Compensatory force plate responses to single or multiple limb lameness induction in horses using a hoof clamp technique

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Dedication

This project is dedicated to my father, Laurence F. Swaab.

Abstract

Reasons for Performing Study: Previous equine research has combined subjective analysis with kinematic or kinetic data to describe lameness, but has only shown evidence of compensatory mechanisms for only single forelimb and hindlimb lameness, not multiple limb lameness.

Objectives: To create a consistent, controlled and immediately reversible lameness using a circumferential hoof clamp technique and measure the resultant changes in ground reaction forces. To compare the changes in ground reaction forces in both the limb(s) in which lameness was induced and in the sound limbs among a variety of individual and multiple-limb lameness scenarios to detect possible patterns in lameness and compensation in the sound limbs.

Materials and Methods: Lameness was induced in 8 horses by tightening a circumferential hoof clamp, on an individual forelimb, or hindlimb, an ipsilaterally paired forelimb/hindlimb, a contralaterally paired forelimb/hindlimb, and bilateral forelimbs and hindlimbs. Kinetic analysis was performed with a fore plate prior to (baseline) and after lameness induction. The percent change in ground reaction forces (vertical and longitudinal) from baseline were calculated for all limbs for each lameness scenario. Changes were examined within each of four ground reaction forces (peak vertical force, vertical impulse, breaking impulse and propulsion impulse) to determine whether consistent patterns emerged in the lame limbs or the sound limbs that might indicate compensation. The magnitude of percent change from baseline was also compared between lame and sound limbs.

Results: Using the circumferential hoof clamp technique, we were able to induce a consistent, controlled, and immediately reversible grade 2 out of 5 lameness in individual and multiple limbs. In general, peak vertical force, vertical impulse, and braking impulse decreased, and propulsion impulse increased in the lame limb(s). The forelimbs tended to decrease most consistently in the peak vertical force and vertical impulse, while hindlimbs tended decrease most consistently in the braking impulse. The majority of compensation seemed to come from the contralateral limb, directly opposite the lame limb (i.e. the sound forelimb compensated for a lame forelimb, and the sound hindlimb compensated for a lame hindlimb). Compensation tended to occur through increased vertical and braking impulses in the sound limb(s). The magnitude of percent change from baseline was small for the majority of forces, but was consistent and was associated with a visible lameness.

Conclusions and Potential Relevance: Definite patterns were seen in ground reaction forces in both lameness and compensation. This information may help equine practitioners understand how horses alter their ground reaction forces in response to single and multiple limb lameness by determining primary versus compensatory change, and to clarify some of the complexities of multiple limb lameness.

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Chapter 1

Literature Review

Importance of Lameness to the Equine Industry

Lameness in the horse is the single largest cause of equine morbidity, loss of use, and loss in value. In 1998 the USDA's national animal health monitoring system estimated the cost of lameness in the United States to range from $678 million to $1 billion (with a conservative estimate of $448 million of this stemming from loss of use, $195 million due to the cost of veterinary care and other treatment costs, and $35 million from loss to death).[1] In comparison, the total cost of colic in the same study was estimated to be $115 million. The annual incidence of lameness in this study was calculated to be 8.5-13.7 events/100 horses, 200-300% greater than colic (4.2 events/100 horses).[1] A 1994 prospective study of the Michigan horse population included 2,469 individual horses.[2] Lameness was ranked by horse operator/owners as the number one health problem affecting the equine industry. The scientific findings corroborated this perception. Amongst the top five diseases affecting horses included in the study: lameness had the highest annual incidence density, the second highest average duration per case and average days lost per case (second only to neurologic problems), and the fifth highest case fatality risk (below systemic problems, colic, non-colic gastrointestinal problems, and neurologic problems).[2]

The horse racing industry is physically demanding and depends upon performance soundness for profitability. As a result, lameness brings a high cost to the horse industry, in both monetary terms and performance lost. Large proportions of Thoroughbred racehorses suffer from the effects of lameness during their career. In a study of 42 Thoroughbred horses purchased at yearling sales for race training and resale as 2-year-olds in-training ("pinhooking"), lameness was the most important cause of training failure, with a median of 26 days lost during approximately 5 months of training.[3] Training failure, in turn, was shown to cause a significant loss of revenue upon resale. All horses were trained at the same center, and causes of training failure and their outcomes were recorded.[3] In a similar prospective study on pinhooked horses, 37 of 40 Thoroughbred horses became lame, and the frequency of new lameness cases increased throughout the study (i.e. the longer the horses were in training).[4] Median number of days horses lost to training was similar with 14 horses incurring a forelimb injury (13 training days lost), 18 horses incurring a hind limb injury (16 training days lost) and 5 horses with injuries in both limbs (15 training days lost). These studies demonstrate that lameness leads to lost performance with more cost to owners.

To minimize losses associated with lameness, early and accurate diagnosis allowing for appropriate treatment is essential. Lameness clinicians observe the horse in motion to detect gait alterations associated with pain/lameness in one or multiple limbs. The American Association of Equine Practitioners (AAEP) developed a common lameness grading scale (**Table 1.1**) to standardize the description of lameness and provide a common narrative for veterinarians and lay horse people to use.[5] Despite consensus on a grading scale, the localization of the lameness to one limb or multiple limbs remains the equine practitioner's first major challenge in accurate and timely diagnosis. This task becomes more complicated by the common occurrence of multiple limb lameness. Researchers have attempted to describe gait alteration patterns seen in lame horses; however the use of subjects with naturally-occurring lameness, adds a degree of complexity, and therefore tends to be reserved for studies focused on the response to diagnostic or therapeutic interventions.[6-11] In order to provide a more generalized description of gait alterations seen in lame horses, researchers have focused on the more controlled purposeful induction of lameness. While researchers can control the limb/limbs in which lameness is induced, they have variable control over the degree and duration of lameness, depending on the technique they choose. Some techniques used to induce lameness will be discussed herein.

Methods of Lameness Induction

Methods used to induce lameness vary in how lameness is physically created, how consistent and predictable the lameness is, and how completely and quickly reversible the lameness is. Some techniques, such as the creation of osteoarthritis (via creation of an intra-articular osteochondral fragment) or tendonitis/desmitis (through mechanical or chemical trauma to a tendon/ligament)[12-14] create relatively irreversible forms of lameness.[15-19] Researchers typically use these techniques to evaluate the pathophysiology and response to treatment (similar to research on naturally occurring lameness), but only assess lameness as a result of the primary pathology. Many of these studies culminate in the sacrifice of the subjects to allow for histopathology and other post-mortem evaluation of the tissues. These types of lameness induction are therefore inappropriate for use in research studies wherein the primary goal is to describe lameness patterns. This review will focus on the reversible forms of lameness induction designed to study the effects and signs of lameness itself, rather than underlying pathology, since the intent of the project detailed in Chapter 2 of this thesis was to create an easily reversible lameness for the primary study of gait alterations. It is important to note the differences between lameness induction techniques regarding reversibility, lameness degree, duration, and potential risks.

The creation of synovitis has been commonly used to induce and study lameness since its appearance in the veterinary literature in a pony study published in 1987.[20] The initial intent of the technique was to replicate the effects of septic arthritis, rather than simply the creation of lameness,[20-21] but the model has subsequently been used to induce reversible lameness.[22-28] Lameness due to induction of synovitis results from inflammation that causes clinical signs of heat, effusion, and resentment of palpation and flexion. Clinicopathological changes include increased synovial fluid protein, white blood cell counts, and alkaline phosphatase.[20] A variety of inductive agents have been used. The bacterial endotoxin, lipopolysaccharide (LPS), has been found to have a dose dependent effect. However, excessive LPS dosages do not lead to additional inflammation or lameness.[21] Other agents include Freund's complete adjuvant,[23] amphotericin B,[22, 25] and sterile carrageenan.[24] These studies include categorization of lameness, indicating efficacy as a lameness model and allowing evaluation of response to treatment.[20-25] Others utilize synovitis without in depth investigation of the lameness per se.[29]

Induced synovitis causes lameness that is variable in both severity and duration. Variability between studies is seen due to differences in the joints used, evaluation times, and gaits used for evaluation. Injection of LPS into the intercarpal joint resulted in lameness that began 1 to 2 hours post-injection, peaked by 2 to 3 hours, persisted at the walk for 8 to 10 hours, and resolved by 1.5 to 2 days.[20] In another study using distal intertarsal and tarsometatarsal joint injection of LPS, 7 of 8 horses showed lameness at the walk within 8 hours of joint-injection, with resolution by 12 to 36 hours in 4 of the 7 horses.[26] A similar study using LPS injection in the distal intertarsal and tarsometatarsal joints showed grade 1 to 2 lameness at 24 hours post-injection (1 horse had a more severe grade 3 lameness at this time that decreased to grade 1 by 30 hours post-injection). Horses all returned to soundness by 2 weeks post-injection.[27] Although the synovitis model does reliably induce lameness, the method has multiple limitations including varying degrees and duration of lameness. Optimal dosages for synovitis-inducing preparations have not been determined. This technique also carries risk of causing septic arthritis as a result of intra-synovial injection.[30]

Lameness has been induced by increased intra-synovial pressure, rather than intra-articular inflammation. This technique may have fewer negative side effects than synovitis models. Pain is created through neural stretch receptors in the joint capsule by increasing the volume of fluid in the joint. With time, excess fluid is resorbed, which eliminates the lameness, provided the fluid is non-irritating and sterile. In one study, lameness was induced in 5 sound horses by injecting 35 ml of sterile saline into the metacarpophalangeal joint.[31] Lameness ranged from grade 1 to 5, and all horses regained soundness by 2 hours after injection and remained sound. Because of the short duration and variability of lameness, prolonged or repeat measurements would not be possible. Lameness has also been induced by injection of 10 ml of autologous blood into the metacarpophalangeal joint.[32] In a study of 8 horses, the mean change in lameness from baseline was grade 3.8 ± 1.4 (range 2 to 5) with the majority of horses reaching peak lameness by 4 hours, and having the lameness resolve by 24 hours. Injection of either saline or blood effectively created lameness of variable grades that resolved more quickly than that caused by the synovitis model. However, prolonged evaluation would require repeat induction. These methods of lameness induction both carry some risk of synovial infection.

The solar pressure method of lameness induction uses a modified shoe with nuts welded to various parts of the inner rim of the shoe or an adjustable heart-bar. Round headed screws threaded into these nuts puts pressure on the solar corium, or the heart-bar is adjusted to place pressure on the frog, thereby inducing lameness.[33-41] In a study of 5 horses, one foot was placed in an adjustable heart-bar shoe, and the screw was tightened 1 hour prior to administration of the anti-inflammatory medication being evaluated.[35] All horses reached a lameness that was evident at the walk. The initial exercise protocol had to be changed because some horses (presumed to be control horses with no anti-inflammatory treatment) were too lame to perform the work required.[35] In another study, an adjustable heart bar shoe was used to create solar pressure to induce a grade 5 lameness to assess the analgesic effects of capsaicin applied over the palmar digital nerves.[36] No lameness was noted at the end of the trial among treated horses, and control horses regained soundness by 15 minutes following screw removal. By using round headed screws to place pressure on the solar corium, other investigators achieved 3 grades of lameness: (1) only visible at the trot, (2) obvious at the trot and slightly visible at the walk, and (3) obvious at the walk and trot.[40] They saw kinematic evidence of lameness (decreased hoof arc and joint extension on the lame limb, with increased extension on the non-lame limb). Sole-pressure models appear to give more control over lameness grade than synovitis models. The lameness is immediately reversible upon removal of solar pressure, and re-introduction of lameness is more readily obtained. However, residual effects in forelimbs have been reported following removal of solar pressure.[41] Apparently, repeated application of focal sole pressure may result in sole bruising.[42]

A circular clamp applied around the hoof wall to create circumferential pressure also induces an immediately reversible lameness.[43] Researchers have used a stainless steel pipe clamp with an adjustable screw that can be tightened and loosened to adjust the amount of pressure. Using incremental clamp tightening, they were able to create repeatable lameness of grades 2 and 3 which immediately resolved with clamp loosening.[43] This method appears similar to the solar pressure model in creation of a predictable, consistent lameness that allows creation of various lameness grades. It may have less risk of bruising than solar pressure and does not require farriery skills.

Challenges of Subjective Lameness Evaluation

Subjective lameness examination remains the most common means of evaluating lameness both clinically and in research settings; however, multiple studies have shown low repeatability and significant bias. One study compared a visual lameness grading scale (based on the AAEP descriptions) to a purely numerical scale to see if the use of the unique scale improved agreement among observers.[44] They did not find any improvement using the numerical scale when compared to the visual scale, and observers were found to agree with each other regarding grade of lameness only 56% (numerical scale) and 60% (visual scale) of the time.

One source of bias affecting subjective lameness evaluation is the experience of the observer. A study demonstrated that expert large and small animal clinicians out-performed inexperienced veterinary students in diagnosing simulated hindlimb lameness, although observers performed equally well detecting non-lameness associated asymmetry.[45] Therefore the difference in performance was due to the learned ability to detect specific lameness-associated gait alterations. Another study looked at the repeatability of observations, measured using the sums of the differences, which was greatest for equine orthopedic experts, followed by final year veterinary students, and poorest for non-expert clinicians.[46] Previous knowledge about the horses' condition is another source of bias affecting subjective lameness evaluation. A significantly greater difference between scores was detected when observers were told that the videos they were scoring were made pre- or post-nerve blocks, compared to when the videos were viewed in a blinded order.[46] The depth of examination performed can also influence the precision of lameness diagnosis. In one study in which experienced equine practitioners performed complete lameness exams, there was greater agreement regarding lame limb than other studies using videotapes of treadmill exams alone. However, agreement was still reported as only "marginally acceptable."[47] Therefore, despite attempts to improve the consistency and accuracy of lameness grading, subjective evaluation remains biased.

In a study comparing subjective analysis to kinetic force plate data, 10 of 22 horses were placed into the grade 1 lameness category (as defined by the authors) based on fore plate findings of a < 2% asymmetry.[48] However, 7 of these 10 horses were classified as sound based on subjective evaluation. A significant agreement was seen between subjective and objective analysis when looking at which category horses fell into (sound, forelimb lameness, or hindlimb lameness) and when looking at which limb was lame, but not for grade of lameness. Subjective analysis may be appropriate to determine large changes in asymmetry and to pinpoint lameness to a specific limb, but it may not be sensitive enough for subtle lameness or for accurate grading.

Based on the data presented above, it is evident that subjective analysis is not ideal for use in lameness research. Subjective lameness analysis can be biased by lameness experience of the observers and un-blinded knowledge about horses in a study. The depth of evaluation (i.e. observers watching horses on video, in person, or following a more complete lameness exam) can also alter the results of a study, and use of different grading scales make it difficult to compare study results. Although different objective measurement techniques may not agree with each other or with subjective analysis, they provide more reliable methods for research purposes. For these reasons, objective methods of lameness evaluation are becoming more common for the analysis of lameness.

