Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2020:12
Faculty of Veterinary Medicine and Animal Science

Evaluation of vertical movement asymmetries in riding horses

-relevance to equine orthopaedics

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Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2020

Acta Universitatis Agriculturae Sueciae
2020:12

Cover: Withers markers on ‘Tira Mi Su’, owner Charlotte Frisch.
(Photo: Elin Holmroos)

ISSN 1652-6880
ISBN (print version) 978-91-7760- 542-3
ISBN (electronic version) 978-91-7760-543-0
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Print: SLU Service/Repro, Uppsala 2020

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Abstract

Disorders of the locomotor apparatus are very common in sports horses. Pain and dysfunction associated with these conditions have a negative impact on horse welfare. The main component in lameness evaluation is detection of vertical movement asymmetries but the inter-rater agreement among veterinarians is low. Therefore, modern methods of detection and quantification of movement asymmetry have been developed.

The aim of this thesis was to help improve equine welfare by providing a better scientific basis for interpretation of movement asymmetries. This could support riders and veterinarians in detecting lameness at an early stage and improve orthopaedic diagnostics.

To investigate a possible association between movement asymmetry and presence of painful orthopaedic conditions, NSAID (meloxicam) treatment was performed in asymmetrically moving, but presumed sound horses. Interestingly, this did not decrease the magnitude of asymmetry. Other reasons for asymmetric movement and the clinical efficacy of treatment with meloxicam in relation to a potentially present pathology therefore need to be addressed.

The influence of the rider's seating style on vertical movement symmetry in trot was evaluated in 26 horses. 'Rising trot' induced systematic changes, the most prominent being a decreased pelvic rise, mimicking push-off lameness in the hindlimb of the diagonal on which the rider was sitting in 'rising trot'.

The potential of the relationship between the direction of head and withers movement asymmetry parameters to assist in locating the primary lame limb was investigated in horses with induced lameness. The findings were then verified in horses with naturally occurring lameness. The results showed that head and withers movement asymmetry parameters indicate the same forelimb in horses with forelimb lameness, but indicate opposite forelimbs in horses with hindlimb lameness and compensatory head movement asymmetry.

The results presented in this thesis extend existing knowledge about the origin and significance of movement asymmetries in riding horses and compensatory mechanisms in lame horses.

Keywords: compensatory lameness, withers asymmetry, optical motion capture, inertial measurement units, NSAID, rising trot, rider, lameness, equine, kinematics

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Dedication

To Olle, my family and friends <3

"It's a dangerous business, Frodo, going out of your door. You step into the road, and if you don't keep your feet, there is no knowing where you might be swept off to."

J. R. R. Tolkien. The Lord of the Rings

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Persson-Sjodin E.*, Hernlund E., Pfau T., Haubro Andersen P., Holm Forsström K., Rhodin M. (2019). Effect of meloxicam treatment on movement asymmetry in riding horses in training. *PLoS ONE*, 14(8), pp. e0221117.

II Persson-Sjodin E.*, Hernlund E., Pfau T., Haubro Andersen P., Rhodin M. (2018). Influence of seating styles on head and pelvic vertical movement symmetry in horses ridden at trot. *PLoS ONE*, 13(4), pp. e0195341.

III Rhodin, M.*, Persson-Sjodin, E., Egenvall, A., Serra Bragança, F.M., Pfau, T., Roepstorff, L., Weishaupt, M.A., Thomsen, M.H., van Weeren, P.R., Hernlund, E. (2018). Vertical movement symmetry of the withers in horses with induced forelimb and hindlimb lameness at trot. *Equine Veterinary Journal*, 50(6), pp. 818-824.

IV Persson-Sjodin, E.*, Hernlund, E., Pfau, T., Haubro Andersen, P., Holm Forsström, K., Byström, A., Serra Bragança, F.M., Hardeman, A., Greve, L., Egenvall, A., Rhodin, M. Vertical movement symmetry of the withers in horses with naturally occurring forelimb and hindlimb lameness at trot. (manuscript)

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The contribution of Emma Persson-Sjödin to the papers included in this thesis was as follows:

I Main responsibility for part of the data acquisition, main responsibility for data analysis, main responsibility for summarising results, main responsibility for writing and critically revising the article with input from co-authors.

II Shared responsibility for design of the study, took part in all data acquisition, shared responsibility for data analysis, main responsibility for summarising results, main responsibility for writing and critically revising the article with input from co-authors.

III Shared responsibility for data analysis and summarising results, shared responsibility for drafting and critical revision of the article.

IV Shared responsibility for design of the study, shared responsibility for data acquisition, main responsibility for data analysis, main responsibility for summarising results, main responsibility for writing and critically revising the article with input from co-authors.

Abbreviations

OMC	Optical motion capture
IMU	Inertial measurement unit
ROM	Range of motion
NSAID	Nonsteroidal anti-inflammatory drug
Mindiff	Difference in minimum position
Maxdiff	Difference in maximum position
HDmin	Difference in minimum position of the head
HDmax	Difference in maximum position of the head
WDmin	Difference in minimum position of the withers
WDmax	Difference in maximum position of the withers
PDmin	Difference in minimum position of the pelvis
PDmax	Difference in maximum position of the pelvis
HDRup	Difference in range up of the head
WDRup	Difference in range up of the withers
PDRup	Difference in range up of the pelvis

1 Introduction

1.1 General introduction

Disorders of the locomotor apparatus are the most common reason for equine veterinary consultation (Penell *et al.*, 2005; Nielsen *et al.*, 2014). Locomotor pathology is also believed to be the most common cause of euthanasia in the Swedish riding horse population (Egenvall *et al.*, 2006). Pain and dysfunction associated with these conditions have a negative impact on horse welfare and can be assumed to contribute to decreased performance in sports horses. Unrecognised pain and suffering in sports horses might also ultimately undermine the ethics of keeping them as companion animals. This emphasises the importance of early detection and accurate diagnosis of orthopaedic disorders. When a diagnosis is obtained, correct and prompt treatment can be initiated, mitigating the risk of the pathology progressing into irreversible stages such as cartilage degeneration and osteophytes due to sustained joint inflammation (McIlwraith *et al.*, 2010; Olive *et al.*, 2010; Goldring and Otero, 2011).

When an orthopaedic disorder is suspected, a lameness examination is conducted to investigate the presence and cause of pain and pathology. Most orthopaedic disorders are painful and therefore cause the horse to alter its movement pattern. The principal component of a lameness examination is therefore detection of vertical movement asymmetries, such as the well-known ‘head nod’ and ‘pelvic hike’. Currently, such asymmetries are mainly detected by subjective evaluation of the horse’s movement under a number of different conditions. This generally includes the observation of the horse while walking, trotting and cantering, in straight line and circles, and sometimes also while ridden (Baxter and Stashak, 2011). However, pinpointing the limb from which suspected lameness is originating has been proven to be a challenging task.

Multiple studies have shown that the inter-rater agreement among veterinarians performing this task is low (Fuller *et al.*, 2006; Hewetson *et al.*, 2006; Keegan *et al.*, 2010; Hammarberg *et al.*, 2016; Leelamankong *et al.*, 2019). A factor probably contributing to the diagnostic difficulty, expressed by low reproducibility, is the limited human capacity for visual perception of asymmetry (Parkes *et al.*, 2009) and the limited temporal resolution of the human eye (Holcombe, 2009).

Once vertical movement asymmetries have been identified, and a suspected painful limb is pinpointed, the next step is to identify the injured anatomical structure. This is generally achieved through diagnostic analgesia, in terms of location guided by flexion tests and palpation (Baxter and Stashak, 2011). Diagnostic analgesia causes reversible loss of nociception from a specific joint or anatomical region and the resulting reduction in pain increases the symmetry of the horse's movement pattern (Keegan *et al.*, 1997; Maliye *et al.*, 2013; Pfau *et al.*, 2014; Rungsri *et al.*, 2014). Subjective assessment of movement symmetry is used to evaluate the response to diagnostic analgesia, but is influenced by expectation bias (Arkell *et al.*, 2006) and is also subject to the aforementioned limitations of visual assessment.

These diagnostic challenges summarised above have led to much research into objective systems that can assist the veterinarian in detection and quantification of movement asymmetry. Modern methods by which vertical movement asymmetry can be easily detected and documented have been developed. The sensitivity of objectively measured movement asymmetry in detection of orthopaedic pain originating from a limb is high (Peloso *et al.*, 1993; Buchner *et al.*, 1996; Kramer *et al.*, 2000, 2004; Keegan *et al.*, 2001; Rhodin *et al.*, 2013; Tóth *et al.*, 2014), but the specificity is not well investigated. Furthermore, vertical movement asymmetries are common even in sports horses that are presumably sound (Rhodin *et al.*, 2017). Other reasons for movement asymmetry, such as biological variation, inherent laterality and conformational asymmetries, may thus exist.

Asymmetric vertical movement is an important symptom of orthopaedic disorder, but it may also be a biological variation. More knowledge of interpretation of movement asymmetries in different settings is needed in order to enable lameness to be detected more accurately and at an earlier stage. The aim of this thesis was therefore to investigate how the output of modern movement symmetry analysis can be understood and applied under different circumstances. The specific aims and hypotheses and objectives of the work are presented in Chapters 2 and 3.

In the following sections, targeted overviews are provided of the main methodologies involved, and the current state of knowledge of subject areas covered in the thesis. Current concepts of objective symmetry analysis in horses are described in section 1.2, while the prevalence of movement asymmetries in the riding horse population is reviewed in section 1.3. The complex clinical issues of ameliorating or reducing orthopaedic pain, by analgesic testing, and the use of non-steroidal anti-inflammatory drugs are described in section 1.4. Background on how the rider can influence movement asymmetry in the ridden horse is provided in section 1.5. Finally, two clinically important concepts, namely compensatory asymmetries in lame horses and the hitherto rather overlooked significance of withers movement asymmetry are summarised in sections 1.6 and 1.7, respectively.

Equine biomechanics is very much an interdisciplinary field of research encompassing veterinary sciences and engineering sciences. The focus of this thesis is on veterinary medicine, and not on more technical aspects pertaining to methods of data collection or analysis of biomechanical signals. Two different objective motion analysis systems were used in this thesis, based on convenience for the different studies, but without the intention of evaluating or comparing the systems as such.

Defining what constitutes lameness seems at first glance reassuringly simple, but has recently sparked much debate (van Weeren *et al.*, 2017; Adair *et al.*, 2018; Bathe, Judy and Dyson, 2018). Virtually all classifications of lameness in the literature allude to an underlying pathological condition, *e.g. "Lameness is an indication of a structural or functional disorder in one or more limbs or the back that is evident when the horse is standing or at movement"* (Baxter and Stashak, 2011) and *"Lameness is simply a clinical sign – a manifestation of the signs of inflammation, including pain, or a mechanical defect – that results in a gait abnormality characterized by limping"* (Ross, 2011a). In this thesis, the word 'lameness' is being used when there is evidence, or at least a strong suspicion, of pain and/or pathology, while the word 'asymmetry' is used in other cases of deviation from symmetrical vertical movement.

1.2 Measuring movement asymmetry

1.2.1 Kinetics

Kinetics is the study of the forces that cause movement, relating to the equine body in this thesis. Stationary force plates have long been used for this application (Morris and Seeherman, 1987; Merkens and Schamhardt, 1988) and this approach is still considered the gold standard for lameness detection. The most commonly reported changes associated with lameness in trot are a reduction in peak vertical force, a reduced vertical impulse and a reduced peak horizontal braking force in the lame limb (Morris and Seeherman, 1987; Clayton *et al.*, 2000; Weishaupt *et al.*, 2004; Ishihara *et al*., 2005; Weishaupt *et al.*, 2006). These parameters directly quantify the decreased loading of the lame limb and thus have the potential to guide the clinical decision process in a lameness evaluation. However, without a treadmill with an integrated force-measuring system enabling collection of data on multiple consecutive strides, currently only a setup available at a single location (Weishaupt *et al.*, 2002), the data collection process is cumbersome and time-consuming. Seamless integration into clinical everyday practice is currently better achieved with kinematic systems and these have therefore acquired more widespread clinical use. For this reason, together with the greater ease of using kinematic systems under field conditions, kinematic instead of kinetic systems were employed in the studies presented in this thesis.

1.2.2 Kinematics

Kinematics involves describing and quantifying both the linear and angular position of the equine body and their time derivatives velocity and acceleration. In the past, this was achieved by high-speed cinematography (Fredricson *et al.*, 1980), digitalised partly by hand in a time-consuming process. Since then, continuous technical advances through systems enabling collection of data at higher recording speeds and in three dimensions (van Weeren *et al.*, 1990) have led to today's optical motion capture (OMC) systems (Hardeman *et al.*, 2019) which are able to display the results almost instantly. Utilising an array of cameras, these systems can be used not only to measure horses trotting on a treadmill, but also during locomotion over ground in clinical lameness assessments. However, the use of OMC systems in ambulatory clinical work or in many field studies is impeded by the laborious set up process. The cameras need to be carefully and securely positioned around the intended measuring volume, making it time-consuming to move them from one location to another.

An alternative method for kinematic measurements, developed in parallel with OMC, is based on body-mounted accelerometers (Barrey *et al.*, 1994). Technical advances have enabled development of wireless sensors, combination of accelerometers with gyroscopes and magnetometers and miniaturisation of these into small inertial measurement units (IMU). Accelerometer- and IMU-based systems enable measurement of vertical movement asymmetry during lameness evaluations (Pfau *et al*., 2005; Halling Thomsen *et al.*, 2010; Keegan *et al.*, 2011; Bosch *et al.*, 2018) and also under a variety of field conditions, due to the ease of setup. The main drawback with these systems is the reduced accuracy compared with OMC when measuring displacement. The reasons behind this relate to the lack of capacity for direct displacement measurements and to the resulting integration errors caused by factors such as sensor drift (Peham, 2013). The focus of most previous research regarding the use of kinematics in lameness assessments has been on the vertical movement of the horse's head and trunk and on changes in temporal and angular limb motion (for review see Serra Bragança *et al*., 2018). In commercial systems currently used in clinical practice the most commonly used parameters quantify asymmetry of upper body vertical displacement (Pfau *et al*., 2005; Keegan *et al.*, 2011; Bosch *et al.*, 2018; Hardeman *et al.*, 2019). Vertical asymmetry parameters have also been evaluated in the majority of recent research within this area. The widespread use of vertical displacement, rather than vertical velocity or acceleration, is probably in part due to its closeness to what is visually appreciated, potentially contributing to a more straightforward interpretation for the clinicians. Ease-of-use of objective symmetry analysis systems is important, as it facilitates integration into the clinical every-day situation and could result in more horses benefitting from increased orthopaedic diagnostic accuracy.

