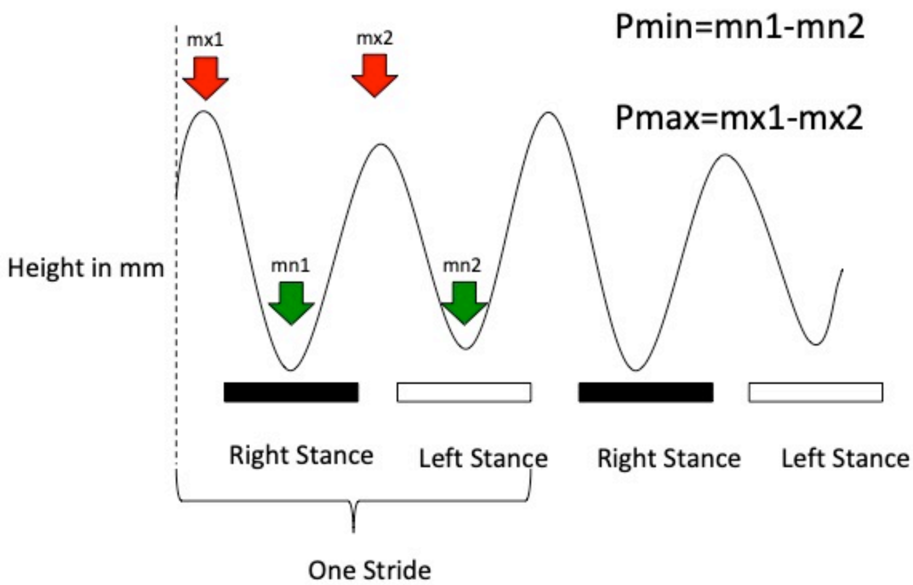

Figure 6. Schematic of pelvic height trajectory pattern of a left hindlimb impact and right hindlimb pushoff lameness. The solid black bars indicate estimates of right hindlimb stance, and the white bars are estimates of left hindlimb stance. P_{min} is determined by subtracting minimum pelvic height during left hindlimb stance (mn2) from minimum pelvic height during right hindlimb stance (mn1). P_{max} is determined by subtracting maximum pelvic height during right hindlimb stance (mx2) from maximum pelvic height during left hindlimb stance (mx1). P_{min} and P_{max} units are in millimeters (mm).