Objective Lameness Evaluation

There are a variety of techniques used to objectively quantify lameness. Kinematic analysis tracks the motion of multiple points on the horse, such as the head, body, and limbs.[49] Descriptions related to spatial (such as displacement of head/neck, sacrum, tuber coxae, joint angles, hoof arc, etc.) and temporal (stride duration, time spent with a limb/limbs in weight-bearing, or time spent in swing-phase, stride frequency, etc.) factors can be analyzed. A variety of asymmetries associated with lameness can be detected using this method. For instance, alteration of a joint angle is an indication of lameness in kinematic studies with different studies highlighting changes in various joints.[26-27, 40, 50] Other findings in lame limbs include changes in stride components such as protraction/retraction, length, duration and hoof arc.[26, 37, 40, 51] Changes in carriage of the head, neck, trunk and croup are also described in kinematic studies.[26, 39, 50, 52]

Kinetic analysis measures multiple ground reaction forces created when the limb strikes the ground as measured by a force plate that transduces these signal into graphical representations of the forces (**Figure 1.1**). Forces are measured over time in the vertical (up and down) (**Figure 1.2**), horizontal (side-to-side) and longitudinal (braking and propulsion) (**Figure 1.3**) directions relative to movement of the horse. When a limb lands on the ground the force in the vertical direction begins to increase to a maximum point which represents full weight bearing. During this time, the longitudinal braking force is also increasing and represents another direction of force that coincides with the direction in which the horse is moving. At some point in the stride, the horse begins to place less force on the limb in the vertical direction, so that the vertical force curve begins to return to baseline. The horse also completes the braking portion of the stride when forward motion is no longer occurring so the braking force curve also returns to baseline. Then the horse begins to push off the ground, causing the propulsion curve to increase. As push-off is being completed, the propulsion force curve also returns to baseline. The horizontal forces represent the side-to-side motion of the hoof as it interacts with the force plate, but will not be discussed in detail because they have been found to be more useful to detect gait changes associated with ataxia rather than lameness.[53] Kinetic variables such as the maximum value a force reaches (peak ground reaction force) can be used to describe and compare the gaits. The area under the force-time curve can also be calculated and used in gait analysis, thereby providing an indication of both magnitude of the force and time over which the force was created. These forces can then be used to describe the gait and are expected to decrease with lameness as the horse attempts to minimize weight bearing to minimize discomfort.[49]

Kinetic studies have revealed various changes in ground reaction forces that occur with lameness. In one study, a single forelimb or hindlimb lameness was created by solar pressure.[33] Decreased peak vertical and longitudinal forces were noted. Changes in the horizontal direction were minimal. These changes were all present even when the lameness was subclinical (not detected visually by observers).[33] In another kinetic study synovitis was induced in the metacarpophalangeal joint of 32 horses and compared subjective lameness scores and kinetic values.[54] Significant decreases from baseline were seen in virtually all vertical and longitudinal forces for various subjective lameness grades. Significant associations were found between subjective lameness scores and the majority of kinetic parameters. Peak vertical force and vertical impulse both showed the strongest correlations with subjective scores and had the lowest variability. Both peak vertical force and vertical impulse decreased significantly in mild and sub-clinical lameness, with peak vertical force showing the highest sensitivity and specificity in detecting lameness.[54]

Evidence of Lameness Compensation

While the majority of research has focused on changes seen in the lame limb only, a few studies have investigated compensatory changes seen in other limbs.[27, 50, 52, 55-57] In a distal tarsal joint synovitis model, decreased peak vertical force and vertical impulse were observed in the lame limb, while decreased vertical impulse was seen in the diagonal forelimb and increased braking impulse in the contralateral hindlimb.[27] However, other studies have suggested there may be false lameness due to these compensatory effects.[52] In other words, a horse may appear lame in one limb, but it is actually not; the horse is just transferring force away from the actual lame limb. For example, false compensatory lameness was identified after local anesthesia in lame horses and in sound horses with induced lameness.[52] In one horse with induced forelimb lameness, a true contralateral hindlimb lameness only became apparent following removal of the forelimb screw. The most consistent pattern of lameness transfer identified was a primary hindlimb lameness that caused a false ipsilateral forelimb lameness. The authors concluded that a more severe forelimb lameness may be necessary to induce more consistent changes in the motion of the hind limbs.[52] This study provided support for the "law of sides," (where a forelimb lameness creates a false contralateral hindlimb lameness and a hindlimb lameness creates a false ipsilateral forelimb lameness),[49] and suggested some mechanisms for lameness compensation as shown by the kinematic alterations creating false lameness in other limbs. Naturally-occurring lameness was compared to clinically sound horses in another kinematic study.[50] Symmetry indices were compared between lame and sound horses. Hindlimb lameness provided more convincing evidence of compensation than forelimb lameness. Changes seen during hindlimb lameness were attributed to compensatory movements in the head and trunk.[50]

In two kinetic studies on lameness at the trot, compensatory mechanisms during individual forelimb or hindlimb lameness were evaluated.[55-56] Horses compensated by shifting the vertical impulse from the lame forelimb or hindlimb to the sound contralateral limb (forelimb or hindlimb respectively).[55-56] Vertical impulse and PVF both increased in the sound hindlimb contralateral to the lame forelimb, at the most severe grade of lameness.[55] Kinetic evidence of compensation among sound limbs during individual forelimb and hindlimb lameness has also been reported using data collected at a walk.[57] Vertical force decreased in the lame forelimb, but increased in all three sound limbs. Longitudinal forces also decreased in the lame forelimb and increased in the contralateral fore- and ipsilateral hindlimbs. Similarly, vertical force also decreased in the lame hindlimb, with increases in the contralateral forelimb; less so in the ipsilateral forelimb and contralateral hindlimb. Braking force also decreased in the lame hindlimb while propulsion force increased in the contralateral hindlimb. Longitudinal forces increased slightly in both forelimbs in compensation. Combined, these studies provided evidence of lameness compensation by demonstrating decreased kinetic forces in the lame limb both in terms of magnitude of force and gait timing. This is accompanied by relative increases in other limbs indicating compensation to decrease discomfort in the lame limb by relative overloading of the sound limbs.

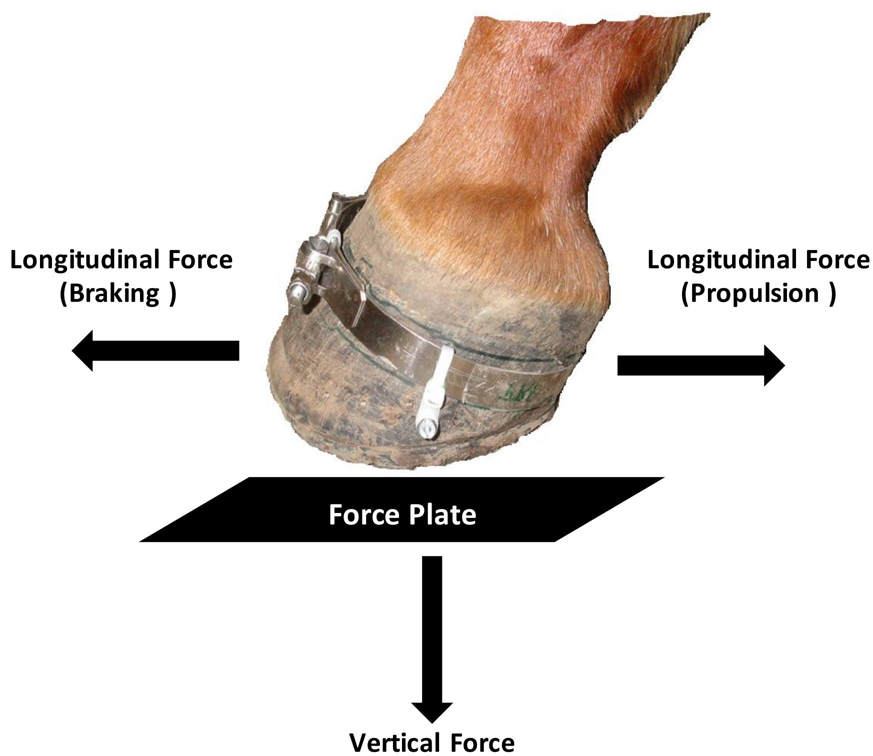
A better understanding of compensation in all limbs, particularly during multiple limb lameness conditions would improve the ability to diagnose lameness. It may help clinicians to differentiate true lameness from compensatory gait changes resulting in more effective lameness treatment.

Table 1.1. American Association of Equine Practitioners (AAEP) subjective lameness grading system

AAEP Lameness Grade	Description
0	Lameness not perceptible under any circumstances
1	Lameness difficult to observe; not consistently apparent regardless of circumstances (e.g., weight carrying, circling, inclines, hard surface)
2	Lameness difficult to observe at a walk or trot in a straight line; consistently apparent under some circumstances (e.g., weight carrying, circling, inclines, hard surface)
3	Lameness consistently observable at a trot under all circumstances
4	Lameness obvious; marked nodding, hitching, and/or shortened stride
5	Lameness obvious, minimal weight bearing in motion or rest; inability to move

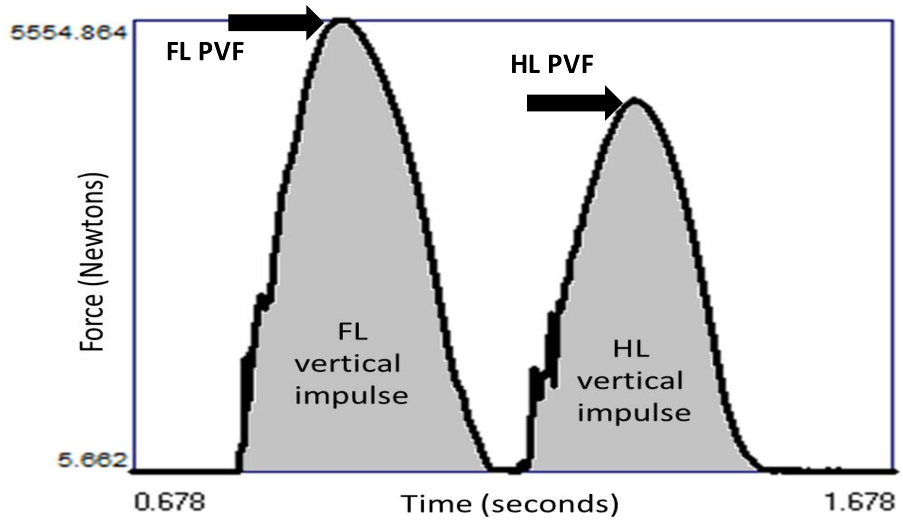
Table was adapted from Baxter et al. 2011 [5]

Figure 1.1. Ground reaction forces obtained using force plate analysis



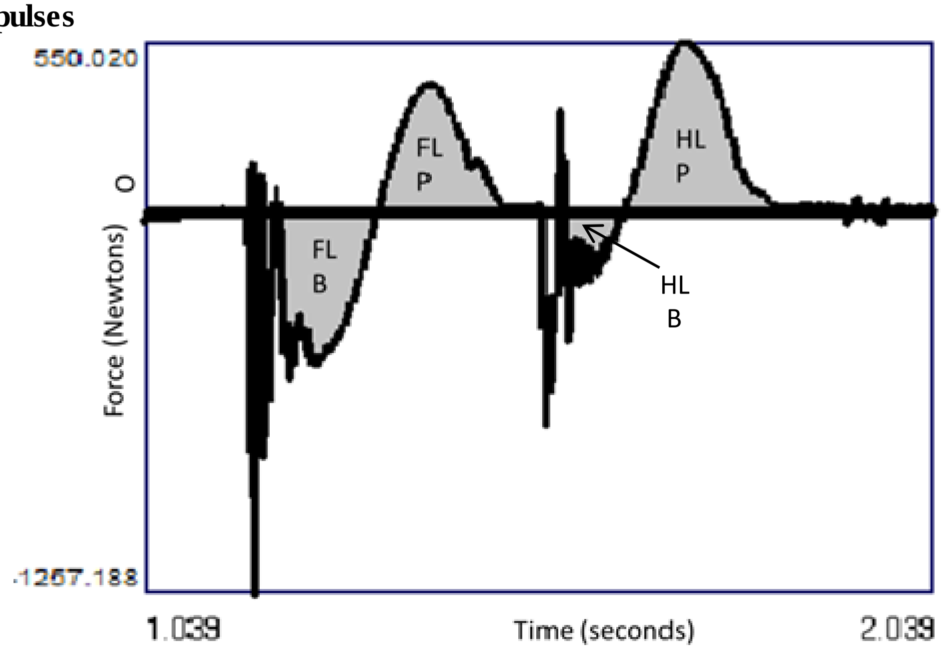
Forces in the vertical axis (Fz) are used to determine peak vertical force and vertical impulse. Forces in the longitudinal axis (Fy) are used to determine braking and propulsion impulses along the direction the horse is traveling.

Figure 1.2. Vertical forces: Used to determine peak vertical force (PVF) and vertical impulse



Peak vertical force (PVF) is determined by finding the highest point on each curve (marked by arrows) for a forelimb (FL) and its ipsilateral hindlimb (HL). Vertical impulse is determined by calculating the area under the force-time curve (indicated by the shaded areas beneath curves).

Figure 1.3. Longitudinal forces: Used to determine braking and propulsion impulses



The areas under the force-time curves (shaded in gray) were calculated in order to determine the longitudinal impulses for forelimb braking (FL B), forelimb propulsion (FL P), ipsilateral hindlimb braking (HL B) and ipsilateral hindlimb propulsion (HL P), respectively. By convention, braking forces are negative and propulsion forces are positive, but absolute values are used for analyses.