1.2.3 Kinematic measurement of asymmetry in trot

Trot is the most commonly used gait in kinematic analysis aimed at lameness detection. It is a symmetrical two-beat gait with alternating loading of the two diagonal limb pairs. At trot in a straight line, the head and the tubera sacrale of the pelvis rise and fall twice during a complete stride cycle describing a typical double sinusoidal pattern. With increasing lameness, this sinusoidal pattern shows increasing amount of asymmetry between the two stride halves (Peloso *et al.*, 1993; Buchner *et al.*, 1996). In lame horses, the head or pelvis has a higher minimum position during midstance of the lame limb compared with midstance of the contralateral non-lame limb (Figure 1). This asymmetry can be measured by calculating the difference between the two minimum positions, the mindiff (Keegan *et al.*, 2000, 2001; Kramer *et al.*, 2004; Kelmer *et al.*, 2005; Rhodin *et al.*, 2013; Tóth *et al.*, 2014). Another common adaptation of the horse in order to avoid pain in an extremity, is to reduce the maximum position reached, by the head or pelvis, directly following the stance phase of the lame limb, compared with the position after the sound stance (Figure 1). This difference in the maximum vertical position (maxdiff) has also been shown to be a reliable parameter for quantifying lameness (Kramer *et al.*, 2004; Kelmer *et al.*, 2005; Rhodin *et al.*, 2013; Tóth *et al.*, 2014).

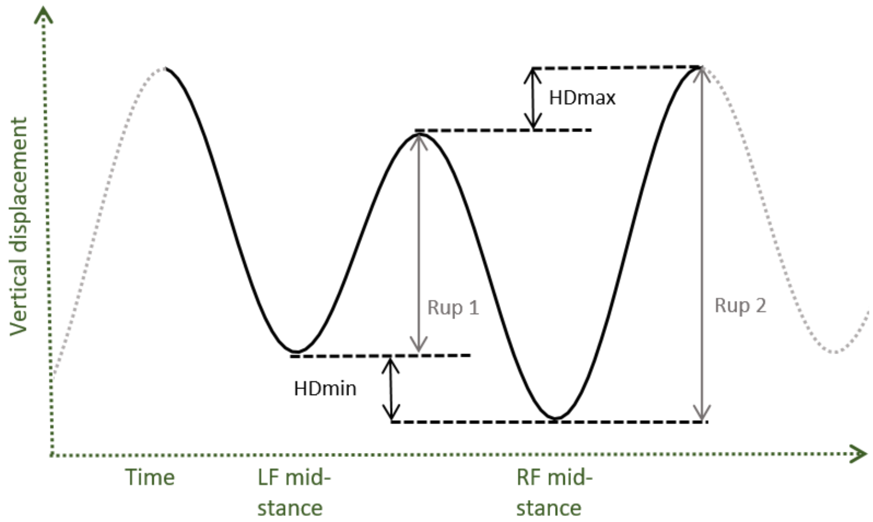

Figure 1. Example of vertical displacement of the head in a horse with left forelimb lameness, resulting in negative HDmin, HDmax and HDRup (Rup 1–Rup 2) values. Pelvic and withers movement asymmetry parameters are calculated in the same way but from vertical withers and pelvis displacement signals.

The relationship of the min- and maxdiff parameters to the actual decrease in loading of the lame limb has been investigated. Keegan *et al.* (2012) demonstrated a clear relationship between the combined min- and maxdiff and the difference in peak vertical force in horses with forelimb lameness. Horizontal forces were not measured in that study. In another study the relation between min- and maxdiff and the ground reaction forces of the hindlimbs was investigated (Bell *et al.*, 2016). An increase in absolute mindiff was most strongly associated with a decrease in peak vertical force, reflecting decreased weight-bearing of the hindlimb. An increase in absolute maxdiff (push-off asymmetry) on the other hand, was most strongly correlated to a slightly reduced vertical ground reaction impulse and increased horizontal impulse in the second half of the stance phase of the lame hindlimb.

The asymmetry in vertical movement that can be quantified by mindiff and maxdiff can also be measured as a decrease in the total amplitude of upward vertical displacement of the head and pelvis during the stance of the lame limb. This asymmetry can be quantified as the difference in upward range between contralateral steps or as a symmetry index (Peloso *et al.*, 1993; Buchner *et al.*, 1996).

The head, withers and pelvis all have a similar total range of motion (ROM) in a sound horse (Peloso *et al.*, 1993; Buchner *et al.*, 1996; Heim *et al.*, 2016). Due to the increased ROM during sound limb stance, total ROM increases for all landmarks in lame horses but most markedly for the head (Peloso *et al.*, 1993; Buchner *et al.*, 1996; Keegan *et al.*, 2000). Due to this, the head-derived mindiff, maxdiff and difference in upward range are all generally larger than their pelvic-derived counterparts for the same subjective degree of lameness (Buchner *et al.*, 1996; Kelmer *et al.*, 2005).

All the parameters mentioned above quantify contralateral differences. One disadvantage is that none of these will detect asymmetry in cases of bilateral lameness of equivalent severity during straight line motion (Buchner *et al.*, 1995; Pourcelot *et al.*, 1997; Keegan *et al.*, 2012). The same problem is also inherent to visual lameness evaluation conducted during straight line locomotion. The common solution in the clinical situation is to assess the horse on the lunge, a condition that while helpful, also introduces additional confounders, as discussed further below.

In addition to changes in head and pelvic (tubera sacrale) asymmetry, as described above, lameness has also been shown to significantly alter other objectively measurable asymmetry parameters. Some of these, such as the movement symmetry of the tubera coxae (May and Wyn-Jones, 1987; Buchner *et al.*, 1996; Kramer *et al.*, 2000) and limb joint angle kinematics (Ratzlaff *et al.*, 1982; Buchner *et al.*, 1996; Clayton *et al.*, 2000; Keegan *et al.*, 2000; Kramer *et al.*, 2000; van Loon *et al.*, 2010) are used as visual cues by some clinicians. Of these, tuber coxae movement is utilised in some, but not all, commercially available systems. The reason is probably that the aim when constructing systems for clinical use is to measure a minimum of easily accessible locations, in order to decrease instrumentation and interpretation time. The less frequent use of these parameters in objective clinical movement symmetry analysis is also the main reason why they were not utilised in the studies included in this thesis.

Other parameters that have been found to change significantly after lameness induction are the relative amplitudes of the different frequency components describing the vertical displacement curve (Peham *et al.*, 1996; Kramer *et al.*, 2004), the acceleration symmetry of the whole trunk (Barrey *et al.*, 1994; Thomsen *et al.*, 2010) and the range of motion of the back (Gómez Álvarez *et al.*, 2007, 2008). Again, these are not used as frequently in objective systems in widespread clinical use. The reason might relate to their abstraction from what is visually apprehended.

1.2.4 Influence of speed

Speed is known to influence both the kinetics and kinematics of the trot. Temporal stride parameters are affected, *e.g.* an increase in stride frequency with increasing speed is generally seen (Leach and Drevemo, 1991; Robert *et al.*, 2002; Weishaupt *et al.*, 2010; Starke *et al.*, 2013; Moorman *et al.*, 2017; Cruz *et al.*, 2018). The only exception is in ridden high-level dressage horses, which instead increased speed almost solely by increasing stride length (Clayton, 1995). Furthermore, as a function of decreased stance duration, increased peak vertical forces are seen with increasing speed, most prominent in the forelimbs (McLaughlin *et al.*, 1996; Dutto *et al.*, 2004; Weishaupt *et al.*, 2010).

Kinematically, there is a decrease in upper body vertical range of motion with increasing speed (Peham *et al.*, 2000; Robert *et al.*, 2002; Starke *et al.*, 2013). Regarding vertical asymmetry parameters, an increase in measured asymmetry has been observed with increasing speed in horses with a high degree of initial asymmetry (Peham *et al.*, 2000). Conversely, horses that are sound or display a low degree of asymmetry in straight line trot show no increase in asymmetry with increasing speed (Peham *et al.*, 1998, 2000; Halling Thomsen *et al.*, 2010; Starke *et al.*, 2013). However, during trot in a circle, movement asymmetry has been shown to increase with increasing speed (Starke *et al.*, 2013). With regards to intra-trial variation, the optimal speed for gait evaluation seems to vary between horses (Peham *et al.*, 1998). Sound horses stay within a narrow range of speed when led by the same handler (Degueurce *et al.*, 1997; Galisteo *et al.*, 1998; Hardeman *et al.*, 2019), while lame horses tend to decrease their preferred over ground speed (Deuel, Schamhardt and Merkens, 1995; Clayton *et al.*, 2000). When planning a study, there is therefore reason to tightly control speed within the individual horse or to correct for changes in speed between conditions, especially during lungeing and for horses with a high degree of asymmetry.

1.2.5 Circle-induced asymmetry

Evaluation of the horse while lungeing is a standard part of most lameness and pre-purchase examinations since circular movement may reveal subtle or bilateral lameness that might otherwise remain undetected (Baxter, 2011). Knowledge of systematic biomechanical changes induced by circular motion is thus important for interpretation of both subjective and objective movement analyses.

In order to follow a circular track in trot, the horse produces centripetal force with both the inner and outer limb (Chateau *et al.*, 2013) and the body leans towards the inside of the circle to an increasing degree with increasing speed and decreasing circle radius (Pfau *et al.*, 2012). This creates asymmetry in dorsoventral movement of the upper body landmarks commonly used for vertical symmetry measures.

The most consistent systematic movement adaptation seen is in pelvic movement and mimics an inside hindlimb lameness, with higher minimum position of the pelvis (mindiff) during the inside hindlimb stance (Pfau *et al.*, 2012, 2016; Starke *et al.*, 2012; Rhodin *et al.*, 2016). Some studies also report evidence of a lower maximum position reached by the pelvis after outside hindlimb stance (maxdiff) (Pfau *et al.*, 2016; Rhodin *et al.*, 2016), but this asymmetry was of lower magnitude and was less consistently found.

For the head movement, a small mindiff, mimicking inside forelimb lameness has been observed on both hard (Starke *et al.*, 2012) and soft surfaces (Pfau *et al.*, 2016). However, the overall finding in another study was a small head mindiff attributed to the outside limb (Rhodin *et al.*, 2016), although the standard deviation of head mindiff was large, and a mindiff attributed to the inside forelimb was almost as common. The contrast between these studies might also relate to the methodological difference of measuring acceleration along the sensor based (aiming for dorsoventral in the horse reference frame) versus the true vertical axis. The parameter quantifying the difference in maximum position (maxdiff) of the head inconsistently differs from straight line locomotion when on the circle, but the common tendency is a decrease in upward head movement after inside forelimb stance (Pfau *et al.*, 2016; Rhodin *et al.*, 2016).

In one previous study, naturally occurring forelimb asymmetries were shown to be exacerbated when the limb to which the asymmetry was attributed to was on the inside of the circle (Pfau *et al.*, 2016). In another, induced forelimb lameness was most prominent with the lame limb positioned to the outside of the circle (Rhodin *et al.*, 2013). Induced hind limb lameness, measured as the mindiff of the pelvis, became most prominent with the lame limb positioned as the inside limb (Rhodin *et al.*, 2013).

These systematic adaptations to the circular track in horses both with and without pre-existing asymmetries need to be accounted for in studies evaluating horses in circular motion.

1.3 Prevalence of asymmetry in the riding horse population

Objective movement symmetry analysis systems have been developed to assist equine practitioners in the challenging task of detecting and diagnosing lameness. A number of commercially available systems are now on the market and can be utilised in equine practice on a day-to-day basis. However, in the individual horse it may not always be obvious whether measured asymmetries are of clinical importance, *i.e.* should be defined as lameness. Contributing to this uncertainty is the fact that many horses in full training, and not treated for lameness recently, still display asymmetric movement patterns.

One of the above mentioned systems was used to assess the horses in a previous asymmetry prevalence study of 222 riding horses that were in training and perceived as free from lameness by their owners (Rhodin *et al.*, 2017). Using the currently recommended thresholds for this system (Keegan *et al.*, 2011), 73% of the horses were classified as asymmetric (Rhodin *et al.*, 2017). The measured mean asymmetry values for both forelimbs and hindlimbs were in the same range as in horses with clinically relevant movement deficits measured with the same objective system (Maliye, Voute and Marshall, 2015; Maliye and Marshall, 2016). Other studies detected asymmetries above the aforementioned thresholds in 47% out of 201 horses (Rhodin *et al.*, 2016) or values outside normal ranges according to Buchner *et al*. (1996) in 67% of 27 riding horses in training (Pfau *et al.*, 2016). These findings are in agreement with those in studies using subjective lameness scoring in which 60% of 236 (Gunst *et al.*, 2019), 53% of 57 (Dyson and Greve, 2016) and 38% of 506 (Greve and Dyson, 2014) horses in regular work were classified as lame. Asymmetry that is presumably non-painful can also be induced, at least short term, via artificially induced limb length discrepancies (Vertz *et al.*, 2018). Thus, based solely on asymmetry grade, in many cases it cannot be decided which horses have underlying pain and pathology vs. in which horses the asymmetry may represent natural biological variation in their movement patterns.

The ability to make this distinction would be valuable. In horses in full training, reliable discrimination between asymmetry and lameness is of particular interest to enable detection of orthopaedic diseases at an early stage. In some horses presented to veterinary practices and hospitals unnecessary further investigations could be avoided, including exposure to the risk of complications following diagnostic analgesia.

1.4 NSAID treatment of musculoskeletal pain

Analgesic testing is sometimes utilised, in order to either rule in or rule out the presence of pain in orthopaedic cases. Examples are asymmetric horses where pain is suspected, but diagnostic anaesthesia has failed to confirm its presence or the suspected region is inaccessible for blocks. Nonsteroidal anti-inflammatory drugs (NSAIDs) are commonly used for this purpose. In addition, NSAIDs are frequently used analgesic drugs for musculoskeletal pain in horses (Goodrich and Nixon, 2006). The analgesic effect is mediated by inhibition of a number of cyclooxygenase (COX) enzymes, leading to a reduction in prostaglandin synthesis (Vane, 1971). Peripherally the reduced prostaglandin concentration leads to decreased sensitisation of nociceptors (Moriyama *et al.*, 2005) and thus a reduction in inflammatory pain and sensitisation. NSAIDs also have a less well-characterised central analgesic action at the level of the spinal horn (Malmberg and Yaksh, 1992a, 1992b).