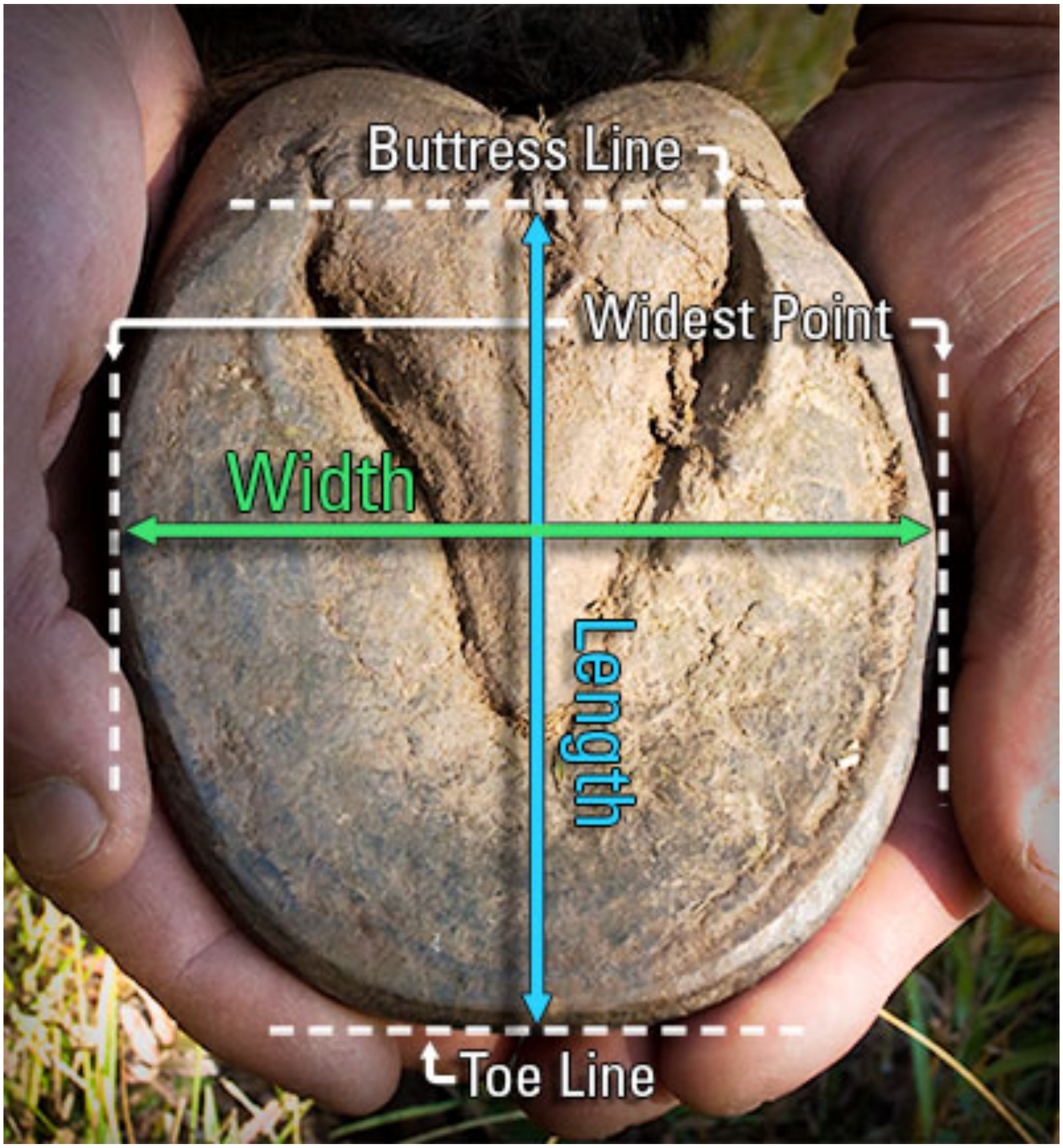

Figure 7. Easyboot Glue on shoe measurements to determine size shoe. Measure the width of the hoof across the widest point. Measure the length of the hoof from the toe to the buttress line of the heel. The buttress line is the farthest weight bearing point of the heel where the hoof wall ends.

Figure 8. Images showing Easyboot Glue-On shoe attached to hind hoof with Elastikon® 3-inch elastic tape.

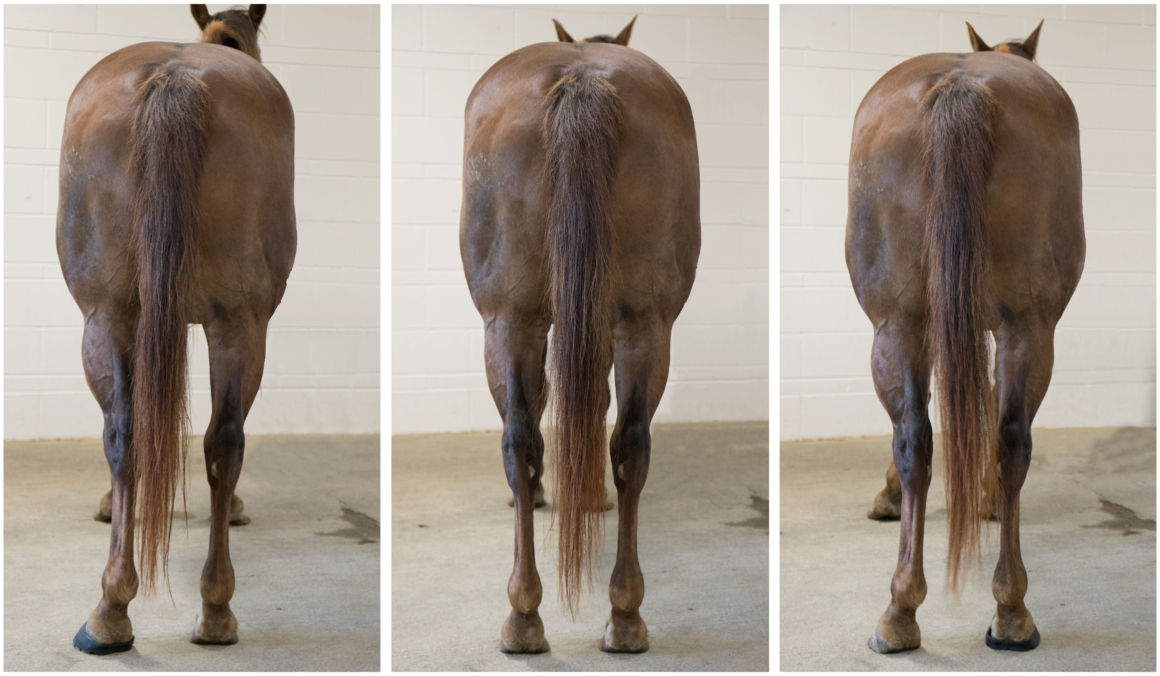

Figure 9. Full length images of hindlimbs. Center image shows horse standing square without elevation and symmetrical pelvis. Left image shows horse standing square with left hindlimb elevation causing elevation of left side of pelvis. Right image shows horse standing square with right hindlimb elevation causing elevation of right side of pelvis.

