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Clinical objective assessment of diagnostic anaesthesia and investigation of compensatory lameness in the horse

Sylvia Maliye

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School of Veterinary Medicine

College of Medical, Veterinary and Life Sciences

University of Glasgow

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Abstract

Objectives: Objective assessment of lameness in a clinical setting has been limited by the need for complex equipment. The introduction of a commercially available inertial sensor-based system of lameness diagnosis has made objective lameness assessment clinically available. The objective of the first part of this study was to validate the use of an inertial sensor-based system of lameness diagnosis to objectively identify a positive response to diagnostic anaesthesia of the equine foot. The second part of the study objectively examined clinical compensatory lameness, investigating the relationship between primary and compensatory lameness.

Study design: A retrospective study of data obtained from horses that underwent clinical diagnostic anaesthesia while instrumented with an inertial sensor-based system of lameness diagnosis between August 2011 and October 2014 was performed.

Method: Horses were grouped as positive or negative (referring to the change to lameness) depending on the response to diagnostic anaesthesia. Those horses categorized as positive were further grouped into those with forelimb lameness only, hindlimb lameness only, ipsilateral limb lameness, or contralateral limb lameness. Kinematic parameters of head and pelvic movement asymmetry were measured and the change in the parameters was calculated. The effect of diagnostic anaesthesia was determined using the Mann-Whitney rank sum test.

Results:

Assessment of local anaesthesia of the foot in horses with forelimb lameness: A positive response to diagnostic anaesthesia resulted in a significant improvement to the symmetry of movement in the affected limb. ROC curve analysis showed that the change in head movement asymmetry (vector sum) is an excellent diagnostic test (AUC=1.0).

Forelimb compensatory lameness study: Improvement in forelimb lameness resulted in a significant decrease in pelvic movement asymmetry associated with the contralateral hindlimb ($p<0.05$). This was associated with improvement in push-off from the contralateral limb ($p<0.01$).

Hindlimb compensatory lameness study: Improvement in hindlimb lameness resulted in a significant decrease in head movement asymmetry associated with the ipsilateral forelimb ($p<0.05$).

Conclusions: It is possible to classify changes that occur and assess the response following a diagnostic anaesthesia procedure using an inertial sensor-based system of lameness diagnosis. Significant change to hindlimb movement following diagnostic anaesthesia of the forelimb in horses with forelimb lameness was demonstrated. In addition, significant change to forelimb movement following diagnostic anaesthesia of the hindlimb of horses with hindlimb lameness was demonstrated. In summary, this study supports the use of the inertial sensor-based system of lameness diagnosis in objective assessment of lameness in the horse, and provides significant evidence to support the “law of sides” in horses with naturally occurring lameness. Furthermore, the objective assessment of lameness is possible in a range of clinical settings.

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Author's declaration

I declare that, except where explicit reference is made to the work of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution. The entire work is an original study. Where data has been published in a scientific journal, it has been clearly stated at the beginning of the chapter.

All data were collected with client informed consent. The studies undertaken as part of this thesis were granted approval by the Ethics and Welfare Committee of the University of Glasgow.

Signature:

Printed name:

Abbreviations

AAEP- American Association of Equine Practitioners

ASNB- Abaxial sesamoid (nerve block)

DDFT- Deep digital flexor tendon

DFTS- Digital flexor tendon sheath

DIPJ- Distal interphalangeal joint

FC- Forelimb lameness with contralateral hindlimb lameness

FI- Forelimb lameness with ipsilateral hindlimb lameness

FL- Forelimb (LF or RF; left forelimb or right forelimb)

FO- Forelimb lameness only

HC- Hindlimb lameness with contralateral forelimb lameness

HDMax- The mean difference in millimetres in maximum head height after the stance phases of the right and left forelimb

HDMin- The mean difference in millimetres in minimum head height during the stance phases of the right and left forelimb

HI- Hindlimb lameness with ipsilateral forelimb lameness

HL- Hindlimb (LH or RH; left hindlimb or right hindlimb)

HO- Hindlimb lameness only

HMA- Head movement asymmetry, a general measure of vertical head movement asymmetry

IQR- Interquartile range; the difference between upper (75^{th} percentile) and lower quartiles (25^{th} percentile)

MCPJ- Metacarpophalangeal joint

OA- Osteoarthritis

PDNB- Palmar digital (nerve block)

PDMax- The mean difference in millimetres in maximum pelvic height after the stance phases of the right and left hindlimb

PDMin- The mean difference in millimetres in minimum pelvic height during the stance phases of the right and left hindlimb

PMA- Pelvic movement asymmetry, a general measure of vertical pelvic movement asymmetry

SDFT- Superficial digital flexor tendon

SDSL- Straight distal sesamoidean ligament

VS- Vector sum, $\sqrt{((HDMax)^2+(HDMin)^2)}$

CHAPTER 1:

Lameness and objective assessment of lameness in the horse

1.1 Assessment of lameness, repeatability, scales used

Lameness examinations originally were entirely reliant upon subjective evaluation of the horse's gait. The introduction of the American Association of Equine Practitioners (AAEP) lameness grading scale has given clinicians the ability to standardise grading of severity to some degree. However studies have demonstrated that the repeatability of subjective evaluation of lameness in horses and agreement between clinicians can be poor. Keegan *et al.* (2001) carried out a study which concluded that even after a full lameness examination, experienced clinicians still only agreed upon whether a limb was lame or not 72.9% of the time on average, with agreement being slightly higher for forelimb lameness than for hindlimb lameness. The AAEP scale defines a grade 1 lameness as a lameness that is difficult to observe and not consistently apparent, regardless of circumstances. Grade 2 lameness is defined as being difficult to observe at a walk or when trotting in a straight line, but is consistently apparent under certain circumstances (e.g. when lunging). Grade 3 lameness is described as being consistently observable at a trot under all circumstances. An AAEP lameness score less than 1.5 resulted in agreement only 61.9% of the time. Inter-observer reliability has been shown to be poor in some cases, particularly for less experienced clinicians and for patients demonstrating low-grade lameness (Keegan *et al.*, 1998). Numerical and verbal rating scales have been compared and no significant bias was found amongst the 16 observers mean scores when using either scale (Hewetson *et al.*, 2006). Agreement between observers in this study was a little lower than seen previously; 56% using a numerical rating scale and 60% using a verbal rating scale modelled on the AAEP lameness scale. Intra-observer agreement was achieved in 58% of the observations when using a numeric scale and 60% was achieved using a visual scale. Even though no significant bias was seen amongst observers mean scores when using either scale, it was demonstrated that differences between scores exist and they should not be used interchangeably (Hewetson *et al.*, 2006). Another study reported inter-observer agreement of 70% (Thomsen *et al.*, 2010). However Fuller *et al.* (2006) demonstrated that inter-assessor reliability of lameness scoring was only just acceptable.

The need for objective measures for quantifying lameness so that changes can be more accurately appreciated and recorded in a repeatable manner during diagnostic lameness examinations was demonstrated in a study (Keegan *et al.*, 1998) which concluded that the inter-observer agreement in the change in lameness score following a palmar digital nerve block was poor. Video recordings of lameness examinations have been found to be useful for many purposes including assessing intra-observer repeatability of lameness evaluations with an average of 75% repeatability seen in a study of proximal hindlimb flexion in horses (Armentrout *et al.*, 2012). This study again emphasised the need for an objective means of lameness assessment, even though repeatability in this study was much better than in previous studies.

1.2 Force plates, video-based analysis and inertial sensor-based systems of lameness diagnosis

The gold standard measure for evaluation of lameness in horses is generally accepted to be the stationary force plate as it has all the qualities necessary to attain this standard (Adams and Stashak, 2011) and correlates well with subjective assessment of lameness using a grading system (Ishihara *et al.*, 2009). This has been shown to provide repeatable, accurate, highly sensitive and specific measurements of kinetics in horses. Measurements in the reduction in ground reaction force (GRF) of a horse's limb are obtained. In its simplest form these plates measure only vertical GRF, however more advanced plates measure vertical, horizontal and transverse GRF. The plate is a direct method of identifying and quantifying lameness in horses. This gold standard technique is however impractical for use by clinicians in practice due to the equipment required to obtain measurements. Installation and maintainance is complex and expensive. Video-based motion analysis systems, which are based on kinematics, have been used to provide an objective method of analysis of lameness in horses. Since either a treadmill or multiple cameras are required, again there are severe limitations to this system's use. Symmetry of the vertical head movement is correlated with the vertical movement of the forelimb in order to quantify lameness. The introduction of various inertial sensor-based systems of lameness diagnosis has allowed kinematic analysis to become more accessible compared with the previous method of kinematic gait analysis using video-based systems. These inertial systems can be easy to instrument (fit to the horse) and are user friendly. Good correlation between the video-based and accelerometer/gyroscopic-based systems has been demonstrated (Keegan *et al.*, 2004) with excellent and good levels of agreement between the forelimb and hindlimb measurements respectively. Four transducers were used in some of the older systems with wires needing to be securely positioned. The great advantage that these accelerometer-gyroscopic systems have provided over subjective observation is the ability to analyse many parts of the stride. Although a video-based system provides at least the same amount of information, the advantage that the inertial sensor-based systems have is that they are easy to instrument and use and require far less equipment and can thus be easily applied to a clinical setting. Individual lame strides can now be divided into phases (impact, midstance, impact, breakover) and it is possible to investigate and quantify compensatory lameness that may be occurring secondarily. The current models transmit data wirelessly.

An inertial sensor-based system of lameness diagnosis has been compared with stationary force plate for detection of the more severely affected limb in cases of bilateral forelimb lameness and demonstrated good sensitivity (Keegan *et al.*, 2012). Such cases can be challenging to assess in practice. By using measurements in upward head movement asymmetry at the end of the stance phase and downward movement asymmetry during the first half of the stance phase it was demonstrated that it is possible to correctly identify the lamer forelimb in 78% of bilateral forelimb lameness cases. An overall measurement of head movement asymmetry during the trial allowed correct classification of the lamer forelimb in 83% of cases. A recent study by (McCracken *et al.*, 2012) provided evidence that such inertial sensor-based systems of lameness diagnosis are in fact very sensitive and able to identify lower grades of lameness than a consensus of three experienced veterinarians. Low-grade lameness cases have been frequently reported to be challenging for observers. This study induced lameness in horses by placing shoes that allowed lameness induction via sole pressure. Incremental increases in pressure were induced. Indeed the inertial sensor-based system of lameness diagnosis correctly selected the affected limb in 58% of the trials when the lameness was at a lower level than that required by the subjective evaluation performed by three experienced veterinarians. In only 33% of the trials did the observers identify the affected limb at the same level of lameness as that required by the inertial sensor-based system of lameness diagnosis. In five instances the observers were able to identify the affected limbs prior to the sensor system, however in these trials there appeared to be high variability in the data or all criteria for both evaluations in a trial were not met.

1.3 Use of inertial sensor-based lameness systems of lameness diagnosis

Recent advances in this inertial sensor-based system of lameness diagnosis technology have enabled movement of normal horses to be better understood such as the biomechanics of the sacroiliac joint (Goff *et al.*, 2010). In order to fully assess lameness in horses a good working knowledge of normal biomechanics is essential. Keegan et al (2011) demonstrated that the use of two accelerometers, one placed on the head and the other on the pelvis midline croup region-(between the tubera sacralia, and a right forelimb gyroscope can provide repeatable measurements of head and torso asymmetry, with repeatability being slightly greater for the latter (Figure 1.1). Repeatability is essential for any diagnostic tool to be reliable and for results to be useful. The availability of such a tool, which allows measurement and quantification of changes in gait parameters to be made in a repeatable manner, is thus a powerful advancement. Hence this is an exciting time for kinematic research to aid with the diagnosis of lameness in horses.

Kinematic measurements of gait have been used to determine improvement of lameness in horses with navicular disease after palmar digital nerve block in treadmill studies (Keegan *et al.*, 1997). The accessibility of inertial sensors means that further studies can easily be performed. Appropriate measures to quantify the severity of lameness have been identified. These include the difference in maximum and minimum height of the head and pelvis between the right and left portions of the stride. Since these parameters do not vary with the average asymmetry over the examination and they have relatively low standard deviation when compared with other measures they are regarded as the most reliable. It would be beneficial to undertake studies to identify threshold values for inertial sensor-based systems to allow assessment of responses to diagnostic procedures to be made and to provide guidelines for practitioners to use when assessing lame horses with the aid of such sensor systems in practice. Marshall *et al.* (2012) identified that significant changes occur in pelvic movement asymmetry and maximum pelvic height following flexion tests in horses that are in regular work. Thus inertial sensor-based systems of lameness diagnosis can objectively assess responses to flexion tests. Cut-off values, with adequate sensitivity and specificity (0.71, 0.65 respectively) to identify a positive response were obtained in this study. Individual responses to flexion tests have been reported to be highly variable both within and between horses (Starke *et al.*, 2012). An additional complicating factor has been that clinicians differ greatly in their assessment of such responses. Hence validation of objective measures to assess responses is needed. Research into establishing further cut-off values for other diagnostic procedures is required to guide veterinarians undertaking lameness examinations using this objective system. The system has been used to make comparisons of baseline lameness examinations compared with post diagnostic anaesthesia analyses (Figure 1.2), however the data has not been validated. Thus further studies into the use of this system are warranted.

Figure 1.1: Photographs of a horse instrumented with the **"**Lameness Locator®" inertial sensor based lameness system. Accelerometers are placed on the midline on the head (A) and between the tubera sacrale (B) and a gyroscope (C) is fitted to the pastern of the right forelimb. Photograph taken by S.Maliye at the Weipers Centre Equine Hospital.

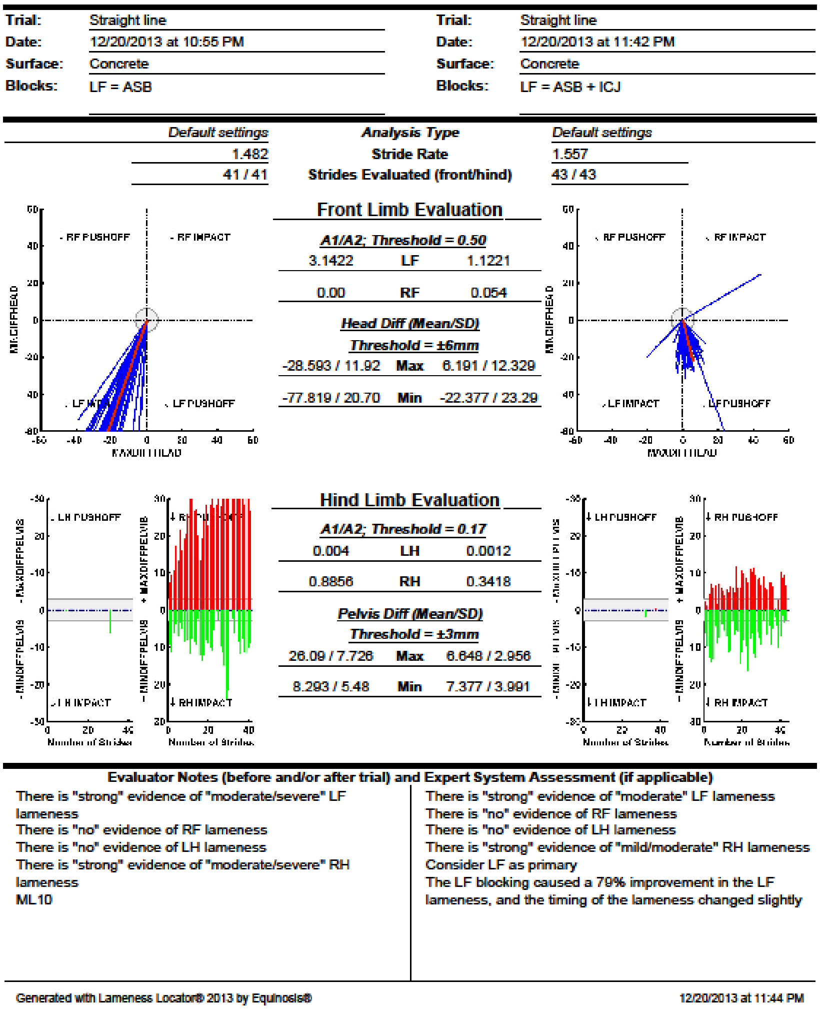

Figure 1.2: Lameness Locator® report in a clinical case for comparison before and after diagnostic anaesthesia of the left intercarpal joint.

1.4 Background and aims of the current study

Lameness examinations can clearly be fairly complex. Tools to objectively measure motion and changes in the horse's gait following diagnostic procedures undertaken in a clinical setting will enable more accurate and repeatable conclusions to be formulated by observers who in the past had been entirely reliant upon subjective measures. Additionally, there is need to further understand and standardise procedures carried out during lameness examinations, such as flexion tests and diagnostic anaesthesia. Inertial sensor based systems providing repeatable, objective measures have also been helpful in this area by aiding in the understanding of the effect that such procedures are having on a horse's gait (Starke et al., 2012).