Chapter 2

Compensatory force plate responses to single or multiple limb lameness induction in horses using a hoof clamp technique

Compensatory force plate responses to single or multiple limb lameness induction in horses using a hoof clamp technique

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INTRODUCTION

Lameness has long been the most common costly disease to affect the horse industry. In order to minimize losses due to lameness, equine practitioners must be able to diagnose lameness accurately, so they can provide targeted treatment. One obstacle practitioner's face is the inherent subjectivity in the most common method of lameness diagnosis. In a clinical setting, lameness diagnosticians rely primarily on visual signs indicative of gait asymmetry to detect lameness. They look for specific patterns that suggest a horse is favoring a limb/limbs over the others. Inter-observer variability in subjective lameness analysis can vary greatly. Localization of lameness is further complicated by lameness in multiple limbs.[47, 52] Some of the gait alterations seen in lame horses can actually mimic lameness in other limbs, thus resulting in a false or referred lameness elsewhere.[49] It is difficult to determine whether a horse has two (or more) true lame limbs, or if there is one primary lameness (related to pain) and a second referred/compensatory lameness (due to the horse's gait alterations). It has been shown that elimination of the primary lameness in one limb through the use of local or regional anesthesia helps determine whether the second lameness is a result of pain or if it is a compensatory gait change that disappears when the primary lameness is blocked.[58]

An understanding of how horses compensate for lameness would help distinguish true lameness from false lameness due to compensatory gait alterations. It may also explain multiple concurrent lameness. There are few studies that address lameness compensation as a primary aim.[52, 55-57] These studies focus on primary lameness in one limb and do not address compensation in multiple limb lameness.

We proposed that use of a hoof clamp[43] would create predictable and repeatable lameness in single and multiple limbs, without need for an extended recuperation between data collection times. The aims of this study were to describe ground reaction force changes in one or more limbs with induced lameness, and to observe compensatory changes in ground reaction forces in non-lame limbs. We hypothesized that horses will have decreased ground reaction forces in the lame limb compared to baseline values, and that compensation for the lameness will occur through redistribution of forces among the remaining limbs. Additionally, we expected that the pattern of compensation would depend on the limbs involved.

MATERIALS AND METHODS

Experimental Design

A subjective grade 2 out of 5 lameness (using the AAEP lameness scale) (**Table 1.1**) was induced using a hoof clamp technique. The hoof clamp[a] was used to create lameness by placing circumferential pressure around the hoof wall, and the lameness was immediately reversible upon loosening the clamp. Lameness was induced in an individual fore- or hindlimb, and in paired limbs (including ipsilateral and contralateral forelimb/hindlimb pairs, and bilateral forelimbs and hindlimbs). Resulting peak vertical force, vertical impulse, braking impulse, and propulsion impulse were determined for each induced lameness. Percent change in forces between baseline and lameness were compared. The proportion of horses with an increase or decrease in ground reaction forces from baseline was determined in lame and sound limbs.

Horses

A total of 8 adult Quarter Horses (mean age ± SD was 7.5 ± 2 years, median 6 years, range 5-10 years) were included in this study. Horses included 4 mares and 4 geldings that weighed between 487 and 595 kg (537 ± 37 kg). Prior to their inclusion in the current study, horses were used as sound control horses for another study, in which they were acclimated to force plate examinations. They were rested prior to the start of the present study (mean 21 ± 14 days; range of 5 to 44 days). Subjective lameness exams were performed by an ACVS boarded surgeon and a resident (TNT, MES). All horses had grade 0 to 1 (on the AAEP scale) naturally-occurring lameness that was localized and provided appropriate treatment, if necessary, prior to data collection. All experimental procedures were approved by the University of Minnesota Institutional Laboratory Animal Care and Use Committee (Protocol #1007A86632).

Hoof Clamp Application

Prior to the beginning of the experiment, horses had routine farrier work performed including balanced trimming and the placement of shock absorptive shoes[b] in the forelimbs and bar shoes in the hindlimbs to prevent distal migration of the clamps. Stainless steel pipe clamps[a] were used that had a circumferential range of 102 to129 mm and a width of 19 mm. A variety of clamp circumferences were purchased and clamps were individually fit to each hoof on each horse. Horses either wore the same circumference clamp on all 4 feet or one size smaller on the hind feet. The width of the plantar portion of the clamps (and palmar portion in horse 3, with small feet) was reduced by approximately 50% to prevent impingement on the heel bulbs or coronary band (**Figure 2.1**). In order to decrease the plantar width, a semi-circular area was marked on the distal and plantar portion of the clamp beginning approximately where the heels contacted the ground and reaching a maximal height at the middle of the clamp (~9 mm). This section of metal was removed using a dremel[c] tool. Edges were smoothed to prevent irritation. Clamps were placed on the hoof with the cut edge facing distally and were angled slightly dorsoproximal to palmaro-/plantarodistal to maximize contact with the hoof (**Figure 2.2 a, b**). To prevent slippage, the clamp was secured to the hoof. Three holes were drilled into the insensitive laminae of the dorsal, lateral and medial hoof walls using an 5/32 inch diameter drill bit[d] to a depth of 3/16 inch. Tape was placed around the drill bit 3/16 inch from its tip to serve as a depth gauge (**Figure 2.2 c**). Three cable ties[e] were passed around the clamp and screws[f] were placed through the eye holes in the cable ties distal to the hoof clamp and were secured into the holes in the hoof wall. This was done to prevent clamps from slipping proximally when tightened. Screw placement varied slightly by horse and was determined by finding the location on the hoof for best conformity and pressure distribution without impingement on the coronary band. This required pushing the clamp down so its palmaro-/plantarodistal edge touched the proximal surface of the shoe. Adjustments were made to avoid previous nail holes or nail clinches. Occasionally, screw holes in the laminae became stripped and had to be replaced. Holes were placed more dorsomedially or dorsolaterally, instead of medial or lateral to allow the clamp to lie flush with the hoof wall and provide easier screw placement.

The adjusting bolts used to tighten and loosen the clamps were placed laterally on all feet to avoid trauma in case of interference (**Figure 2.2 d**). The bolt on the clamp was incrementally tightened until a subjective grade 2 lameness became evident when the horse was trotted on an asphalt surface. For bilateral forelimb or bilateral hindlimb lameness, lameness was induced in one limb first (limb with pre-existing lameness if present in the horse) and then the contralateral clamp was tightened until the gait became symmetrical, indicative of a bilateral lameness. A light protective covering of rolled cotton and self-adhesive bandage[g] was placed over all clamps to prevent injury during data collection (**Figure 2.2 e**). Between trials, drill holes in the hoof wall for screw placement were plugged with the ends of cotton-tipped applicators, and covered with duct tape. When screw threads in the hoof wall stripped, screws were replaced with a larger diameter screw or a new hole was drilled. Holes were filled with polymethylmethacrylate[h] material following completion of the study.

Lameness Induction

Lameness was reversibly induced by tightening the circumferential stainless steel pipe clamp[a] around the hoof. Clamps were placed on all hooves each time data was collected, but the clamps were only tightened in the limb(s) in which lameness was induced (**Figure 2.2 f**). Single and paired limbs in which lameness was induced were equally distributed among horses, and bilateral forelimb and hindlimb lameness was induced in all horses (**Table 2.1**). In horses with preexisting lameness, the lame limb(s) were preferentially used for lameness induction to minimize potential interference. Baseline force plate data were collected and video recordings made each day prior to lameness induction. Designated clamps were then tightened to induce a subjective grade

2 out of 5 lameness in the affected limb(s), force plate data was collected, and video recordings were made. To limit the amount of time the clamps were tightened, each induced lameness was limited to ≤ 30 minutes. This limited the overall time a horse spent with a tightened clamp to ≤ 60 minutes per collection day. Two different lameness scenarios were induced on data collection timepoints 1 and 2 (**Table 2.2**).

Data Collection

Horses were led through a calibrated motion analysis runway by an experienced handler. The runway contained an in-ground force plate[i] with associated software and computer[j]. The force plate was covered by a rubber mat to reduce detection by the horse and improve footing. An acceptable trial required placement of ipsilateral fore and hindlimbs squarely within the plate (without contact by other feet), at a velocity within a pre-determined range (0.9 to 1.7 m/s at the walk, 2.8 to 3.3 m/s at the trot) with < 10% acceleration. Velocity and acceleration were measured using a wireless timing device with 3 photo-transmitter/receiver pairs[k]. Trials that diverged from these parameters were immediately excluded. At least 5 acceptable trials for both left and right sides were obtained for each lameness.

On the first data collection timepoint, baseline (no clamps tightened), unilateral forelimb lameness, and ipsilaterally paired forelimb/hindlimb lameness (using same forelimb as in the unilateral forelimb lameness) data were collected. At the second data collection timepoint, baseline (no clamps tightened), unilateral hindlimb lameness, and contralaterally paired forelimb/hindlimb lameness (using same hindlimb as in the unilateral hindlimb lameness) data were collected. At the third data collection timepoint, baseline (no clamps tightened), and bilateral forelimb lameness data were collected. At the final data collection timepoint, baseline (no clamps tightened) and bilateral hindlimb lameness data were collected (**Table 2.2**). Data collection dates were separated by at least 48 hours to allow for optimal recovery of horses, which received 2.2 to 4.4 mg/kg of phenylbutazone[l] orally once per day between data collections. Phenylbutazone was not administered within 12 hours prior to data collection.

Kinetic Gait Analysis

Ground reaction forces were obtained using the DMAS6 reporter software[m] for each limb for baseline and for all 6 lameness induction scenarios (**Table 2.2**). Values were obtained for vertical axis, including peak vertical force (PVF) and vertical impulse, and longitudinal axis, including braking and propulsion impulses (areas under the force-time curves) (**Figures 1.1, 1.2 and 1.3**). Absolute values were used for analysis of longitudinal forces. Due to variability, particularly in peak amplitude of braking forces, only impulse data was used for braking and propulsion (**Figure 1.3**). The peak vertical force value indicated the maximal amplitude that was reached in the vertical vector. In contrast, the impulse was the calculated value of the area under the force-time curve. The impulse was therefore affected both by the magnitude of force achieved as well as by the time over which the force is produced. All values were transformed from Newtons to Newtons/kilogram to correct for weight differences among horses. For all ground reaction forces being examined, percent change from baseline was calculated for each limb during all 6 lameness scenarios using the equation [(value during lameness - baseline value)/baseline value]*100 = % change from baseline. A negative change indicated a decrease from baseline and a positive change indicated an increase from baseline.

Statistical Analysis

Analysis of box plots was used to identify outliers. Extreme studentized deviate tests[n] were performed to identify and remove outliers from raw data and percent change from baseline data. Descriptive statistics were performed. Average percent change from baseline ± standard deviation for PVF, vertical impulse, and braking and propulsion impulses were calculated from 5 trials per horse for each limb for all 6 lameness scenarios. The proportions of horses with an average increase or decrease from baseline were reported for each limb (lame limb/s and sound limbs) for all 6 lameness scenarios. The number of horses in the denominator of these proportions was sometimes reported as less than 8, which occurred when one or more data points were removed because they were considered outliers. If more than half of the remaining observations (following outlier removal) decreased from baseline in the limb in which the clamp(s) was/were tightened, this was taken as an indication of lameness. If, conversely, more than half of the remaining observations increased from baseline in the remaining limb(s) without the clamp(s) tightened, this was taken as an indication of compensation.

Post hoc analysis was performed on percent change from baseline for each force (PVF, vertical impulse, braking and propulsion impulse) and this magnitude of change from baseline was compared between lame and sound limbs. Data was grouped according to the number of points falling into discrete ranges (*e.g.* <5%, 5-10% etc.) to determine the range that was most commonly represented for each force and to determine differences between lame and sound limbs.

RESULTS

Circumferential Hoof Clamp Induced Lameness

Tightening of clamps resulted in induction of lameness in the selected limb(s) in all horses. Lameness resulted immediately after clamp tightening and a subjective grade 2 lameness was consistently achieved and maintained. Clamp placement was uncomplicated. No injuries or residual lameness were noted after clamp removal or at the next data collection ≥ 48 hours later. One horse with a pre-existing lameness appeared more lame in the affected limb after clamp removal. It was not determined whether this was due to clamp application or worsening of the existing problem.

Individual Forelimb Lameness

Decreased PVF in the lame forelimb was the most consistent change from baseline in all horses (8/8). Vertical impulse (6/8) and braking impulse (5/8) also decreased in the majority of lame forelimbs, while propulsion impulse increased (6/8). The majority of compensation was seen in the contralateral forelimb, with less contribution from the ipsilateral hindlimb. Vertical impulse (5/7) and braking impulse (7/8) tended to increase in the contralateral forelimb, meaning horses compensated using the contralateral forelimb by prolonging applied vertical and braking forces over time in this limb. Most horses did not show evidence of compensation in either hindlimb, with the exception of braking impulse (4/7) in the ipsilateral hindlimb (**Figure 2.3.1, Table 2.3, and Figure 2.3.2**).

Individual Hindlimb Lameness

Decreased braking in the lame hindlimb was the most consistent change from baseline (8/8). Vertical impulse (6/8) and PVF (5/8) also decreased in the majority of lame hindlimbs, while propulsion impulse increased (6/8). The majority of compensation was seen in the contralateral hindlimb, with lesser contributions from both forelimbs. PVF (6/8), vertical impulse (6/8) and braking impulse (6/8) all increased in the contralateral hindlimbs. Vertical impulse increased (5/8) and PVF decreased (5/8) in the ipsilateral forelimb, meaning horses did not strike the ground with as much vertical force, but kept the limb on the ground for a longer period of time. Braking impulse also increased (5/8) in the contralateral forelimb (**Figure 2.4.1, Table 2.4, and Figure 2.4.2**).

Ipsilaterally Paired Forelimb/Hindlimb Lameness

Decreased vertical impulses (8/8 both forelimbs and hindlimbs) and PVF (8/8 forelimbs, 7/8 hindlimbs) were the most consistent changes from baseline in ipsilaterally paired forelimb/hindlimb lameness. Braking impulse also decreased in the majority of lame hindlimbs (6/8), but no pattern was seen in braking among lame forelimbs. Propulsion tended to increase in lame forelimbs (6/8) and decrease in lame hindlimbs (4/7). The majority of horses also had decreased PVF in the remaining sound limbs. Compensation was seen in both the contralateral forelimb and hindlimb. Braking impulse increased in both the contralateral forelimb (5/7) and hindlimb (6/7), and vertical impulse increased in the contralateral forelimb (4/7) (**Figure 2.5.1, Table 2.5, and Figure 2.5.2**).

Contralaterally Paired Forelimb/ Hindlimb Lameness

Decreases in PVF (8/8 forelimbs, 5/8 hindlimbs), vertical impulse (8/8 forelimbs, 6/8 hindlimbs) and braking impulse (7/8 forelimbs, 8/8 hindlimbs) were present in the majority of lame limbs during contralaterally paired forelimb/hindlimb lameness. Propulsion also increased in the majority of lame forelimbs (7/8) and hindlimbs (7/7). Increasing vertical impulse in the contralateral forelimb (7/8) was the most consistent compensatory change with additional compensation through increased braking impulse in the sound forelimb (5/8). In the sound hindlimb, braking impulse increased (5/8), as did PVF (4/7) (**Figure 2.6.1, Table 2.6, and Figure 2.6.2**).