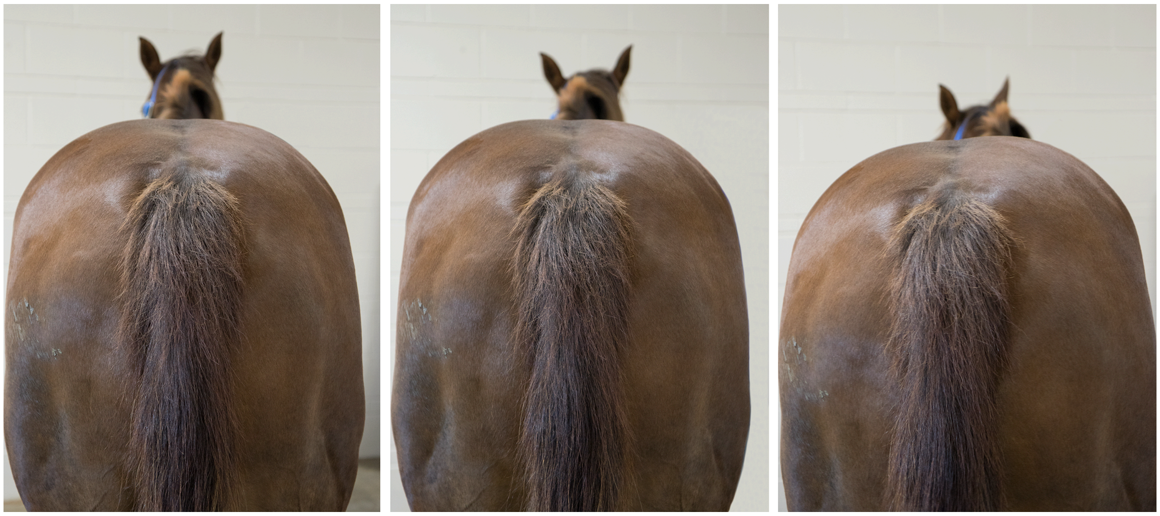

Figure 10. Close up images of the pelvis. Center image shows horse standing square without elevation and symmetrical pelvis. Left image shows horse standing square with left hindlimb elevation causing elevation of left side of pelvis. Right image shows horse standing square with right hindlimb elevation causing elevation of right side of pelvis.