The objective of the current study was firstly to investigate the use of an inertial sensor based lameness system to distinguish the response to diagnostic anaesthesia performed in clinical cases demonstrating forelimb lameness. Diagnostic anaesthesia is a commonly undertaken technique in practice being able to apply an objective system to guide assessment of the response to the procedure would be beneficial. Further objectives included investigating compensatory lameness in horses with hindlimb lameness and with forelimb lameness. Compensatory lameness is a reported phenomenon, however it has not been described and adequately characterised in a moderately sized population of horses with naturally occurring lameness in a clinical setting. It is the author's subjective opinion that compensatory lameness is very frequently encountered in clinical cases and thus it is necessary to bare this in mind when assessing a lame horse. Lameness in more than one limb is frequently observed in clinical practice and it is necessary to consider the effect of compensatory lameness and to correctly identify the primary lame limb in order to effectively investigate the primary lameness. By further investigating the incidence of compensatory lameness in clinical cases using objective means, its importance may be accurately identified and its characteristics may become better understood.

CHAPTER 2:

Use of an inertial, sensor-based lameness system of lameness diagnosis to distinguish between positive and negative subjective responses to diagnostic anaesthesia of the foot in horses with forelimb lameness

The data presented in this chapter has been published in part:

Maliye S, Voute LC and Marshall JF (2013). “An inertial sensor based system can objectively assess diagnostic anaesthesia of the equine foot”. Equine Veterinary Journal **45**, 26-30.

2.1 Study design and objectives

Marshall et al. (2012) demonstrated that inertial sensor-based systems are able to objectively assess the response to proximal hindlimb flexion tests. This was the first study to use an inertial sensor based lameness system in a clinical setting with a view to aiding clinicians during lameness investigations. Significant changes occur in pelvic movement asymmetry (PMA) and maximum pelvic height following positive responses to flexion tests in normal horses. Cut off values, with adequate sensitivity and specificity (0.71, 0.65 respectively), were obtained in this study in order to identify a positive response. Individual responses to flexion tests have been reported to be highly variable both within and between horses, but an additional complicating factor in assessing responses has been that clinicians differ greatly in their assessment of such responses. Hence validation of objective measures to assess responses to diagnostic procedures is needed to enable accurate assessment to be made.

Diagnostic anaesthesia is frequently undertaken in clinical practice. However, easy to use tools to objectively assess the response along with guidelines are currently not available. The aim of the first part of this study was to ascertain whether an inertial sensor-based system could be used to distinguish between a positive and a negative response to diagnostic anaesthesia (“nerve block”) of the foot, and to objectively assess the effect of a positive response on the trot. Additionally, objective analysis of the movement of lame horses with naturally occurring lameness in a clinical setting has not previously been undertaken. Local anaesthesia of the foot was chosen as it is very frequently performed and is thus representative of local anaesthesia undertaken in a clinical setting. The author’s hypothesis (H1) was that the Equinosis[a] inertial sensor based lameness system could distinguish between a positive and a negative response to a nerve block of the foot. The null hypothesis was thus that the inertial sensor based lameness system could not distinguish between a positive and a negative response to a nerve block of the foot. The aim was to compare changes in all forelimb parameters (movement asymmetry and head movement) and hindlimb movement asymmetry parameters, as measured by the Equinosis system, between subjectively classified positive and negative response groups. If this system could be used in this manner, then additionally it would be beneficial to establish guidelines for practioners to use when assessing a lame horse and using diagnostic anaesthesia to localise the lameness.

2.2 Materials and methods; horses, lameness examinations, diagnostic anaesthesia

2.2.1 Horses

Medical records of adult horses undergoing examination for lameness at the Weipers Centre Equine Hospital, between August 2011 and December 2012 were retrospectively reviewed. Horses (13 mares, 10 geldings; representing 8 Thoroughbreds, 2 ponies, 1 Thoroughbred cross, 2 Irish Sport horses, 1 Fjord, 2 Hanoverians, 2 Dutch Warmbloods, 4 Warmbloods and 1 Warmblood Cross), which underwent diagnostic anaesthesia of the medial and lateral palmar digital nerves of one (n=23) forelimb and had inertial sensor gait analysis performed were included for further analysis. Horses with hindlimb lameness were excluded. In cases of bilateral forelimb lameness, each horse was included in the study only once for a procedure performed on one limb.

2.2.2 Lameness Examination

Data was obtained whilst the horse was trotted in a straight line on a level concrete surface with a fairly loose lead rope. A minimum of 30 strides was required for the data to be accepted for the study. This involved the horse trotting four times the length of a concrete paved covered lameness hall. Frequently more involved assessment of the horse's gait had been performed during each investigation, including lunging on a soft surface and lunging on a hard surface in order to allow full assessment of the horse's gait by the observers. Data from these parts of the investigation were not included in this study. The lame limb was identified by a veterinarian experienced in lameness diagnosis (John F Marshall or Lance Voute), and the severity of lameness was graded according to the modified AAEP scale (0-5). Following confirmation of desensitization by application of blunt pressure distal to the site of diagnostic anaesthesia, the horse was again trotted in a straight line in similar manner to the baseline examination. The response to diagnostic anaesthesia was subjectively classified as positive or negative depending on whether a significant change in gait was observed by a veterinarian experienced in lameness diagnosis (John F Marshall, Lance Voute) blinded to the kinematic data. There are inevitable limitations to using a less sensitive technique (visual assessment) to validate a more sensitive technique (inertial sensor-based system of lameness diagnosis), which is further explored in the discussion.

The modified AAEP lameness scale is defined as follows:

Grade 1- lameness that is difficult to detect and inconsistent.

Grade 2- lameness that is difficult to detect, but consistent.

Grade 3- lameness that is consistently observable in a straight line.

Grade 4- obvious lameness with marked head nod.

This scale is based on that reported by Schumacher *et al.*, 2000.

2.2.3 Equipment

A commercially available sensor system[a] was used to evaluate objectively lameness as previously described (Keegan et al., 2011, Marshall et al., 2012). The mean difference in millimetres in maximum head height after the stance phases of the right and left forelimb (HDMax) and similarly the minimum head height (HDMin) representing the difference in millimetres in minimum head height during the stance phases of the right and left forelimb, were recorded. Additionally, head movement asymmetry assigned to the stride of the limb (HMA) on which diagnostic anaesthesia was performed (blocked limb), the contralateral forelimb and pelvic movement asymmetry (PMA) assigned to both the ipsilateral and the contralateral hindlimbs was measured and stride number was recorded. HMA and PMA were calculated for each stride and assigned for that stride to either the blocked or unblocked forelimb and to either the contralateral or ipsilateral hindlimb to the blocked forelimb. Assignment to the limb was determined by the sign (+/-) of HDMin with negative values assigned to the left limb and positive values assigned to the right limb. Mean measures of HMA and PMA were calculated for all strides collected for each limb by dividing the sum of HMA and PMA for the strides assigned to that limb and dividing by the total number of strides collected. Data were collected pre and post diagnostic anaesthesia.

Terminology used by Equinosis: HMA and PMA are the same as the A1/A2 ratio for the forelimbs and hindlimbs respectively. HDMax and PDMax refer to MaxDiff Head and MaxDiff Pelvis for fore and hindlimbs respectively. HDMin and PDMin refer to MinDiff Head and MinDiff Pelvis for fore and hindlimbs respectively.

2.2.4 Diagnostic Anaesthesia

Anaesthesia of the palmar digital nerves (PDNB) was performed using a standard technique. Sensation at the heel bulbs was tested using a blunt probe prior to performing diagnostic anaesthesia on the lame limb. A 0.51mm x1.59cm needle was inserted at the proximal margin of the ungular cartilage on the lateral and medial sides in a distal direction and injecting 1.5ml of mepivicaine (Intra-Epicaine)[b] at each site. Similarly, anaesthesia of the palmar digital nerves and their dorsal branches (abaxial sesamoid, ASNB) was performed by inserting a 0.64mm x1.59cm needle at the base of the proximal sesamoid bones with the needle directed distally and injecting 1.5ml of mepivicaine (per site) on the lateral and medial side (Schumacher et al., 2004).

2.3 Data Analysis

The vector sum, VS, of HDMax and HDMin was calculated as $\sqrt{((HDMax)^2+(HDMin)^2)}$ for all examinations and served as a measure of head movement asymmetry. Vector sum (VS) was calculated for each horse for pre and post data, and assigned a sign according to the sign of HDMin of the pre and post data (i.e. VS was sign corrected). Thereafter, VS (both pre and post) of all forelimb lamenesses classified as left in origin (according to the HDMin sign of the baseline examination), was multiplied by -1 in order to allow comparison of right and left forelimb lamenesses and pre and post anaesthesia results of VS were compared and the change in VS was subsequently calculated.

The difference (Δ) in each parameter between the examination prior and immediately following the diagnostic anaesthesia was calculated for all groups. Corrections were made for HDMax/HDMin in order to take into account the origin of forelimb lameness (left or right forelimb), since these are signed according to the origin of the lameness, so that the data for all horses could be fairly compared. A negative delta value this signified improvement to the lameness regardless of its origin (left or right).

A Shapiro-Wilk normality test was performed on all data sets before non-parametric data analysis was performed. The subjective lameness grades for the positive and negative response groups were compared using a Wilcoxon Rank Sum test. Thereafter, a Kruskal-Wallis One Way analysis of Variance (ANOVA) based on ranks was performed on all inertial-sensor data sets. Statistical analyses were performed using commercially available software.[c] Statistical significance was set $P<0.05$.

To generate cut off values to differentiate between a positive and negative response to either of the two diagnostic anaesthesia procedures performed (PDNB or ASNB nerve blocks), Receiver Operating Characteristic (ROC) curves were generated for ΔVS, ΔHDMax and ΔHDMin, and ΔHMA for the blocked limb. These curves generally measure the true positive response rate compared with the false positive response rate. The areas under each curve were measured in order to measure the accuracy of the parameter to serve as a good diagnostic test (Gardner et al., 2006). In the case of this study, a positive Equinosis reading in the presence of negative clinical evaluation may actually be a true positive.

2.4 Results

In total 14 PDNB and 9 ASNB nerve blocks met the inclusion criteria for this part of the study. The response to diagnostic anaesthesia was subjectively grouped as positive (n=14) and negative (n=9) by observers' clinical impression of the lameness. The horses included in the analysis and their distribution into groups is displayed in Table 2.1. The site of lameness and diagnostic anaesthesia technique undertaken has been reported alongside the diagnosis made in each case.

All horses in this study were lame in one or both forelimbs (modified AAEP grade 1-3). There was no significant difference ($P=0.84$) in lameness grade between the two groups (the median grade of both the positive and negative group was 2/5, and interquartile range (difference between the 75^{th} and 25^{th} percentiles), IQR, of both was 2, 2). In cases where the nerve blocks had been performed on both forelimbs (n=3), this was due to lameness becoming apparent in the other forelimb after initial diagnostic anaesthesia had commenced on the more severely affected limb, however in these cases only data from one nerve block was included in order to avoid including the same horse in the analysis twice.

The data describing the distributions of the parameters (for delta values i.e. the change in parameter following the diagnostic anaesthesia undertaken) for the positive and negative groups is shown in Table 2.2. The data is presented as median and IQR.

There was a significant decrease in HMA assigned to the blocked limb, PMA assigned to the contralateral hindlimb and VS following diagnostic anaesthesia in the positive response group ($p<0.05$) (Figure 2.1A-C). There was no significant effect of blocking on these parameters in the negative response group. The median ΔHMA of the blocked and contralateral forelimbs was significantly greater in the positive response group (median -0.32, Interquartile range, the difference between upper (75^{th} percentile) and lower quartiles, (25^{th} percentile) (IQR), -0.95 -0.18, and median 0.071, IQR 0.011 0.22 respectively) than in the negative response group (median 0.33, IQR -0.05 0.46, median -0.01, IQR -0.08 0.01 respectively) with $P<0.001$and $P<0.01$ respectively (Figure 2.1A).

There was a significant decrease in PMA assigned to the contralateral hindlimb (median -0.04, IQR -0.14- -0.03) in the positive response group ($P<0.05$) (Figure 2.1B) following a positive response to diagnostic anaesthesia of the foot. There was no significant change in PMA in the negative response group (median 0.02, IQR -0.04 – 0.04). No statistically significant difference was found between the two response groups in the ipsilateral hindlimb (Figure 2.1B).

There was a significant difference in the ΔHDMax between the positive (median -9.88mm, IQR -25.01- -0.90mm) and negative (median 2.57, IQR -3.94 6.18) response groups ($P<0.01$). There was also a significant difference in ΔHDMin between the positive (median -15.59mm, IQR -36.45 -2.90mm), and negative (median 9.67mm, IQR 1.48 11.93mm) groups ($P<0.001$) as shown in Figure 2.1C. Additionally, there was a significant difference in the ΔVS between the positive (median -19.237mm, IQR -30.263 -5.450mm) and negative (median 8.515mm, IQR 0.823 13.789mm) response groups (P<0.001).

Horse number	Result	Diagnostic analgesia site	Diagnosis
1	Positive	PDNB LF	Lateromedial (LM) and dorso-palmar (DP) foot imbalance
2	Positive	PDNB LF	Palmar heel pain, white line disease
3	Positive	ASNB LF	Bilateral DP foot imbalance, deep digital flexor tendonitis
4	Positive	ASNB RF	Bilateral navicular disease
5	Positive	PDNB RF	Osteoarthritis (OA) of the DIPJ
6	Positive	PDNB LF	Bilateral forelimb palmar heel pain
7	Positive	ASNB LF	Navicular disease-moderate to severe
8	Positive	ASNB LF	LF straight distal sesmoidean ligament desmitis
9	Positive	ASNB RF	LM foot imbalance, DIPJ OA
10	Positive	ASNB LF	Lateromedial foot imbalance, DIPJ OA
11	Positive	ASNB RF	RF SDFT injury
12	Positive	PDNB LF	Bilateral navicular disease. DP and LM foot imbalance
13	Positive	PDNB LF	Bilateral navicular disease
14	Positive	PDNB RF	Distal phalanx fracture
15	Negative	PDNB RF	Active periosteal reaction of right metacarpal bone II
16	Negative	PDNB RF	Subchondral bone injury affecting both medial femoral condyles.
17	Negative	PDNB RF	No significant findings, lameness was very mild, no diagnosis made.
18	Negative	PDNB RF	Unlocalised, significant improvement following low 4 point.
19	Negative	PDNB RF	Bilateral hindlimb proximal suspensory ligament desmitis
20	Negative	PDNB LF	Tendonitis of lateral aspect of LH DDFT
21	Negative	PDNB RF	Bilateral navicular disease
22	Negative	ASNB LF	LH coxofemoral joint disease
23	Negative	ASNB RF	Superficial digital flexor tendonitis at level of accessory carpal bone

Table 2.1: Location of the analysed diagnostic anaesthesia procedure performed and associated diagnoses for positive and negative responses to the nerve blocks performed.

Parameter (+/-ve)	Median	IQR
ΔHMA Blocked Limb (+ve)	-0.316	-0.946, -0.179
ΔHMA Blocked Limb (-ve)	-0.0455	-0.0455, 0.460
ΔHMA Contralateral Forelimb (+ve)	0.0709	0.0113, 0.218
ΔHMA Contralateral Forelimb (-ve)	-0.0135	-0.761, 0.00615
ΔPMA Ipsilateral Hindlimb (+ve)	0.0631	0.0250, 0.107
ΔPMA Ipsilateral Hindlimb (-ve)	0.0105	0.0003000, 0.0411
ΔPMA Contralateral Hindlimb (+ve)	-0.0406	-0.139, -0.0264
ΔPMA Contralateral Hindlimb (-ve)	0.0160	-0.0441, 0.0431
ΔHDMax (+ve)	-9.879	-25.013, -0.898
ΔHDMax (-ve)	2.569	-3.936, 6.184
ΔHDMin (+ve)	-15.585	-36.453, -2.891
ΔHDMin (-ve)	9.665	1.479, 11.933
ΔVS (+ve)	-19.237	-30.263, -5.450
ΔVS (-ve)	8.515	0.823, 13.789

Table 2.2: Description of the parameters (for delta values i.e. the change in parameter following the diagnostic anaesthesia undertaken) for the positive and negative groups. The data are presented as median and IQR.