Bilateral Forelimb Lameness

Decreased PVF (8/8 bilaterally) was the most consistent change from baseline in lame limbs for bilateral forelimb lameness. Vertical impulse also decreased (4/7 left forelimb, and 6/8 right forelimb), but less consistently than PVF. An increase in propulsion impulse was also seen in both forelimbs (7/7 left forelimb, 6/8 right forelimb), while the braking impulse decreased (4/8 left forelimb, 5/8 right forelimb). The only evidence of compensation from the sound hindlimbs was seen as increased braking (6/8 left hindlimb and 7/8 right hindlimb). Consistent decreases in propulsion of both hindlimbs (8/8 left hindlimb and 7/7 right hindlimb) was also seen, while PVF and vertical impulses decreased in hindlimbs (**Figure 2.7.1, Table 2.7, and Figure 2.7.2**).

Bilateral Hindlimb Lameness

Decreased PVF (7/8 bilaterally) was the most consistent change from baseline seen in lame limbs during the bilateral hindlimb lameness. Concurrent decreases in the vertical impulse (6/8 left hindlimb, 4/8 right hindlimb) were also noted. In contrast to all other induced lameness scenarios, both hindlimbs showed increases in braking impulse (5/8 left hind, 6/8 right hind) with decreased propulsion impulses (5/7 left hindlimb, 6/7 right hindlimb). Compensation from the forelimbs was indicated by increased vertical impulse (5/6 left forelimb, 6/7 right forelimb), and possibly via increased propulsion impulses (7/8 left forelimb, 6/8 right forelimb) (**Figure 2.8.1, Table 2.8, and Figure 2.8.2**).

Magnitude of Percent Change from Baseline

Post hoc analysis was performed to determine the range(s) of percent change from baseline for the lame and sound limbs for each force (PVF, vertical impulse, braking impulse and propulsion impulse) **(Tables 2.9-2.12)**. The overall range of percent change from baseline was greater in both longitudinal forces (0-76% for braking impulse and 0-41% for propulsion impulse) than the vertical forces (0-16% for PVF and 0-12% for vertical impulse), indicating greater variability in the longitudinal forces. The range in which the most braking impulses fell into (10-20% for both sound and lame limbs) **(Table 2.12)** was greater than PVF (1-5% in sound limbs and 5-10% in lame limbs), vertical impulse (1-5% in both sound and lame limbs), and propulsion impulse (0-5% in the sound limbs and 5-10% in lame limbs) **(Tables 2.9-2.12)**.

DISCUSSION

We found that the circumferential hoof clamp method was an effective way to induce an immediately reversible, controlled grade 2 out of 5 lameness in either an individual forelimb or hindlimb or in multiple limbs. We saw unique patterns in lame limbs, including consistently decreased peak vertical force and vertical impulse in the forelimbs and decreased breaking impulse in the hindlimbs. The propulsion impulse tended to change in the opposite direction as the braking impulse. The most consistent source of compensation tended to be the contralateral limb in the same half of the body as the lame limb (i.e. contralateral forelimb during a forelimb lameness and contralateral hindlimb during a hindlimb lameness). The most consistent compensatory increases were seen in the vertical impulse and braking impulse forces. Some lameness scenarios, such as the bilateral hindlimb lameness showed unique patterns. Following post hoc analysis it appears that changes with even small magnitude of percent change from baseline should be considered potentially important.

Hoof clamp application consistently resulted in a controlled grade 2 lameness that was immediately reversible when clamps were removed. Clamps were placed on all four feet for each of the data collection days in all horses. Any changes in gait due to the untightened clamp alone would be expected to occur evenly in all 4 limbs. However, clamps were well tolerated by all horses and no noticeable gait changes were seen with untightened clamps during baseline data collections. Horses subjectively returned to the current baseline after loosening the clamps. This method of lameness induction appeared to be more predictable and reversible than some of the previously reported lameness induction techniques with minimal complications.[20-21, 31-32]

Although our clamp technique resulted in consistent and reversible lameness, the method required some refinement. The degree of lameness created (2 out of 5) was determined for each lameness by the investigators collecting data (MES, JMA, DG) and directed by the principal investigator (TNT). Therefore, the grade of lameness that was created may vary from other observers' impressions of what a grade 2 out of 5 lameness should look like. The video tape recordings made during data collection could be used to validate the degree of lameness achieved. Subjective analysis had to be used however after we were unable to create a grade 2 lameness using a torque wrench. An electronic torque did not begin to read the force applied until the lameness induced was a subjective grade 4 (likely due to clamp fit variations). We attempted to then use the number of turns of the nut to create a standardized lameness, but that often resulted in a variable lameness (grade 1-3). This did, however, provide the information that one could induce a grade 1 to 4 lameness using the clamp technique and that lameness severity could be easily changed.

We observed day to day variability in the baseline measurements of many horses. This may have been due to the presence of the clamps on each foot, but that is unlikely because none were tightened during baseline recording and there were no differences in technique between baseline measurements. This day to day variability was expected and is the reason new baseline data was collected at each data collection timepoint. This allowed us to make more accurate comparisons of changes after clamp tightening, so that we knew any changes from baseline for that day were truly a result of lameness and not simply from variation of baseline values.

Some clamps were used 3-4 times to induce lameness during the 6 different lameness combinations created throughout the study. Repeated use of the same clamps subjectively appeared to decrease the effectiveness of lameness induction over time. Therefore, in some horses, the clamps had to be maximally tightened in order to obtain a grade 2 lameness. It is likely the metal clamp deformed as it conformed to the foot, thus altering the force on the hoof capsule after repeated tightening. It is possible that a smaller clamp size or the use of a new clamp for each lameness scenario would have been optimal. Only one clamp loosened on one horse throughout the entire study. The lameness that was affected was repeated at a later date with no problems (initial data collected with improperly tightened clamp was discarded).

When observing lame and sound limbs, some important patterns emerge from this study. One consistent change among lame limbs is the tendency for vertical forces to decrease **(Figures 2.3.1-2.3.8, Tables 2.3-2.8, and Figures 2.3.2-2.8.2**). In almost all lameness conditions the peak vertical force (most consistently) and vertical impulses decreased in the lame limb(s) in which the hoof clamps were tightened. This finding is consistent with previous kinetic studies where increasing lameness leads to progressively decreased peak vertical force,[33] to a greater extent than vertical impulse during both an individual forelimb and hindlimb lameness.[55-56] Peak forces in general have been shown to decrease more than impulses.[33] In a synovitis induced lameness model, peak vertical force was found to be the most sensitive and specific force indicative of lameness, and significant decreases in both peak vertical force and vertical impulse were seen even during sub-clinical (not visible to observers) lameness.[54] Kinematic studies also suggest less vertical forces on the lame limb through gait alterations such as decreased vertical acceleration of the head and decreased displacement of the tuber sacrale, and decreased fetlock extension.[39] Our study, however, generally showed a more consistent decrease in vertical forces in the lame forelimbs than in the lame hindlimbs. This is similar to previous studies where there were greater decreases among peak vertical forces and vertical impulses in the lame forelimbs than the lame hindlimbs, even though both lameness conditions resulted in significant changes from baseline.[55-56]

In the hindlimbs, decreased breaking impulse was a consistent pattern of change in the lame limb. Forelimbs also showed decreased braking impulse, but less consistently than the vertical forces **(Figures 2.3.1-2.4.1 and 2.6.1, Tables 2.3-2.4 and 2.6, and Figures 2.3.2-2.4.2 and 2.6.2)**. Many kinetic studies tend to focus predominantly on vertical forces,[55-56] with minimal to no reference to longitudinal forces; in those that do examine longitudinal forces, only forelimb lameness was described.[54] Therefore, it is difficult to find such trends in previous literature that can be compared to our study. One study using both forelimb and hindlimb lameness and looking at forces in all 3 vectors found decreased longitudinal forces in both lame fore- and hindlimbs, but due to the use of an index technique using scoring based on 93 ground reaction force variables, it becomes difficult to determine the contribution of individual forces.[33] Some kinematic evidence exists which may help explain these differences between fore- and hindlimbs. Greater vertical hoof velocity at the time of contact with the ground and then greater vertical acceleration has been seen in the sound forelimb, while greater velocity at the time of ground contact and following acceleration in the braking direction were detected in the sound hindlimb.[6] The front foot was found to become parallel to the ground more quickly than the hind foot, due to a greater hoof angle at the time of ground contact in the hindlimb. This greater angle and longer time to become parallel indicate that the forelimb moves to a position where vertical forces become more important, while the hindlimb spends more time under the influence of braking forces.

An additional pattern seen among lame limbs in our study was the tendency for the propulsion impulse to change in the opposite direction of the braking impulse. For example, as the braking impulse tended to decrease in the lame limbs, the propulsion impulse often increased in these limbs **(Figures 2.3.1-2.4.1 and 2.6.1-2.8.1, Tables 2.3-2.4, and 2.6-2.8, and Figures 2.3.2-2.4.2, and 2.6.2-2.8.2)**. This has not been previously reported. It is likely due to the fact that the two forces occur in opposite directions along the same longitudinal plain and are, therefore, mutually exclusive. It is predicted then, that during lameness, as less of the stride is spent in braking, relatively more of the stride will be spent in propulsion and vice versa. The timing at which horses switch from breaking to propulsion forces ($52.5 \pm 2.7\%$ in the forelimb and $42.2 \pm 2.6\%$ in the hindlimb) were found to be rather consistent among sound horses.[59] This timing seems likely to be adjusted when horses experience lameness, as described in the current study, and could be further calculated.

One notable exception to the previously described patterns in lameness occurred during bilateral hindlimb lameness **(Figure 2.8.1, Table 2.8, and Figure 2.8.2)**. For this lameness the major change from previous patterns was the tendency for braking impulse to *increase* in the lame limbs. This may be because during the clamp-induced bilateral hindlimb lameness, the horse loses the contralateral hindlimb as a source of compensation and pushing off the lame limb now becomes more painful than braking on it. All previous hindlimb lameness scenarios had demonstrated decreased braking impulses. This finding is similar to previously analyzed but unpublished data from a group of clinical cases diagnosed with osteoarthritis of the distal tarsal joints (distal intertarsal and tarsometatarasl joints) where horses were bilaterally lame in the hindlimbs (Swaab, unpublished data).

In addition to patterns seen in the lame limbs, the current study also revealed some unique patterns among the sound, compensating, limbs. One pattern shows that the major source of compensation was the contralateral limb in the same half of the horse's body as the lame limb, i.e. the contralateral forelimb compensates for a forelimb lameness and the contralateral hindlimb compensates for a hindlimb lameness. We did note other sources of compensation, i.e. a forelimb compensating for a hindlimb lameness and vice versa, but this occurred less consistently than compensation in the same half of the horse's body (**Figure 2.3.1-2.6.1, Tables 2.3-2.6, and Figures 2.3.2-2.6.2**). Similar patterns of compensation were seen in other kinetic studies. One author showed significant compensation through increased vertical impulse in the contralateral forelimb during an individual forelimb lameness and in the contralateral hindlimb during an individual hindlimb lameness.[55-56] These studies demonstrated that the vertical impulse and peak vertical force also increased in the contralateral hindlimb, during the individual forelimb lameness, but with more severe lameness than used in the current study. Different patterns of compensation were found in a study performed at the walk, with compensation coming from multiple limbs.[57] The compensation was sometimes stronger in the contralateral limb, but all three sound limbs often provided some compensation. This difference in compensation patterns is likely due to the difference in gait as well as lameness severity, since different combinations and numbers of limbs were concurrently weight-bearing.

Compensation tended to occur through increases in vertical impulse and breaking impulse in the sound limbs of the current study (**Figures 2.3.1-2.8.1, Tables 2.3-2.8 and Figures 2.3.2-2.8.2).** It is important to note that in the vertical vector, at least, that compensation is most consistent via increases in the vertical impulse in the sound limbs, rather than via increased peak vertical force. This decreased peak vertical force and vertical impulse in the lame limb with compensation occurring only through increased vertical impulse in sound limbs, was also described in another study at a similar degree of lameness.[55] Our data showed two instances where compensation does occur through increased peak vertical force; however, this only occurred via increases in the hindlimbs **(Figures 2.4.1 and 2.6.1, Tables 2.4 and 2.6, and Figures 2.4.2 and 2.6.2).** The compensation pattern seen in hindlimbs only may be due to the carriage of more weight and more vertical forces in the forelimbs than the hindlimbs,[59] associated with the carriage of the head and neck. This unequal distribution may therefore allow for less uptake of additional forces by the forelimbs. It seems, instead, lameness compensation may occur through changes in the timing of the gait, particularly for the forelimbs. This is supported by the increased vertical impulse in the compensating limbs despite a tendency for the peak vertical force to decrease in those limbs. Impulse is a measure of force over time meaning time must be increasing if force is decreasing. Changes in gait timing were also noted in other studies which showed horses decrease the rate of vertical loading by the lame limbs.[55-56] Kinematic studies have found altered gait timing during lameness, particularly in the forelimbs.[37] A study looking at induced hindlimb lameness at the trot saw a statistically significant increase in breaking impulse in the contralateral sound hindlimb despite the lack of a significant decrease in breaking in the lame limb.[27]

Many of the alterations in forces involved a relatively small percent change from baseline. To determine the frequency and relative importance of these changes, we performed additional post hoc data analysis to determine the range(s) of percent change from baseline for the lame and sound limbs for each force (PVF, vertical impulse, braking impulse and propulsion impulse) **(Tables 2.9-2.12)**. This data demonstrates that apparently small percent changes from baseline in many of the forces (PVF, vertical impulse and propulsion impulse) **(Tables 2.9-2.10 and 2.12)** were associated with a visually appreciable grade 2 lameness. The threshold of how much a given kinetic force must change from baseline before a visual change in a horse's gait is achieved is unknown; however, the changes seen in this study appear more subtle than what has previously been reported. For example, the majority of our data points for PVF fell between 5-10% change from baseline for lame limbs. Previous researchers have shown anywhere from a 3.4%,[27] to a 7-9% decrease in peak vertical force,[55-56] to a 19.6% decrease with similar lameness severity.[54] Reported (or calculated) % change from baseline in vertical impulse a grade 2 lameness have been found to range from a 2.6% decrease in a sound supporting limb[27] to a 6-7% decrease in the lame hindlimb or forelimb[55-56] to 18.1% decrease in the lame limb.[54] This is much greater than our data which demonstrated that points for vertical impulse fell between 1 to 5% for the lame and sound limbs. The more extreme differences may be due to a difference in the grading of lameness as the study with the greatest magnitude of change from baseline was designed to correlate subjective and objective lameness grading.[54] However, based on our findings, it appears important to consider all changes from baseline. Even those with a small magnitude are potentially important and capable of inducing consistent gait alterations typical of lameness, especially in vertical forces and impulses. Breaking impulse, in contrast, seems more malleable as it undergoes greater magnitude of percent change from baseline.