Inertial Sensor System Report: Straight line trotting, hard surface

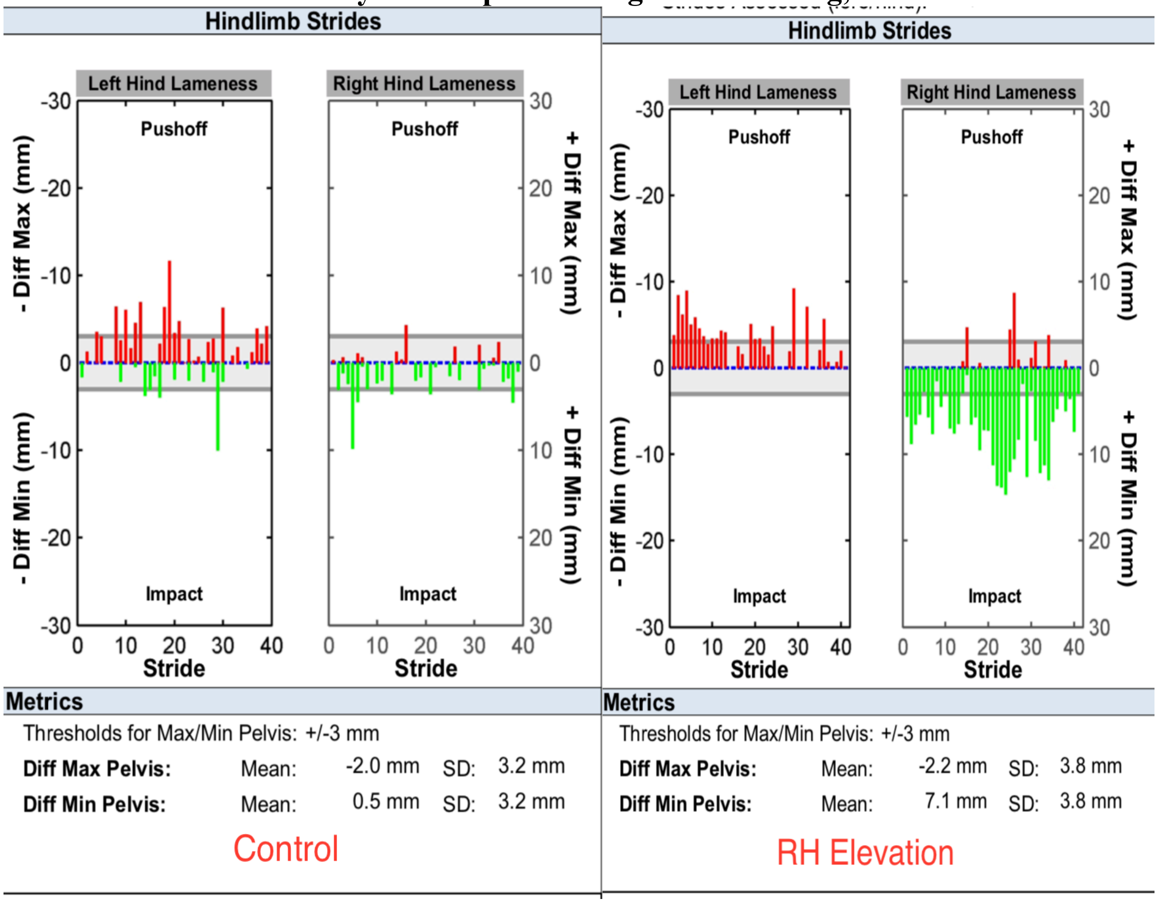

Figure 11. P_{min} and P_{max} plots from straight line, hard surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

Inertial Sensor System Report: Straight line trotting, soft surface

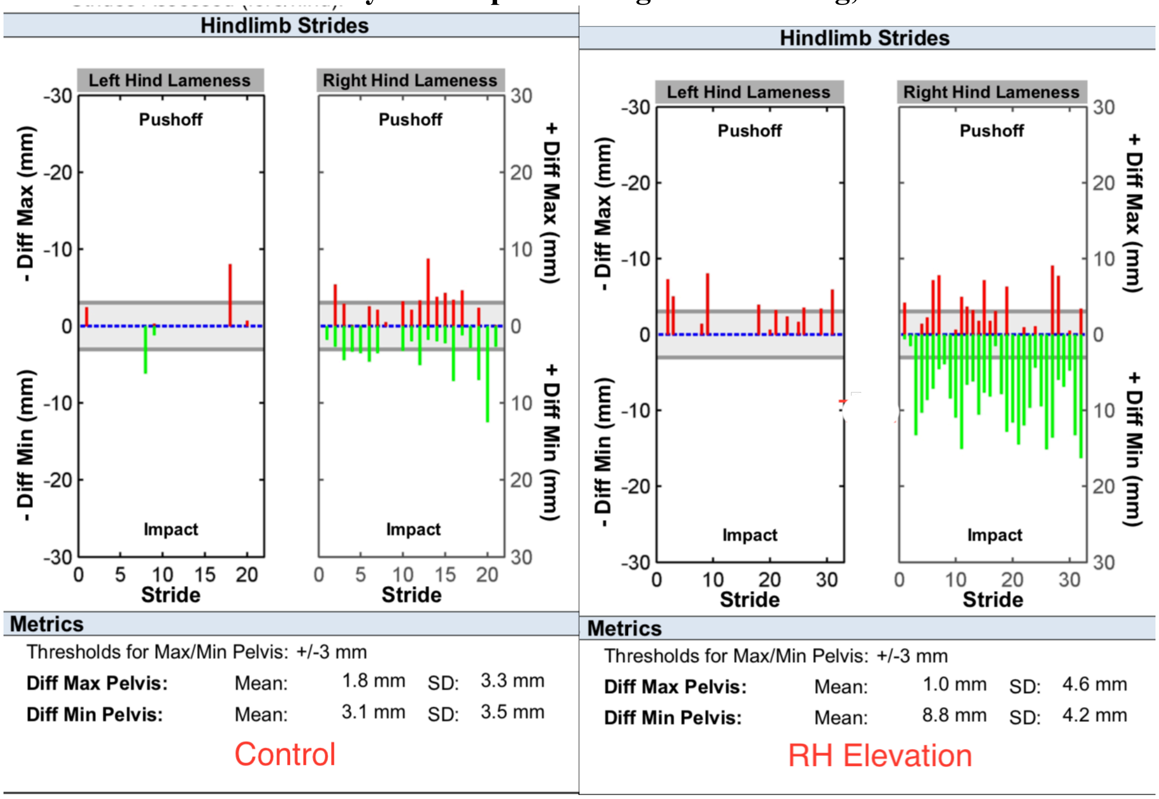

Figure 12. P_{min} and P_{max} plots from straight line, soft surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