There are two main isoforms of COX enzymes, COX-1 and inducible COX-2. COX-1 is expressed in most tissues and participates in normal tissue homeostasis. COX-2 is mainly found in activated inflammatory cells but has been shown also to have some constitutive expression (review: Zeilhofer, 2007). Extensive research effort has been invested in the development of more selective COX-2 inhibitors in the hope of effectively attenuating inflammation with reduced side effects.

In horses NSAIDs have been shown to be effective in alleviating orthopaedic pain from chronic or induced lameness (Erkert *et al.*, 2005; Hu *et al.*, 2005; Schoonover *et al*., 2005; Symonds *et al.*, 2006; Doucet *et al.*, 2008; Foreman *et al.*, 2008, 2010, 2012; Back *et al.*, 2009; Van Loon *et al.*, 2013). However, in another study of chronic lameness, a combination of two NSAIDs were needed to achieve a significant effect (Keegan *et al.*, 2008).

1.4.1 Meloxicam

Meloxicam is one of the latest marketed NSAIDs for horses. Oral suspension of meloxicam is approved in the European Union since 1998 (European Medicines Agency, 2018) for the treatment of acute and chronic locomotive disorders and is commonly used in many European countries with this indication. It is an NSAID belonging to the oxicam class and a more selective COX-2 inhibitor than phenylbutazone and flunixin *(*Beretta *et al*., 2005).

During experimental conditions meloxicam treatment has been shown to result in a reduction in lameness scores. Visual lameness scores were reduced after meloxicam treatment in horses with synovitis induced by Freund's adjuvant (Toutain and Cester, 2004). Similarly, in studies of experimental lipopolysaccharide-induced lameness, meloxicam treatment was reported to result in a reduction in objectively measured head movement asymmetry (UCVM Class of 2016, Banse and Cribb, 2017) and in visual lameness score (De Grauw *et al.*, 2009). However, in an experimental hoof pressure model, expected to induce predominantly nociceptive (mechanical) pain, meloxicam did not reduce visual lameness score compared with a placebo (UCVM Class of 2016, Banse and Cribb, 2017). Finally, treatment with meloxicam has been shown to suppress markers of inflammation ($PGE_{2,}$ substance P and bradykinin) and markers of cartilage degradation in synovial fluid in lipopolysaccharide-induced joints (De Grauw *et al.*, 2009).

During clinical conditions, meloxicam was reported to be slightly more effective in alleviating lameness than vedaprofen (Friton, Philipp and Kleemann, 2006). Administration of meloxicam has also been shown to be efficacious for control of post-operative pain and inflammation after orthopaedic surgery (Walliser *et al.*, 2015). Both experimental and clinical evidence thus support that meloxicam generally reduces musculoskeletal pain of inflammatory origin.

1.5 Influence of the rider on movement symmetry

There has been growing interest in the study of horse-rider interaction during recent decades. The overall incentives are the important welfare implications and the equestrian community's desire to develop the sport and art of riding. Ethological and welfare perspectives (for review see: Williams and Tabor, 2017) as well as biomechanical perspectives, such as kinematics of the rider and saddle (for review see: Clayton and Hobbs, 2017) have been explored. The rider's influence on vertical movement symmetry of the horse has been studied to a lesser extent, despite its high relevance. By far, the most common situation to observe the horse in motion is whilst being ridden. Knowledge of how the rider influences movement symmetry of the horse may thus aid observers and riders in detection of low-grade lameness. In addition, assessment of the horse under saddle is essential for select cases during lameness evaluations (Licka, Kapaun and Peham, 2004; Greve and Dyson, 2014; Dyson and Greve, 2016; Swanson, 2011), underlining the importance for a correct subjective or objective evaluation in this setting.

Riding can be performed using several different seating styles. In 'sitting trot', the rider remains seated in the saddle during the entire stride cycle. In 'two point seat' the rider's trunk is elevated above the saddle by standing and supporting full weight in the stirrups. In 'rising trot', also known as 'posting', the rider descends from the standing position to sit down in the saddle during the second part of the stance phase of one diagonal pair of limbs, to subsequently rise up during the end of that same stance and stand up in the stirrups during the stance phase of the other diagonal. During 'rising trot' in circles or turns, the equestrian community defines the 'correct diagonal' as the rider sitting down when the outside forelimb and inside hindlimb are in stance (*i.e.* on a right circle sitting down during left forelimb-right hindlimb stance and standing up in the stirrups during right forelimb–left hindlimb stance). Interestingly, the reason for this definition has not been documented.

Generally, the weight of a rider has been shown to increase lumbar extension (de Cocq, van Weeren and Back, 2004; de Cocq *et al.*, 2009) and increase the range of flexion extension (de Cocq *et al.*, 2009), but decrease the total vertical range of motion (ROM) of the lumbar back (Heim *et al.*, 2016). In 'two point seat' the forces exerted on the horse's back by the rider are evened out, with reduced peak forces throughout the stride compared with 'sitting trot' (Peham *et al.*, 2010). In 'rising trot' the lumbar vertical ROM is significantly greater than in 'sitting trot' (Heim *et al.*, 2016). Comparing the sitting and standing phase within 'rising trot' there are increased peak forces (de Cocq *et al.*, 2010; Peham *et al.*, 2010; Martin *et al.*, 2016) and a reduced range of flexion extension (Martin *et al.*, 2017) in the sitting phase. In conclusion, with the rider in a seated position, compared with a standing position, the vertical range of movement of the horse's back is reduced and the peak vertical forces exerted on it are increased.

Different seating styles thus affect the movement of the horse's back differently. Roepstorff *et al.* (2009) investigated the kinematic and kinetic movement symmetry of the horse with the rider performing 'rising trot' on horses trotting on a treadmill and found that the uneven biphasic loading from the 'rising trot' affected the motion symmetry of the horse's head, pelvis and lumbar back. During the sitting stance, the head reached a lower minimum position compared with the stance phase when the rider was standing. After push-off from the sitting diagonal, the head reached a higher maximum position whereas the lumbar back reached a lower position. Increased vertical ground reaction forces during the sitting hindlimb stance were also found (Roepstorff *et al.*, 2009).

Robartes *et al.* (2013) measured horse kinematics in 23 horse-rider pairs with the aim of comparing the movement symmetry during 'rising trot' and unridden exercise on the straight and on the circle. They found that the combination of 'rising trot' and the circle significantly decreased the horses' movement symmetry compared with straight line unridden trot. The effect was most profound for the hindlimbs, with a higher minimum position of the pelvis during inner hindlimb midstance in all circular exercise conditions and a decreased height reached by the pelvis after push-off from the inner hindlimb during rising trot on the circle. Both the mindiff and the maxdiff mimic inside hindlimb lameness in this case. The head showed consistent deviation from symmetry during ridden exercise on the circle, with a head nod down during outside forelimb stance mimicking an inside forelimb lameness (Robartes *et al*., 2013). Despite the significant influence on movement symmetry, no previous study has compared the effect of several different seating styles on the vertical movement symmetry of the horse.

The rider's skill level is also of some significance. The variability of the horse's motion pattern has been shown to be affected by the rider's skill, with less variability seen under an experienced rider (Peham *et al*., 2001; Peham *et al.*, 2004). This impacts the choice of rider when planning a study.

The rider's skill also potentially influences the vertical movement symmetry of the horse. Licka et al. (2004) compared the effect of a novice and an experienced rider on pre-existing movement asymmetry in 20 horses. There was no general effect on the degree of asymmetry with the addition of a rider in sitting trot. However, under the experienced rider there was a small increase in asymmetry in the hindlimb asymmetric group of horses. The effects of ‘rising trot’ and ‘two point seat’ on pre-existing asymmetries and the effects of combining these seating styles with trot in a circle have not been studied previously.

1.6 Compensatory movement asymmetry

In the current literature, compensatory asymmetry, or sometimes compensatory lameness, usually refers to a vertical movement asymmetry originating from a primary lameness located within the opposite end of the horse’s body. Asymmetry might be the better descriptor, since these compensatory movements are not due to pain in the seemingly affected limb. Compensatory asymmetry is alleviated if the primary lameness located within the other end of the body is blocked or an induced lameness is reversed. Compensatory asymmetry is not to be confused with secondary lameness which signifies a true lameness in another limb as a consequence of increased or changed loading due to the primary lameness.

Compensatory asymmetry has been demonstrated in straight line trot (May and Wyn-Jones, 1987; Buchner *et al.*, 1996; Uhlir *et al.*, 1997; Weishaupt *et al.*, 2004, 2006; Kelmer *et al.*, 2005; Maliye *et al*., 2015; Maliye and Marshall, 2016) and on the lunge (Rhodin *et al.*, 2013). In response to induced or naturally occurring hindlimb lameness a compensatory head nod down during the diagonal forelimb stance is visually evident. Kinematic measurement has revealed reduced acceleration during ipsilateral forelimb stance (Uhlir *et al*. 1997), thereby a reduction in upward vertical range of motion (Buchner *et al.*, 1996) and a higher minimum position (mindiff) during stance and a reduced maximum point reached (maxdiff) after stance (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013; Maliye and Marshall, 2016). All these changes in head movement mimic a forelimb lameness in the ipsilateral forelimb. From the head movement, one might expect to see a decreased loading of the ipsilateral forelimb, instead a slight reduction in vertical impulse is seen in the diagonal forelimb (Weishaupt *et al.*, 2004). It is noteworthy that these compensatory head movement asymmetries are not apparent in all horses with hindlimb lameness (Uhlir *et al.*, 1997; Kelmer *et al.*, 2005; Maliye and Marshall, 2016; Rhodin *et al.*, 2018).

Horses with primary forelimb lameness seemingly demonstrate a more complex pattern of compensation. Evidence of a pelvic asymmetry mimicking diagonal hindlimb lameness dominates in both induced lameness (Buchner *et* *al*., 1996; Uhlir *et al.*, 1997) and naturally occurring lameness (Maliye *et al*., 2015). When examined more closely, this compensatory asymmetry consists of a reduced vertical acceleration from the diagonal hindlimb, and thereby a reduction in upward range of motion and a reduced height reached (maxdiff) by the pelvis after diagonal hindlimb stance (Buchner *et al.*, 1996; Uhlir *et al.*, 1997; Maliye *et al*., 2015). In horses with hindlimb lameness, the maxdiff of the pelvis has been shown to be associated primarily with an increase in horizontal accelerative forces in the lame limb (Bell *et al.*, 2016). In horses with forelimb lameness, the vertical asymmetry of the pelvis has not been measures in conjunction with horizontal forces. However, Morris and Seeherman (1987) demonstrated an increase in horizontal accelerative forces in the diagonal hindlimb in horses with forelimb lameness, indicating the same association.

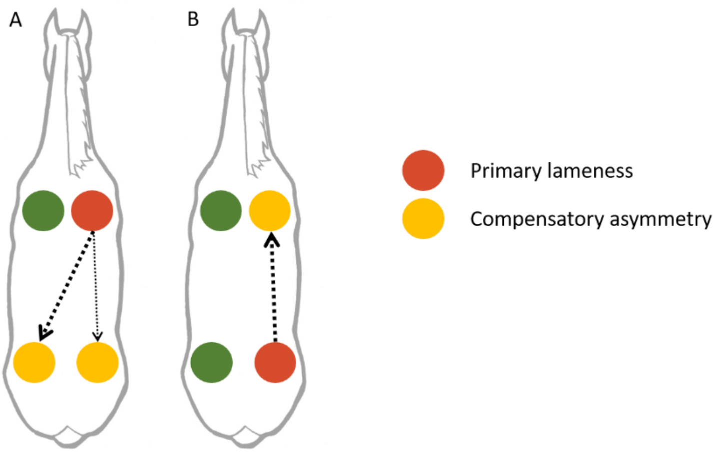

Figure 2. Schematic representation of the location of compensatory head and pelvic asymmetries (yellow) previously found in studies of (A) horses with primary right forelimb lameness (red) and (B) primary right hindlimb lameness (red) (Illustration: Amanda Dahlgren).

In addition, some studies of horses with induced lameness report compensatory changes resembling lameness in both the diagonal and the ipsilateral hindlimb (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). Apart from diagonal compensatory changes in agreement with those described above, there is also evidence of a slight compensatory asymmetry mimicking weight-bearing lameness in the ipsilateral hindlimb, measured as a higher minimum position (mindiff) during mid stance (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). This measured ipsilateral asymmetry is in agreement with a reduction in ipsilateral fetlock hyperextension (Buchner *et al.*, 1996) and kinetic measurements demonstrating a reduced load carried by the ipsilateral hindlimb (Morris and Seeherman, 1987; Weishaupt *et* *al.*, 2006). It can be concluded that there is evidence of kinematic changes indicating compensatory asymmetry in both hindlimbs but that contralateral compensatory asymmetry dominates.

Among the different compensatory asymmetries, the most prominent in relation to the primary lameness is the head nod down seen in some individuals with hindlimb lameness (Kelmer *et al*., 2005; Rhodin *et al*., 2013). In many horses, this is equal to or larger than the primary hindlimb lameness (Rhodin *et al.*, 2013). A clinical pitfall is mistaking this for primary ipsilateral forelimb lameness. Misinterpretation of compensatory head asymmetries may delay a correct diagnosis since an investigation may be initiated in the wrong limb. This could also be a contributing factor to the low inter-rater agreement between veterinarians regarding low-grade hindlimb lameness (Keegan *et al.*, 2010). A reliable way to distinguish compensatory head movement asymmetry from true primary forelimb lameness thus has the potential to facilitate accurate diagnosis of lameness.

1.7 Withers movement symmetry in lame horses

Withers movement asymmetry was investigated already in early studies of kinematic changes due to lameness (Peloso *et al.*, 1993; Kübber *et al.*, 1994; Buchner *et al.*, 1996). The withers asymmetry parameters was shown to be less affected by forelimb lameness compared to head parameters. With the aim of these studies being the identification of sensitive markers for forelimb lameness the withers movement was concluded to be an inferior indicator and might even fail in the detection of subtle lameness (Buchner *et al.*, 1996).

However, withers movement asymmetry could be a possible aid in locating the primary lameness. As described above a hindlimb lameness can give rise to a head movement asymmetry mimicking ipsilateral forelimb lameness that is equal to, or larger than, the primary hindlimb lameness (Rhodin *et al.*, 2013). In clinical practice, these compensatory head movement asymmetries need to be differentiated from true forelimb lameness.