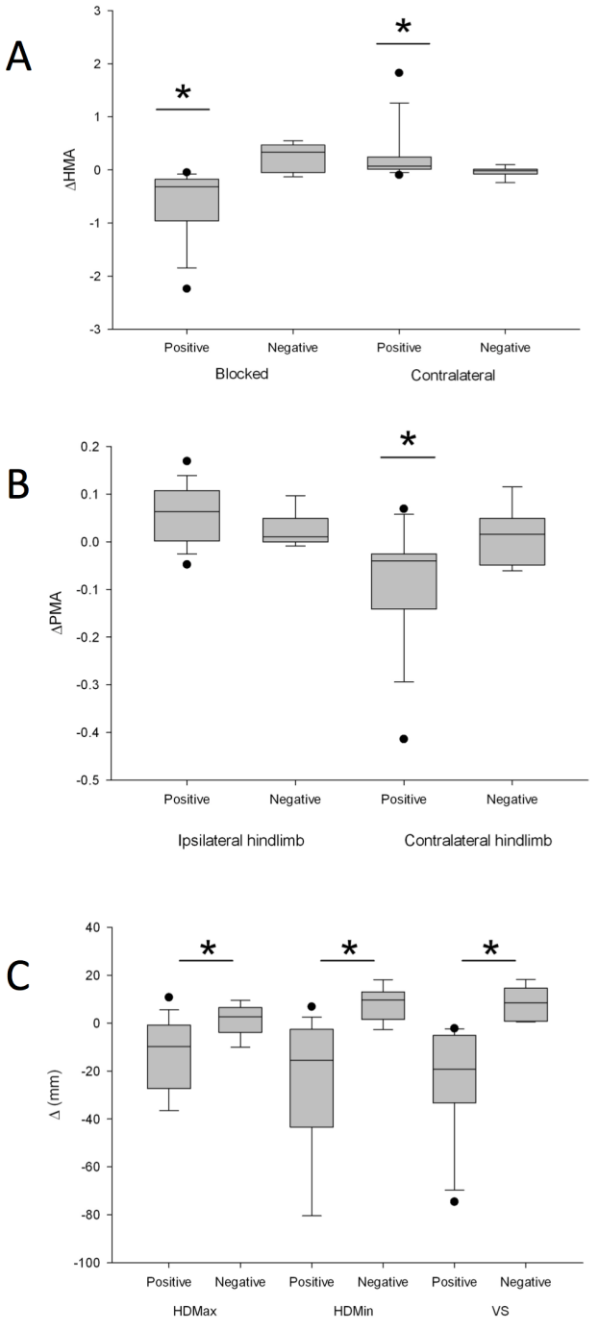

Figure 2.1: Box and whisker plots representing the data for (A) ΔHMA ratio (measure of asymmetry of movement) noted in the Blocked forelimb and Contralateral forelimb, (B) ΔPMA ratio assigned to the Ipsilateral hind limb and Contralateral hind limb, and (C) ΔMaximum Head Difference, ΔMinimum Head Difference and ΔVS in both the positive and negative response groups. There was a significant decrease in asymmetry (assigned to the respective limb) following a positive response to diagnostic anaesthesia noted in the blocked and contralateral hindlimbs, and a significant increase in asymmetry assigned to the contralateral forelimb. ΔHDMax, ΔHDMin and ΔVS measurements significantly changed in the positive response groups. No such significant change was noted in the negative response groups. *****Significant change in parameter between the pre and post-anaesthesia data ($P<0.05$).

ROC analysis was undertaken as it represents a measure of the true positive response rate compared with the false positive rate. This was undertaken in order to identify whether or not ΔHMA, ΔHDMax, ΔHDMin and VS would be useful diagnostic tests to identify a positive response. The analysis determined that the ΔHMA of the blocked limb, ΔHDMax, ΔHDMin and VS are useful diagnostic tests for identifying a positive response to anaesthesia (Figure 2.2; Area under curve=0.98, 0.83, 0.96 and 1.0 respectively). This represents high accuracy for ΔHMA, ΔHDMin and VS and moderate accuracy for ΔHDMax. A change in HMA of -0.08 was determined to have sensitivity of 0.92 and specificity of 0.89. A change in HDMax of -4.00 mm was determined to have sensitivity of 0.71 and specificity of 0.78. A change of HDMin of -0.19 mm with a specificity of 0.93 was determined to have sensitivity of 0.89. A change of VS of -3.39mm was determined to have a sensitivity of 0.86 and specificity of 1.0. A change of VS of -2.46mm was determined to have a sensitivity of 0.93 and specificity of 1.0 (Figure 2.2).

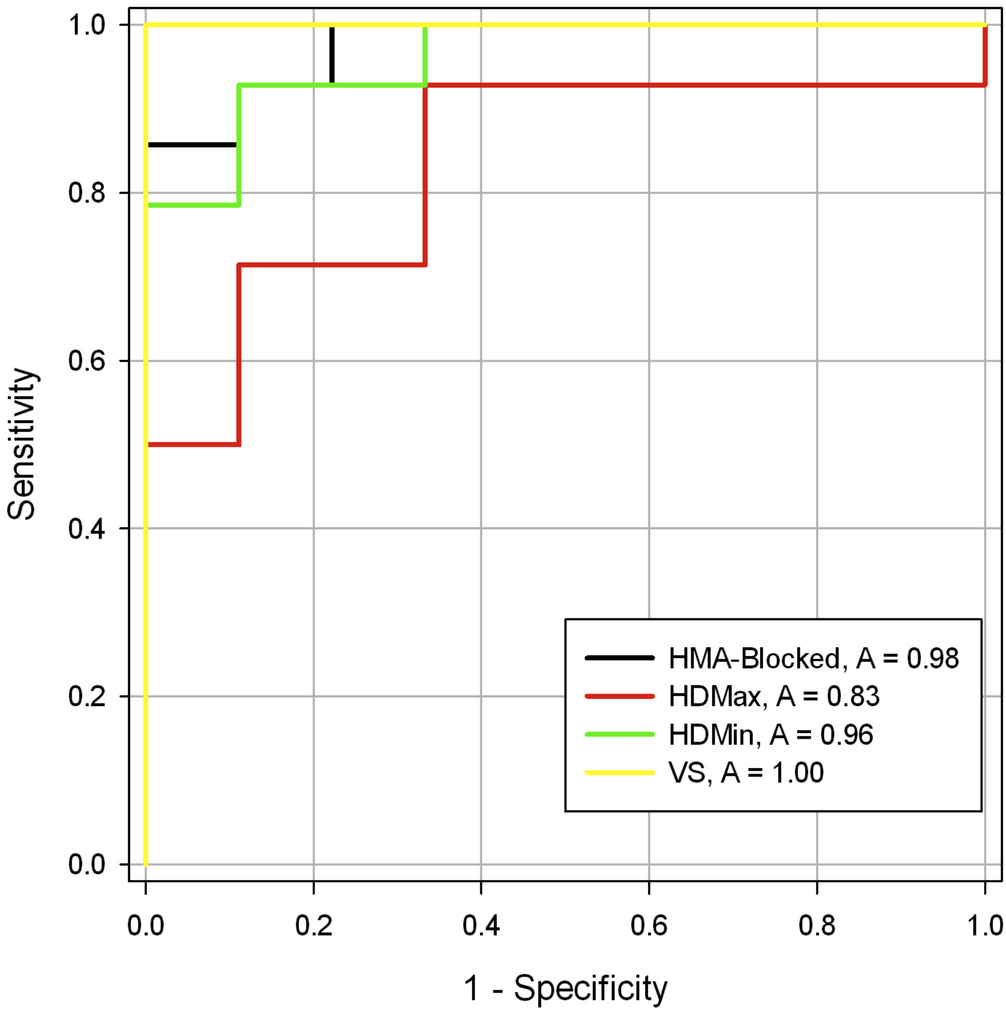

Figure 2.2: Receiver Operating Characteristic curves for the change in head movement asymmetry assigned to the blocked limb (ΔHMA, black) and change in Maximum Head Difference (ΔHDMax, red), Minimum Head Difference in mm (ΔHDMin, green) and VS (ΔVS, yellow). ΔHMA of the blocked limb, ΔHDMax, ΔHDMin and VS are useful diagnostic tests for identifying a positive response to anaesthesia. Area under curve=0.98 (ΔHMA), 0.83 (ΔHDMax), 0.96 (ΔHDMin) and 1.00 (ΔVS).

2.5 Discussion

In this study population it has been demonstrated that a positive response to a palmar digital or an abaxial sesamoid nerve block results in a significant change to the symmetry of movement both in the affected limb, contralateral forelimb and contralateral hindlimb which can be objectively assessed and quantified by an inertial sensor-based system of lameness diagnosis. Analysis of the data presented provides evidence to show that an inertial sensor-based system of lameness diagnosis can distinguish between a positive and a negative response to a nerve block since a significant difference was noted between the positive and negative response groups for almost all the parameters measured. Therefore the null hypothesis may be rejected. The significant change to the symmetry of movement between the forelimbs following a positive response to one of the nerve blocks performed is not unexpected as it is generally accepted that temporary abolition of the source of pain by diagnostic anaesthesia should result in restoration of symmetry of movement, i.e. equal and opposite movement on both forelimbs.

A significant change to the symmetry of movement of the head and pelvis is identified. HDMax and HDMin significantly decrease with a positive response to diagnostic anaesthesia. During the stance phase and weight bearing, reflected in HDMin, as lameness improves the downward movement of the head on the blocked limb will increase as weight bearing becomes more even between the two limbs. Thus, the difference in head height between the two forelimbs during weight bearing becomes less, i.e. HDMin decreases with a positive response to diagnostic anaesthesia of the foot. Similarly HDMax, describing the difference in maximum head height after the stance phases of the right and left forelimbs, also decreases reflecting improvement in lameness following a positive response to diagnostic anaesthesia. Improvement in lameness is associated with greater push off from the lame limb resulting in greater maximum head height on the lame limb and a resultant decrease in HDMax since the apparent difference in head height after the stance phase of each forelimb becomes less as the actual maximum values of head height after the stance phase of each forelimb become more comparable once lameness is abolished.

A positive response to a PDNB or an ASNB nerve block results in a significant change to head movement, both during the stance phase (reflected in HDMin) and after the stance phase (reflected in HDMax) in this population of horses. Head movement is closely observed and alterations assessed during lameness investigations and thus these findings are of clinical significance. Analysis of the data presented in this chapter supports the importance of observing head movement when assessing lameness and changes to lameness, as both head movement during the stance phase and after the stance phase significantly change with improvement to the lameness. A decrease in HDMax will be seen by the observer as less vertical upward head movement after the stance phase of the contralateral forelimb compared to prior to the block. This is the result of increased push off from the lame limb and a relative reduction in push off on the contralateral forelimb as lameness improves, as mentioned previously. A change in HDMin signifying improvement in lameness will be seen as more downward movement of the head during the stance phase of the lame limb compared with that prior to the block. During lameness the horse will bear more weight during the stance phase of the contralateral forelimb, resulting in an apparent drop of the head or ‘head nod’ on the sound limb (Merkens *et al.*, 1988). Following a positive response to diagnostic anaesthesia the difference in minimum head height is reduced and the apparent difference in head height or ‘head nod’ is abolished due to more downward movement of the head during weight-bearing on the blocked limb. Depending on the timing of the lameness (e.g. beginning of stance phase compared with end of stance phase) the changes to these two parameters reflecting improvement to the lameness may differ. Further work to determine the change in gait that is most appreciated by the observer is warranted.

The data presented provides the first analysis of naturally occurring lameness in a moderately sized population of horses and supports previous findings that identified compensatory contralateral hindlimb lameness in horses with induced forelimb lameness (Uhlir *et al.*, 1997). It has been previously reported that a positive response of forelimb lameness to diagnostic anaesthesia can affect contralateral hindlimb movement when the forelimb lameness is severe. However this finding may have been affected by the small population size, inclusion of horses with hindlimb in addition to forelimb lameness, and inclusion of horses with experimentally induced lameness (Uhlir *et al.*, 1997). In contrast, the analysis of the current data was undertaken with a sufficient number of horses to reach clinical significance, using horses with naturally occurring forelimb lameness and with horses with hindlimb lameness excluded. This may have contributed to the conclusion that asymmetry of contralateral hindlimb movement due to primary forelimb lameness is a consistent pattern and is not restricted to horses with severe forelimb lameness (median lameness grade was only 2/5 in the current population of horses presented in this chapter). The findings are also more likely to be representative of lameness observed in clinical cases as all horses in this study were assessed in a clinical setting and the lameness observed was naturally occurring.

Analysis of the current data provides evidence supportive of the existence of compensatory lameness in horses with forelimb lameness since a significant change to the symmetry of movement associated with the contralateral hindlimb (however not the ipsilateral hindlimb) was identified. Analysis of pelvic movement parameters (maximum and minimum pelvic height) was not undertaken during this part of the study as it was not necessary to address the hypothesis. However, this analysis may reveal further evidence of the existence of compensatory lameness and may further characterise compensatory lameness in cases with primary forelimb lameness. This will be explored in Chapter 4. The current findings provide information that is particularly important in assessing apparent multi-limb lameness, which highlights the importance of viewing the horse's response to a procedure as a whole. An important part of this analysis was to identify cut-off values, which may be used as guidelines to assess a positive response to a PDNB or ASNB nerve block, which may be particularly useful to less experienced clinicians. Tools to guide assessment of responses are particularly helpful for challenging, low level lameness. Cut-off values have been identified with high sensitivity and high specificity. These "cut-offs" do however need to be interpreted with caution as they are based on the agreement of the Equinosis readings with clinical impressions, which can lead to false positives. The author would have expected the Equinosis sensitivity and specificity calculations to be higher if the inertial sensor-based system had been compared to an objective technique, such as a force plate.

Limitations of the study need to be considered and include possible variations in data collection due to the nature of some horses not calmly trotting during the lameness evaluation procedure, only two observers carrying out the analysis of the response to the nerve block and though mares were overrepresented, a broad range of breeds were included in the study. The effect of the former should have been minimised by only including data where a minimum of 30 strides were collected. Each horse was only included in the study once to avoid misrepresenting the data, however this resulted in a loss of power within the analysis. Despite the latter, significant changes within the majority of the variables measured before and after diagnostic anaesthesia were noted. Clinical impressions were used to group the horse's responses into "positives" and "negatives". Using this less sensitive technique of visual assessment to validate the inertial sensor-based system of lameness diagnosis inevitably results in the positibility of a positive response having been missed by the observer, that would not have been missed by the inertial sensor-based system. Using an objective measurement technique for measuring movement asymmetry rather than visual assessment to form the "gold standard" would have been a better approach. There is a risk of over representing "false positives", where there was a positive Equinosis reading but a negative clinical impression. This would have negatively affected the specificity calculation of the Equinosis technique.

Investigation with the aim to determine whether an inertial sensor-based system of lameness diagnosis can be used to identify the foot as the source of lameness may prove interesting in the future. Further studies examining inertial sensor-based data obtained from horses with foot pathology confirmed by diagnostic imaging may provide important information.

2.6 Conclusion

The clinical application of an inertial sensor-based system of lameness diagnosis in lameness investigation has been demonstrated in this study. The findings provide significant evidence in order to reject the null hypothesis. In conclusion, it has been shown that it is possible to quantify changes that occur following a diagnostic anaesthesia procedure using this tool. Inertial sensor-based systems of lameness diagnosis can provide useful data not only for quantification of change, but also for classification of responses to procedures performed routinely in practice (such as diagnostic anaesthesia performed in this chapter) and cut-off values have been identified with good sensitivity and specificity to assess the response to diagnostic anaesthesia of the foot. These "cut-off" values can provide guidelines for practitioners performing and assessing the response to diagnostic anaesthesia of the foot in practice. An objective means of measuring lameness in a clinical setting has not been available prior to this time and the current findings thus suggest that this system has significant potential applications in a clinical setting.

Communication between veterinarians can be improved by standard quantification of changes that have occurred following diagnostic procedures, as has been undertaken by using this inertial sensor-based system of lameness diagnosis in this manner. This system has the potential to considerably improve both repeatability in assessment and accurate objective recording of lameness severity and characteristics. It may be possible to use this system to monitor progression of disease and responses to treatments. An important finding was that forelimb lameness results in a significant alteration to symmetry of movement of the contralateral hindlimb, which has implications for the investigation of multi-limb lameness. Though the "rule of sides" is well known (Uhlir *et al.*, 1997, Kelmer *et al.*, 2005, Weishaupt *et al.*, 2006 and 2008, Keegan *et al.*, 2007 and Ross *et al.*, 2010), the analysis of the data shows that this pattern is common even for relatively low level lameness and likely to be under recognised clinically. This will be explored in more detail in the latter parts of this thesis.