Inertial Sensor System Report: Lungeing to the left, hard surface

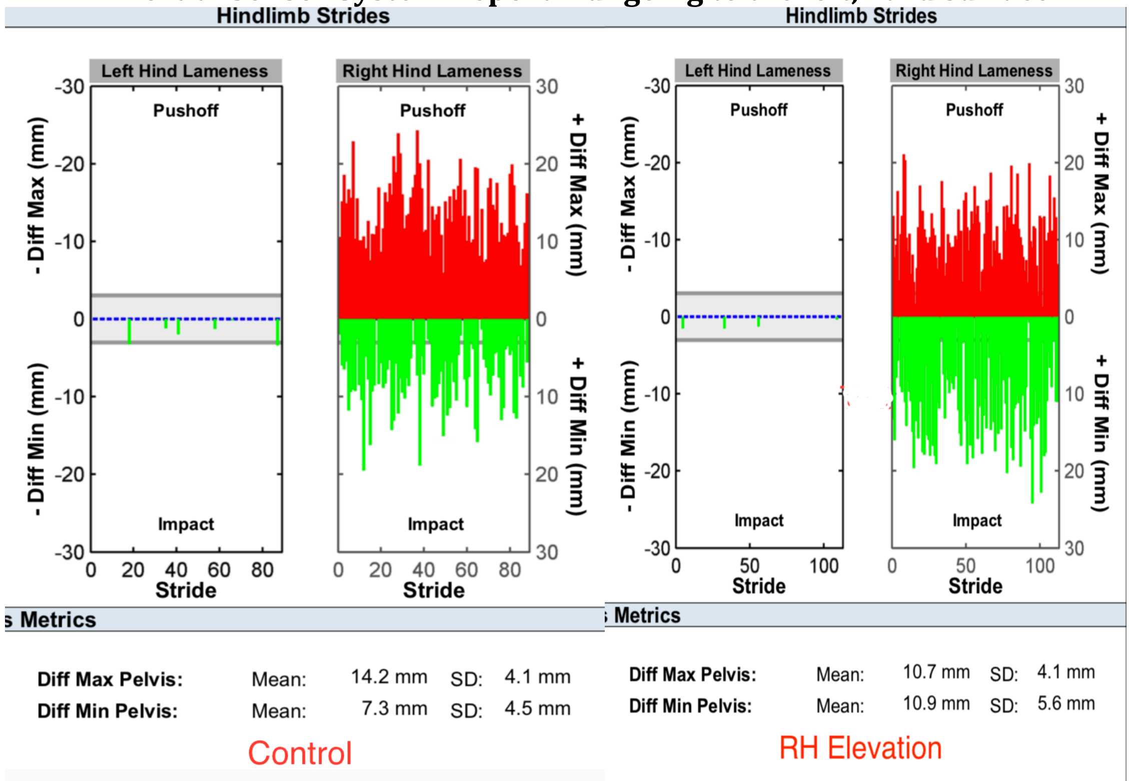

Figure 13. P_{min} and P_{max} plots from lungeing to the left, hard surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

Inertial Sensor System Report: Lungeing to the right, hard surface

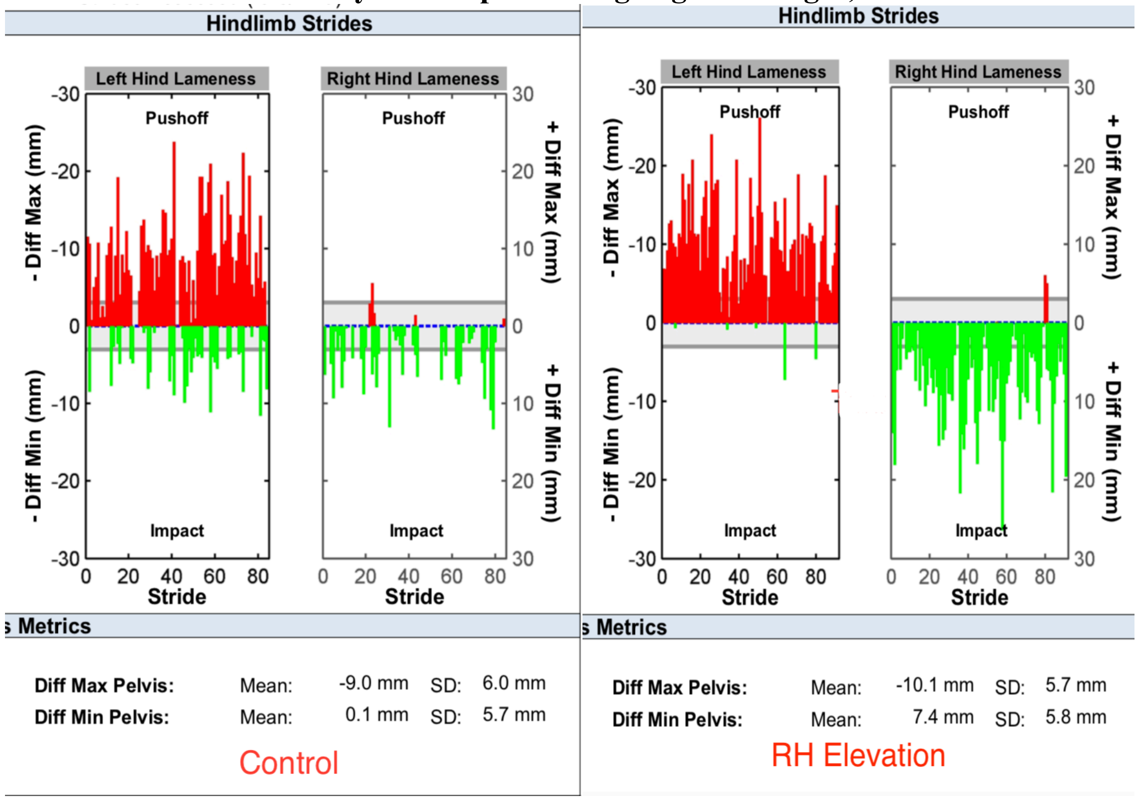

Figure 14. P_{min} and P_{max} plots from lungeing to right, hard surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