Buchner *et al*. (1996) found that the movement symmetry of the withers was affected in horses with induced, moderate forelimb and hindlimb lameness. When forelimb lameness was induced, the withers retained a higher minimum position during the lame forelimb midstance compared with the sound limb. In addition, the total vertical upward movement amplitude of the withers from the lame limb mid-stance minimum to the swing phase maximum was decreased. Both the head and the withers thus indicated a decreased loading of the lame forelimb. After induction of hindlimb lameness, the movement of the withers was also affected, but to a slightly smaller degree. After induction of moderate lameness, there was a reduction in the upward range of movement of the withers, from midstance minimum to swing phase maximum of the diagonal limb pair including the lame hindlimb. With hindlimb lameness, withers asymmetry thus mimicked lameness in the diagonal forelimb (Buchner *et al.*, 1996). According to these findings, in horses with concurrent ipsilateral (same sided) head and pelvic movement asymmetries, withers movement asymmetry would be observed towards different directions depending on whether the forelimb or the hindlimb is the primary source of lameness. Therefore, withers movement may be useful to distinguish between a head nod of a primary or compensatory nature, thus warranting further investigation.

No previous study has examined withers movement in horses with naturally occurring lameness of known localisation. However, in a study by Pfau *et al.* (2018), vertical head, withers and pelvic movement asymmetry was measured utilising inertial sensors in 163 Thoroughbreds in training trotting in a straight line. The true origin of the measured vertical asymmetries was not known in these horses, but the relationship between the direction of head and withers asymmetry predicted the relationship between head and pelvic asymmetry in 69-77% of the horses. In horses with an ipsilateral head-withers asymmetry relationship, the majority presented with diagonal head-pelvis asymmetry, and were thus thought to have a primary forelimb lameness. Horses, in which the direction of head-withers asymmetry parameters indicated opposite forelimbs, instead mainly had ipsilateral head-pelvic asymmetry indicative of a primary hindlimb lameness. It would be valuable to investigate this in depth in horses with naturally occurring lameness and a known location of the lameness.

2 Aims of the thesis

The overall aim of this thesis was to improve equine welfare and support the ethics of keeping horses, by providing knowledge that can support riders and veterinarians in detecting lameness at an early stage and improve orthopaedic diagnostics.

Specific objectives were to:

- Determine whether movement asymmetries in riding horses, in training and perceived as free from lameness by their owner, are affected by anti-inflammatory treatment with meloxicam (Paper I).
- Quantify how the rider's seating style ('sitting', 'two point seat' or 'rising trot') influences movement symmetry in horses trotting in a straight line and on the circle (Paper II).
- Evaluate the effect of the rider on pre-existing movement asymmetries (Paper II).
- Investigate the association between head, withers and pelvis movement asymmetry in horses with induced forelimb and hindlimb lameness (Paper III).
- Evaluate whether movement symmetry of the withers can be used to discriminate a compensatory head nod in horses with hindlimb lameness from a head movement asymmetry due to primary forelimb lameness (Paper III)
- Describe compensatory movement asymmetry associations in horses with naturally occurring lameness in a clinical setting (Paper IV).
- Determine whether the relationship between the direction of head and withers movement asymmetry parameters generally differs between horses with primary forelimb lameness and horses with primary hindlimb lameness (Paper IV).

3 Hypotheses

The following hypotheses were tested:

- Horses in training presenting with vertical movement asymmetries show a reduction in degree of movement asymmetry on group level during meloxicam treatment (Paper I).
- Rising trot and riding in a circle induce systematic changes in the movement symmetry of the horse. These asymmetries attenuate or reduce any pre-existing movement asymmetries depending on whether the seating style-induced and circle-induced asymmetries coincide or are inverse in direction to the pre-existing asymmetry (Paper II).
- In horses with induced forelimb lameness, the head and withers show synchronised asymmetries (*e.g.* both indicating right forelimb), while in horses with induced hindlimb lameness, the head and withers show movement asymmetries of opposite directions (*e.g.* pelvis indicating right hindlimb, head indicating right forelimb, withers indicating left forelimb) (Paper III).
- In horses with naturally occurring lameness compensatory patterns would present as previously described, i.e. ipsilateral forelimb asymmetry in horses with primary hindlimb lameness and diagonal push-off asymmetry and ipsilateral weight-bearing hindlimb asymmetry in horses with primary forelimb lameness (Paper IV).
- In horses with naturally occurring lameness, head and withers movement asymmetry parameters indicate the same forelimb (have the same sign) in horses with a positive response to diagnostic analgesia of a forelimb, and opposite forelimbs in horses with a positive response to diagnostic analgesia of a hindlimb (Paper IV).

4 Materials and methods

This chapter provides a summary of the materials and methods used in Papers I-IV. More detailed descriptions can be found in each paper.

4.1 Study designs

4.1.1 Paper I

An experimental study was performed to investigate the effect of treatment with meloxicam on movement asymmetries in warmblood riding horses. Horses in full training, considered free from lameness by their owners and not recently treated for lameness, were screened for the presence of vertical movement asymmetry utilising an inertial measurement unit (IMU) system that is described in detail in section 4.3 of this thesis. Horses presenting with asymmetry values above thresholds of absolute value >6 mm for the head or absolute value >3 mm for the pelvis parameters were included in the study. In a crossover design, each horse was treated with meloxicam, a nonsteroidal anti-inflammatory drug, or a placebo for four days, followed by a 14 to 16 day washout period between treatments. Objective movement symmetry data were collected at four time points during the study: before treatment on day 1 and after treatment on day 4 of both treatment periods. Horses were trotted in hand on a straight line and lunged in a circle in both directions. Each horse's most prominent asymmetry at the initial measurement was chosen and the treatment effect was assessed on this parameter.

4.1.2 Paper II

This study assessed the effect of rider seating style on the vertical movement symmetry in riding horses. One experienced rider rode all 26 horses in the study and each horse's vertical movement symmetry was measured with the same IMU system as in Paper I, during 15 different conditions performed in random order. These conditions included trotting in straight lines and circles, unridden and ridden. In the ridden conditions, the rider performed three different seating styles ('sitting', 'two-point seat' and 'rising trot'). The 'rising trot' in circles was performed on both the correct and the incorrect diagonal as defined by the equestrian community. Effectively, this produced four different seating conditions, all of which were tested.

Although not intentionally recruited, some of the horses included in the study presented with pre-existing movement asymmetries. These horses were selected for a subset where the rider's influence on pre-existing asymmetries was evaluated.

4.1.3 Paper III

An experimental study was performed to investigate compensatory vertical asymmetry in 10 horses with induced lameness. Lameness was induced in all four limbs, one at a time, with a sole pressure model utilising a modified horseshoe (Merkens and Schamhardt, 1988). Forelimb and hindlimb lameness was induced on separate days, in randomised order. Kinematic data were collected during trot on a treadmill, before, during and after each lameness induction, using an optical motion capture system (for a detailed description of the system see section 4.3). Only trials with successful inductions, as judged by a determined minimum change in the induced parameter, were included. In addition to studying the effect of induction across all horses, the effect was also assessed in a subset of the hindlimb induction group that demonstrated compensatory ipsilateral head movement asymmetry.

4.1.4 Paper IV

In a multicentre cross-sectional study, medical records and objective movement symmetry data, collected as part of routine lameness investigations of horses presenting to four different equine practices, were retrospectively reviewed. Horses were included if objective movement analysis was carried out both before and after diagnostic analgesia, if both trials consisted of at least eight strides and if the inclusion criteria for one or more lameness groups were met (criteria based on a certain degree of initial lameness and with a positive response to diagnostic analgesia on a single limb, see Table 1).

Table 1. *Selection criteria for the six lameness groups in Paper IV*

Lameness group	Selection criteria 1[a]	Selection criteria 2[b]
Group 1 (HDmin)	HDmin > 15 mm at initial	HDmin decrease of minimum 70%
Group 2 (HDmax)	HDmax > 15 mm at initial	HDmax decrease of minimum 70%
Group 3 (HDRup)	HDRup > 20 mm at initial	HDRup decrease of minimum 70%
Group 4 (PDmin)	PDmin > 7 mm at initial	PDmin decrease of minimum 70%
Group 5 (PDmax)	PDmax > 7 mm at initial	PDmax decrease of minimum 70%
Group 6 (PDRup)	PDRup: > 10 mm at initial	PDRup decrease of minimum 70%

a. Absolute mean value at initial measurement. The measurement was included only if the standard deviation was smaller than the trial mean.

b. Mean value at initial measurement and mean value after diagnostic analgesia were compared.

4.2 Study populations

The protocol in Paper I was approved by the Ethics Committee for Animal Experiments, Uppsala, Sweden, application number C 48/13 and C 92/15. The study protocol of Paper II was approved by the Ethical Committee for Animal Experiments, Uppsala, Sweden. The experimental protocol of Paper III was approved by the Animal Health and Welfare Commission of the canton of Zurich (permission number 51/2013). Informed consent was obtained from all horse owners in all four Papers.

The horses in Papers I-II were in full training, considered free from lameness according to their owners and not recently treated for problems originating from the locomotor apparatus. The horses in Paper III were all examined by an experienced veterinarian and considered free from lameness. The study population in Paper IV presented to the participating clinics for lameness evaluation and thus most of their owners suspected they were lame.

In Papers I-III all horses were riding horses of warmblood type. In Paper IV the study population was more heterogeneous, including ponies, Quarter Horses and Icelandic horses.

The horses in Paper I consisted of a mixed population of privately owned horses and horses belonging to larger equestrian centres. In Paper II all horses belonged to the Swedish National Equestrian Centre at Strömsholm. The horses in Papers III-IV were privately owned.

4.3 Kinematic measurements

4.3.1 Inertial measurement unit system

The IMU system used in Papers I and II consisted of three sensors (Lameness Locator, Equinosis, Columbia, MO, USA). One was a uni-axial gyroscope with a range of ±300˚/s, which was attached with a specially designed neoprene wrap to the dorsum of the right forelimb pastern. The other two were uni-axial accelerometers with a range of ± 6 gravitational acceleration, one of which was attached to the poll with a felt head bumper and one of which was taped to the midline between the two tubera sacrale. All sensors had mass 28 g and dimensions 3.2 x 3.0 x 2.0 cm. Data were digitally recorded (8 bits) at 200 Hz and transmitted via Bluetooth to a handheld computer.

The sensor data were analysed with the software included in the IMU system. Recorded vertical acceleration data from the head and pelvis sensors were first converted to vertical displacement values via a double integration and error correcting algorithm (Keegan *et al.*, 2002). Unwanted low-frequency components of the signal were then removed using a moving-window, curve-fitting technique as described in Keegan *et al.*, (2001). Stride splitting was performed based on angular sagittal plane velocity data from the gyroscope in the limb-mounted sensor. The custom-written software also aims to correct for the size of the horse by normalising the stride-by-stride difference to the amplitude of the second harmonic, representing the total vertical range of motion without the asymmetry contribution, for each stride before the trial means are calculated. Plots of head asymmetry parameters in the software output were scrutinised and outliers (up to maximum 10% of the strides) were removed.

Thresholds for asymmetry of head (absolute value >6 mm) and pelvic (absolute value >3 mm) parameters, for use in detecting clinical lameness in conjunction with a full lameness examination, are provided by the manufacturer of the IMU system (Equinosis, 2016). These thresholds closely resemble the confidence intervals for repeatability of the system (Keegan *et al.*, 2011). Due to their widespread clinical use, they have previously been applied in a number of studies (Maliye *et al.*, 2015; Maliye and Marshall, 2016; Rhodin *et al.*, 2016, 2017).

4.3.2 Optical motion capture system

The optical motion capture system used in Papers III-IV consisted of infra-red 3D motion capture cameras covering a calibrated volume. The horses were equipped with spherical markers (Figure 3) fastened to predefined anatomical landmarks. The horses were measured on a treadmill in Paper III and during over ground locomotion in Paper IV.

The three-dimensional coordinates of each marker were automatically calculated by the motion capture software Qualisys Track Manager (Qualisys AB, Motion Capture Systems, 411 05, Göteborg, Sweden, version 2.11-2019.3) and correct tracking was later checked by visual inspection. Marker coordinates were exported to Matlab (MathWorks, 3 Apple Hill Drive, 01760, Natick, USA) for further analysis using custom-written scripts. The vertical displacement signal of head, withers and pelvis was high-pass filtered using a 4th order zero-phase Butterworth filter with the cut-off frequency adjusted, based on the stride frequency of the horse in each trial as described in Serra Bragança *et al.* (2020). Stride segmentation was performed using the maximum protraction of the left hindlimb (Paper III) or pelvic rotation indices (Paper IV). Strides with excessive movement were excluded either by removing strides with head asymmetry parameters outside two standard deviations from the trial mean (Paper III) or strides with head or pelvis range of motion > 40% for head or > 20% for pelvis from the trial mean (Paper IV).

Figure 3. Frontal plane spherical reflective markers used on some horses in Paper IV, the ventral midline marker was used in the analysis (Photo: Elin Holmroos).

4.3.3 Asymmetry parameters

In all four studies, the main outcome variables examined consisted of vertical movement symmetry parameters that quantify the magnitude of asymmetry and attributes the asymmetry to a specific limb (see Table 2 for descriptions and Figure 1 (Section 1.2) for a graphical representation).

Table 2. *Description of the asymmetry parameters used in this thesis*

Parameter	Description
HDmin/WDmin/PDmin	Mean difference across all strides, between the local vertical displacement minima for the head/withers/pelvis reached during right versus left limb stance, in mm[1]
HDmax/WDmax/PDmax	Mean difference across all strides, between the maximum head/withers/pelvis height reached after right limb stance versus after left limb stance, in mm[1]
HDRup/WDRup/PDRup	Mean difference across all strides, between the total vertical upward range of motion of the head/withers/pelvis during right versus left limb stance, in mm[1]

1. Positive values indicate asymmetry attributed to right forelimb/hindlimb and negative values represent asymmetries attributed to the left forelimb/hindlimb. HD: head difference, WD: withers difference, PD: pelvis difference.

4.4 Drug administration, plasma sample collection and analysis (Paper I)

Meloxicam (Inflacam, Virbac, Kolding, Denmark) at the recommended dose of 0.6 mg/kg or placebo was administered *per os* once daily on day 1–4 of each treatment period by the researchers or a local representative. Plasma samples to confirm adequate meloxicam concentration were obtained by venepuncture and analysed by high-performance liquid chromatography with tandem mass spectrometry detection (HPLC-MS/MS, Recipharm OT Chemistry AB, Uppsala, Sweden, lower detection limit 10 ng/mL). Horses were kept in the study if the plasma concentration was above 195 ng/mL, which is the previously published plasma concentration for reduction in lameness score after meloxicam treatment (Toutain and Cester, 2004), or below 20 ng/mL during any of the other sampling occasions.