Expansion of this initial part of this study may be of benefit to aid practitioners performing diagnostic regional anaesthesia of other anatomical sites to assess responses to these procedures. This would be of particular benefit for cases that may be challenging to assess, such as horses with low level lameness or bilateral lameness. Additionally, through use of inertial sensor-based systems of lameness diagnosis, lameness can be more reliably related to phases of the stride than could have previously been undertaken by observation only, and thus clinicians may gain a deeper insight into and greater understanding of lameness in the future by using this system in clinical cases. Further investigation of compensatory lameness as briefly noted but incompletely explored in this chapter is warranted and will be undertaken in later chapters.

[a] LamenessLocator®, Equinosis LLC, Columbia, MO USA

[b] Intra-Epicaine (2% mepivacaine hydrochloride) Dechra, Staffordshire, U.K

[c] Sigmaplot 11.2 Systat Software Inc, Chicago IL USA

CHAPTER 3:

Kinematic assessment of the horse's gait and elucidating compensatory lameness: current knowledge

3.1 Introduction

Compensatory load redistribution as a result of primary forelimb or hindlimb lameness is a well-known phenomenon commonly referred to as the "rule of sides" (Uhlir *et al.*, 1997, Kelmer *et al.*, 2005, Weishaupt *et al.*, 2006 and 2008 and Keegan *et al.*, 2007, Ross *et al*., 2010). This phenomenon can result in the clinical observation of 'false' or compensatory lameness and potentially lead to a delay or misdiagnosis of orthopaedic disease. It refers to the observation of a false lameness, for example right hindlimb lameness resulting in alterations in symmetry and load distribution that may be interpreted as right forelimb (ipsilateral forelimb) lameness. Conversely right forelimb lameness has been reported to lead to alterations in load and symmetry frequently interpreted as left hindlimb (contralateral hindlimb) lameness. This phenomenon was supported in the first part of this Masters thesis when analysis of forelimb lameness and diagnostic anaesthesia of the foot was performed (see Chapter 2).

Compensatory load redistribution in naturally occurring lameness has been neither fully characterised nor confirmed in a significant number of clinical cases. Patterns of compensatory load redistribution have been described in only a very limited number of horses with clinical or experimentally induced lameness and examination has been restricted to a treadmill . Studies by Buchner *et al.*, 1996a,b; Uhlir *et al.*, 1997; Vorstenbosch *et al.*, 1997; Weishaupt *et al.*, 2004 and 2006 all report these patterns and these will be discussed briefly in the following subsections.

3.2 Forelimb lameness and its compensatory effects

A previous study of induced forelimb lameness of varying (subtle, mild and moderate) severity in 11 clinically sound horses using the solar pressure model provided evidence of compensatory load redistribution. The study described a selective decrease in diagonal impulse in the lame diagonal; the impulse was shifted in the lame diagonal to the hindlimb and in the sound diagonal to the forelimb (Weishaupt *et al.*, 2006). Apart from in the lame diagonal where peak forces increased slightly in cases with induced moderate lameness, no equivalent compensatory overload situation was identified in the other limbs (Weishaupt *et al.*, 2006).

In a study of a mixed population of horses with experimentally induced and naturally occurring forelimb lameness, compensatory supporting limb lameness was identified in the contralateral hindlimb in 6 out of 10 horses (Uhlir *et al.*, 1997). 5 of these horses had lameness induced by inducing solar pressure using a screw and the remaining 5 were cases with naturally occurring lameness. The study also identified compensatory ipsilateral forelimb lameness in all four horses with true hindlimb lameness.

An experimental study of lameness induced by pressure to the sole of the fore or hindlimb found that contrary to the subtle and mild lameness groups, no obvious changes in movement of the head, tubera sacralia and withers was noted in cases with subclinical lameness. The latter was defined as lameness that could not be detected visually by experienced clinicians. However the vertical lift off acceleration of the affected forelimb was decreased in the subclinical lameness group (Orito *et al.*, 2007). In the subclinical hindlimb lameness cases the lift off points of both hindhooves of both the treated and sound hindlimb shifted posteriad. The authors suggested that the trunk might have shifted anterior to reduce the load to the affected hindlimb.

Buchner *et al.* (1996a, b) aimed to further elucidate compensatory lameness by applying three degrees of solar pressure to 11 clinically sound horses. Hyperextension of the metacarpophalangeal joint and flexion of the distal interphalangeal joint during the stance phase decreased significantly in the lame limb in both fore and hindlimb lameness. In the contralateral non-lame limbs a compensatory increase in joint hyperextension occurred. Flexion of the proximal joints increased with increasing lameness. Hyperextension of the metacarpophalangeal joint and flexion of the distal interphalangeal joints during the stance phase in the lame limb were found to be the most useful indicators of lameness in both the forelimb and hindlimb. During both fore and hindlimb lameness, the vertical velocity of the trunk at impact of the lame limb significantly decreased. During the lame stance phase the trunk was kept higher above the ground, maximal acceleration decreased and displacement amplitude was smaller than without lameness. The study identified that the maximal vertical acceleration of the head and displacement amplitude of the tuber sacrale proved to be the best indicators to quantify a fore and hindlimb lameness respectively (Buchner *et al.*, 1996a). Peak displacement of the withers and tuber coxae were also quantified at different phases of the stride. Movements of the head were more expressed than movements of the withers in the cases with forelimb lameness. The reverse was true during hindlimb lameness. During hindlimb lameness withers movement changes were small during the stance phase of the lame hindlimb, however head movement was unchanged during the stance phase of the lame hindlimb. The displacement amplitude of head movement decreased during the stance phase of the nonlame hindlimb.

3.3 Hindlimb lameness and its compensatory effects

A study by Uhlir *et al.* (1997) identified compensatory ipsilateral forelimb lameness in each of the four horses with true hindlimb lameness while trotting on a treadmill in accordance with the “rule of sides”. Several load redistribution mechanisms have been identified in induced hindlimb lameness models including one referring to the effect on the forelimbs. It was previously reported that the contralateral forelimb carries on average 3.6% more of the diagonal vertical impulse during moderate induced hindlimb lameness (Weishaupt *et al.*, 2004). An experimental study of forelimb and hindlimb lameness in normal horses demonstrated a compensatory increase in extension of the metacarpophalangeal joint and flexion of the distal interphalangeal joint in the contralateral non-lame limb (Buchner *et al.*, 1996b). Following induction of an intermediate lameness in the experimental study (Buchner *et al.*, 1996) head displacement amplitudes were decreased during the stance phase of the non-lame hindlimb and maximum acceleration decreased in these horses.

3.4 Subclinical compensatory lameness

The author and Orito *et al.* (2007) defines subclinical as a lameness that cannot be detected visually by experienced observers. There is limited information reported about the existence of subclinical compensatory lameness. An experimental study of lameness induced by pressure to the sole of the fore or hindlimb found that contrary to the subtle and mild lameness groups, no obvious changes in the head, tuber sacrale and withers was noted in cases with subclinical lameness. However the vertical lift off acceleration of the affected forelimb was decreased in the subclinical lameness group (Orito *et al.*, 1997).

The prevalence of subclinical compensatory lameness has not been reported, however evidence from the first part of this thesis (Chapter 2) suggests that it is high in horses with forelimb lameness. A decrease in contralateral hindlimb movement asymmetry following diagnostic anaesthesia of clinical primary forelimb lameness using an inertial sensor-based system of lameness diagnosis provided evidence of significant load redistribution in horses (Maliye *et al.*, 2013).

3.5 Compensatory lameness described in canines

Examination of compensatory lameness in dogs has been restricted to treadmill studies. Bockstahler *et al.* (2009) described the pattern of compensatory load redistribution in dogs with naturally occurring osteoarthritis of the elbow joint and induced weight-bearing lameness of the forelimbs compared with clinically sounds dogs. Naturally occurring osteoarthritis of the elbow joint resulted in reduced load on the affected limb and increased load on the contralateral hindlimb. The dogs with induced lameness showed comparable, but less marked alterations. This study relied upon the measurement of ground reaction forces on a treadmill. The experimental model used pressure exerted by a syringe cup, which could not be easily controlled and thus the induced lameness produced may have led to less marked changes in the animals' gait. Body weight may also have affected some of the measured parameters. Different load redistribution was identified in forelimb compared with hindlimb lameness. Mean and maximal vertical force during the stance phase was significantly larger in the two lame groups than in the sound group for the contralateral hindlimb, but no such changes were noted in the ipsilateral hindlimb.

A study into the compensatory effects of induced hindlimb lameness in dogs revealed that vertical force was decreased in the ipsilateral hindlimb and increased in the contralateral hindlimb (Fischer *et al.*, 2013). Peak force increased in the ipsilateral forelimb, however no change was noted for mean force and impulse when the dogs were walked or trotted. In the contralateral forelimb the peak force was unchanged, but the mean force was noted to significantly increase and the vertical impulse was noted to only increase during walking. During walking, the contralateral fore and hindlimbs stance duration increased during walking and trotting and decreased in the ipsilateral forelimb during walking. The compensatory mechanisms were similar regardless of the gait (Fischer *et al*, 2013).

3.6 Summary, objectives and need for further investigation

The above studies demonstrate the need to further investigate compensatory lameness. The patterns of compensatory hindlimb lameness identified in horses with forelimb lameness in Uhlir and Weishaupt's studies are similar, and are commonly referred to as "the rule of sides", however the true prevalence of this phenomenon is unknown. Investigations into the gait of canines with forelimb lameness also identified increased load on the contralateral hindlimb, thus this phenomenon also exists in other species. The studies reported in this chapter support the existence of ipsilateral forelimb lameness in horses with hindlimb lameness.

The aim of further investigation as part of this study was to identify the number of horses showing evidence of compensatory lameness and to objectively characterise the compensatory load redistribution observed in a moderately sized population of horses with naturally occurring forelimb and hindlimb lameness during clinical examination. This would be undertaken by examining the effect of alleviating lameness through diagnostic anaesthesia. Objective kinematic measurements of gait would be obtained using an inertial sensor-based system of lameness diagnosis, “Equinosis”. Buchner *et al.* (1996a) found the displacement amplitude of the tuber sacrale to be the best indicator to quantify the hindlimb lameness, thus there is supporting evidence for using the pelvic position parameters generated by the “Equinosis” system (PDMax and PDMin). An additional aim was to further characterise patterns of naturally occurring compensatory lameness relative to limb loading, as this has not been reported previously.

Multi-limb lameness can be challenging to assess and it is important to assess the significance of compensatory lameness that may be present prior to undergoing diagnostic anaesthesia to localise the primary lameness. Observing the effect of forelimb blocking on hindlimb movement and vice versa may also prove beneficial in aiding identification of a positive response to diagnostic anaesthesia.

CHAPTER 4:

The compensatory effect of clinical forelimb lameness on movement of the pelvis in the horse; using the Lameness Locator and diagnostic anaesthesia to characterise the effect on hindlimb and forelimb movement

4.1 Study design

The hypothesis was that forelimb lameness results in significant load redistribution and alteration to symmetry of movement of the hindlimbs, which appears as compensatory contralateral hindlimb lameness. The null hypothesis was thus that forelimb lameness does not result in significant load redistribution and alteration to symmetry of movement to the hindlimbs. Evidence to support the alternative hypothesis was presented in Chapter 2 and is supported by the literature discussed in Chapter 3.

An inertial sensor-based system of lameness diagnosis (Equinosis) was used in the investigation, in order to objectively investigate compensatory load redistribution in horses with clinical forelimb lameness by examining the effect of alleviating lameness through diagnostic anaesthesia in a population of horses with clinical multi-limb lameness.

Multi-limb lameness can be challenging to assess. Therefore when examining the lame horse it is important to assess the significance of compensatory lameness that may be present prior to performing diagnostic anaesthesia to localise the primary lameness, in order to correctly identify the latter. The potential existence of compensatory lameness is thus important to consider when undertaking clinical lameness investigations. Additionally, observing the effect of forelimb blocking on hindimb movement may be of value in determining the response to diagnostic anaesthesia in practice.

4.2 Materials and Methods

4.2.1 Medical record review

Medical records of horses that underwent lameness investigation between September 2011 and October 2013 that included the use of an inertial sensor-based system of lameness diagnosis (Lameness Locator, Equinosis LLC) were retrospectively reviewed. Those horses that underwent diagnostic anaesthesia that resulted in significant improvement in lameness were included for further analysis. Significant improvement was defined both objectively using the guidelines provided by the manufacturers of Equinosis and subjectively (see section 4.2.3 "Lameness examinations and diagnostic anaesthesia").

4.2.2 Kinematic lameness analysis

A commercially available inertial sensor-based system of lameness diagnosis (Lameness Locator, Equinosis LLC [a]) was used during all lameness examinations to objectively evaluate lameness by measuring eight parameters as previously described (Keegan *et al.*, 2011, Maliye *et al.*, 2013 and Marshall *et al.*, 2012). A minimum of 30 strides was required for the data to be accepted for the study. The mean difference in millimetres in maximum head height (HDMax) after the stance phases of the right and left forelimb and similarly the minimum head height (HDMin) representing the difference in millimetres in minimum head height during the stance phases of the right and left forelimb were recorded. The mean difference in millimetres in maximum pelvic height (PDMax) after the stance phases of the right and left hindlimb and similarly the minimum pelvic height (PDMin) representing the difference in millimetres in minimum pelvic height during the stance phases of the right and left hindlimb were also recorded. Additionally, general measures of vertical head and pelvic movement asymmetry were calculated and assigned to either right or left forelimbs (HMA) and hindlimbs (PMA) as for the previous first part of the thesis (Chapter 2).

4.2.3 Lameness examinations and diagnostic anaesthesia

All horses included in the study underwent a complete examination, including a minimum of walk and trot in a straight line and lunging in a circle in both directions on hard and soft surfaces, by a veterinarian experienced in lameness diagnosis (John F Marshall or Lance C Voute). The primary lame limb was subjectively identified and the severity of lameness graded according to the modified AAEP scale (0-5).

Inclusion criteria for forelimb lameness: Horses were included for further analysis only if the following objective conditions for confirmation of lameness were met (1) HMA of greater than 0.5 for forelimb lameness (2) HDMax and/or HDMin of greater than ±6mm for forelimb lameness. For all horses, the presence or absence of lameness had been determined subjectively (and now objectively) for all limbs.

Immediately prior to diagnostic anaesthesia each horse was trotted in a straight line on a level concrete surface with a fairly loose lead rope for the purposes of control kinematic data collection. Skin sensation of the distal limb was tested as part of the physical examination process using a blunt probe prior to performing regional anaesthesia.

Thereafter, the diagnostic anaesthesia procedure was performed as determined by the clinician (John F Marshall or Lance C Voute). Following confirmation of desensitization by application of blunt pressure distal to the site of diagnostic anaesthesia, the horse was again trotted in a straight line in similar manner to the control examination. In cases where an intra-articular local anaesthesia block was performed the horse was trotted 10 minutes following the diagnostic procedure. The response to the diagnostic procedure was categorised by both subjective observation of a significant improvement in gait by the observing clinician (John F Marshall or Lance C Voute) and change in objective kinematic data as previously described (Maliye *et al.*, 2013).

Identification of a positive response: Forelimb lameness was defined by the criteria provided by Equinosis, the manufacturer of the inertial sensor-based system of lameness diagnosis. One or more of the parameters needed to be above threshold for the forelimb lameness cases (HMA of the affected forelimb above 0.5, HDMax/HDMin >-/+6mm) provided the clinician performing the investigation had confirmed this forelimb to be the site of lameness. A positive response was defined as a decrease in HMA of the blocked limb to below threshold of 0.5, or a decrease of HDMax/HDMin of greater than 50% with supportive evidence of a change in HMA. These thresholds were chosen as it was thought that they would adequately represent a marked improvement to the lameness. Horses were only included if the subjective assessment by the clinician performing the lameness investigation agreed with the objective assessment.

4.2.4 Classification of lameness

All horses were classified by the presence or absence of evidence of lameness in the other limbs. The primary lame limb had previously been identified during the initial lameness assessment undertaken by the primary lameness clinician. Horses were therefore grouped as (1) primary forelimb lameness only (FO), (2) primary forelimb with contralateral hindlimb lameness (FC) or (3) primary forelimb with ipsilateral hindlimb lameness (FI). The horses were also analysed as a whole group, with all subgroups combined, F-all (4).

4.2.5 Data analysis

Each horse served as its own control. The vector sum, VS, of HDMax and HDMin was calculated as $\sqrt{((HDMax)^2+(HDMin)^2)}$ for all examinations and served as a measure of head movement asymmetry. Following calculation of the change in magnitude of VS following diagnostic anaesthesia, the VS was assigned to the left or right side depending on the signs of HDMin (Keegan *et al.*, 2012), since HDMin is always positive for a right forelimb lameness and always negative for a left forelimb lameness (Keegan, 2012). It was thus possible and necessary to take account for the cases where the individual horse switched from being lame in one forelimb to being lame in the contralateral forelimb. A change from a positive to a negative HDMin value was reflected as a negative VS value since the horse had become left forelimb lame.