Inertial Sensor System Report: Lungeing to left, soft surface

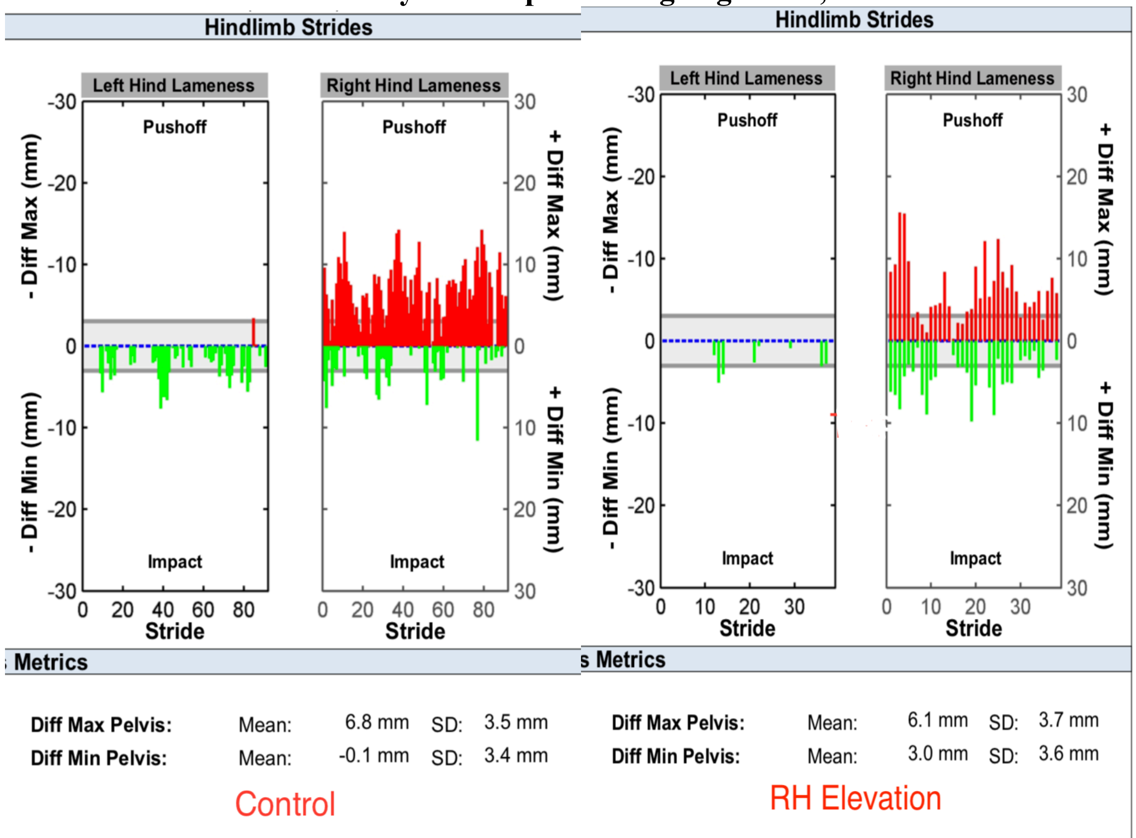

Figure 15. P_{min} and P_{max} plots from lungeing to left, soft surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