4.5 Statistical methods

Statistical analyses were performed using either the statistical software SAS (SAS Institute Inc., USA) (Paper II) or R software (The R Foundation for Statistical Computing, Vienna, Austria) (Papers I, III and IV). A mixed model approach was used for statistical analysis in Papers I-III. This approach was chosen mainly due to the need to account for repeated observations by including horse as a random variable and sometimes for other hierarchal structures in the data. The data in Paper IV was analysed with simple linear regression and paired t-tests. To confirm an adequate model fit, normality of residuals was verified using q-q plots and homoscedasticity was ensured by plotting the residuals against the fitted values. The level of significance was $p \leq 0.05$ in all four papers.

5 Main results

This section summarises the main results from the studies. More detailed descriptions can be found in Papers I-IV.

5.1 Effect of meloxicam treatment

Initially 140 horses were screened, 82 horses presented with asymmetry values above the objective system thresholds and 66 horses were finally included in the study. The effect of meloxicam treatment was not statistically significant in trot on the straight line (Figure 4) or the lunge, on either a soft or hard surface. There was also no significant effect of treatment for the top 30% most asymmetric horses in straight line trot.

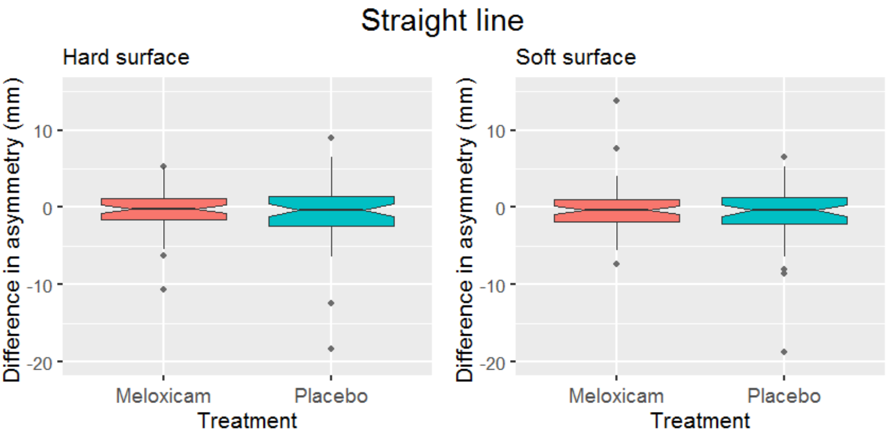

Figure 4. Difference in the main asymmetry parameter between pre-treatment on day 1 and post treatment on day 4 of each treatment (meloxicam and placebo) across 57 horses on a hard surface and 58 horses on a soft surface. Negative values indicate a reduction in asymmetry during the treatment period. No significant effect of treatment was found (p = 0.31 for hard surface, p = 0.48 for soft surface). (Reproduced with permission from: Persson-Sjodin *et al*. (2019) Effect of

meloxicam treatment on movement asymmetry in riding horses in training. *PLoS ONE.* 14(8) pp: e0221117.)

5.2 Influence of rider seating style

From the 26 horses included in Paper II, data on 387 trials were successfully collected. During the baseline condition 18 of the horses presented with one or more head and/or pelvic asymmetry parameters above recommended thresholds for the IMU system.

The symmetrical seating styles of ‘sitting trot’ and ‘two point seat’ did not influence the vertical movement symmetry of the head and pelvis in either the full dataset or the subset of horses with pre-existing asymmetries. In contrast, ‘rising trot’ significantly influenced the movement asymmetry, primarily of the pelvis (Figure 5). The pelvis descended to a lower minimum position during the stance phase when the rider was sitting and reached a lower maximum position after push-off from the same limb, when the rider was concurrently rising. The head showed an increased maximum height after push-off from the forelimb, during which stance the rider was sitting. When ridden in a circle, the asymmetry induced by ‘rising trot’ on the correct diagonal counteracted the circle-induced asymmetry, rendering the horse generally more symmetrical.

In the subset of horses with small pre-existing movement asymmetries, the asymmetry induced by ‘rising trot’ and the circular track increased or decreased the horse’s baseline asymmetry depending on the sitting diagonal and direction on the circle. PDmax asymmetry increased when the rider was sitting down during the stance of the hindlimb the asymmetry was attributed to, whereas PDmin asymmetry decreased.

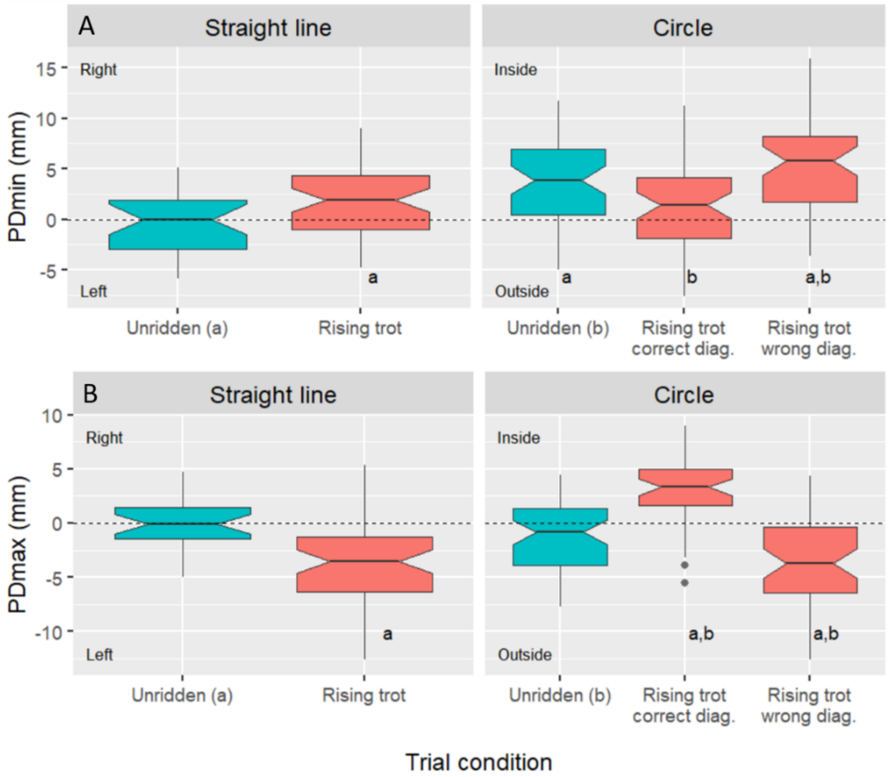

Figure 5. The (**A**) PDmin and (**B**) PDmax across conditions in 26 horses. Significant differences from 'unridden straight' is indicated by **a**. Significant differences from 'unridden circle' is indicated by **b**. Grey dots indicate outliers. **Right** and **Left** indicates right sided (positive) and left sided (negative) attributed asymmetries respectively. **Inside** and **Outside** indicates the asymmetry being attributed to the inside (positive) and outside (negative) hindlimb respectively. Note that during rising trot in a straight line the rider is sitting down during the stance of RF/LH and that circles are performed to the right.

5.3 Withers movement symmetry in horses with induced lameness

Induction of lameness was successful for all but three hindlimb inductions and the forelimb and hindlimb dataset used for analysis consisted of 1183 and 1182 strides, respectively. Mixed-model output from the horses with induced hindlimb lameness showed an increase in withers asymmetry of 0.35-0.55 mm for each mm increase in pelvic asymmetry. The direction of the asymmetry was towards the diagonal side, indicating diagonal forelimb lameness. With induced forelimb lameness the withers asymmetry increased by 0.05-0.10 mm and both head and withers asymmetry indicated lameness in the forelimb with induced lameness.

Six horses showed compensatory head movement asymmetry after both hindlimb lameness inductions and an additional four horses after either left or right lameness induction. In these horses, the withers asymmetry also increased, by 0.42-0.55 mm for each mm increase in pelvic asymmetry, and indicated lameness in the diagonal forelimb.

5.4 Withers movement symmetry in horses with naturally occurring lameness

In total, data from 945 horses with measurements performed during lameness investigations including diagnostic analgesia were reviewed. After applying all inclusion criteria and removal of measurements with too few strides, missing markers and other technical errors, 237 horses were included in the analysis.

The relationships between the direction of head and withers movement asymmetries for the lameness groups are presented in Table 3. In the groups of forelimb lame horses (Group 1 & 2), 78-83% of horses displayed head and withers asymmetry parameters indicating the same forelimb. In contrast, in the groups of hindlimb lame horses (Group 4 & 5), 68-69% of horses showed head and withers asymmetry parameters indicating opposite forelimbs. In the subsets of Group 4 and 5, with ipsilateral HDmin asymmetry >15 mm at initial measurement, 82-83% showed head and withers asymmetries attributed to opposite forelimbs.

Table 3. *Relationships between the direction (sign) of head and withers movement asymmetry*

		Lameness group[a]					
Sign of HDmin[b]	Sign of WDmin[b]	Group 1 (RF HDmin)	Group 2 (RF HDmax)	Group 4 (RH PDmin)	Group 5 (RH PDmax)	Group 4 (RH PDmin) with RF HDmin[c]	Group 5 (RH PDmax) with RF HDmin[c]
RF	RF	83%	78%	6%	9%	18%	17%
LF	RF	-	7%	2%	1%	-	-
LF	LF	-	2%	23%	22%	-	-
RF	LF	17%	13%	69%	68%	82%	83%
No. of horses		77	54	51	68	17	18

Data from horses with lameness in the left limb were mirrored by multiplying their asymmetry parameters by -1, effectively rendering all horses initially right limb lame.

a. Groups selected based on initial lameness parameters and a positive response to diagnostic analgesia.

b. Direction (sign) of asymmetry parameter irrespective of magnitude.

c. Ipsilateral (RF) HDmin >15 mm before diagnostic analgesia.

In the three lameness groups selected for response to forelimb diagnostic analgesia (Groups 1-3), the change in WDmin/WDRup was positively correlated to the change in the HD parameter representing lameness (Figure 6). In the three groups selected for response to hindlimb diagnostic analgesia (Groups 4-6), the change in WDmin/WDRup was negatively correlated to the change in the PD parameter representing lameness (Figure 6).

In Group 1 (HDmin) and Group 3 (HDRup), the model-estimated change (slope) in PDmax/PDRup was -0.18 to -0.12 mm for each mm change in the head asymmetry parameter. This is indicative of a decrease in PDmax/PDRup attributed to the hindlimb diagonal to the blocked forelimb. In the three groups selected for response to hindlimb diagnostic analgesia (Groups 4-6), there was no significant correlation between the change in the pelvic asymmetry parameter and the change in the head asymmetry parameters. However, when evaluated with a paired sample t-test, there was a significant decrease in the mean value of HDmin after diagnostic analgesia of a hindlimb in Group 4 (mean difference -8.6mm; $P<0.001$) and Group 5 (mean difference -7.2mm; $P<0.001$), and a significant decrease in the mean HDRup in Group 6 (mean difference -7.6mm; $P<0.001$).

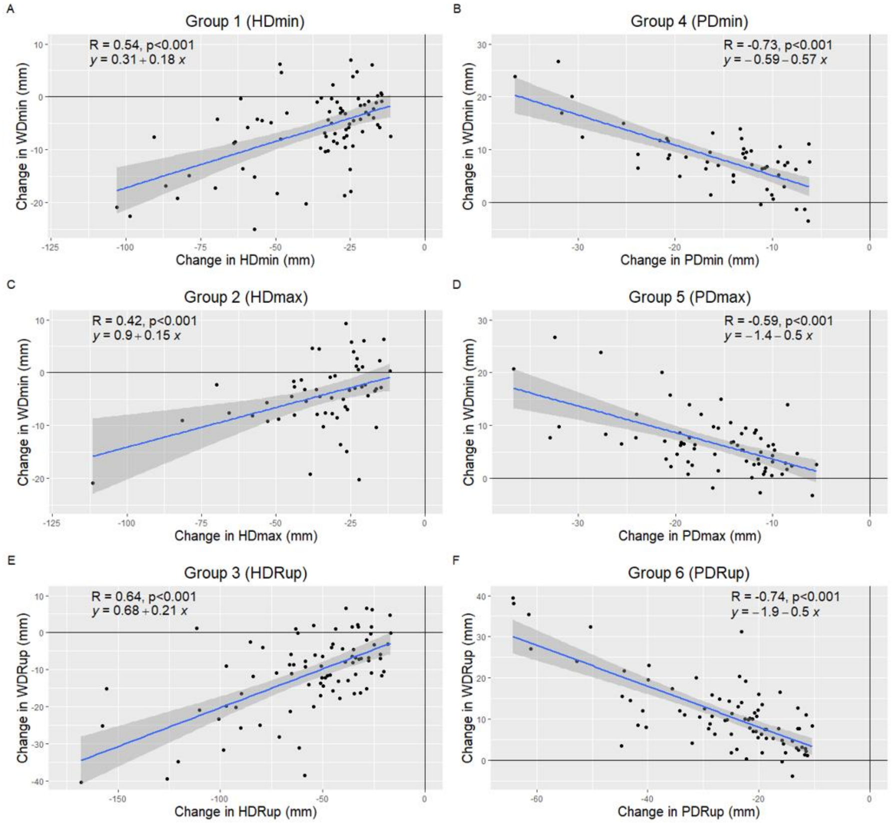

Figure 6. Linear correlation of the change in the initial lameness parameter of each lameness group to the change in withers asymmetry. Before calculating the change in asymmetry, data from horses with lameness in the left limb were mirrored by multiplying all their asymmetry parameters by -1, effectively rendering all horses initially right limb lame.

6 General discussion

6.1 Discussion of main results

6.1.1 Effect of meloxicam on movement asymmetries

The effect of treatment with meloxicam on movement asymmetries in warmblood riding horses in full training was assessed in Paper I. Interestingly, no significant effect of treatment on movement asymmetry was found in the study population. This suggests either that the movement asymmetries in these horses were not generally caused by pain, but rather derived from biological variations such as laterality or conformation, or that treatment with meloxicam did not effectively moderate existing pain.