By comparing percent change from baseline range that contained the greatest number of lame limbs to the range containing the greatest number of sound limbs, it becomes clear that some forces have a similar magnitude of change from baseline in both lame and sound limbs while others have a greater change in the lame limbs. For example, since PVF and propulsion impulse forces had greater ranges of change in the lame limb than the sound limb **(Tables 2.9 and 2.12)** indicating that horses are more likely to alter their gait the most in response to pain in the lame limb. They then distribute the remaining change to a lesser degree amongst the remaining sound limbs. However, forces in which the greatest number of sound and lame limbs fell into the same % change from baseline range (vertical impulse and braking impulse) (**Table 2.10 and 2.11**) indicate that these impulses are important to the horse's ability to compensate for lameness since the lame limb did not change more than the sound limb. This may be because these measures are both impulses, which can be altered not only by increasing/decreasing the magnitude of the force, but also by changing the time over which the force is distributed (making them more amenable to compensatory adjustments). This contrasts PVF which is a pure measure of magnitude without a time component. Other researchers haven't shown such a discrepancy between the magnitude of percent change between breaking impulse and forces such as PVF and vertical impulse.[54]

The current study has provided valuable information regarding lameness and compensation. The focus on multiple paired-limb lameness scenarios is unique, and describes lameness conditions frequently seen in clinical practice. Our study has also looked at multiple ground reaction forces and indicated which forces seem most important in forelimb and hindlimb lameness and which forces tend to be most consistently utilized in the horses' efforts to compensate for lameness. The information here will be valuable both to equine practitioners and for the design of future research in order to improve the accuracy of lameness diagnosis. Despite the advances provided, the study reported in this chapter had some limitations. The small number of horses is one limitation. The addition of more horses may make patterns in both lameness and compensation more clear, providing further insight into lameness and compensation during single and multiple limb lameness. The increase in the power of the study may make it easier to pursue further statistical analysis to detect significant changes. As described in the current thesis, many of our horses actually had one or more mild lameness, despite being considered sound. This has also been reported in other studies where kinetic asymmetries were detected despite a lack of any objective indication of lameness,[54] Horses in the current study were treated prior to use in order to minimize issues with pre-existing lameness. However, all horses still had grade 1 to 2 lameness present, so we attempted to use any naturally lame limbs for a starting point in our induced lameness (*e.g.* if the horse had a left forelimb lameness, the left forelimb would be used in the individual forelimb lameness and in the paired lameness). However, we still included these horses in the analyses for bilateral forelimb and hindlimb lameness, which may have affected those results. In addition, 3 to 4 horses had mild forelimb and hindlimb lameness, so occasionally the lame limbs were not included in all lameness scenarios.

Overall, this study provided new insight into the changes horses' experience in lame and sound limbs in a variety of induced lameness scenarios. We have defined which ground reaction forces tend to decrease in response to lameness and which increase as compensatory mechanisms to help horses minimize pain and potential injury to lame limbs. Differences among limbs were more striking than those among different lameness scenarios. Vertical forces and braking impulse tended to decrease in lame limbs (with concurrent increased propulsion impulse), and vertical impulse and braking impulse tended to increase in the opposite contralateral limb. Lame forelimbs seemed to more consistently decrease in the vertical forces, while lame hindlimbs seemed to more consistently decrease in the braking impulse. Definite patterns were seen in ground reaction forces in both lameness and compensation in this study. This information may help equine practitioners understand how horses alter their ground reaction forces in response to single and multiple limb lameness by determining primary versus compensatory change, and to clarify some of the complexities of multiple limb lameness.

FOOTNOTES

a) HPS Stainless Steel T-Bolt Clamps, HPS Performance Silicone Hoses, City of Industry, CA.

b) Forelimb shoes, Equiflex, Moab Utah

c) Dremel rotary tool, Robert Bosch Tool Corporation, Mount Prospect, IL 60056

d)"Montana Brand" and is a 5/32" titanium bit, Ronan MT

e) Zip tie, Cable Ties Plus Inc, Kingston, MA

f) Handi-Pack Part #83751 10-24 x 3/8" and 10-32 x 3/8" slotted hex head machine screw, zinc

g) Vetrap 3M™ Vetrap™ St Paul MN 55144-1000

h) Techovit, J-61Lb liquid, J-61pb powder, Jogensen Laboratories, Inc. Veterinary Specialties, Loveland, CO.

i) Force plate (900 mm x 900 mm, 8,000# capacity 6 component), Model # BP900900-8K-3200, manufactured by Advanced Mechanical Technology, Inc., Watertown, MA

j) Motion Imaging Corporation, motion analysis hardware, Simi Valley, CA

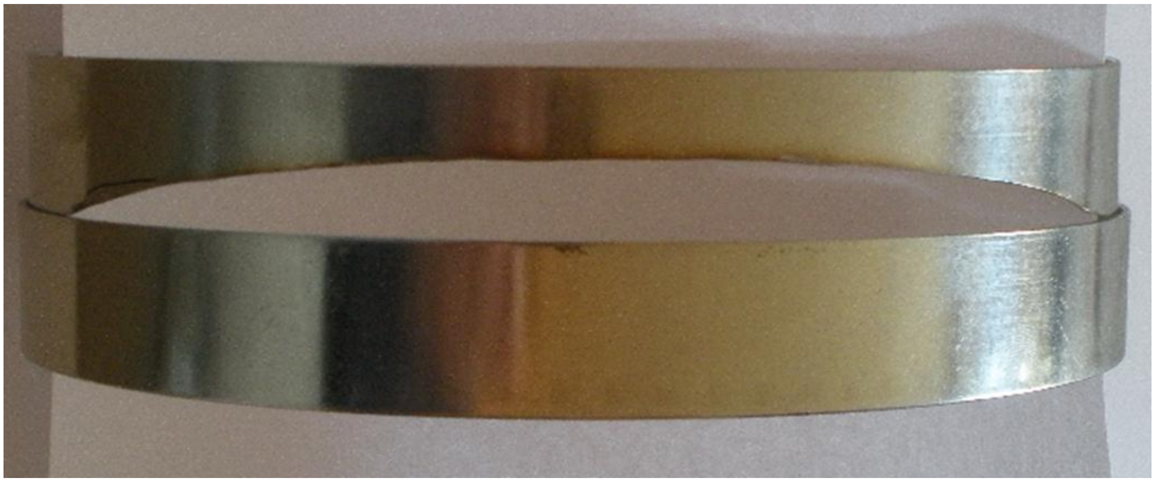
k) Polaris Wireless Timer; FarmTek Inc, Wylie, TX

l) Phenylbutazone, Schering-Plough Animal Health, Union, NJ.

m) DMAS 6 reporter, Motion Imaging Corp, Simi Valley California) SPSS, Pearson Higher Education, USA

n) SPSS statistical software Armonk, New York 10504

Figure 2.1 Plantar aspect of clamp following alterations.



The plantar portion of the top clamp has been reduced in width by ~1/2 to avoid contact with heel bulbs/coronary band (See Figure 2.2b). The segment between approximately where the heels contact the ground has been removed in a semi-circular pattern using a dremel tool, and the cut edge has been smoothed. The clamp on the bottom is unaltered and included for comparison.

Figure 2.2. Images of hoof clamps in place

a. Dorsal view of clamp in place, note medial, lateral and dorsal screws through zip ties that pass around clamp to prevent proximal displacement when clamp is tightened.
b. Plantar view of clamp in place, note decreased diameter of plantar portion of clamp, beginning at approximately the point where the heel meets the ground/shoe. Note position of plantar clamp almost contacting shoe.
c. Drilling the holes for screw placement to keep the clamp in place. The dorsal hole has already been drilled, lateral hole being drilled. White tape around drill bit serving to stop drilling before reaching sensitive laminae.
d. Tightening the clamps to induce lameness for study, using commercial socket wrench.
e. Protective wraps over clamps, nuts to be tightened during data collection each day left slightly uncovered for access.
f. Horse with all 4 clamps in place, as performed for each day of data collection.

Table 2.1. Limbs with lameness induced, listed by horse

Horse	Individual Forelimb Lameness	Ipsilateral Paired Lameness	Individual Hindlimb Lameness	Contralateral Paired Lameness
1	RF	RFRH	LH	RFLH
2	RF	RFRH	LH	RFLH
3	RF	RFRH	LH	RFLH
4	LF	LFLH	RH	LFRH
5	LF	LFLH	RH	LFRH
6	RF	RFRH	RH	LFRH
7	LF	LFLH	RH	LFRH
8	LF	LFLH	LH	RFLH

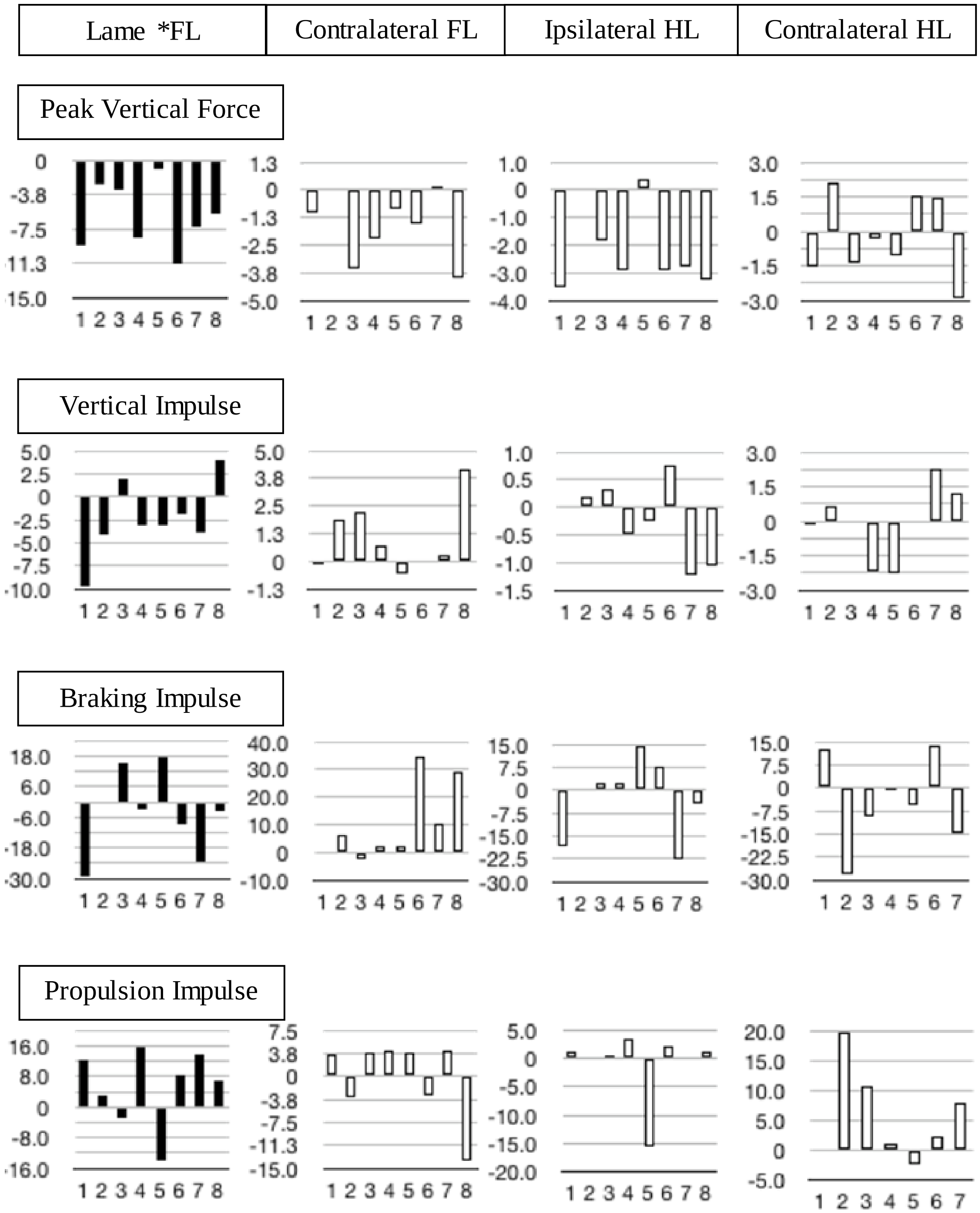
The pattern of lameness induction for individual forelimb, hindlimb and paired ipsilateral and contralateral forelimb/hindlimb lameness is listed for each horse. Equal numbers of each individual and limb combination were induced. In addition, all 8 horses had both bilateral forelimb and bilateral hindlimb lameness induced (not included in this table).

Table 2.2. Order of lameness induction for horses

Data Collection Timepoint (Day)	Baseline	First Induced Lameness	Second Induced Lameness
1	Baseline (no clamps tightened)	Individual Forelimb Clamp Tightened	Forelimb and Ipsilateral Hindlimb Clamps Tightened
2 (≥ 2 days after timepoint 1)	Baseline (no clamps tightened)	Individual Hindlimb Clamp Tightened	Forelimb and Contralateral Hindlimb Clamps Tightened
3 (≥ 4 days after timepoint 1)	Baseline (no clamps tightened)	Bilateral Forelimbs Clamps Tightened	N/A
4 (≥ 6 days after timepoint 1)	Baseline (no clamps tightened)	Bilateral Hindlimbs Clamps Tightened	N/A.

Lameness was induced in the limb(s) listed as having the clamp(s) tightened at each data collection point. (See note in text about deviation from this pattern for horse number 2)

Figure 2.3.1. Percent change from baseline with individual forelimb lameness



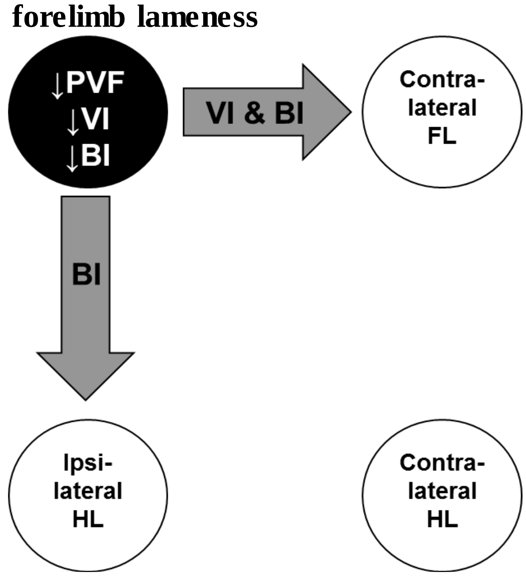
Limb with clamps tightened (lameness induced) in black bars. Limbs without clamps tightened (sound limbs) in white bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. FL=forelimb, HL=Hindlimb. Sound limbs are described in relation to lame limb(s).