Subsequently the change (delta value) in all parameters following diagnostic anaesthesia was calculated for all horses by subtracting the pre-diagnostic anaesthesia data (control) from the post anaesthesia data. A negative change would thus signify improvement to lameness regardless of whether the lameness was left or right. Likewise a positive change would signify worsening of the forelimb lameness regardless of the origin of the lameness. Thus all negative delta values signified improvement to the baseline lameness and positive values signified worsening of the lameness regardless of whether or not the lameness was left or right in origin.

A Shapiro-Wilk normality test was performed prior to data analysis. All parameters were described as the mean ± standard deviation (SD) or median and inter-quartile range (IQR) as appropriate. The percentage change of each parameter following diagnostic anaesthesia was calculated. The median and interquartile range of the percentage change in each parameter following diagnostic anaesthesia was calculated. Baseline kinematic parameters (all nine in turn) were compared between all four groups. The effect of diagnostic anaesthesia on all nine kinematic parameters within each group was determined by a paired t-test or signed rank test as appropriate. All statistical analyses were performed using commercially available software (SigmaPlot 11.2, Systat Software LLC [b]).

Correlation analysis was performed using a Spearman's test, to assess the relationship between ∆PMA of the ipsilateral and ∆contralateral hindlimb, ∆PDMax and ∆PDMin with ∆HMA assigned to the blocked limb, ∆HDMax, ∆HDMin and the ∆Vector Sum. This was performed for all four groups (FC, FO, FI and F-all) between each variable. Statistical significance was set at 5%.

4.3 Results

A total of 28 horses with primary forelimb lameness met the inclusion criteria for this study. Horses with primary forelimb lameness were grouped as follows: Group FO included 8/28 (29%), Group FC included 14/28 (50%), and Group FI included 6/28 (21%). The data in Table 4.1 describes the data by dividing the horses into groups identifying the site of diagnostic anaesthesia and states the diagnosis made for that horse.

4.3.1 Effect of diagnostic anaesthesia on forelimb kinematic parameters in horses with primary forelimb lameness

There was a significant decrease in HMA assigned to the blocked forelimb in all four groups (FO $p<0.05$, FI $p<0.05$, FC $p<0.001$, F-all $p<0.01$ Figure 4.1A, 4.1C, 4.1E, Figure 4.2 left). There was a significant increase in HMA assigned to the contralateral forelimb in all four groups (FO $p<0.05$, FI $p<0.05$, FC $p<0.001$, F-all $p<0.01$ Figure 4.1A, 4.1C, 4.1E, Figure 4.2 left).

There was a significant decrease in HDMin in all four groups (FO $p<0.05$, FC $p<0.001$, FI $p<0.05$, Figure 4.1B, 4.1D, 4.1F and F-all $p<0.001$ Figure 4.2 right) and in HDMax in the FO, FC and F-all ($p<0.05$, $p=0.001$, $p <0.001$ respectively, Figure 4.1B, 4.1D, 4.2 right). Vector sum significantly decreased following diagnostic anaesthesia in all four groups (FO $p<0.05$, FI $p<0.05$, FC $p<0.01$, F-all $p<0.001$ Figure 4.1, 4.2 right).

4.3.2 Effect of diagnostic anaesthesia on hindlimb kinematic parameters in horses with primary forelimb lameness

In the FO and FC groups, there was a significant decrease in the PMA assigned to the contralateral hindlimb, and a significant increase in the PMA assigned to the ipsilateral hind limb following diagnostic anaesthesia ($p<0.05$, Figure 4.1A, 4.1C). This pattern was identical in the analysis of the data as a whole in the F-all group ($p<0.001$ for ipsilateral and contralateral hindlimb, Figure 4.2 left). There was no significant effect of diagnostic anaesthesia on PMA of the contralateral or ipsilateral hindlimb in the FI group. PDMax significantly decreased in the FC group ($p<0.001$) and in the F-all group ($p<0.01$). There was no significant effect of diagnostic anaesthesia on PDMin in any forelimb group (Figure 4.1B, 4.1D, 4.1F, 4.2 right).

Median values (baseline and post anaesthesia) for all kinematic parameters within each group are reported (Table 4.2).

Horse	Group	Forelimb	Diagnostic anaesthesia	Diagnosis
1	FO	RF	PDNB	Palmar heel pain
2	FO	RF	PDNB	Distal phalanx fracture
3	FO	RF	ASNB	Navicular disease
4	FO	LF	ASNB	Navicular disease
5	FO	LF	ASNB	DIPJ OA
6	FO	LF	ASNB	DDFT tendonitis
7	FO	LF	DIPJ	DIPJ OA
8	FO	RF	DFTS	DFTS synovitis
9	FC	LF	PDNB	Navicular disease
10	FC	LF	PDNB	DDFT tendonitis
11	FC	LF	PDNB	DDFT tendonitis
12	FC	RF	PDNB	DIPJ OA
13	FC	LF	ASNB	Unilateral laminitis
14	FC	RF	ASNB	Navicular disease
15	FC	LF	ASNB	SDSL desmitis
16	FC	LF	Low 4 point	MCPJ OA
17	FC	LF	Low 4 point	DDFT tendonitis
18	FC	RF	Median and ulnar nerves	SDFT tendonitis
19	FC	LF	Median and ulnar nerves	MCII osteopathy
20	FC	RF	DFTS	DDFT tendonitis
21	FC	LF	Radiocarpal joint	Radiocarpal joint OA
22	FC	LF	Intercarpal joint	Intercarpal joint OA
23	FI	LF	PDNB	Navicular disease
24	FI	RF	PDNB	Navicular disease
25	FI	LF	ASNB	PIPJ OA
26	FI	RF	Lateral palmar nerve	SL desmitis
27	FI	LF	DIPJ	DIPJ OA
28	FI	LF	MCPJ	MCPJ OA

Table 4.1: Table describing the affected forelimb, diagnostic anaesthesia technique, and diagnosis of horses included in the study.

Abbreviations: PDNB Palmar digital, ASNB abaxial sesamoid, DIPJ distal interphalangeal joint, PIPJ proximal interphalangeal joint, SDFT superficial digital flexor tendon, DDFT deep digital flexor tendon, DFTS digital flexor tendon sheath, SL suspensory ligament, SDSL straight distal sesamoidean ligament, MCPJ metacarpophalangeal joint, OA osteoarthritis

Parameter/Group	HMA Blocked forelimb	HMA Contralateral forelimb	PMA Ipsilateral hindlimb	PMA Contralateral hindlimb	HDMax	HDMin	Vector sum	PDMax	PDMin
FO-Baseline	0.70	0.03	0.07	0.14	9.85*	11.89*	15.28*	1.79	1.04
FO-Post anaesthesia	0.32*	0.16*	0.15*	0.07*	-1.44	-1.87	-3.03	1.34	0.10
FC-Baseline	1.14	0.02	0.02	0.28	13.79	20.57	30.25	7.18	2.32
FC-Post anaesthesia	0.54*	0.11*	0.05*	0.21*	3.58*	5.22*	11.61*	1.63*	1.82
FI-Baseline	0.70	0.07	0.23	0.07	5.88	11.33	14.19	2.46	6.00
FI-Post anaesthesia	0.33*	0.39*	0.26	0.02	2.68	-1.23*	-6.78*	1.03	6.30
F-all-Baseline	0.84	0.02	0.06	0.17	10.63	13.87	18.25	3.62	1.84
F-all-Post anaesthesia	0.43*	0.13*	0.14*	0.08*	1.60*	3.49*	5.22*	1.34*	1.54

Table 4.2: Median values of kinematic parameters (baseline and post anaesthesia) for the horses in each group.

*Significant difference in medians between baseline and post diagnostic anaesthesia.

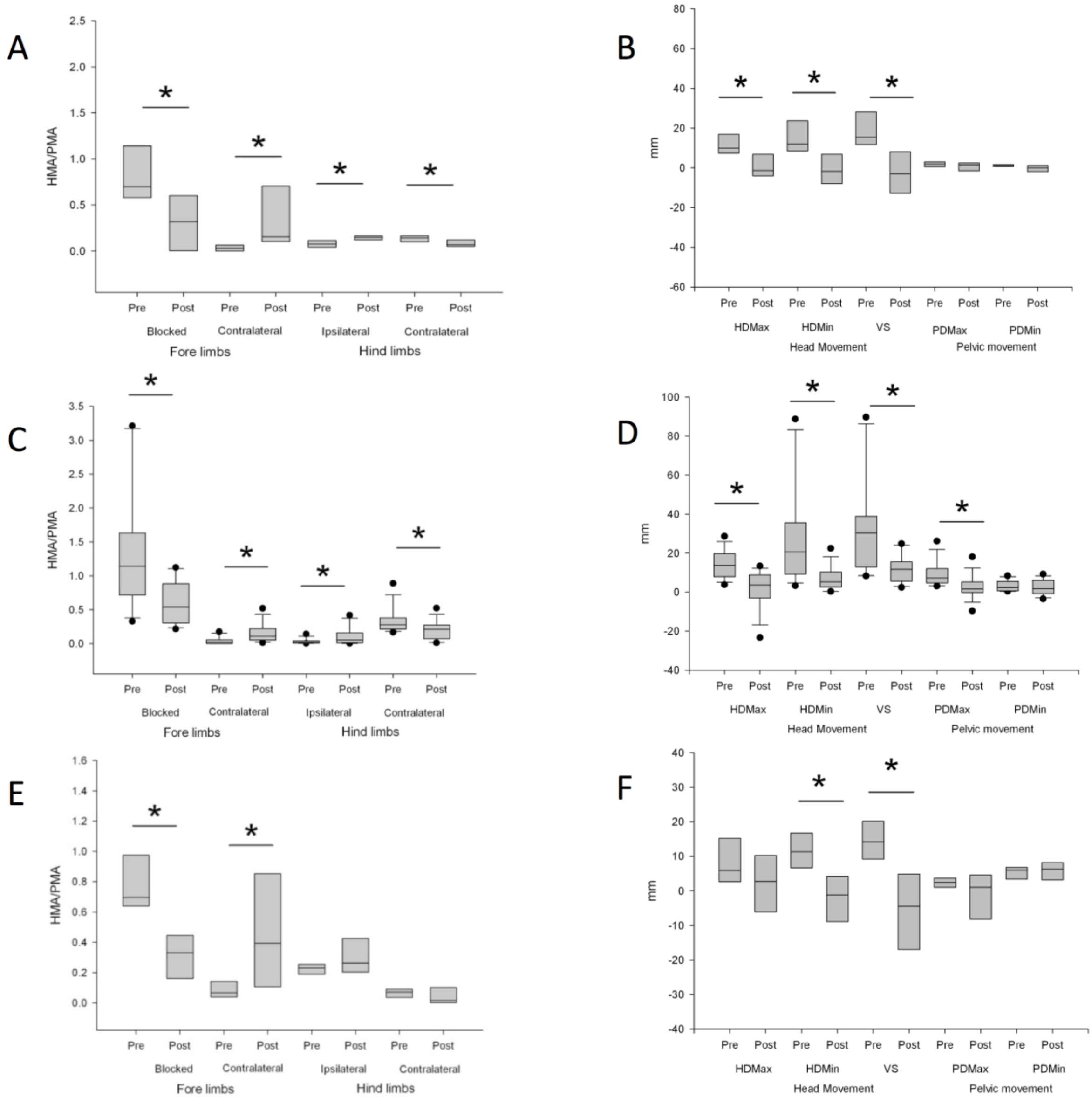

Figure 4.1: Box and whisker plots showing movement symmetry assigned to each limb (FO only, (A), FC, (C), FI, (E)); HDMax, HDMin, PDMax, PDMin and VS associated with the FO only group (B), FC group (D) and FI group (F) pre (prior to diagnostic anaesthesia) and post (after diagnostic anaesthesia) performed on the lame forelimb.

***** Significant difference (p<0.05)

Analysis of the data as a whole (F-all) using a paired Signed Rank test revealed that there was a significant difference between the parameters measured pre and post anaesthesia for all parameters except PDMin. See box and whisker plots shown in Figure 4.2.

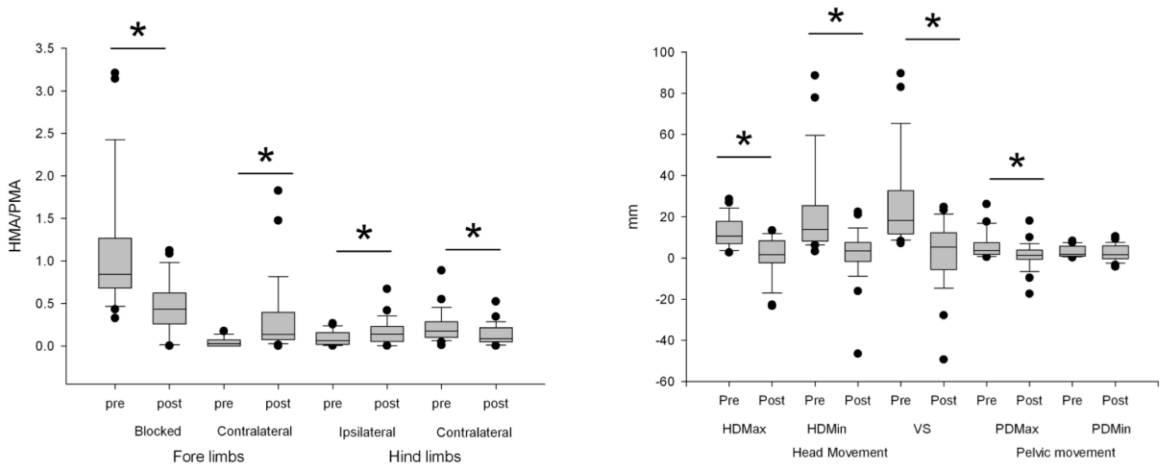

Figure 4.2: Box and whisker plots showing movement symmetry assigned to each limb (left) and head and pelvic movement asymmetry parameters (HDMax, HDMin, VS, PDMax, and PDMin; right) pre (prior to diagnostic anaesthesia) and post (after diagnostic anaesthesia) performed on the lame forelimb. The data collected in this part of the study was analysed as a whole (F-all).

***** Significant difference (p<0.05)

4.3.3 Correlation analysis of the effect of diagnostic anaesthesia on forelimb movement in horses with primary forelimb lameness

Spearman's rank correlation analysis revealed a significant positive correlation between the change in HMA associated with the blocked limb and change in PMA associated with the contralateral hindlimb in groups FO (r=0.95, p<0.01) and FC (r=0.68, p<0.01), and between the change in vector sum and the change in contralateral hindlimb PMA in F-all, FO and FC groups. There was a significant correlation between vector sum and PDMax in F-all (r=0.54, p<0.01) and group FC (r=0.80, p<0.01).

A significant negative correlation was identified between the change in HMA of the blocked forelimb and change in PMA of the ipsilateral hindlimb, and between the change in vector sum and the change in PMA of the ipsilateral hindlimb in both the F-all and FO groups.

Significant positive correlations were identified between the change in HMA associated with the blocked limb and the change in PDMax, and the change in vector sum and change in PDMax in the F-all and FC group. A summary of significant correlation analyses is provided in Table 4.3.

Group	Correlation parameters		r value	p value
	Forelimb	**Hindlimb**		
FC	ΔHMA (blocked limb)	ΔPMA (contralateral hindlimb)	0.684	<0.01
FC	ΔHMA (blocked limb)	ΔPDMax	0.736	<0.01
FC	ΔHDMax	ΔPMA	0.745	<0.01
FC	ΔHDMax	ΔPDMax	0.873	<0.01
FC	ΔHDMin	ΔPDMax	0.600	<0.05
FC	ΔVS	ΔPMA (contralateral hindlimb)	0.631	<0.05
FC	ΔVS	ΔPDMax	0.798	<0.01
FO	ΔHMA (blocked)	ΔPMA (contralateral hindlimb)	0.952	<0.01
FO	ΔHMA (blocked)	ΔPMA (ipsilateral hindlimb)	-0.857	<0.01
FO	ΔHDMin	ΔPMA (contralateral hindlimb)	0.786	<0.05
FO	ΔHDMin	ΔPMA (ipsilateral hindlimb)	-0.905	<0.01
FO	ΔHDMin	ΔPDMax	0.69	<0.05

Table 4.3: Spearmans rank correlation analysis between the change to the parameters shown within the forelimb lameness group with evidence of contralateral hindlimb lameness (marked FC), and the forelimb only group (marked FO) is given for all significant correlations only. Spearman's rank correlation coefficient, r, is given along with corresponding p values.