Meloxicam is a commonly used analgesic in equine practice, for the treatment of locomotor pathology and sometimes for analgesic testing. Examples of the latter are cases of poor performance or instances where pain is suspected, but diagnostic analgesia cannot confirm its presence. If the movement symmetry increases or performance is enhanced during treatment, but returns towards baseline after discontinuation, an undiagnosed painful condition should be suspected. However, it is important to note that in the absence of a response to treatment, the existence of pain cannot be excluded. Similarly, in the study population in Paper I, a response to meloxicam treatment, seen as a general reduction in asymmetry in these horses, would have been an indicator of the presence of pain. In the study situation, pain cannot be ruled out, as it might simply be the result of meloxicam being inefficient for the pain in question.

Meloxicam is a selective COX-2 inhibitor (Beretta *et al.*, 2005) and would be expected to be effective in alleviating pain of inflammatory origin via reduction of prostaglandin synthesis (Vane, 1971). Pain of acute inflammatory origin is thus a less likely cause of the movement asymmetries in these horses. However, it does not exclude other types of pain being present, such as chronic or neuropathic pain. While the literature generally shows NSAIDs to be effective in horses with chronic lameness (Erkert *et al.*, 2005; Hu *et al.*, 2005; Schoonover *et* al., 2005; Doucet *et al.*, 2008; Back *et al.*, 2009), this is not always the case (Keegan *et al.*, 2008). It is also noteworthy that meloxicam was not the substance evaluated in any of these studies. In addition, meloxicam was not effective in reducing pain in a hoof pressure lameness model (UCVM Class of 2016, Banse and Cribb, 2017), which would be expected to be predominantly nociceptive (mechanical) pain. Thus, while meloxicam was chosen due to its common use in the Nordic countries and suggested lower risk of gastrointestinal complications (D'Arcy-Moskwa *et al.*, 2012; Noble *et al.*, 2012), it should be considered that another drug might have been more efficacious. It would also have been interesting to try to reduce the asymmetries in horses not responsive to meloxicam by using diagnostic analgesia, but this was not a possibility in the owner-reported sound population studied.

The failure to detect a significant effect of meloxicam on movement asymmetry might also be due to the composition of the study population, which may have included horses with and without pain-related movement asymmetries. With higher degrees of asymmetry, the assumption in this thesis was that the probability of an underlying painful pathology being present would increase. Therefore the effect was also tested in a subset containing the top 30% most asymmetric horses. The mean asymmetry values in the subset population were similar for the forelimb-related parameters and higher for the hindlimb-related parameters, compared with asymmetries in clinically lame horses responsive to diagnostic analgesia (Maliye *et al*., 2015; Maliye and Marshall, 2016). However, no treatment effect was found in this subset either.

The only significant effect in the statistical models was a small mean decrease in stride frequency during both treatments, resulting in a small mean decrease in asymmetry. This decreased stride frequency probably represents a small decrease in speed as the horses became accustomed to the study situation, as seen in another study examining horses over several days (Hardeman *et al.*, 2019). Assuming that the decrease in stride frequency represents a decrease in speed, the decreased asymmetry is in agreement with findings in a previous study (Starke *et al.*, 2013).

Considerable variation over time in the measured asymmetries, irrespective of treatment, was evident for a number of horses in Paper I. This variation might have been lessened by only including horses with a 'stable' asymmetry over time. However, apart from most probably rendering the study population significantly smaller, this variation over time seems representative of the general population, as it agrees with that seen in riding horses and thoroughbreds in regular use (Sepulveda Caviedes *et al*., 2018; Hardeman *et al.*, 2019). The variation over time in lame horses has so far only been studied between two consecutive days in horses with forelimb lameness (Rungsri *et al.*, 2014), which nevertheless showed considerable day-to-day variation. If this is generally true in lame horses, this phenomenon has to be considered when evaluating the response to treatment in a clinical setting and when assessing a horse for soundness, for example during a pre-purchase examination, warranting further studies in the future.

6.1.2 Influence of rider seating style

In Paper II, the influence of commonly used rider seating styles, in combination with straight and circular tracks, on the vertical movement symmetry of the horse was investigated. Among seating styles, the 'rising trot' was shown to significantly alter the movement symmetry of the horse, with the main effect on pelvic movement symmetry.

The pelvis reached a lower maximum pelvic position after push-off when the rider was concurrently rising in agreement with the movement asymmetry measured at L5 in Roepstorff *et al.* (2009). This probably occurs due to the downward momentum induced when the rider actively rises and counteracts the hindlimb push-off. This PDmax mimics push-off lameness in the hindlimb on which the rider is sitting in 'rising trot'. A change in PDmin was also seen with a lower minimum position of the pelvis during the stance phase when the rider was sitting. This probably reflects increased loading of that hindlimb, as seen in the relatively increased vertical ground reaction force (Roepstorff *et al.*, 2009), and mimics weight-bearing lameness in the limb in stance when the rider is standing.

Regarding head movement asymmetry, HDmax showed an increased maximum height reached by the head after push-off from the forelimb in stance while the rider was sitting. This could be due to the rider interfering with the normal movement by raising her hands as she rises and thus encouraging the horse's head in an upward direction through the bit. This HDmax is in agreement with findings in Roepstorff *et al.* (2009), where in addition an effect on HDmin was seen, in contrast to the results presented in Paper II.

In contrast to the findings in straight line in Paper II, Robartes *et al*. (2013) observed no significant effect of the 'rising trot' in straight line. This discrepancy could be due to the much larger inter-horse variation seen during straight line locomotion in that study, probably as a consequence of less experienced riders, less educated horses and more variable surface conditions. In Paper II, one intermediate-level rider was used to minimize possible variation between riders, in order to study the influence of the different conditions on the vertical movement asymmetry of the horses. The use of only one rider means that caution has to be applied when generalising the results, as riders can themselves be asymmetric in their movement patterns (Symes and Ellis, 2009; Hobbs *et al.*, 2014; Engell *et al.*, 2018). However, the main effects seen in Paper II did not differ between directions or rising diagonals, indicating no major influence of rider asymmetry on the results in that study.

In contrast to the demonstrated influence of ‘rising trot’ symmetrical seating styles, such as ‘sitting trot’ or ‘two point seat’, did not significantly influence the movement symmetry of the horses. This makes sense from a mechanical perspective, if it is assumed that the symmetry of movement of the horse is not affected by the addition of the rider’s weight *per se*, but rather by the oscillation of this added weight as the rider rises to the trot (Roepstorff *et al.*, 2009; de Cocq *et al.*, 2010; Peham *et al.*, 2010; Martin *et al.*, 2016). This is consistent with findings in Paper II and in a recent study, where the ‘rising trot’ induced PDmax asymmetry that was attributed to the hindlimb on which the rider was sitting (Dyson *et al.*, 2019). It is also reasonable for the magnitude of this PDmax asymmetry to increase with increasing rider weight, as demonstrated in that study.

When the ridden exercise is performed in a circle, asymmetries induced by circular movement also start influencing the symmetry of movement of the horse (Pfau *et al.*, 2012, 2016; Starke *et al.*, 2012; Rhodin *et al.*, 2016). ‘Rising trot’ on the correct diagonal on the circle (sitting during outside forelimb/inside hindlimb diagonal stance) induced a PDmin asymmetry of opposite direction to the circle-induced asymmetry. This rider-induced asymmetry seemingly counteracted the circle-induced asymmetry. Based on the PDmin values, the horses in Paper II became significantly more symmetrical with the rider performing ‘rising trot’, compared with lungeing in the same direction. Furthermore, rising on the incorrect diagonal in a circle induced the highest degree of asymmetry for all asymmetry parameters combined. This suggests a biomechanical explanation for the conventional equestrian recommendation on the use of a certain ‘correct diagonal’ in rising trot in a circle.

PDmax was distinctly more affected by ‘rising trot’ than by riding in a circle. As seen in straight line, there was a PDmax attributable to the hindlimb during which stance the rider was sitting, and no additional effect was seen when the horse was ridden in a circle. Although unridden exercise in a circle did not induce changes in HDmin (compared with in-hand straight line), there were some significant effects with the addition of a rider to the circular motion, irrespective of seating style. The effect was similar to that on sound and asymmetric (HDmin) horses on the lunge observed by Pfau *et al.* (2016), *i.e.* reduced downward movement during the inside forelimb stance, mimicking inner forelimb lameness. It could be speculated that this is due to the rider influencing the head position or body lean of the horse.

Lame horses were not intentionally sought out for Paper II, but part of the presumed sound study population presented with pre-existing movement asymmetry. These horses were used as a proxy to test the rider's influence on lame horses. Conditions that increase the baseline asymmetry are particularly interesting as these might assist in visual detection of lameness by increasing the asymmetry above the visual detection threshold (Parkes *et al.*, 2009).

In the orthopaedic textbook "*Lameness in Horses*" (Ross, 2011b), hindlimb lameness is said to increase if the rider in rising trot is sitting while the affected limb is in stance, but the type of hindlimb lameness (weight-bearing and/or push-off) is not stated. The results in Paper II confirmed the ability of 'rising trot' to affect the magnitude of asymmetry, but the effect was shown to be totally opposing depending on the type of asymmetry. If the outcome in asymmetric horses in the study population were to be extrapolated to lame horses push-off hindlimb lameness would increase when the rider sits during the lame stance whereas weght-bearing hindlimb lameness would decrease. Thus, the textbook statement seemingly holds true only for horses with predominant push-off lameness (PDmax asymmetry). In contrast to the findings in Paper II Licka *et al.* (2004) observed an increase in hindlimb asymmetry when horses were ridden by an experienced rider in 'sitting trot'. A higher degree of collection might contribute to this discrepancy but it is also worth mentioning that the increase in asymmetry seen in Licka *et al.* was very small on a group level.

In general, the asymmetry measured during a given condition appeared to be a simple summation of the baseline asymmetry of the horse and the asymmetries induced by the rider and those induced by a circular track. Horses with a PDmin asymmetry attributed to the right hindlimb showed increased asymmetry on a straight line if the rider was seated during the left hindlimb stance, thus combining the baseline asymmetry with the asymmetry induced by the rising trot. The same horses had the highest degree of asymmetry when trotting in a circle to the right with the rider rising on the incorrect diagonal. Then the circle-induced PDmin asymmetry (Pfau *et al.*, 2012, 2016; Starke *et al.*, 2012; Rhodin *et al.*, 2016) was also added. This addition of asymmetries is in accordance with the summation of induced hindlimb lameness and circle-induced asymmetry previously reported by Rhodin *et al.*, (2013).

The effect of the rider on head movement asymmetry was less pronounced and consisted mainly of a decrease in asymmetry during some conditions compared with baseline. The only condition in which head asymmetry was shown to increase was in horses with HDmin asymmetry, when the limb to which the asymmetry was attributed was to the inside of the circle and the rider was simultaneously rising on the incorrect diagonal. As the rider has been shown to be able to influence the movement of the horse's head (Schöllhorn *et al.*, 2006), it could be speculated that the head nod in horses with forelimb lameness could be concealed by rider stabilisation via the reins. The results in Paper II partly contradicted this, since even though the main significant changes were decreases in asymmetry, the head movement asymmetry was not decreased with the rider in the symmetric seating style 'sitting trot', in agreement with a previous study (Licka *et al.*, 2004). However, these results should be extrapolated with caution to lame horses, as this effect might be greater in horses with more pronounced head movement asymmetry.

In conclusion, 'rising trot' can seemingly both amplify and obscure pre-existing movement asymmetries. However, the asymmetry values in the study population in Paper II were generally lower than the mean values in a larger prevalence study (Rhodin *et al.*, 2017). Thus, to ascertain that these findings hold true for lame horses, they need to be investigated further in horses with a higher degree of asymmetry and diagnosed clinical lameness.

6.1.3 Compensatory asymmetries

In Paper IV, compensatory movement asymmetry patterns were investigated in horses with naturally occurring lameness and a positive response to diagnostic analgesia. On group level, the horses with hindlimb lameness showed evidence of a compensatory asymmetry resembling ipsilateral forelimb lameness as seen in previous studies (May and Wyn-Jones, 1987; Buchner *et al.*, 1996; Uhlir *et al.*, 1997; Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). However, on closer inspection only 26-33% had a HDmin of a magnitude that was large enough to be easily mistaken for a primary forelimb lameness. This was similar to the proportion observed in Paper III and in another study of horses with clinical lameness (Maliye and Marshall, 2016). Thus, the results in Paper IV confirm that the compensatory ipsilateral head asymmetry can be prominent compared with the hindlimb lameness causing it, as has been previously demonstrated (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). However, it only seems to be present in some horses with hindlimb lameness.

Another noteworthy finding in Paper IV was that there was no significant linear correlation between the change in hindlimb asymmetry parameters responsive to diagnostic analgesia and the change in any of the head asymmetry parameters. This indicates that the size of the compensatory head asymmetry, when present, is not directly dependent on the size of the pelvic movement asymmetry. This is in agreement with Maliye and Marshall (2016), who also studied horses with clinical hindlimb lameness. Different horses thus seemingly use different compensatory strategies, at least for mild to moderate degrees of lameness. Factors such as conformation, duration of lameness and concurrent limb and back problems might determine the strategy utilised by horses to decrease the loading on the lame limb.

In contrast, a significant correlation between change in the hindlimb asymmetry parameter and changes in head asymmetry parameters was found in two studies of horses with induced hindlimb lameness (Kelmer *et al*., 2005; Rhodin *et al*., 2013). Apart from differences in the nature and duration of lameness, those studies also included horses with a distinctly higher degree of hindlimb asymmetry. In Kelmer *et al.* (2005), the correlation was quite dependent on observations in the more severely lame horses. In conclusion, it cannot be excluded that a similar correlation would have been detected in Paper IV with the inclusion of more horses with a higher degree of lameness.

It is also worth noting that if the lameness parameters of the left hindlimb lame horses in Paper IV were not mirrored by multiplying their trial means by -1, the correlation was significant ($p<0.001$), but with a comparatively low correlation coefficient ($R = 0.21$) and large standard error of the slope. A larger spread of the values along both axes when both negative and positive values are utilised seems to enhance the ability of the model to identify a linear fit between the change in PDmin and the change in HDmin. However, the current way of analysing this is probably more representative of the true biological variability in the data.