Table 2.3. Change from baseline with individual forelimb lameness

Change from Baseline (Mean ± SD %)	Lame *FL	Contralateral FL	Ipsilateral HL	Contralateral HL
Peak Vertical Force	8 of 8 ↓ (-6.1 ± 3.6)	6 of 7 ↓ (-1.9 ± 1.5)	6 of 7 ↓ (-2.4 ± 1.3)	5 of 8 ↓ (-0.3 ± 1.8)
Vertical Impulse	6 of 8 ↓ (-2.5 ± 4.2)	5 of 7 ↑ (1.2 ± 1.7)	4 of 7 ↓ (-0.2 ± 0.7)	4 of 7 ↓ (-0.1± 1.7)
Braking Impulse	5 of 8 ↓ (-4.3 ± 16.4)	7 of 8 ↑ (10.5 ± 13.8)	4 of 7 ↑ (-2.6 ± 13.4)	5 of 7 ↓ (-4.5 ± 14.9)
Propulsion Impulse	6 of 8 ↑ (5.4 ± 9.9)	5 of 8 ↑ (-0.1 ± 6.4)	5 of 7 ↑ (-1.0 ± 6.6)	5 of 7 ↑ (5.6 ± 7.8)

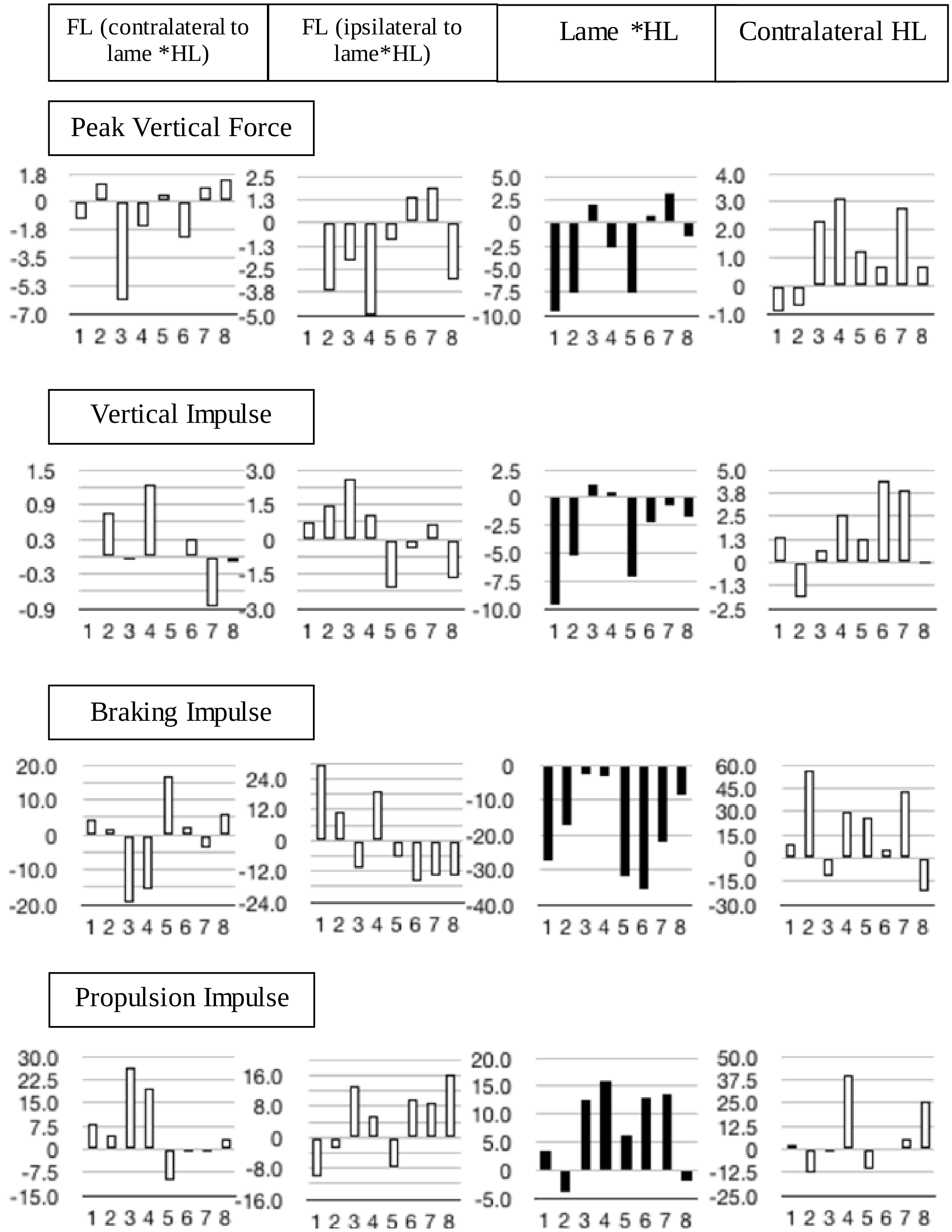
Lame limb (clamp tightened) indicated via *. Contralateral and ipsilateral designations are in relation to the lame limb. FL=forelimb, HL=hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.3.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 7).

Figure 2.3.2 Individual forelimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs, and are labeled according to their relationship to the lame limb. Gray arrows indicate the most likely transfer of forces in a compensatory effort. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL=forelimb, HL=hindlimb.

Figure 2.4.1. Percent change from baseline with individual hindlimb lameness



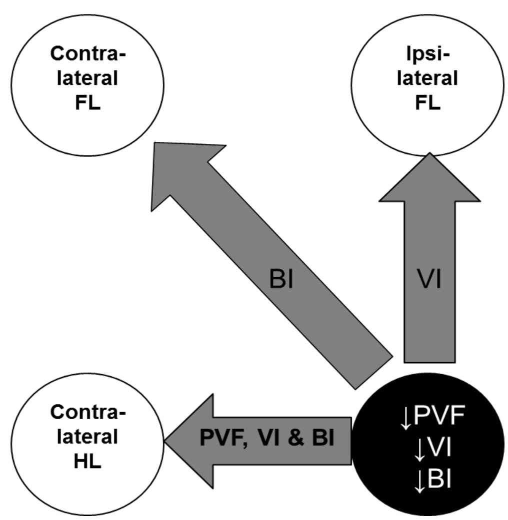
Limb with clamps tightened (lameness induced) in white bars and designated with an *. Limbs without clamps tightened in black bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. FL=forelimb, HL=hindlimb.

Table 2.4. Change from baseline with individual hindlimb lameness

Change from Baseline (Mean ± SD %)	Contralateral FL	Ipsilateral FL	*Lame HL	Contralateral HL
Peak Vertical Force	4 of 8 ~ (-0.9 ± 2.5)	5 of 8 ↓ (-1.4 ± 2.4)	5 of 8 ↓ (-2.8 ± 4.9)	6 of 8 ↑ (1.2 ± 1.5)
Vertical Impulse	3 of 6 ~ (0.2 ± 0.7)	5 of 8 ↑ (0.3 ± 1.6)	6 of 8 ↓ (-3.1 ± 3.9)	6 of 8 ↑ (1.5 ± 2.1)
Braking Impulse	5 of 8 ↑ (-0.8 ± 11.8)	5 of 8↓ (-0.1 ± 17.5)	8 of 8↓ (-18.6 ± 12.8)	6 of 8 ↑ (17.1 ± 26.7)
Propulsion Impulse	5 of 8 ↑ (6.4 ± 11.8)	5 of 8 ↑ (4.1 ± 9.8)	6 of 8 ↑ (7.4 ± 7.6)	4 of 8 ~ (6.2 ± 18.1)

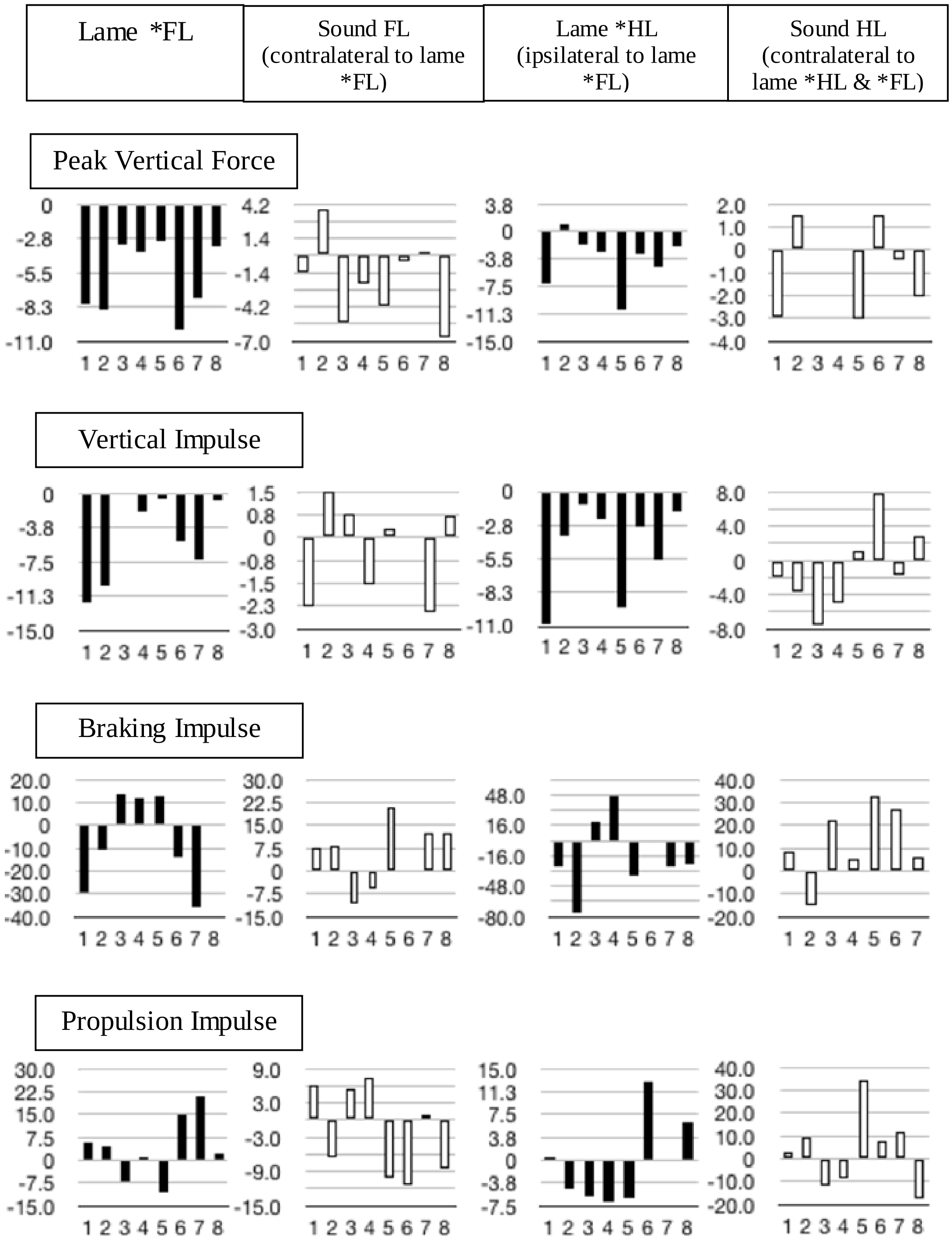
Lame limb (clamp tightened) indicated via *. Contralateral and ipsilateral designations are in relation to the lame limbs. FL=forelimb, HL=hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.4.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 6).

Figure 2.4.2. Individual hindlimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs, and are labeled according to their relationship to the lame limb. Gray arrows indicate the most likely transfer of forces in a compensatory effort. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL=forelimb, HL=hindlimb.

Figure 2.5.1. Percent change from baseline with ipsilaterally paired forelimb/hindlimb lameness



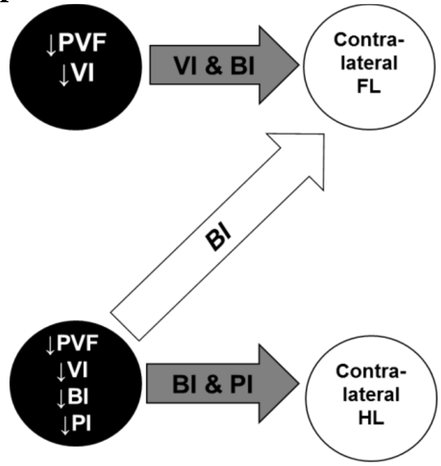
Limbs with clamps tightened (lameness induced) in white bars and designated with an *. Limbs without clamps tightened in black bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. FL=forelimb, HL=hindlimb.