4.4 Discussion

This part of the study investigating compensatory load redistribution in clinical equine lameness by examining the effect of reducing lameness through diagnostic anaesthesia and measurement of kinematic parameters prior to and following diagnostic anaesthesia, has demonstrated the effect of lameness on the other limbs in horses with naturally occurring lameness under clinical examination conditions. This is in contrast to earlier studies that have used experimentally induced lameness and/or treadmill examination as a model of load re-distribution (Buchner *et al.*, 1996a, 1996b; Orito *et al.*, 2007; Uhlir *et al.*, 1997; Weishaupt *et al.*, 2006). The data shows that a significant proportion of forelimb lameness cases have a concurrent 'false' or 'compensatory' lameness affecting other limbs that is improved by diagnostic anaesthesia of the lame forelimb. Of the 28 horses included in this study, a total of 14/28 or 50% had subjective and objective evidence of forelimb and contralateral hindlimb lameness. A total of 6/28 or 21% of horses had evidence of forelimb and ipsilateral hindlimb lameness. This supports previous findings that compensatory hindlimb lameness in horses with primary forelimb lameness is most frequently observed as contralateral hindlimb lameness. This illustrates the importance of identifying the primary lame limb in diagnostic lameness investigations. The data supports rejection of the null hypothesis as significant evidence of a change (following diagnostic anaesthesia) to hindlimb parameters was noted, most notably affecting symmetry of the contralateral hindlimb and PDMax.

The findings of this part of the study are similar to the data analysed in cases where diagnostic anaesthesia of the foot was undertaken (Chapter 2 and Maliye *et al.*, 2013); a significant effect of diagnostic anaesthesia on kinematic parameters of movement asymmetry (referring to head/forelimb movement) following diagnostic anaesthesia of the blocked forelimb was identified. This has been discussed in more detail within Chapter 2 and reasons have been provided. The data in this chapter thus supports this general trend and Vector sum and HDMin were shown to be useful measures of head movement and were found to significantly change in all four groups. HDMax reduced significantly in all groups except the ipsilateral hindlimb group. It thus appears that the difference between the minimum head height during the right and left forelimb stance phase is more likely to reduce in most cases with forelimb lameness following a positive response to diagnostic anaesthesia. Lameness is thus associated with less downward movement of the head since in all cases HDMin significantly reduced following a positive response to diagnostic anaesthesia of the affected limb. Forelimb lameness regardless of source thus results in changes to the distribution of load, which may be observed as less downward movement of the head associated with the lame limb during lameness.

Hindlimb kinematic parameters in horses with primary forelimb lameness changed in many horses following the diagnostic anaesthesia nerve block performed. There was a significant alteration in pelvic movement asymmetry associated with both hindlimbs in the FO, FC and F-all forelimb lameness groups following the diagnostic anaesthesia nerve block. Specifically, the PMA assigned to the contralateral hindlimb decreased while the PMA assigned to the ipsilateral hindlimb increased following a positive response to the diagnostic anaesthesia nerve block in the lame forelimb. A similar finding was previously reported following diagnostic anaesthesia of forelimb lameness localised to the foot (Maliye *et al.*, 2013) and an explanation has been provided in Chapter 2. However, the previous study did not investigate the reason for this increased contralateral hindlimb asymmetry further (Chapter 2, Maliye *et al.*, 2013). The data in this chapter showed that in forelimb lameness cases with evidence of contralateral hindlimb lameness (Group FC), there was a significant decrease in PDMax following a positive block. This implies that compensatory lameness or load re-distribution in this group is associated with the push-off component of the stride. The finding was restricted to the two largest groups (FC and F-all) and this may reflect reduced power in detecting a change in the smaller groups or it may reflect a real difference in alteration to distribution of weight and symmetry between the groups. Specifically, forelimb lameness resulted in a decrease in push-off from the contralateral hindlimb that was improved by the diagnostic anaesthesia nerve block. Previous experimental studies have demonstrated a shift in loading from the lame forelimb to the diagonal hindlimb (Vorstenbosch *et al.*, 1997; Weishaupt *et al.*, 2006). Therefore, the reduction in push-off may be a reflection of increased loading off the limb. The previous studies have disagreed on whether forelimb lameness results in a compensatory weight-bearing ipsilateral hindlimb lameness (Weishaupt *et al.*, 2006), or a contralateral hindlimb lameness (Uhlir *et al.*, 1997) using ground-reaction force measurement and kinematics respectively. Weishaupt noted lowering of the sacrum during the stance phase of the contralateral hindlimb, which he interpreted as ipsilateral weightbearing lameness. The data presented in this chapter does not support changes in pelvic height during the stance phase/weightbearing (reflected in PDMin) as changing significantly in cases with forelimb lameness since a significant change in PDMin was not found in any of the four groups following the diagnostic anaesthesia nerve block of the affected forelimb. The current data representing naturally occurring lameness during a clinical examination is in agreement with the previous treadmill kinematic study that identified contralateral hindlimb lameness (Uhlir *et al.*, 1997).

A previous experimental study described ipsilateral hindlimb lameness in two horses and found that diagnostic anaesthesia of the forelimb or removal of induced lameness resulted in decreased asymmetry of movement in the ipsilateral hindlimb (Uhlir *et al.*, 1997). The data presented in this chapter shows that although there was a significant effect of diagnostic anaesthesia on the forelimb lameness, there was no significant change in any of the measured hindlimb kinematic parameters in the FI group. This difference may reflect the differences in experimental methods, data analysis and horse populations. These findings suggest that the lameness in the ipsilateral hindlimb of these horses analysed and presented in this chapter was a ‘true’ lameness and not the result of compensatory load distribution. By further analysing the individual case records of the 6 horses in this group it was unfortunately not possible to draw conclusions regarding the source of the hindlimb lameness in these cases. In one case the hindlimb symmetry was reported to have improved, thus it was thought that the hindlimb lameness was in part compensatory hence no further investigation was undertaken. In three cases no investigation of the hindlimb lameness was undertaken. In one case an extensive investigation of the ipsilateral hindlimb lameness was undertaken (local anaesthesia-low 6 point, deep branch of the lateral plantar nerve, tarosmetatarsal joint, medial femorotibial joint, tibial and peroneal) without alteration to the hindlimb lameness. In the final case an attempt was made to undertake diagnostic anaesthesia but this could not be safely undertaken, however evidence of mild osteoarthritis of the distal tarsal joints was noted on radiographs obtained and this may have been the source of hindlimb lameness observed. There is thus evidence to suggest that in some cases a second source of lameness (hindlimb) exists, in another case the lameness could not be localized (despite diagnostic anaesthesia) and although this may support the possibility that the hindlimb lameness in this case is compensatory, this may also not be the case as there are situations when a lameness cannot be successfully localized by diagnostic anaesthesia. The observers in the final case noted that the hindlimb symmetry improved (but was not abolished) following the diagnostic anaesthesia of the forelimb, and thus was thought to be compensatory in part. It is thus difficult to draw conclusions for the limited numbers of cases in this group. Further analysis of horses showing forelimb lameness and ipsilateral hindlimb lameness is thus warranted.

Correlation analysis revealed positive correlations between change in HMA (blocked limb) with the change in PMA associated with the contralateral hindlimb in both FO and FC groups. This supports the theory of forelimb lameness resulting in compensatory contralateral hindlimb lameness. In the FC group HDMax also positively correlated with PMA (contralateral hindlimb), thus further supporting this. HMA (blocked limb) negatively correlated with PMA (ipsilateral hindlimb) in the FO group, and a similar though insignificant trend was noted in the FC group. This may be explained by the shift in weight distribution away from the ipsilateral hindlimb during lameness i.e. relative asymmetry more significantly assigned to the contralateral hindlimb during lameness. The latter would result in an apparent decrease in PMA assigned to the ipsilateral hindlimb. HDMin positively correlated with PDMax in both groups. This may suggest that the impact component of a forelimb lameness (head movement) and push off component of pelvic movement may frequently occur together and change in a similar manner. In the FC group the hindlimb pelvic push off component (PDMax) positively correlates with HMA (blocked limb) and HDMax too, thus suggesting that the pelvic push off component in this group generally more closely correlates with all kinematic forelimb parameters (HMA-blocked limb, HDMax and HDMin) than in the FO group. In the FO group the pelvic push off component (PDMax) strongly correlates with the impact component of forelimb (HDMin), but none of the other variables. HDMin correlates with all hindlimb kinematic parameters except PDMin in the FO group; an explanation may be that the impact component of head movement in this group is more frequently seen than in the FC group i.e. the characteristics of the forelimb lameness type seen in the two groups FO and FC may be different.

Overall, the analysis of forelimb diagnostic anaesthesia provides significant clinical evidence that forelimb lameness results in significant compensatory load distribution that is manifest as contralateral hindlimb lameness. The horses in the FI group failed to show changes in asymmetry assigned to the hindlimbs, which was in contrast to the other three groups. They also failed to show a change in vertical pelvic movement, which was in contrast to the FC and forelimb F-all where a significant change in vertical pelvic movement was detected. Furthermore, while a previous study found evidence of compensatory contralateral limb lameness in horses with severe forelimb lameness (Uhlir *et al.*, 1997), this study has demonstrated detectable and significant load redistribution in the horse with mild or moderate forelimb lameness and both with and without observed hindlimb lameness. Analysis of the horses as a whole group has increased the power to detect significant changes in all parameters measured, thereby maximising the provision of information concerning kinematics/movement in these horses. By analysing the groups according to the existence of evidence of hindlimb lameness this has allowed identification of compensatory lameness in horses with evidence of contralateral hindlimb lameness. It has also allowed identification of the existence of subclinical compensatory lameness. Additionally, the forelimb only (FO) group possibly best represents horses with forelimb lameness (no confounding with the possible existence of true hindlimb lameness) and thus analysis of these horses separately was thought to be important.

4.5 Conclusions

Analysis of the current data presented has expanded upon previous studies by characterising the compensatory hindlimb lameness observed in clinical cases with primary forelimb lameness in addition to objectively supporting the "law of sides" in a moderately sized population of horses. The data supports rejection of the null hypothesis as significant evidence of a change to hindlimb parameters following diagnostic anaesthesia was noted in many horses, most notably affecting symmetry associated with the contralateral hindlimb and PDMax.

The data presented in this chapter shows that although there was a significant effect of diagnostic anaesthesia on the forelimb lameness, there was no significant change in any of the measured hindlimb kinematic parameters in horses with ipsilateral hindlimb lameness. These findings suggest that the lameness in the ipsilateral hindlimb of these horses analysed and presented in this chapter was a 'true' lameness and not the result of compensatory load distribution. The change to the hindlimb parameters in the FC group provides supporting evidence to suggest that this contralateral hindlimb lameness is not a true lameness.

The findings of this study demonstrate that when assessing the lame horse it is important to eliminate hindlimb lameness as a possible cause of forelimb lameness and vice versa prior to performing further diagnostic techniques. Analysis of the data has demonstrated that subclinical compensatory lameness commonly occurs. It is thus useful when assessing the response to diagnostic anaesthesia in horses with forelimb and hindlimb lameness to define the effect on both the hind and forelimb movement. The findings of this analysis, therefore has important implications for lameness examinations and the investigation of lameness, in particular multi-limb lameness.

a. Lameness Locator, Equinosis LLC
b. SigmaPlot 11.2, Systat Software LL

CHAPTER 5:

The compensatory effect of clinical hindlimb lameness on head movement in the horse; using kinematic measurements in clinical cases and diagnostic anaesthesia to characterise the effect

5.1 Objectives, hypothesis and study design

Several load-shifting mechanisms have been identified in induced hindlimb lameness models including one referring to the effect on the forelimbs. It was reported that the contralateral forelimb carries on average 3.6% more of the diagonal vertical impulse during moderate hindlimb lameness (Weishaupt *et al.*, 2004). Kinematic analysis of horses with naturally occurring lameness and the occurrence of compensatory lameness in such cases is currently limited to individual cases, which does not allow general trends to be confirmed. In one study all four horses with naturally occurring hindlimb lameness showed evidence of ipsilateral forelimb lameness (Uhlir *et al.*, 1997). In a second study of horses with induced hindlimb lameness (Weishaupt *et al.*, 2004) the vertical impulse was shifted to the contralateral forelimb during the lame diagonal stance.

When assessing multi-limb lameness, in order to correctly identify the primary source of lameness, it is important to assess the significance of compensatory lameness that may be present prior to performing diagnostic anaesthesia. The existence of compensatory lameness is thus important to consider when undertaking clinical lameness investigations and establishing the prevalence of this effect. Characterising the compensatory lameness in clinical cases is therefore important. Additionally, observing the effect of diagnostic anaesthesia of the hindlimb on forelimb movement may be of value in determining the response to diagnostic anaesthesia in practice.

The hypothesis (H1) was that hindlimb lameness results in significant load redistribution, which may be observed as ipsilateral forelimb lameness. Fore example, right hindlimb lameness results in load redistribution observed as right forelimb lameness. The null hypothesis was that hindlimb lameness does not result in significant load redistribution on the forelimbs. This hypothesis is supported by findings in individual cases of lameness as mentioned in Chapter 3 and by the “rule of sides” (Uhlir *et al.*, 1997, Kelmer *et al.*, 2005, Weishaupt *et al.*, 2006 and 2008, Keegan *et al.*, 2007 and Ross *et al*., 2010). The “rule of sides” refers to the observation of a false lameness, for example right hindlimb lameness resulting in alterations in symmetry and load distribution that may be interpreted as right forelimb (ipsilateral forelimb) lameness. Conversely right forelimb lameness has been reported to lead to alterations in load and symmetry frequently interpreted as left hindlimb (contralateral hindlimb) lameness.

In order to test the hypothesis, an inertial sensor-based system of lameness diagnosis (Equinosis) was used to objectively investigate compensatory load redistribution in horses with clinical hindlimb lameness by examining the effect of alleviating lameness through diagnostic anaesthesia. The hypothesis was addressed by analysing kinematic parameters of forelimb movement. Analysis of changes to head movement asymmetry assigned to each forelimb and changes to vertical head height (and vector sum representing HDMax and HDMin) was thus undertaken. If significant changes were detected within these parameters following improvement to the lameness after a positive response to diagnostic anaesthesia had occurred, this would be supportive of the H1 hypothesis. The aims in this small study were to identify the proportion of horses exhibiting characteristics of compensatory forelimb lameness, to establish the characteristics of the compensatory component and to establish if there is a correlation between hindlimb and compensatory forelimb parameters in cases with hindlimb lameness.

5.2 Materials and Methods

5.2.1 Medical record review

Data obtained during lameness investigations performed between September 2011 and October 2014 at the Weipers Centre Equine Hospital, University of Glasgow, that included the use of an inertial sensor-based system of lameness diagnosis (Lameness Locator, Equinosis LLC) were retrospectively reviewed. Horses diagnosed with hindlimb lameness that had a positive response to diagnostic anaesthesia of the hindlimb as determined by subjective and objective assessment were included in further analysis. Horses were grouped for further analysis as (1) clinical hindlimb lameness only (HO), (2) hindlimb and ipsilateral forelimb lameness (HI) or (3) hindlimb and contralateral forelimb lameness (HC) according to objective criteria (see later) and the baseline examination findings. Additionally all horses were analysed together as the group (4) H-all, “all groups combined”.

5.2.2 Lameness examinations and diagnostic anaesthesia

Each horse undergoing diagnostic anaesthesia of a hindlimb was trotted in a straight line on a level concrete surface with a fairly loose lead rope during data collection. A minimum of 30 strides was required for the data to be accepted for the study. Sensation to the heel bulbs of both hindlimbs were tested using a blunt probe prior to performing regional anaesthesia as part of the physical examination process. Thereafter, the diagnostic anaesthesia procedure chosen by the attending clinician experienced in lameness diagnosis (John F Marshall or Lance C Voute) was performed on the limb identified as being the lame hindlimb. In cases where a horse was bilaterally hindlimb lame only the lamer hindlimb was included. Following confirmation of desensitization by application of blunt pressure distal to the site of diagnostic anaesthesia, the horse was again trotted in a straight line in similar manner to the baseline examination. In cases where intra-articular local anaesthesia was performed the horse was trotted 10 minutes following the diagnostic procedure. The response to the diagnostic anaesthesia was categorised by objective data (see later for criteria) and subjectively by the primary investigator and only those horses where a positive response occurred were included in this study.

5.2.3 Kinematic lameness analysis

A commercially available inertial sensor-based system of lameness diagnosis[b] was used to objectively evaluate lameness by measuring eight parameters as previously described (Keegan *et al.*, 2006 and Marshall *et al.*, 2012, Chapter 1). The mean difference in millimetres in maximum head height (HDMax) after the stance phases of the right and left forelimb and similarly minimum head height (HDMin) representing the mean difference in millimetres in minimum head height during the stance phases of the right and left forelimb were recorded. The mean difference in millimetres in maximum pelvic height (PDMax) after the stance phases of the right and left hindlimb and also the minimum pelvic height (PDMin) representing the difference in millimetres in minimum pelvic height during the stance phases of the right and left hindlimb were recorded. Additionally, general measures of vertical head and pelvic movement asymmetry were calculated and assigned to either right or left forelimbs (HMA) and hindlimbs (PMA) by the software and these measurements were recorded. Data were collected prior to and following the diagnostic anaesthesia procedure.