In the horses with forelimb lameness, the change in pelvic asymmetry showed a compensation mimicking diagonal hindlimb lameness, in agreement with findings in previous studies (Buchner *et al.*, 1996; Uhlir *et al.*, 1997; Maliye *et al.*, 2013). The maximum point reached after push-off from the diagonal hindlimb was reduced compared with the ipsilateral hindlimb (PDmax), as has been previously shown (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013; Maliye, Voute and Marshall, 2015). Assuming a similar relationship between asymmetry and force distribution as seen in hindlimb lame horses (Bell *et al.*, 2016), this maxdiff probably corresponds to the increased horizontal acceleration forces (Morris and Seeherman, 1987). This increased forward thrust with less pelvic rise could be to compensate for the reduced use of the lame forelimb, keeping the horse moving forward but avoiding pivoting the torso down on the lame forelimb.

In addition to the diagonal PDmax, a smaller ipsilateral compensatory weight-bearing asymmetry (PDmin) has been demonstrated in horses with induced lameness (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). This is in agreement with reduced loading of the ipsilateral hindlimb (Morris and Seeherman, 1987; Weishaupt *et al.*, 2006). However, this ipsilateral PDmin has yet to be demonstrated in horses with naturally occurring lameness (Maliye and Marshall,

2016) and was not seen in the study population in Paper IV. This also agrees with the previous findings in thoroughbreds with ipsilateral head and withers asymmetry (Pfau *et al.*, 2018). This particular compensatory mechanism could therefore be speculated to be specific for sole pressure-induced lameness, or to occur only at higher degrees of lameness. The latter is somewhat supported by the fact that when divided by lameness grade, ipsilateral hindlimb asymmetry is evident only in the higher degrees of lameness (Kelmer *et al.*, 2005; Weishaupt *et al.*, 2006).

The correlation of the change in suspected compensatory asymmetries with the change in lameness after successful diagnostic analgesia was investigated in Paper IV. In horses with multiple-limb lameness, which might be present in the study population, investigating the change is only fully valid if the combination of asymmetry from true lameness and compensatory asymmetry is combined in an additive way. This seems to be the case when induced lameness is combined with circle induced asymmetry (Rhodin *et al*., 2013; Pfau *et al*., 2016) or naturally occurring asymmetry with asymmetry induced by rising trot (Persson-Sjodin *et al.*, 2018). However, to my knowledge no study to date has examined compensatory patterns in multi-limb lame horses.

For several reasons, the results in Paper IV should not be considered a perfect representation of the prevalence of different compensatory patterns in lame horses. The compensatory patterns could only be investigated in horses with a positive response to diagnostic analgesia, and are thus unknown in horses with a lack of positive response. Horses with diagnostic analgesia performed on multiple limbs were excluded if they did not have a positive response in the primary limb blocked, thereby excluding some cases of multiple-limb lameness. Furthermore, the examining veterinarians were allowed to access the objective movement asymmetry data, possibly influencing their decision on the location at which to initiate diagnostic analgesia. The horses included were blocked in the correct limb, as seen from the positive response to diagnostic analgesia, but some horses with unusual compensatory patterns might potentially have been excluded. Nonetheless, as discussed above, the compensatory patterns generally confirmed those seen in earlier studies of both induced and naturally occurring lameness, and therefore still probably represent patterns that can be expected to occur commonly.

6.1.4 Withers movement symmetry in lame horses

The relationship between the head and the withers was the main focus in Papers III and IV in this thesis. The main objective was to find a way to more readily identify the primary lame limb in hindlimb lame horses with a compensatory head movement asymmetry. Therefore, withers asymmetry was first investigated in horses with induced lameness (Paper III) and then the findings were verified in horses with naturally occurring lameness (Paper IV).

The results of both studies showed generally ipsilateral head-withers asymmetry parameters (direction of asymmetry indicating the same forelimb) in horses with forelimb lameness and head-withers asymmetry attributed to opposite forelimbs in horses with hindlimb lameness. In clinical practice, this finding is probably most useful for distinguishing between true forelimb lameness and compensatory head movement asymmetry originating from a primary hindlimb lameness (Buchner *et al.*, 1996; Uhlir *et al.*, 1997; Kelmer *et al.*, 2005; Rhodin *et al.*, 2013). Therefore, in Paper IV this was investigated further in hindlimb lame horses with a head movement asymmetry deemed large enough to be easily mistaken for a primary forelimb lameness. This was only seen in 26-33% of the hindlimb lame horses but, despite the large head asymmetry, 82-83% of the horses showed withers asymmetry indicating the opposite forelimb compared to the head asymmetry.

Mainly warmblood riding horses were assessed in both Papers III and IV. Extrapolation to other breeds should be done with caution, but a study in thoroughbreds indicates a similar directional relationship (Pfau *et al.*, 2018).

In forelimb lameness, the conformity between head and withers asymmetry is intuitive, both agreeing with the reduced loading of the lame forelimb (Morris and Seeherman, 1987; Clayton *et al.*, 2000; Ishihara *et al*., 2005; Weishaupt *et al.*, 2006). In horses with hindlimb lameness and a compensatory head movement asymmetry, the head asymmetry represents a more pronounced head nod down during the diagonal stance including the lame hindlimb (Kelmer *et al.*, 2005; Rhodin *et al.*, 2013; Maliye and Marshall, 2016). This head nod probably shifts the load within the lame diagonal towards the diagonal forelimb (Weishaupt *et al.*, 2004). During the lame diagonal stance the trunk is instead kept higher (Buchner *et al.*, 1996) resulting in a higher minimum position of both withers and pelvis. Consequently, the difference in minimum position of head and withers will be attributed to opposite forelimbs. In Paper IV the change in WDmin for each mm change in the parameter representing the blocked lameness was larger for pelvic parameters than for head parameters. This was presumably at least partly due to the generally relatively larger magnitude of the head compared with the pelvic asymmetry, due to the larger ROM of the head, but a difference in effect size is also possible. The focus in Paper IV was on WDmin, since the estimated change was greater than for WDmax, especially in correlation to the hindlimb parameters. However, the difference in maximum position (WDmax) followed the same pattern and can also be used.

Although the majority of horses displayed head and withers asymmetry relationships in accordance with the theory tested, some deviated from this pattern. Concurrent lameness in additional limbs can be suspected to be the reason in some cases, especially in the clinical cases in Paper IV but also to some degree in the induced horses in Paper III, as not all horses were trotting perfectly symmetrically before induction. Multiple concurrent lameness problems might generally add complexity in the clinical situation and sometimes distort the expected withers patterns. As discussed above, the data in Paper IV are not perfect from a prevalence perspective, but the results still represents patterns that can probably be expected to be commonly occurring.

Movement of the withers can be difficult to observe in straight line trot, as it is either obscured by the head when viewed from the front or difficult to distinguish clearly when the observer is standing behind the horse. This can be solved by viewing the horse from the side, but this is mostly done during lungeing, and it is not known how lungeing affects movement symmetry of the withers in lame horses. The small magnitude of asymmetries of withers movement (compared with head movement) may also play a role when assessing withers movement visually, due to the limitations of the human visual system in perceiving small movement asymmetries (Parkes *et al.*, 2009). However, withers movement can be measured using one of several commercially available systems (Keegan *et al.*, 2011; Bosch *et al.*, 2018; Pfau *et al.*, 2018; Hardeman *et al.*, 2019). This is an additional incentive for utilising these systems in daily clinical practice.

6.2 Additional aspects of material and methods

6.2.1 Objective movement analysis - benefits and limitations

Objective movement analysis systems enable quantification of vertical movement asymmetry during lameness evaluations. The temporal resolution of these systems is much higher than that of the human eye (Holcombe, 2009) and, as they are not restricted by the limited visual field of a human observer, they are able to evaluate many more strides. Furthermore, they can assist in overcoming expectation bias when evaluating the response to diagnostic analgesia (Arkell *et al.*, 2006). Finally, if previous measurements are available, they can be used to objectively measure improvement during treatment and rehabilitation.

However, there are certain limitations. A horse that does not trot up well, stumbles or in other ways fails to move representatively will generate data that are as difficult to interpret as visual evaluation of the same horse. While objective movement analysis systems are excellent at measuring vertical movement asymmetry (Pfau *et al.*, 2005; Keegan *et al.*, 2011), these parameters do not necessarily contain all information valuable to lameness evaluation, and additional features picked up by the human observer might be missed by the systems. Finally, it should always be kept in mind that these systems do not measure pain. Objective movement analysis systems thus cannot determine whether this asymmetry is due to underlying pain and pathology.

6.2.2 Thresholds for screening

Ideally, there would be thresholds of vertical movement symmetry that could be used for screening, and that could discriminate between sound horses and horses suffering from pain and/or orthopaedic problems. However, separating sound and lame horses based on asymmetry magnitude would assume that vertical movement asymmetry of a certain degree is invariably associated with pain and/or pathology. In fact, the results presented in this thesis, and in the published literature, show that asymmetric movement can be induced by many factors. These include extrinsic factors such as lungeing direction (Starke *et al.*, 2012; Pfau *et al.*, 2016; Rhodin *et al.*, 2016) and rider seating style (Robartes *et al.*, 2013) and intrinsic factors such as limb length (Vertz *et al.*, 2018). Factors such as conformation and laterality (McGreevy and Rogers, 2005; Murphy *et al.*, 2005) can also be expected to contribute to biological variation in vertical movement asymmetry.

Adding to the complexity is the apparent overlap in asymmetry magnitude between horses perceived to be free from lameness by the owner (Rhodin *et al.*, 2017) and horses with clinical lameness (Maliye *et al.*, 2015; Maliye and Marshall, 2016). This cuts to the core of the problem that arises when trying to establish thresholds for screening in a population of horses. It is possible to identify and confirm lame horses, but it is not possible to define sound horses as there is no gold standard to ascertain the absence of pain and as horses are unable to self-report.

One way of interpreting this overlap in asymmetry magnitude is that it represents large individual variation in baseline asymmetry, and that a large proportion of sound horses naturally show the same degree of asymmetry as horses with confirmed lameness. If this is true, then comparison of current asymmetry values with longitudinal data from the same specific individual may be highly informative and the best option for determining the significance of a movement asymmetry.

An alternative interpretation of the overlap in asymmetry magnitude is that many horses considered to be sound by their owners are in reality suffering from painful lameness. If this is the case, then these horses should be screened for asymmetry using a threshold with a high negative predictive value, ideally followed up by a reliable analgesic test to avoid unnecessary invasive lameness investigations in false positive cases.

The truth probably lies somewhere in between these two alternative interpretations. Therefore we should in addition aim to gain as much knowledge as possible about the prevalence of lameness and asymmetries and, where possible, the cause of asymmetries in different populations. This will not provide clear-cut thresholds, but may provide a better basis for determining the probability that a movement asymmetry in a specific horse is due to pain and/or pathology.

Despite the issues raised, different thresholds were utilised in all papers included in this thesis. However, the aim was to select representative study populations and not to screen for pain. In Paper I, the thresholds recommended by the IMU system manufacturer for detecting clinical lameness were utilised (Equinosis, 2016). They closely resemble the confidence intervals for repeatability of the system (Keegan *et al.*, 2011) and have gained widespread clinical use. Therefore, these thresholds were previously utilised in a prevalence study (Rhodin *et al.*, 2017). The aim in Paper I was to investigate the effect of meloxicam in a similar population of horses in full training and with vertical movement asymmetries. In Paper II, the same thresholds as in Paper I were used for selecting a subset of horses with movement asymmetries. However, in both of these studies, it was not assumed that the selected horses were actually lame. Thresholds were also used in Papers III and IV, but in those cases to select horses that demonstrated a certain degree of lameness among horses known to be lame.

6.2.3 Data collection in clinical practice

The movement symmetry data for Paper IV were collected during standard clinical lameness investigations in four different locations. Collection of data in this way and from multiple centres allows large quantities of data to be collected from horses with naturally occurring lameness. This creates the opportunity to confirm findings from horses with induced lameness in clinical cases and gain knowledge of the use of objective movement symmetry systems under real-life conditions.

Naturally, there are also disadvantages with data collected under these less controlled clinical conditions. With time constraints, and the natural focus on clinical issues apart from data collection, mistakes can be made in registration and data collection meaning the data cannot be completely trusted. For the data underlying the findings in Paper IV, this called for quite extensive manual or semi-manual post-collection correctional work. An observation from the work performed in Paper IV, was that having a particular person responsible for data collection leads to less erroneous registrations than when data are collected by attending clinicians and assistants. The large amounts of data generated in this way also mean that faults partly need to be identified automatically and unforeseen errors can then be difficult to identify. Examples of this are unexpected duplicate measurements and measurements on multiple horses' registered under the same ID.

In Paper IV, automatic identification of markers was used. This was generally found to perform well, but in rare cases critical errors occurred such as one of the tubera coxae markers being identified as the sacrum marker. Therefore, included measurements had to be manually checked and corrected when necessary.

These issues should not preclude this type of data collection, as it is highly valuable for research purposes, but need to be kept in mind when planning collection and working with this type of data.

6.2.4 Pre-existing and coexisting lameness

A common struggle in many biomechanical studies in horses is to define and find sound study subjects. It is not uncommon for a non negligible proportion of a recruited presumed sound study population to fall outside desired thresholds of symmetry (Licka *et al*., 2004; Robartes *et al*., 2013; Pfau *et al.*, 2016; Rhodin *et al.*, 2016). In this thesis, this was evident in Papers II and III. In Paper II this asymmetric subset was retained, as the degree of asymmetry they displayed is seemingly representative of the owner-reported sound population (Rhodin *et al.*, 2017) and was utilised to study the effect of the rider on these pre-existing movement asymmetries. However, even though these horses were in full training and considered sound by the owner, and the asymmetries were of a low-grade, lameness cannot be completely ruled out.

In Paper III, some horses included in the study showed initial movement asymmetries, mainly in the hindlimbs. The possibility that these asymmetries were due to pain cannot be completely ruled out, even though they were judged to be clinically insignificant by the experienced clinician who examined the horses. Pre-existing pain in the locomotor system could have made the horses less or more prone to adjust their movement pattern in response to the tightened bolt. In the selection of data for analysis, thresholds for lameness were used to ensure that the data included came from successful lameness inductions with sufficient nociceptive stimuli to provoke lameness. This also ensured that the stimuli would override any other possible source of pain. If some horses had slightly painful lesions during the baseline measurements, this could potentially have affected their compensatory patterns. In spite of this, the associations in the data were clear and statistically significant.

7 Concluding remarks

The results presented in this thesis extend existing knowledge about the origin and significance of movement asymmetries in riding horses and the compensatory mechanisms in lame horses. The following specific conclusions can be drawn from the work presented:

- Treatment with four days of meloxicam did not significantly decrease the movement asymmetry measured in horses in training and perceived as free from lameness by their owner. This finding raises new questions as to whether such asymmetries are simply expressions of biological variation or are related to pain/dysfunction not responsive to meloxicam treatment.