Inertial Sensor System Report: Lungeing to right, soft surface

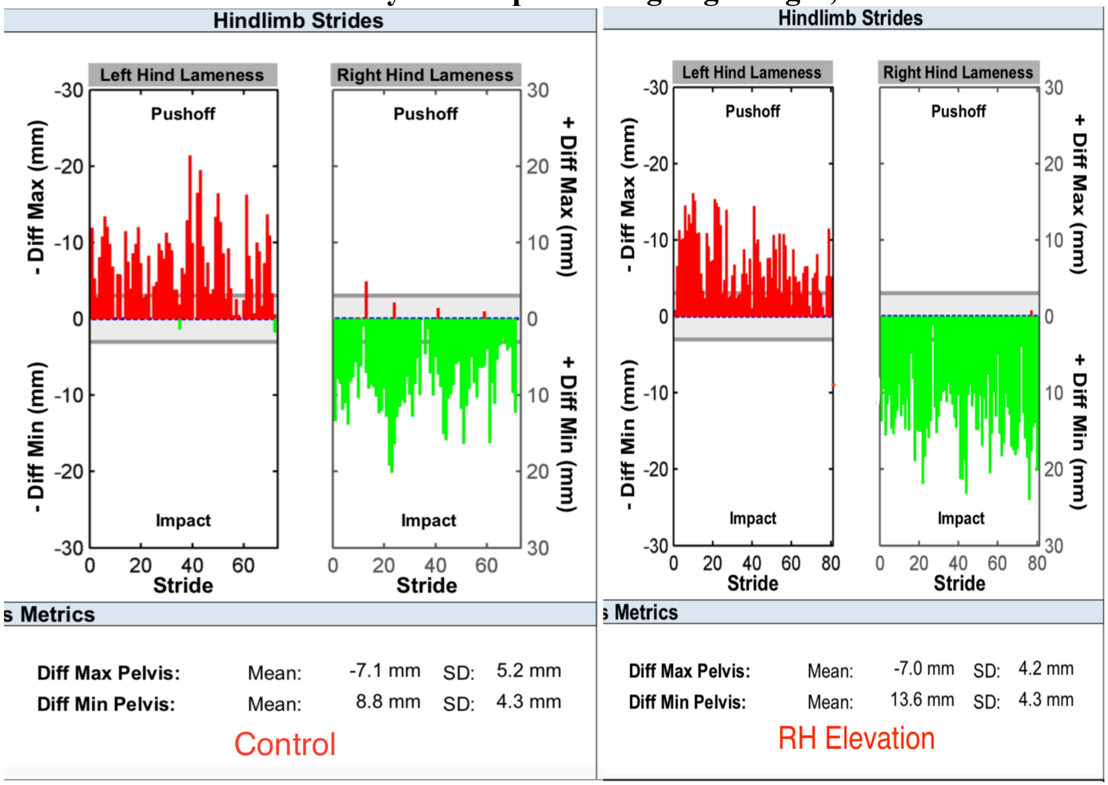

Figure 16. P_{min} and P_{max} plots from lungeing to right, soft surface trial. The plot on the left is without hindlimb elevation. The plot on the right is with right hindlimb elevation. Each individual plot displays results for the left hindlimb on the left and the right hindlimb on the right. P_{min} values are indicated in green and P_{max} values are indicated in red. Each line (green or red) indicates a stride.

TABLES

Table 1. Median P_{min} Values Left Hind Elevation.

Direction	Surface	Shoe Location	Median P_{min*} without elevation (mm)	Median P_{min*} with elevation (mm)	P value
Straight	Hard	LH	1.9	-4.1	**0.0059**
Straight	Soft	LH	1.7	-4.8	**0.0020**
Lunge Left	Hard	LH	-4.3	-10.3	0.3223
Lunge Left	Soft	LH	-8.2	-11.3	**0.0371**
Lunge Right	Hard	LH	10.8	-0.2	**0.0020**
Lunge Right	Soft	LH	12.2	1.3	**0.0039**

Table displays median values for P_{min} with and without elevation on the left hind under all collection circumstances. Bolded values indicated statistical significance.

Table 2. Median P_{min} Values Right Hind Elevation.

Direction	Surface	Shoe Location	Median P_{min*} without elevation (mm)	Median P_{min*} with elevation (mm)	P value
Straight	Hard	RH	3.3	7.5	**0.0313**
Straight	Soft	RH	3.3	9.1	**0.0313**
Lunge Left	Hard	RH	-3.6	-0.5	**0.0313**
Lunge Left	Soft	RH	-4.1	-1.5	**0.0313**
Lunge Right	Hard	RH	6.1	11.6	0.2188
Lunge Right	Soft	RH	10.3	17.56	**0.0313**

Table displays median values for P_{min} with and without elevation on the right hind under all collection circumstances. Bolded values indicated statistical significance.

Table 3. Median P_{max} Values Left Hind Elevated.

Direction	Surface	Shoe Location	Median P_{max*} without elevation (mm)	Median P_{max*} with elevation (mm)	P value
Straight	Hard	LH	0.1	2.9	**0.0098**
Straight	Soft	LH	-0.3	1.3	0.1075
Lunge Left	Hard	LH	-1.7	1.1	**0.0098**
Lunge Left	Soft	LH	1.3	2.5	0.7695
Lunge Right	Hard	LH	-0.7	2.1	0.3750
Lunge Right	Soft	LH	-4.0	-1.7	0.2754

Table displays median values for P_{max} with and without elevation on the left hind under all collection circumstances. Bolded values indicated statistical significance.

Table 4. Median P_{max} Values Right Hind Elevated.