Table 2.5. Change from baseline with ipsilaterally paired forelimb/hindlimb lameness

Change from Baseline (Mean ± SD %)	*Lame FL	Contralateral FL	*Lame HL (Ipsilateral to clamped FL)	Contralateral HL (Contralateral to lame FL)
Peak Vertical Force	8 of 8 ↓ (-5.9 ± 2.8)	6 of 8 ↓ (-2.0 ± 3.4)	7 of 8 ↓ (-3.9 ± 3.6)	4 of 7 ↓ (-0.8 ± 2.0)
Vertical Impulse	8 of 8 ↓ (-4.8 ± 4.6)	4 of 7 ↑ (-0.4 ± 1.6)	8 of 8 ↓ (-4.7 ± 3.7)	5 of 8 ↓ (-1.0 ± 4.9)
Braking Impulse	4 of 8 ~ (-6.4 ± 19.4)	5 of 7 ↑ (6.5 ± 11.0)	6 of 8 ↓ (-15.7 ± 37.1)	6 of 7 ↑ (12.4 ± 16.3)
Propulsion Impulse	6 of 8 ↑ (4.0 ± 10.5)	4 of 8 ~ (-2.1 ± 7.9)	4 of 7 ↓ (-0.6 ± 7.6)	5 of 8 ↑ (3.6 ± 16.5)

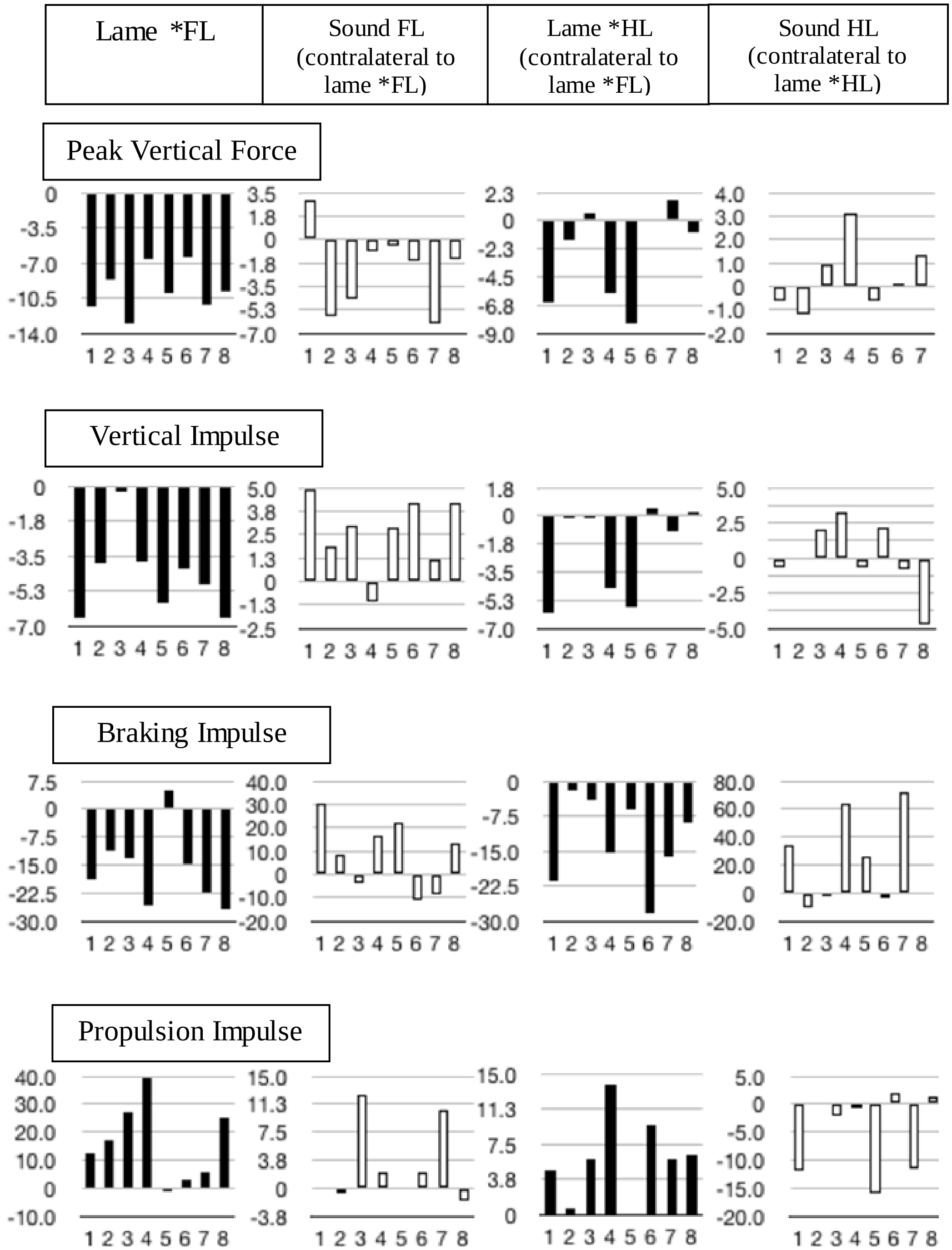
Lame limbs (clamp tightened) indicated via *. Contralateral designations are in relation to the lame limbs. FL=forelimb, HL=hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.5.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 7).

Figure 2.5.2. Ipsilaterally paired forelimb/hindlimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs, and are labeled according to their relationship to the lame limbs. Gray arrows indicate the most likely transfer of forces in a compensatory effort. White arrow indicates possible, but presumed less likely transfer of forces in a compensatory effort, based on individual forelimb and hindlimb lameness and compensation. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL=forelimb, HL=hindlimb.

Figure 2.6.1. Percent change from baseline with contralaterally paired forelimb/hindlimb lameness



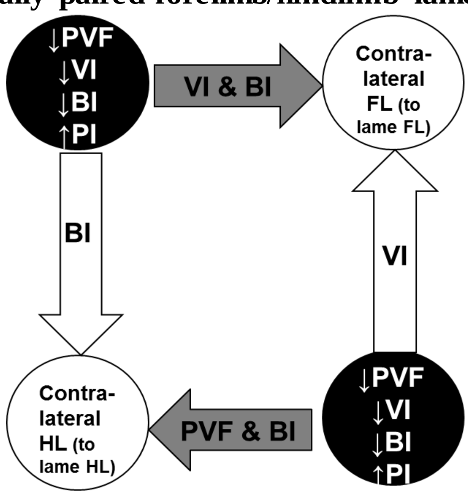
Limbs with clamps tightened (lameness induced) in white bars and designated with an *. Limbs without clamps tightened in black bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. FL=forelimb, HL=hindlimb.

Table 2.6. Change from baseline with contralaterally paired forelimb/hindlimb lameness

Change from Baseline (Mean ± SD %)	*Lame FL	Contralateral FL	*Lame HL (Contralateral to clamped FL)	Contralateral HL (Ipsilateral to clamped FL)
Peak Vertical Force	8 of 8 ↓ (-9.6 ± 2.3)	7 of 8 ↓ (-2.2 ± 3.0)	5 of 8 ↓ (-2.6 ± 3.7)	4 of 7 ↑ (0.4 ± 1.5)
Vertical Impulse	8 of 8 ↓ (-4.5 ± 2.1)	7 of 8 ↑ (2.6 ±2.0)	6 of 8 ↓ (-2.1 ± 2.8)	5 of 8 ↓ (0.1 ± 2.5)
Braking Impulse	7 of 8 ↓ (-16.1 ± 10.4)	5 of 8 ↑ (8.4 ± 15.0)	8 of 8 ↓ (-12.8 ± 9.2)	5 of 8 ↑ (22.6 ± 32.1)
Propulsion Impulse	7 of 8 ↑ (16.0 ± 13.9)	5 of 7 ↑ (3.6 ± 5.6)	7 of 7 ↑ (6.7 ± 4.1)	5 of 7 ↓ (-5.5 ± 7.3)

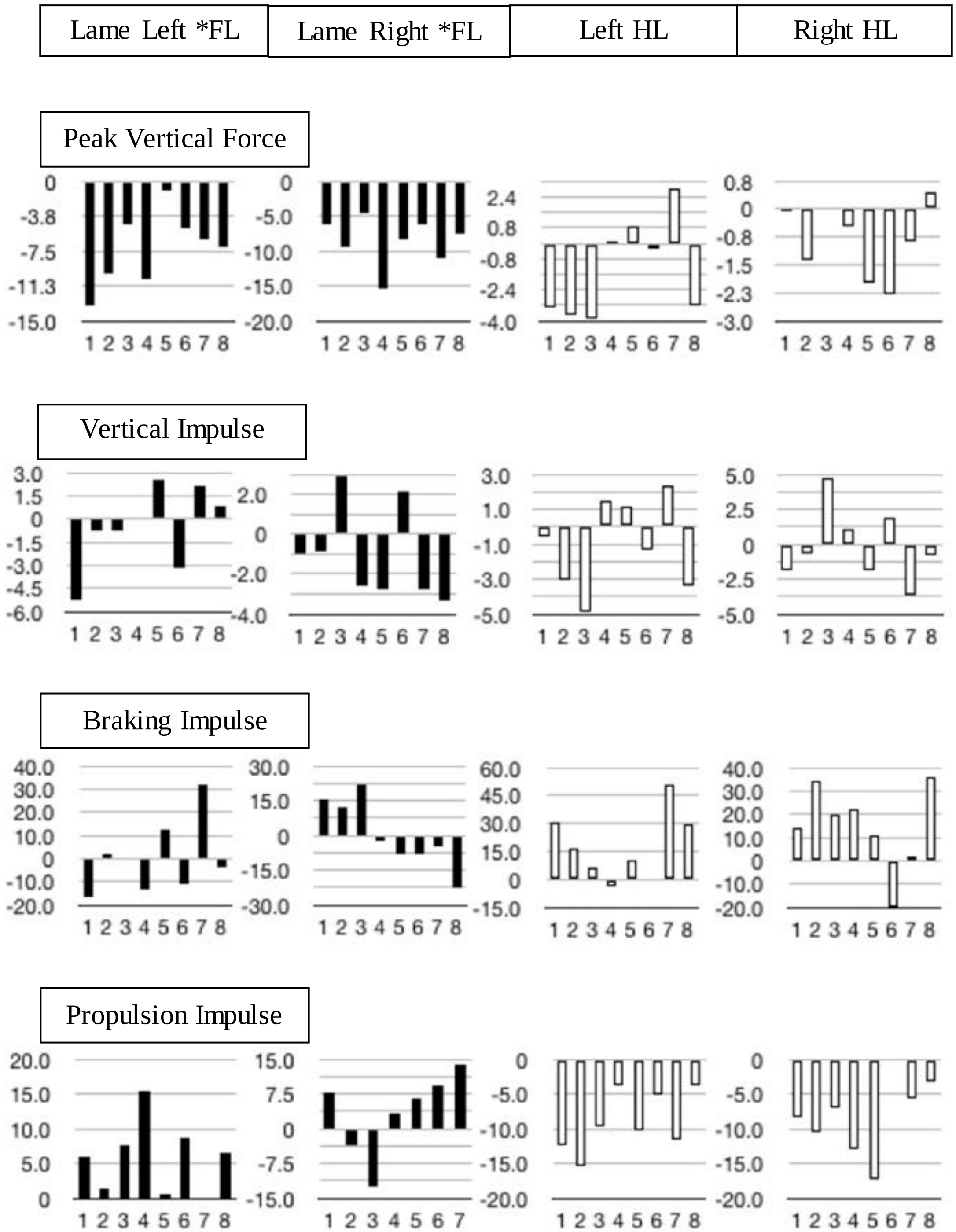
Lame limbs (clamp tightened) indicated via *. Contralateral designations are in relation to the lame limbs. FL=forelimb, HL=hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.6.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 7).

Figure 2.6.2. Contralaterally paired forelimb/hindlimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs, and are labeled according to their relationship to the lame limbs. Gray arrows indicate the most likely transfer of forces in a compensatory effort. White arrows indicate possible, but presumed less likely transfer of forces in a compensatory effort, based on individual forelimb and hindlimb lameness and compensation patterns. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL=forelimb, HL=hindlimb.

Figure 2.7.1 Percent change from baseline with bilateral forelimb lameness.



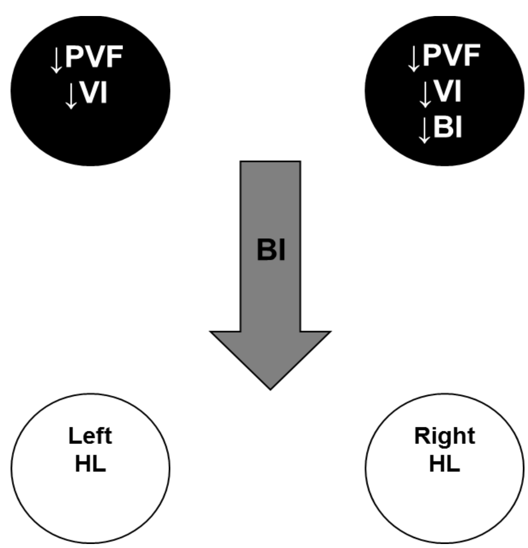
Limbs with clamps tightened (lameness induced) in white bars and designated with an *. Limbs without clamps tightened in black bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. LF=left forelimb, RF=right forelimb, LH=left hindlimb, RH=right hindlimb.

Table 2.7. Change from baseline with bilateral forelimb lameness

Change from Baseline (Mean ± SD %)	*Lame LF	*Lame RF	LH	RH
Peak Vertical Force	8 of 8 ↓ (-7.2 ± 3.9)	8 of 8 ↓ (-8.6 ± 3.4)	5 of 8 ↓ (-1.3 ± 2.5)	6 of 7 ↓ (-0.9 ± 1.0)
Vertical Impulse	4 of 7 ↓ (-0.7 ± 2.8)	6 of 8 ↓ (-1.0 ± 2.4)	5 of 8 ↓ (-1.0 ± 2.6)	5 of 8 ↓ (-0.1 ± 2.6)
Braking Impulse	4 of 8 ~ (0.3 ± 16.0)	5 of 8 ↓ (0.4 ± 14.8)	6 of 8 ↑ (17.6 ± 18.6)	7 of 8 ↑ (14.9 ± 18.0)
Propulsion Impulse	7 of 7 ↑ (6.6 ± 5.0)	5 of 7 ↑ (3.5 ± 9.0)	8 of 8 ↓ (-9.0 ± 4.3)	7 of 7 ↓ (-9.2 ± 4.7)

Lame limbs (clamp tightened) indicated via *. LF=left forelimb, RF=right forelimb, LH=left hindlimb, RH=right hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.7.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 7).

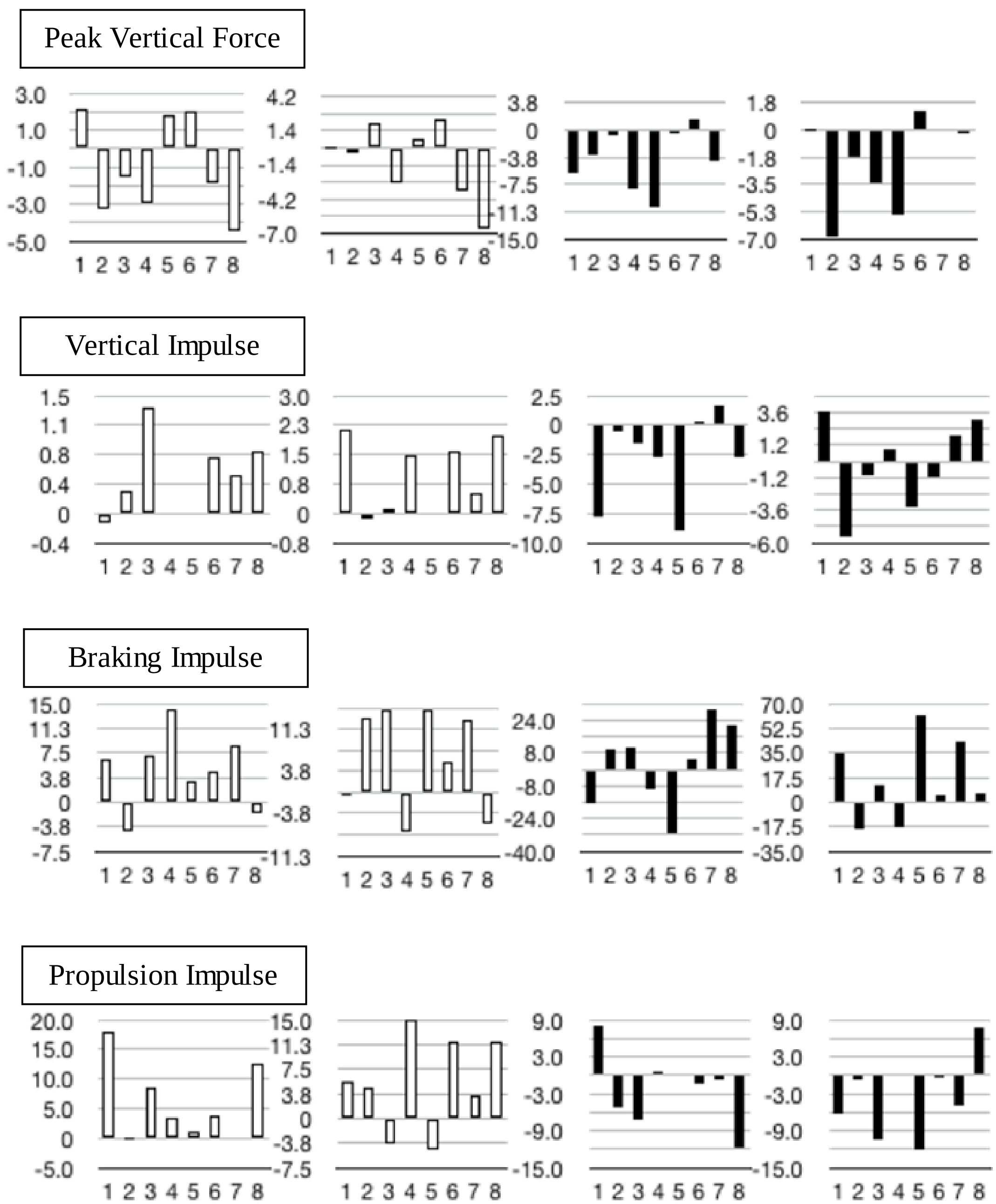
Figure 2.7.2. Bilateral forelimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs. Gray arrow indicates the most likely transfer of forces in a compensatory effort. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL= forelimb, HL=hindlimb.