Horses were included if there was evidence of a unilateral hindlimb lameness as defined objectively as a PMA greater than 0.17 and PDMax and/or PDMin greater than +/-3mm. All cases were further classified according to any evidence of forelimb lameness (hindlimb lameness only, HO, hindlimb lameness and ipsilateral forelimb lameness, HI, or hindlimb lameness and contralateral forelimb lameness, HC). Criteria for forelimb lameness were vector sum greater than 8.5mm in the baseline (pre-anaesthesia data). These criteria had previously been established for identification of lameness by the manufacturers of Equinosis and had been investigated in a previous study (Keegan *et al.*, 2012).

5.2.4 Objective identification of a positive response to the diagnostic anaesthesia

A positive response to the diagnostic anaesthesia procedure undertaken was defined as a change in pelvic movement asymmetry (PMA) assigned to the blocked limb to below threshold ($\leq$0.17) or decrease in mean difference in maximum pelvic height after the stance phase of the right and left hindlimb (PDMax) or decrease in mean difference in minimum pelvic height during the stance phase of the right and left hindlimb (PDMin) of greater than 50% with supportive evidence of a change in PMA. This threshold of 0.17 was chosen since the manufacturers of the Equinosis system have established this to be adequate for the identification of lame horses (Kramer *et al.*, 2004).

5.2.5 Data analysis

Each horse served as its own control. A Shapiro-Wilk normality test was performed on all data sets prior to data analysis. For PDMax/PDMin raw data, corrections were made in order to take into account whether the hindlimb lameness was right or left in the baseline examination (all left hindlimb lamenesses were multiplied by -1), so that both right and left hindlimb lamenesses could be combined for analysis. Similarly for HDMax/HDMin data corrections were made in order to take into account whether the forelimb lameness was left or right in origin (left forelimb lamenesses were multiplied by -1) according to the sign of HDMin in the baseline examination, to allow the data to be combined for analysis. Subsequently the change (delta value) in all parameters following diagnostic anaesthesia was calculated for all horses by subtracting the pre-diagnostic anaesthesia data (control) from the post anaesthesia data. A negative change would thus signify improvement to lameness regardless of whether the lameness was left or right. Likewise a positive change would signify worsening of the forelimb lameness regardless of the origin of the lameness. Thus all negative delta values signified improvement to the baseline lameness and positive values signified worsening of the lameness regardless of whether or not the lameness was left or right in origin.

The vector sum (VS) of HDMax and HDMin was calculated as $\sqrt{((HDMax)^2+(HDMin)^2)}$ for all examinations and served as a measure of head movement asymmetry. Vector sum (VS) was calculated for each horse for pre and post data, and assigned a sign according to the sign of HDMin of the pre and post data (i.e. VS was sign corrected). Thereafter, VS (both pre and post) of all forelimb lamenesses classified as left in origin (according to the HDMin sign of the baseline examination), were multiplied by -1 in order to allow comparison of right and left forelimb lamenesses and pre and post anaesthesia results of VS were compared and the change in VS was subsequently calculated.

The changes (pre and post anaesthesia) to each of these parameters were analysed for each parameter by a paired t-test or signed rank test, depending on the distribution of the population, in order to assess the significance of the change. A comparison of the baseline (pre anaesthesia) parameters obtained was made between the HO, HC and HI groups using a Rank Sum test or t-test as appropriate in order to identify whether or not there was a significant difference in hindlimb lameness characteristics between the three populations. All statistical analyses were performed using commercially available software (SigmaPlot 11.2, Systat Software LLC).

Spearmans or Pearsons Correlation Analysis as appropriate was performed in order to identify correlations between the hindlimb and forelimb parameters measured in both groups. Comparisons were made between hindlimb parameters (change of PMA assigned to each hindlimb, PDMax, PDMin) with each of the forelimb parameters (change of HMA of each forelimb, vector sum, HDMax and HDMin) within each group (HO, HI, HC and H-all). Statistical significance was set at 5%.

5.3 Results

5.3.1 Medical record review

A total of 37 horses met the complete inclusion criteria for this study. These horses were grouped as (1) clinical hindlimb lameness only (HO group, n=19, 51%), (2) Hindlimb and ipsilateral forelimb lameness (HI group, n=10, 27%) or (3) HL and contralateral forelimb lameness (HC group, n=8, 22%). Additionally all groups combined were analysed (n=37). See Table 5.1.

Horse	Group	Hindlimb	Diagnostic anaesthesia	Diagnosis
1	HO	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
2	HO	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
3	HO	LH	TMT joint	OA of distal tarsal joints
4	HO	RH	TMT joint	OA of distal tarsal joints
5	HO	LH	TMT joint	OA of distal tarsal joints
6	HO	RH	TMT joint	OA of distal tarsal joints
7	HO	LH	TMT joint	OA of distal tarsal joints
8	HO	LH	Digital flexor tendon sheath	Annular ligament syndrome
9	HO	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
10	HO	LH	TMT joint	OA of distal tarsal joints
11	HO	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
12	HO	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
13	HO	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
14	HO	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
15	HO	LH	TMT joint	OA of distal tarsal joints
16	HO	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
17	HO	RH	TMT joint	OA of distal tarsal joints
18	HO	RH	TMT joint	OA of distal tarsal joints
19	HO	RH	TMT joint	OA of distal tarsal joints
20	HI	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
21	HI	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
22	HI	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
23	HI	RH	TMT joint	OA of distal tarsal joints
24	HI	LH	TMT joint	OA of distal tarsal joints
25	HI	LH	TMT joint	OA of distal tarsal joints
26	HI	LH	Low 6 point	Plantar proximal phalanx bone chip/fragmentation
27	HI	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
28	HI	RH	TMT joint	OA of distal tarsal joints
29	HI	LH	TMT joint	OA of distal tarsal joints
30	HC	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
31	HC	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
32	HC	RH	TMT joint	OA of distal tarsal joints
33	HC	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
34	HC	RH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
35	HC	LH	Deep branch of lateral plantar nerve	Subtarsal pain
36	HC	LH	Deep branch of lateral plantar nerve	Suspensory ligament desmitis
37	HC	RH	TMT joint	OAof distal tarsal joints

Table 5.1: Table of lameness group, limb, site of diagnostic anaesthesia and respective diagnoses of the horses included in this study. TMT refers to the tarsometatarsal joint. OA refers to osteoarthritis.

The horses included a broad range of breeds and horses of varying ages. The HO group was comprised of horses between 4-22 years of age; 8 mares and 11 geldings; 4TB/TB crosses, 1 Clydesdale, 5 Warmbloods, 1 cob, 1 Connemara x Dutch Warmblood, 2 ponies (Welsh and other) and 4 SPB, 1 Friesian. The HI group comprised of horses between 5-15 years; 6 mares, 4 geldings; 3 TB/TB crosses, 3 Warmbloods/Warmblood crosses, 1 cob and 3 ponies. The HC group comprised of horses between 7-22 years of age; 3 mares, 5 geldings; 5 TB/TBXs, 2 Warmbloods and 1 Sport horse.

5.3.2 Effect of diagnostic anaesthesia on hindlimb movement

PMA assigned to the contralateral hindlimb significantly increased (HO, H-all P<0.001, HI, HC P<0.01) and PMA assigned to the affected (blocked) hindlimb significantly decreased in all groups (HO, HC and H all groups combined P<0.001 and HI P<0.005) following diagnostic anaesthesia (Figure 5.1A-D). A positive response to diagnostic anaesthesia resulted in a significant decrease in PDMax in the HO, HC and H-all groups (P<0.001) and HI (P<0.01). PDMin significantly reduced in all groups (P<0.005) except the HC group (P=0.054, Fig 5.1).

5.3.3 Effect of diagnostic anaesthesia on forelimb movement

HMA assigned to the ipsilateral forelimb significantly reduced in all groups (H-all and HI P<0.001, HO P<0.05) except the HC group (P=0.112). The HMA assigned to the contralateral forelimb significantly increased in the HI group only (P<0.05) following diagnostic anaesthesia performed on the lame hindlimb. HDMax, HDMin and VS all significantly reduced in the HI group (P<0.01, P<0.01, P<0.05 respectively). Neither HDMax, HDMin or VS parameter significantly reduced in the HO group (P=0.07, P=0.271 and P=0.357 respectively). HDMax significantly reduced in the HC group (P<0.05); HDMin and VS did not significantly change. All three parameters (HDMax, HDMin and VS) significantly reduced when the data were analysed as a whole group (P<0.01, P<0.05, P<0.01 respectively). The data are displayed in Figure 5.2.

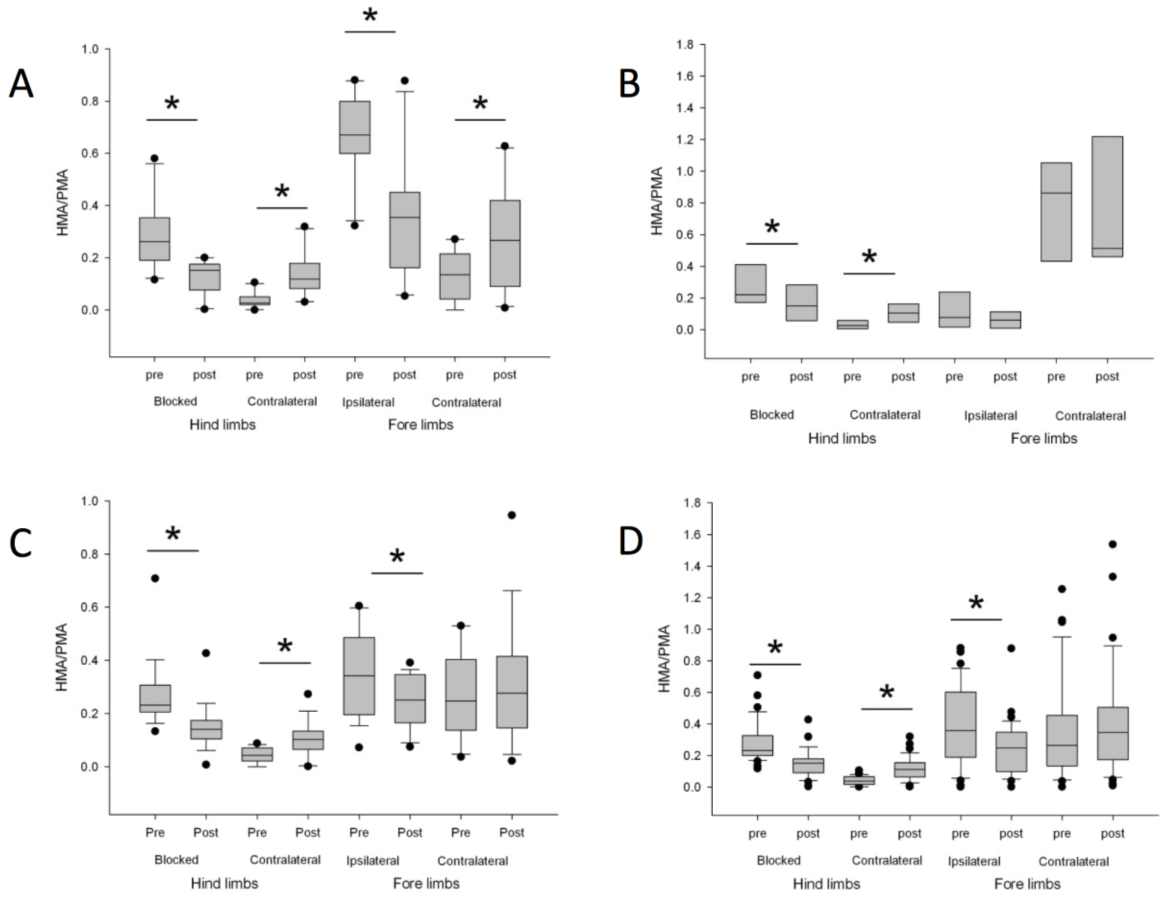

Figure 5.1: Box and whisker plots showing movement asymmetry (HMA for the forelimbs and PMA for the hindlimbs) assigned to each limb (HI (A), HC (B), HO (C) and H-all (D)) prior to diagnostic anaesthesia (pre) and after diagnostic anaesthesia (post) performed on the lame (affected) hindlimb.

***** Significant difference (P<0.05) between pre and post anaesthesia groups.

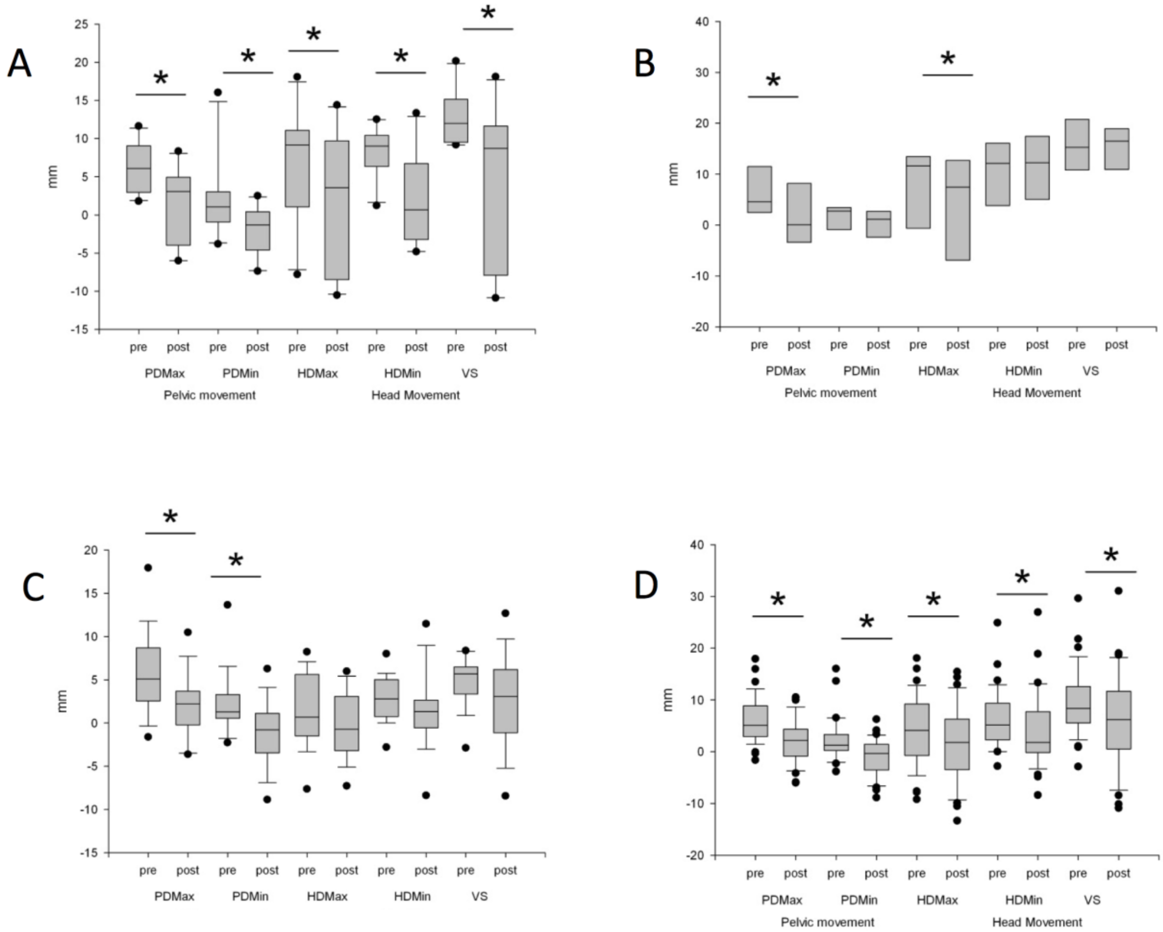

Figure 5.2: Box and whisker plots showing PDMax, PDMin, HDMax, HDMin (in millimetres) and vector sum, VS, associated with the HI (A), HC (B), HO (C) and H-all (D) groups prior to diagnostic anaesthesia (pre) and after diagnostic anaesthesia (post) performed on the lame (affected) hindlimb.

***** Significant difference (P<0.05) between pre and post anaesthesia groups.

Median values (baseline and post anaesthesia) for each of the kinematic parameters within each group are reported (Table 5.2).