Direction	Surface	Shoe Location	Median P_{max*} without elevation (mm)	Median P_{max*} with elevation (mm)	P value
Straight	Hard	RH	1.8	-4.9	0.6875
Straight	Soft	RH	0.9	-4.0	**0.0313**
Lunge Left	Hard	RH	0.1	-3.7	0.0625
Lunge Left	Soft	RH	5.5	3.3	0.4375
Lunge Right	Hard	RH	-1.9	-8.6	0.1563
Lunge Right	Soft	RH	-6.1	-8.5	0.3125

Table displays median values for P_{max} with and without elevation on the right hind under all collection circumstances. Bolded values indicated statistical significance.

Table 5. Median P_{min} Values for Horse 1 of Extended Trial.

Direction	Surface	Shoe Location	P_{min} Control	P_{min} Day 1	P_{min} Day 2	P_{min} Day 3	P_{min} Day 4
Straight	Hard	LH	-17	-35	-1	-7	-7
Straight	Soft	LH	-1	-17	-5	-6	2
Lunge Left	Hard	LH	31	-27	15	-18	-16
Lunge Left	Soft	LH	-32	-30	-9	-10	-16
Lunge Right	Hard	LH	7	-5	11	11	7
Lunge Right	Soft	LH	26	0	4	14	5

Table displays mean values for P_{min} with and without elevation on horse 1 of extended trial under all collection circumstances

Table 6. Median P_{min} Values for Horse 2 of Extended Trial.

Direction	Surface	Shoe Location	P_{min} Control	P_{min} Day 1	P_{min} Day 2	P_{min} Day 3	P_{min} Day 4
Straight	Hard	LH	5	-4	-3	-2	-2
Straight	Soft	LH	2	-2	-3	-5	-6
Lunge-Left	Hard	LH	-5	-10	0	0	-7
Lunge Left	Soft	LH	-4	-14	-6	-7	-9
Lunge Right	Hard	LH	5	2	3	4	1
Lunge Right	Soft	LH	18	0	-3	0	-2

Table displays mean values for P_{min} with and without elevation on horse 2 of extended trial under all collection circumstances.

Table 7. Median P_{min} Values for Horse 3 of Extended Trial.

Direction	Surface	Shoe Location	P_{min} Control	P_{min} Day 1	P_{min} Day 2	P_{min} Day 3	P_{min} Day 4
Straight	Hard	RH	10	21	15	21	19
Straight	Soft	RH	10	18	8	15	9
Lunge Left	Hard	RH	-20	-17	4	-7	-12
Lunge Left	Soft	RH	-35	-22	-16	-12	-17
Lunge Right	Hard	RH	50	51	3	43	43
Lunge Right	Soft	RH	44	50	42	53	41

Table displays mean values for P_{min} with and without elevation on horse 3 of extended trial under all collection circumstances.

Table 8. Mean P_{max} Values for Horse 1 of Extended Trial.

Direction	Surface	Shoe Location	P_{max} Control	P_{max} Day 1	P_{max} Day 2	P_{max} Day 3	P_{max} Day 4
Straight	Hard	LH	-31	-18	-11	-10	-14
Straight	Soft	LH	-16	-6	-4	0	-10
Lunge Left	Hard	LH	24	-7	4	-15	-20
Lunge Left	Soft	LH	11	4	-4	-3	-6
Lunge Right	Hard	LH	-24	-14	-9	-14	-16
Lunge Right	Soft	LH	-20	-15	-11	-14	-11

Table displays mean values for P_{max} with and without elevation on horse 1 of extended trial under all collection circumstances

Table 9. Mean P_{max} Values for Horse 2 of Extended Trial.

Direction	Surface	Shoe Location	P_{max} Control	P_{max} Day 1	P_{max} Day 2	P_{max} Day 3	P_{max} Day 4
Straight	Hard	LH	6	8	5	9	3
Straight	Soft	LH	-2	4	3	4	5
Lunge Left	Hard	LH	7	9	10	12	6
Lunge Left	Soft	LH	7	8	7	5	4
Lunge Right	Hard	LH	-7	-5	-5	0	-4
Lunge Right	Soft	LH	-5	-2	-4	1	-3

Table displays mean values for P_{max} with and without elevation on horse 2 of extended trial under all collection circumstances.

Table 10. Mean P_{max} Values for Horse 3 of Extended Trial.

Direction	**Surface**	**Shoe Location**	**P_{max} Control**	**P_{max} Day 1**	**P_{max} Day 2**	**P_{max} Day 3**	**P_{max} Day 4**
Straight	Hard	RH	-27	-10	4	-10	-8
Straight	Soft	RH	-2	-7	-4	-3	2
Lunge Left	Hard	RH	-12	-11	-1	-2	10
Lunge Left	Soft	RH	9	14	14	11	21
Lunge Right	Hard	RH	-28	-24	4	-1	-25
Lunge Right	Soft	RH	-12	-10	-4	-13	-7

Table displays mean values for P_{max} with and without elevation on horse 3 of extended trial under all collection circumstances

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