Figure 2.8.1. Percent change from baseline with bilateral hindlimb lameness

Left FL	Right FL	Lame Left *HL	Lame Right *HL



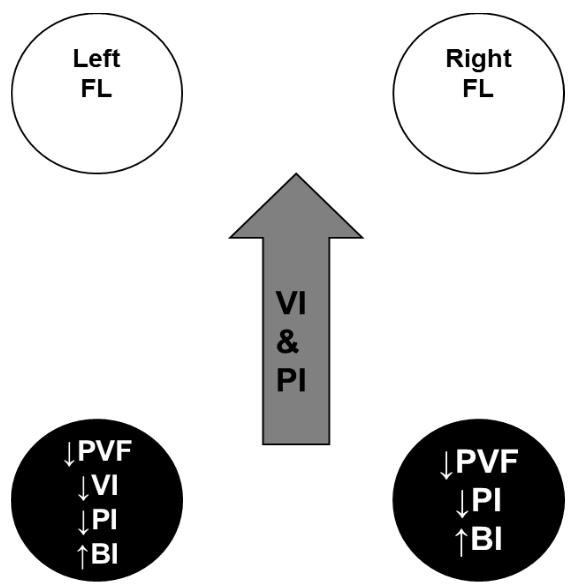
Limbs with clamps tightened (lameness induced) in white bars and designated with an *. Limbs without clamps tightened in black bars. % change from baseline is along the y-axis and horse number (1-8) is along the x-axis. LF=left forelimb, RF=right forelimb, LH=left hindlimb, RH=right hindlimb.

Table 2.8. Change from baseline with bilateral hindlimb lameness

Change from Baseline (Mean ± SD %)	LF	RF	*Lame LH	*Lame RH
Peak Vertical Force	5 of 8 ↓ (-1.0 ± 2.6)	5 of 8 ↓ (-1.1 ± 3.1)	7 of 8 ↓ (-4.0 ± 4.1)	7 of 8 ↓ (-2.0 ± 2.9)
Vertical Impulse	5 of 6 ↑ (0.6 ± 0.5)	6 of 7 ↑ (1.1 ± 0.9)	6 of 8 ↓ (-2.8 ± 3.8)	4 of 8 ~ (-0.2 ± 3.2)
Braking Impulse	6 of 8 ↑ (4.8 ± 5.9)	5 of 8 ↑ (6.0 ± 9.3)	5 of 8 ↑ (2.4 ± 20.2)	6 of 8 ↑ (15.9 ± 28.8)
Propulsion Impulse	7 of 8 ↑ (6.0 ± 6.6)	6 of 8 ↑ (5.4 ± 7.2)	5 of 7 ↓ (-2.5 ± 6.3)	6 of 7 ↓ (-3.8 ± 6.7)

Lame limbs (clamp tightened) indicated via *. LF=left forelimb, RF=right forelimb, LH=left hindlimb, RH=right hindlimb. Upper values indicate proportion of horses that decreased (↓) or increased (↑) from baseline. Values in parentheses show the mean % change from baseline ± SD (See Figure 2.8.1). Eight horses were examined, but outliers were removed as described in the materials and methods (sometimes decreasing the total number of horses to 6 or 7).

Figure 2.8.2. Bilateral hindlimb lameness



Black circles indicate lame limbs. White circles indicate sound limbs. Gray arrow indicates the most likely transfer of forces in a compensatory effort. PVF=peak vertical force, VI=vertical impulse, BI=braking impulse, PI=propulsion impulse, FL=forelimb, HL=hindlimb.

Table 2.9. Data grouped by magnitude of percent change from baseline: Peak Vertical Force

Magnitude of % change from baseline	Average ± SD # of observations (among all lame limbs)	Average ± SD # of observations (among all sound limbs)
<1%	1.0 ± 1.2	2.3 ± 1.2
1-5%	2.7 ± 1.5	**4.9 ± 1.4**
5-10%	**3.1 ± 1.2**	0.4 ± 0.8
>10%	1.2 ± 1.2	0.0 ± 0.0

The data was stratified into incremental % change from baseline ranges. Then the average (± standard deviation) number of data points falling into each data range (out of 8 observations for each limb) was averaged across the various lameness scenarios for all of the lame limbs separately from all of the sound limbs. The bolded value indicates the range containing the most data points.

Table 2.10. Data grouped by magnitude of percent change from baseline: Vertical Impulse

Magnitude of % change from baseline	Average ± SD # of observations (among all lame limbs)	Average ± SD # of observations (among all sound limbs)
<1%	2.0 ± 1.5	2.9 ± 1.7
1-5%	**3.9 ± 2.0**	**4.3 ± 2.1**
5-10%	1.7 ± 0.9	0.2 ± 0.8
>10%	0.3 ± 0.7	0.0 ± 0.0

The data was stratified into incremental % change from baseline ranges. Then the average (± standard deviation) number of data points falling into each data range (out of 8 observations for each limb) was averaged across the various lameness scenarios for all of the lame limbs separately from all of the sound limbs. The bolded value indicates the range containing the most data points.

Table 2.11. Data grouped by magnitude of percent change from baseline: Braking Impulse

Magnitude of % change from baseline	Average ± SD # of observations (among all lame limbs)	Average ± SD # of observations (among all sound limbs)
0-5%	1.5 ± 1.0	1.7 ± 1.6
5-10%	1.0 ± 0.9	1.6 ± 1.1
10-20%	**2.6 ± 1.5**	**2.6 ± 1.6**
20-30%	1.8 ± 1.2	1.0 ± 0.8
30-40%	0.7 ± 0.7	0.5 ± 0.7
>40%	0.4 ± 0.8	0.4 ± 0.7

The data was stratified into incremental % change from baseline ranges. Then the average (± standard deviation) number of data points falling into each data range (out of 8 observations for each limb) was averaged across the various lameness scenarios for all of the lame limbs separately from all of the sound limbs. The bolded value indicates the range containing the most data points.

Table 2.12. Data grouped by magnitude of percent change from baseline: Propulsion Impulse

Magnitude of % change from baseline	Average ± SD # of observations (lame limbs)	Average ± SD # of observations (sound limbs)
0-5% change	2.4 ± 0.5	**3.5 ± 2.0**
5-10% change	**2.6 ± 1.2**	1.6 ± 1.6
10-20% change	2.0 ± 1.2	2.3 ± 0.9
>20% change	0.4 ± 1.0	0.3 ± 0.6

The data was stratified into incremental % change from baseline ranges. Then the average (± standard deviation) number of data points falling into each data range (out of 8 observations for each limb) was averaged across the various lameness scenarios for all of the lame limbs separately from all of the sound limbs. The bolded value indicates the range containing the most data points.

Chapter 3

Future Directions

Kinematic Data

Now that the kinetic data has been explored among the 6 different lameness scenarios in the 8 horses studied here, the opportunity exists to learn even more from these horses through the use of kinematic or motion analysis. We have gained a deeper understanding of how horses adjust/distribute the forces between the hoof and the ground during a multitude of individual and paired lameness. Now through the use of kinematic data, we can determine how they adjust the movement of their bodies through space. The identification of changes in limb carriage, joint angles, head, neck, trunk, body and croup movement along with calculations to determine work performed across different joints will also be very helpful to the understanding of lameness and compensation. The kinematic findings may be quite helpful to the understanding of how horses are able to accomplish the alteration of kinetic forces. Kinematic alterations may also help better extrapolate our findings to equine practitioners in the diagnosis of lameness, since the only multiple limb lameness that was found in the recent literature explored bilateral forelimb lameness.[38] As seen in kinetic forces, kinematic measures are expected to change based on the number and combination of limbs that are lame. Therefore, this data should be able to mimic lameness commonly seen in equine practice, and help explain primary and compensatory trends. Because kinematic data was collected at the same time as kinetic, this goal is easy to accomplish with only data analysis required. No additional experimentation would be required.

Number of Horses

Increasing the number of horses used in the study would help to add power to the study. The addition of more horses may decrease the relatively high standard deviations seen when the average ± standard deviation was calculated for the % change from baseline values among horses. However, due to the individuality of many horses, and variability inherent in gait analysis, the inclusion of additional horses may not alter the standard deviation significantly. The inclusion of additional subjects would also improve the chances of detecting true change if analytical statistics were performed. Because this method of lameness induction is immediately reversible and causes no long-term damage to the horse or persistent lameness, the inclusion of more subjects is unlikely to be prohibitive. For example, horses may be only useful for 1 or 2 of the 6 lameness conditions described in the current thesis due to underlying naturally occurring lameness, but if more horses could be included, only the limb(s) with naturally occurring lameness could be used for induced lameness. The lameness could then be adjusted upwards (*e.g.* a naturally grade 1 out of 5 lameness could be increased to 2 to 4 as dictated by the researcher).

Data at the Walk

Following the collection of data at the trot, during the current study, additional data was collected at the walk until the predetermined time expired. 5 repetitions were collected for most lameness scenarios, and at least 3 were available for all. The analysis of this data may provide additional insight into the gait alterations resulting from lameness and compensation. This data would be more comparable to Merken's studies on compensation, as this study was also performed at the walk.[33, 57]

Objective Lameness Correlation to Subjective Measures

Using the current data, it would be interesting to compare a group of blinded observers' subjective lameness scores (based on video recordings made just prior to data collection) to the magnitude of % change from baseline to see if any correlations exist between the two measures. In addition, video recordings of the horses' gaits were made prior to lameness induction and following loosening of all clamps following lameness induction. Subjective analysis of pre-, intra-, and post-lameness could help determine the accuracy of lameness induction. This would also confirm the return to baseline after data collection (following clamp loosening) and after a period of $\geq$ 48 hours rest (given to the hoses between each set of data collections); indicating the clamp method of lameness induction actually created a reliable and reversible lameness. This type of analysis could also indicate whether or not similar subjective grades of lameness correlate to similar objective measurements or vice versa.

Observation of Multiple Grades of Lameness

An extension to the idea of comparing objective and subjective measurements of lameness would be to create a variety of lameness grades using the hoof clamp method and obtaining both objective (kinetic and kinematic) and subjective (clinician grading according to the AAEP lameness scale) data for study and comparison. This would allow us to see how both lameness and compensation trends strengthen and/or change with increasing lameness. As discussed previously, researchers have found unique patterns of both lameness and compensation, and magnitude of change from baseline at different grades of lameness than was observed during the current thesis project.[33, 54-57] Further study using the hoof clamp technique would allow us to corroborate or dispute these findings. These studies, however, were performed using single limb lameness, so the use of the hoof clamp technique to induce a variety of grades of lameness in multiple limbs at the same time would add unique evidence to the literature. Additional comparison to naturally occurring lameness would allow determination at the effectiveness of the hoof clamp technique at replicating natural lameness. The use of the hoof clamp technique at a more severe lameness would also help determine the degree of reversibility, and determine if it changes following induction of a more severe lameness.

Additional Lame Limbs

Similarly to how induced multiple limb lameness have not previously been reported in the literature, except for one study with bilateral forelimb lameness,[38] lameness induced in 3 or 4 limbs is also absent from previous reporting. It is not impossible, however to see naturally occurring lameness in the horse that affects any number of limbs, up to and including all 4. It would be interesting to see if the degrees and sources (*e.g.* which force(s) increased in a compensatory manner) of compensation changed when the forelimb versus the hindlimb was the only remaining sound limb in a 3 limb lameness. Based on the current thesis project, it might be expected that the sound forelimb is more likely to compensate via increased vertical impulse, and the sound hindlimb more likely to compensate via increased braking impulse. Based on previous experience, clamp tightening order may be optimized if the bilateral forelimb/hindlimb lameness were induced first and a symmetrical gait achieved before the remaining third limb had lameness induced. Based on the reversal of patterns seen in forces during the bilateral hindlimb lameness, it would be interesting to see how horses coped with lameness in all limbs. This may provide insight into subtle gait abnormalities or performance failure among horses that fail to demonstrate an overt lameness. Similarly to how a symmetrical gait can be observed in a horse with a bilateral forelimb or hindlimb lameness, it is likely that horses with lameness in all four limbs have developed methods to compensate thereby making the individual lameness less visible, but no less real and detrimental to the horse.

Additional Lameness Induction Techniques

As described previously, there are multiple methods to induce lameness in horses. It would be interesting to directly compare these methods in the same study. Different types of lameness that naturally occur together (*e.g.* hock arthritis and caudal heel pain) could be separately and/or concurrently mimicked via induced lameness for comparison. We could develop a better understanding of how lameness at different levels of the limb affects horses differently. For example what ground reaction forces are most affected in a lameness originating from the hoof versus a joint versus a more muscular area? We could also detect changes in compensation from other limbs and see if the source of the primary lameness affects compensation in addition to lameness. The addition of kinematic data to this type of study would also help provide the equine practitioner with helpful clues about how to best observe gait changes indicative of lameness and compensation.

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