Parameter/Group	PMA Blocked hindlimb	PMA Contralateral hindlimb	HMA Ipsilateral forelimb	HMA Contralateral forelimb	PDMax	PDMin	HDMax	HDMin	Vector sum
HI-Baseline	0.26	0.03	0.67	0.14	6.09	1.05	9.15	9.00	11.98
HI-Post anaesthesia	0.15*	0.12*	0.35*	0.27*	3.08*	-1.33*	3.56*	0.65*	9.67*
HC-Baseline	0.22	0.03	0.08	0.86	4.60	2.74	11.62	12.13	15.31
HC-Post anaesthesia	0.15*	0.11*	0.06	0.51	0.08*	1.15	7.46*	12.27	16.46
HO-Baseline	0.23	0.04	0.34	0.25	5.10	1.27	0.67	2.78	5.68
HO-Post anaesthesia	0.14*	0.10*	0.25*	0.28	2.20*	-0.81*	-0.73	1.31	3.07
H-all-Baseline	0.23	0.04	0.36	0.26	5.10	1.27	4.15	5.15	8.36
H-all-Post anaesthesia	0.15*	0.11*	0.25*	0.34	2.20*	-0.30*	1.81*	1.77*	7.75*

Table 5.2: Median values of kinematic parameters (baseline and post anaesthesia) for the horses in each group.

*Significant difference in medians between baseline and post diagnostic anaesthesia.

A comparison of the baseline (pre anaesthesia) hindlimb parameters (PMA assigned to the blocked limb, PDMax and PDMin) obtained was made between the HO, HI, HC and H-all groups using a Kruskal One Way analysis based on Ranks, and revealed no significant difference in the hindlimb parameters between the four groups.

No significant correlation between any of the forelimb and hindlimb parameters was identified in any of the four groups.

5.4 Discussion

A forelimb lameness that improved significantly with hindlimb diagnostic anaesthesia was identified in over a quarter of hindlimb lameness cases (27%). All groups analysed showed significant improvement (reduction) to the asymmetry assigned to the ipsilateral forelimb (except the HC group). A significant increase to the asymmetry of the contralateral forelimb was noted in the HI group only. Significant reduction to head height (VS, HDMax and HDMin) was identified in the HI group and in the hindlimb lameness group analysed as a whole (H-all) following diagnostic anaesthesia. A significant reduction in HDMax was identified in the HC group, however HDMin and VS both increased marginally in this group, which is in contrast to all the other groups were a reduction to all three parameters was noted. The reduction in the parameters noted provides evidence to suggest that there is a subclinical compensatory component in these horses. Furthermore the data shows that subclinical compensatory forelimb lameness occurs fairly commonly in horses with hindlimb lameness. Although a reduction to all three parameters pertaining to head movement was noted in the hindlimb lameness only group (HO), none of the changes were significant.

The compensatory forelimb lameness observed in this clinical population was ipsilateral in origin and therefore agrees with previous descriptions as defined by the “law of sides” (Uhlir *et al.*, 1997 and Ross and Dyson *et al.*, 2010). This study has provided the first objective data in a significant number of clinical cases to support this often quoted clinical guideline. Of the cases classified as demonstrating forelimb lameness 55% were classified as ipsilateral. Contralateral forelimb lameness in cases with hindlimb lameness was less commonly reported in these cases, noted in 45% of cases classified as demonstrating forelimb lameness. Further analysis of the data in this contralateral forelimb lameness group revealed that the forelimb lameness observed in this subpopulation has different characteristics to the other three groups. Median HDMin and VS values both increased insignificantly in this group, which as previously mentioned, is in contrast to all the other groups were a reduction to all three parameters was noted. A significant reduction in HDMax (but not HDMin or VS) was noted in this group however no significant change to the asymmetry of the ipsilateral forelimb was noted in this group, which again is in contrast to the other three groups where a significant reduction to the HMA assigned to the ipsilateral forelimb was noted. The median value of HMA (ipsilateral forelimb) was almost unchanged between the pre and post diagnostic anaesthesia data. Vector sum is accepted as being the best parameter to measure head movement, and in this contralateral forelimb lameness group a significant change to this parameter was not noted. Thus the conclusion is that the horses classified as demonstrating contralateral forelimb lameness are in fact horses with true forelimb lameness and thus no improvement to the head movement and forelimb asymmetry parameters or similar trends pertaining to these parameters following diagnostic anaesthesia, as observed within the other groups, is noted in this group. A future study to evaluate the source of forelimb lameness in this population is warranted.

The difference in minimum head height (HDMin) significantly decreased in the HI group and all horses analysed as a whole group following a positive response to local anaesthesia. Although median HDMin reduced following diagnostic anaesthesia in the HO group, this change was not significant (see Figure 5.2C). This may be due to the lack of power due to the relatively small group size, or it may reflect a real difference between the groups. The former seems less likely as the HI group was smaller than the HO group. The finding within the HI group may be explained by the apparent difference in head height during the stance phases of the two forelimbs. Less downward movement of the head on the contralateral forelimb will occur during the stance phase following improvement to the hindlimb lameness and subsequent load re-distribution (Weishaupt *et al.*, 2004) thus the average difference in head height during the stance phases of the right and left forelimbs becomes less. This implies that during hindlimb lameness in this group there is a significant alteration in head movement downwards during the weight-bearing and loading phase as a result of the altered distribution in weight. A study of induced and naturally occurring hindlimb lameness revealed that the head moves down less during the stance phase of the ipsilateral forelimb (Keegan *et al.*, 2004). One would thus expect more downward movement of the head during the stance phase of the ipsilateral forelimb following abolition of the hindlimb lameness, and thus the apparent difference in head height between the weightbearing phases of the two forelimbs becomes less.

In cases classified as demonstrating hindlimb lameness with ipsilateral forelimb lameness (HI group), compensatory forelimb lameness was both impact and loading related (HDMax, HDMin and VS all significantly reduced). However, in cases with only hindlimb lameness (HO) neither push-off (HDMax) or impact/loading (HDMin) significantly changed, nor did the vector sum although the medians of each reduced following the diagnostic anaesthesia undertaken. Increased severity of the hindlimb lameness in the HI group and greater load re-distribution would be a feasible explanation. However, this was not supported by the comparison of the baseline (pre anaesthesia) parameters undertaken between the groups. In none of the hindlimb lameness groups did the severity or characteristics (in terms of movement asymmetry of the respective hindlimb nor impact or push off component referring to PDMax/PDMin in hindlimb lameness) of the primary lameness significantly differ between the subgroups. In the analysis of all horses with hindlimb lameness group the forelimb lameness observed was both impact and loading related (HDMax, HDMin and VS all significantly reduced) in a similar manner to the HI group. Analysis of the kinematic parameters of the HC group revealed that the forelimb lameness in this group may appear to be push-off related (HDMax significantly reduces), however the more reliable parameter vector sum in fact increases marginally.

In forelimb lameness, one would expect to see greater push-off from the sound limb (see Chapter 2). In the case of compensatory lameness, greater push-off from the contralateral forelimb was observed in two groups (HI group and H-all), which will be observed as ipsilateral forelimb lameness. VS only significantly changed in the HI and H all groups combined between pre and post anaesthesia parameters, similarly to HDMax/HDMin. In this population of horses (HI and H-all), all three parameters identified significant changes to head movement asymmetry, however using VS alone perhaps better represents vertical head height in other situations. The HC group may be an example of this since HDMax significantly reduced, however VS insignificantly increased. This highlights the possible danger of overinterpreting a change to one parameter in isolation. Head movement asymmetry (HMA) of the ipsilateral forelimb significantly reduced following a positive response to diagnostic anaesthesia in all groups except the HC group. HMA assigned to the contralateral forelimb only significantly increased in the HI group only. The former may be explained in part by the general decrease in vertical head movement asymmetry following a positive response to diagnostic anaesthesia due to fewer alterations in load redistribution i.e. the return to more symmetrical movement in the absence of lameness. In the data presented in Chapter 2, greater head movement asymmetry of the contralateral forelimb following a positive response to local anaesthesia in a forelimb was noted and a similar phenomenon was noted when analysing the data for the current population. This may be due to the measures of head movement asymmetry (HMA) being relative measures related to the number of asymmetric strides assigned to one forelimb, which inevitably is loosely related to the number of asymmetric strides assigned to the other forelimb. It may also represent a true worsening of the asymmetry of the contralateral forelimb due to the effect of altering sensation to the other forelimb, which may alter the symmetry of movement. In the HC group the median HMA assigned to the contralateral forelimb reduced in contrast to all the other horses, implying that symmetry to that limb was restored and one may suspect that the origin of the lameness in that forelimb in this group is thus perhaps different to the other three groups. The apparent minimal change to the median HMA assigned to the ipsilateral forelimb in this group would support the absence of a compensatory component to this forelimb lameness in this group.

The significant improvement in PMA of the blocked limb and significant worsening of the PMA in the contralateral hindlimb following a positive response is to be expected, as there will be alterations in weight distribution from one hindlimb to another to restore symmetry of movement following improvement to the lameness. This trend was noted in all four groups. Median PDMax and PDMin significantly decreased in all groups (except PDMin in the HC group) implying that the impact and push off component as a result of the hindlimb lameness was reduced by diagnostic anaesthesia. Hindlimb lameness in this population of horses therefore appears to result in alterations to push off and impact in all groups except the HC group where the hindlimb lameness was only push off related.

Given the significant changes noted to the asymmetry of the forelimbs in a fairly large proportion of the horses (changes in the asymmetry of at least one forelimb in all horses except those in the HC group) and given the significant changes in the vertical head movement during and after the stance phase/VS in both the HI group and all horses group, the author believes that there is sufficient evidence to reject the null hypothesis. There is significant load redistribution as a result of hindlimb lameness and this may be observed as ipsilateral forelimb lameness in over a quarter of horses with hindlimb lameness. In a larger proportion of cases this phenomenon is observed sub-clinically.

Limitations to the analysis and findings of the study are in part similar to those in Chapter 2 and 4; variations in horse movement due to only analysing a minimum of 30 strides for each data entry may have had an affect on the data and subjective analysis was reliant on one of only two observers. Additionally, since the source of lameness varies between horses and the diagnostic anaesthesia technique undertaken in each case was one of several possible techniques, it is possible that subtleties may have been missed and that characteristics of lameness associated with certain diagnoses result in specific alterations to specific kinematic parameters which could not be elucidated due to the analysis being undertaken as a group regardless of diagnostic anaesthesia technique performed. However the latter was not an objective, although it would be of interest to further investigate the kinematics associated with specific conditions. Since certain conditions are bilateral, a positive response to diagnostic anaesthesia in some cases resulted in the horse becoming lame on the other hindlimb, thus this may have resulted in a more marked change to the forelimb parameters than in cases with a unilateral condition. This may have resulted in the change in some parameters being overrepresented, for example the parameters associated with limb movement asymmetry (HMA/PMA). However, since the directionality of the vertical pelvic and head movements was taken into account (HDMax/HDMin, PDMax/PDMin), this should only have affected the latter parameters by the magnitude of the delta values being larger than in a case associated only with a unilateral lameness. No significant correlation between any of the forelimb and hindlimb parameters was identified in any of the four groups, which was surprising, and may reflect lack of statistical power of the study.

It is unknown from this study whether specific hindlimb lamenesses have a push off or impact component i.e. if specific types of lameness display more specific kinematic characteristics e.g. horses with osteoarthritis of the distal tarsal joints. One may expect that some hindlimb lamenesses may show characteristics of a push off component only. Further analysis of data from a larger population of horses with hindlimb lameness objectively confirmed and various diagnostic anaesthesia techniques undertaken would possibly reveal the answer. If there were such characteristics identified, it may be possible for clinicians to more rapidly diagnose the source of lameness, by narrowing the possible source of lameness from the beginning of the investigation, purely by assessing the characteristics of the horse’s movement in the baseline examination.

5.5 Conclusions

By analysing the data from this population of horses with hindlimb lameness it has been possible to expand upon previously assumed knowledge by characterising the compensatory forelimb lameness observed in clinical cases, in addition to providing evidence objectively supporting the "law of sides" in a moderately sized population of horses. Analysis of all horses as a whole group revealed that the forelimb lameness consists of a push off and an impact component. HDMax, HDMin and vector sum were significantly reduced following a positive response to diagnostic anaesthesia. When assessing the lame horse it is important to eliminate forelimb lameness as a possible result (compensatory component) of hindlimb lameness prior to performing further diagnostic techniques. In the current population compensatory forelimb lameness was observed in 27% of horses with hindlimb lameness (referring to head height), although significant changes in asymmetry occurred in all four limbs in almost all horses (all horses except in the hindlimb lameness with contralateral forelimb lameness group). The former can be visually detected as the height of the head in space. The latter parameter of head movement asymmetry originates from the number of asymmetric strides assigned to each limb and may refer to horizontal asymmetry of the head. Examination of the data shows that significant changes to the asymmetry of both forelimbs occur in most cases of hindlimb lameness (except the hindlimb with contralateral forelimb lameness group), however significant changes in vertical head movement is only identified in a proportion of these cases (restricted to the HI group in this population). This has implications for lameness investigations. When assessing the response to hindlimb diagnostic anaesthesia in horses with ipsilateral forelimb lameness it is useful to define the effect on both the hind and forelimb movement. Additionally, the data shows that a small (insignificiant) improvement to the head movement asymmetry occurs in many horses following local anaesthesia of the hindlimb, and this is thus phenomenon of ipsilateral forelimb lameness in horses with hindlimb lameness, affects many horses to differing degrees.

Contralateral forelimb lameness in combination with hindlimb lameness was observed in 22% (8/37) of cases with hindlimb lameness and may reflect true forelimb lameness and true hindlimb lameness rather than compensatory forelimb lameness as a result of the primary hindlimb lameness, as the forelimb lameness did not significantly change in this group following a positive response to diagnostic anaesthesia. In groups where there was a significant change to the forelimb parameters the movement asymmetry assigned to at least one of the forelimbs significantly changed. Additionally in two of the groups the vector sum along with HDMax and HDMin significantly reduced. Further investigation into the phenomenon of contralateral forelimb lameness is warranted.

CHAPTER 6:

Practical, objective assessment of lameness in the horse and elucidating compensatory lameness: Summary

The analysis undertaken in this study has led to the conclusion that the “Lameness Locator®” inertial sensor-based system of lameness diagnosis may be used in an easy and effective manner to guide veterinarians undertaking lameness examinations. The need for further objective evaluation of the lame horse has been described by previous studies. This project has provided useful and significant information for clinicians performing lameness examinations both with and without an inertial sensor-based system of lameness diagnosis. The inertial sensor-based system of lameness diagnosis has significant potential and expansion of its use in the future may lead to a better understanding of lameness in horses with specific clinical diagnoses and studies undertaken into its use in evaluating lameness in horses under different conditions may prove beneficial e.g. during lunging.

The first part of this study investigated the use of an inertial sensor-based system of lameness diagnosis as part of lameness evaluations and evidence was provided to support its usefulness in classification of a positive response to a diagnostic anaesthesia. The ability of the system to adequately distinguish a positive from a negative response to a very commonly performed diagnostic anaesthesia (nerve block of the foot) was demonstrated. Evidence of compensatory lameness in the horses in this population was identified as significant improvement in pelvic movement asymmetry of the contralateral hindlimb. This provided supporting evidence of the existence of compensatory lameness in horses with forelimb lameness. In this first part of the investigation the lameness was restricted to lameness of the foot. However, expansion of the investigation was undertaken in Chapter 4. Comprehensive analysis of hindlimb movement and kinematics was performed in depth in order to fully investigate this phenomenon in a larger population of horses with forelimb lameness originating from various sources.

Further investigation into compensatory lameness was undertaken in two parts. Firstly, forelimb lameness was investigated along with its compensatory components, followed by hindlimb lameness and its compensatory effects. An inertial sensor-based system of lameness diagnosis (“Lameness Locator®”) was used to objectively investigate compensatory load redistribution in horses with clinical lameness by examining the effect of alleviating lameness through diagnostic anaesthesia. The study demonstrated that (1) forelimb lameness results in significant load redistribution, which may be observed as contralateral hindlimb lameness and (2) hindlimb lameness results in significant load redistribution, which may be observed as ipsilateral forelimb lameness. This is supported by findings in individual cases of lameness as mentioned in Chapter 3 and by the “rule of sides”.

This project has investigated two important aspects of lameness in the horse: objective assessment of lameness and compensatory lameness in both forelimb and hindlimb lameness. This inertial sensor-based system of lameness diagnosis can be a useful tool in lameness investigations and some guidelines have been provided to aid interpretation of changes to kinematic parameters in this project. Further investigation of the use of this system in lameness examinations would be beneficial and would possibly further support this use of the system in a clinical setting. Investigations of the use of the system in lameness investigations performed under different conditions e.g. during lunging, and investigation of the kinematics of specific conditions e.g. suspensory ligament desmitis versus osteoarthritis of the distal tarsal joints may reveal characteristics associated with specific conditions which may lead to a more rapid diagnosis being made, are potential future avenues to pursue.

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