- ‘Rising trot’, but not ‘sitting trot’ or ‘two point’ seat, induced systematic changes in vertical movement symmetry of the head and pelvis in riding horses. The most prominent effect was decreased pelvic rise mimicking push-off lameness in the hindlimb of the diagonal during which stance the rider was sitting in ‘rising trot’.

- When the horse was ridden in a circle, the asymmetry induced by ‘rising trot’ on the correct diagonal counteracted circle induced asymmetry, rendering the horse more symmetrical. This offers an explanation for the equestrian principle of rising on the ‘correct diagonal’.

- In horses with small pre-existing movement asymmetries, the asymmetry induced by ‘rising trot’ increased or decreased the horse’s baseline asymmetry. Depending on sitting diagonal, this might potentially highlight or mask existing hindlimb asymmetries.

- Some, but not all horses with hindlimb lameness, demonstrated compensatory ipsilateral head asymmetry. In horses with forelimb lameness, a compensatory diagonal decrease in hindlimb push-off was evident. In horses with naturally occurring lameness, there was no evidence of a compensatory ipsilateral hindlimb asymmetry in forelimb lame horses.

- Head and withers movement asymmetry parameters generally indicated the same forelimb in horses with forelimb lameness, but indicated opposite forelimbs in horses with hindlimb lameness. Quantification of withers asymmetry is therefore a useful supplement in clinical objective lameness assessment and might aid in locating the primary lameness in hindlimb lame horses with a compensatory ipsilateral head movement asymmetry.

8 Future considerations

The work in this thesis can assist in interpretation of movement asymmetries under different circumstances, but many aspects still need further investigation. An increased understanding of the prevalence and development over time of movement asymmetries, and how these vary between different horse populations, would be desirable. Increased knowledge of that area could potentially enable easier interpretation of the significance of movement asymmetries in the individual horse. Age, breed, discipline, level of competition and history of orthopaedic problems would be interesting factors to consider.

Other possible ways forward could be prospective studies relating present movement asymmetries to future orthopaedic disease or studies exploring the value of individual baseline data for deciding the significance of new or increased movement asymmetries in an individual horse. Such studies could determine whether newly arisen asymmetries or substantial increases in previously observed asymmetries are the most relevant.

In Paper I, the effect of meloxicam was evaluated in owner-reported sound, albeit asymmetric, horses. Treatment with meloxicam did not generate a reduction in asymmetry, but this does not rule out pain as the cause of asymmetry in these horses. For horses such as these or other horses with movement asymmetries of unknown significance, it would be valuable to further investigate substances for analgesic testing, facial expressions of pain or other tests, to confirm or rule out the presence of pain.

In Paper II, the rider was shown to be able to increase or decrease the horse's baseline asymmetry when performing 'rising trot'. This was studied in an asymmetric subset of horses in full training. These findings should be confirmed in horses with higher degrees of asymmetry and confirmed lameness, to ensure that they hold true for lame horses with orthopaedic pain.

In relation to the findings in Papers III and IV, it would be interesting to further explore compensatory asymmetries and the directional relationship of head and withers asymmetry on the lunge. Compensatory asymmetry on the lunge has so far only been investigated in a study with a small number of horses with induced lameness (Rhodin *et al.*, 2013). Withers movement asymmetry in lame horses on the lunge has not been studied to date. Further research in this area could facilitate interpretation of movement symmetry data collected while lungeing. An additional aspect would be to explore the association between different diagnoses of lameness and the movement pattern on the lunge. It is commonly believed that such a relationship exists, but this belief is not backed by scientific data.

Large-scale collection of clinical data and multicentre collaborations should also be continued. Exploration of large quantities of data might in the future enable distinct lameness patterns to be connected to specific diagnoses and enable development of artificial intelligence tools to assist in lameness investigation.

A final consideration relates back to the aim of this thesis to "improve equine welfare by providing knowledge that can support riders and veterinarians in detecting lameness at an early stage and improve orthopaedic diagnostics". In order to achieve this goal of increased horse welfare, the work presented in this thesis, together with the existing body of knowledge regarding vertical movement asymmetries, needs to be effectively disseminated and taught to lay people and professionals in the horse industry, including equine practitioners.

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Popular science summary

Orthopaedic disorders are very common and a welfare issue in sports horses. Lameness is considered the hallmark clinical sign of orthopaedic pain. If lameness is detected and the underlying problem is correctly diagnosed at an early stage, treatment and rehabilitation have a greater chance of success. Lameness is primarily identified by detecting abnormalities in the horse’s movement pattern. However, there is a surprisingly low degree of consensus between veterinarians when assessing lameness, especially low-grade lameness. Biomechanical research has shown that asymmetric movement of the horse's head and pelvis are good indicators of lameness. This has led to the development of modern objective methods by which vertical movement asymmetry can be easily detected and documented. The aim of this thesis was to increase equine welfare by improving interpretation of movement asymmetries under different circumstances. This can support riders and veterinarians in detecting lameness at an early stage and improve lameness diagnostics.

Objective gait analysis has previously revealed that a large proportion of riding horses in training, perceived as free from lameness by their owners, show movement asymmetries of equal magnitude to horses with mild clinical lameness. To investigate whether these asymmetries are pain-related, horses in training but with movement asymmetries were treated with a nonsteroidal anti-inflammatory drug. Before and after treatment movement symmetry in these horses was measured using an objective system. It was found that treatment did not affect movement symmetry in these horses. This raises new questions as to whether such asymmetries are simply expressions of biological variation or related to pain/dysfunction not responsive to the treatment used.

The most common situation in which riding horses are observed in motion is whilst being ridden. Knowledge of how the rider influences movement symmetry of the horse may thus aid observers and riders in detection of low-grade lameness. It is also common for the veterinarian to ask to see the horse ridden during a lameness work-up. Therefore, the effect of different rider seating

styles on the movement symmetry of horses was investigated in this thesis. Rising trot was shown to induce asymmetric movement that mimicked low-grade hindlimb lameness. Therefore, horses showing mild hindlimb movement asymmetries of equal magnitude that switch hindlimb when the rider switches between left- and right-rising trot should not be taken to be lame. In horses with mild lameness, *i.e.* low-level movement asymmetries without the rider, left- and right-rising trot may attenuate or reduce pre-existing hindlimb asymmetries, depending on rising diagonal. Knowledge that rising trot on one of the two diagonals may emphasise pre-existing asymmetry can be used to discover low grade lameness. It was also found that rising trot on the correct diagonal counteracts circle-induced asymmetry. This offers an explanation for the equestrian principle of rising on the ‘correct diagonal’.

It has previously been shown that lameness of a hindlimb can cause a head nod down, in the exact same manner as if the horse had a lame forelimb. There is a risk of this compensatory head nod being mistaken for a forelimb lameness and consequently that of lameness investigation being initiated in the wrong limb. Therefore, this thesis investigated the potential of the movement symmetry of the withers to aid the equine practitioner in identifying the primary lame limb. It was shown that movement symmetry of the head and withers generally indicates lameness in the same forelimb in cases with forelimb lameness and in opposite forelimbs in cases of hindlimb lameness. Measuring withers movement asymmetry may therefore be helpful in identifying the true origin of the lameness.

The work presented in this thesis assists in interpretation of movement symmetries in riding horses but much still remains to be elucidated. Future research should focus on prevalence and development over time of movement asymmetries to understand their clinical significance and identify risk factors for orthopaedic disorders. In addition, new ways of testing for the presence of pain and improved ability to interpret movement symmetry measurements during lameness evaluations. Most importantly, it is imperative that the increasing knowledge gained from biomechanical research reaches lay people and professionals in the horse industry, including equine practitioners.

Populärvetenskaplig sammanfattning

Ortopediska skador är mycket vanliga hos våra sporthästar och är ett stort djurvälfärdsproblem. Hälta är det vanligaste symtomet på ortopedisk smärta och om den upptäcks tidigt och skadan kan diagnostiseras korrekt ökar chanserna att behandling och rehabilitering ska lyckas och hästen blir frisk.
För att avgöra om hästen är halt och var hältan kommer ifrån studeras hästens rörelser. Det har dock visat sig att denna subjektiva bedömning är mycket svår och osäker, framförallt vid låggradiga hältor. Biomekanisk forskning har visat att asymmetrier i huvudet och korsets vertikala rörelser är bra mått på en fram- respektive bakbenshälta. Med denna kunskap har moderna objektiva metoder utvecklats som enkelt kan mäta och dokumentera asymmetrin i hästens rörelser.

Syftet med denna avhandling var att öka kunskapen om hur man ska tolka asymmetrier i hästens rörelsemönster i olika situationer. Det kan bidra till att djurägare och veterinärer upptäcker en hälta tidigare men även till förbättrad ortopedisk diagnostik, vilket främjar hästens välfärd.

Med objektiva metoder har man kunnat visa att en mycket stor andel av hästar i träning har ett asymmetriskt rörelsemönster trots att ägarna upplever dem som friska. Asymmetrierna är ofta lika stora som de är hos hästar som utreds på klinik för lindriga hältor. För att undersöka om asymmetrierna hos dessa hästar är smärtorsakade behandlades en grupp sådana hästar i den första studien med en anti-inflammatorisk medicin. Effekten av behandlingen utvärderades genom objektiva symmetrimätningar med det sensor-baserade systemet Lameness Locator före och efter behandling. Studien visade att behandlingen inte hade någon effekt på hästarnas rörelseasymmetrier och detta väcker nya frågor. Kan asymmetrierna vara en naturlig biologisk variation eller är de ändå orsakade av smärta som inte svarar på den anti-inflammatoriska behandlingen?

Ridhästar observeras oftast i rörelse med ryttare på ryggen. Kunskap om hur ryttaren påverkar symmetrin i hästens rörelsemönster är därför viktigt då ökad kunskap kan hjälpa ryttare och tränare att tidigt upptäcka en eventuell hälta. Ridprov är en vanlig del av en hältutredning och veterinären måste därför ha kunskap om ryttarens påverkan på hästen för att korrekt kunna tolka hästens rörelsemönster. I studie två studerades därför effekten av ryttarens sits på hästens rörelsemönster. Resultaten visade att vid lättridning fick hästen ett asymmetriskt rörelsemönster som liknade en låggradig bakbenshälta. Om en häst visar en lindrig bakbensasymmetri vid lättridning, som är av samma grad och byter ben när ryttaren byter sittben, ska man inte misstolka den för en hälta. Hos hästar med en låggradig hälta kan lättridningen dölja eller förstärka hältan beroende på vilket sittben man sitter på och detta kan utnyttjas för att tidigt upptäcka en hälta hos hästen. Studien kunde också visa att lättridningen motverkar de asymmetrierna hos hästen som orsakas av voltens böjda spår, vilket ger en biomekanisk förklaring till varför man ska sitta på ”rätt” sittben.

Tidigare studier har visat att bakbenshalta hästar kan nicka med huvudet för att avlasta det onda bakbenet så att de ser ut att vara halta på samma sidas frambén. Det finns en stor risk att man misstar denna huvudnickning för att vara en riktig frambenshälta och att man börjar utreda fel ben vilket fördröjer eller förhindrar att hästen får en korrekt diagnos. I de två sista studierna undersöktes därför om man kan använda mankens rörelse för att skilja en äkta frambenshälta från en falsk (kompensatorisk). Resultatet visade att vid en frambenshälta indikerade huvudets och mankens asymmetrier samma frambén. Vid en bakbenshälta indikerade däremot huvudet och mankens asymmetrier hälta i var sitt frambén. Genom att mäta mankens rörelse kan man därmed få hjälp att direkt avgöra när en huvudnickning är orsakad av en frambenshälta eller när den kommer från en bakbenshälta.

Resultaten från denna avhandling bidrar till en ökad förståelse för hur man ska tolka rörelseasymmetrier hos hästar i olika situationer men ännu kvarstår mycket att undersöka. Framtida studier bör undersöka förekomsten av rörelseasymmetrier i olika populationer och se hur de påverkas av faktorer som ålder, träning, utbildningsnivå, skadehistork och lateralitet. Detta skulle öka förståelsen av asymmetriernas betydelse hos enskilda hästar men även innebära att riskfaktorer för utvecklingen av ortopediska skador hos våra hästar skulle kunna identifieras.

Nya smärtlindringsmetoder eller test för att utvärdera om hästars asymmetrier är smärtorsakade eller ej skulle behöva utvecklas. Ett fortsatt forskningsarbete för att korrekt förstå hästars rörelseasymmetrier samt utvärdera och förbättra de olika momenten vid ortopediska utredningar är också centralt. Men viktigast av allt är att den nya kunskapen når ut till lekmän och professionella inom hästnäringen inklusive veterinärer så den bidrar till ökad hästvälfärd.

Acknowledgements

The work included in this thesis was initiated at the **Department of Clinical Sciences** and then continued at the **Department of Anatomy, Physiology and Biochemistry,** Faculty of Veterinary Medicine and Animal Science, Swedish University of Agricultural Sciences. I want to thank the past and present heads of the departments for their support during the project. Financial support for the work presented in this thesis was generously provided by **The Swedish-Norwegian Foundation for Equine Research** (Stiftelsen Hästforskning) and the **Swedish Research Council Formas.**

Many people contributed to this thesis and helped me along the journey. I want to thank every one of you, at AFB and KV, at UDS, past and present PhD students, colleagues, family and friends. Writing this acknowledgements section was a joy as it highlighted the many wonderful people I am blessed to have in my life.

I would particularly like to express my sincere gratitude to:

My main supervisor **Marie Rhodin**, it is hard to know where to start. Thank you for believing in me and for giving me this opportunity! You are wonderfully supportive and always online/on-phone to solve every sensor (and other type of) crisis. Provider of early morning work-outs, locally produced eggs and midnight feedback. I aspire to someday reach your level of knowledge in equine biomechanics but I will never reach your talent for multitasking or last-minute-but-still-golden-work-skill. They say that the most important criteria for an enjoyable PhD journey is a good main supervisor, I had the best, thank you!

Pia Haubro Andersen, I would not like to read a version of any of my papers, or this thesis for that matter, without your invaluable contribution. Thank you for your excellent guidance, support and constructive criticism. Your questions and input always demands thought and I owe much of my growth during these PhD studies to you.

Karin Holm Forsström for everything you have thought me about lameness evaluation, treatment and rehabilitation of horses. My clinical skills are much owed to you. Also, last but not least, for where to find the best pub and the wining quiz team :)

Thilo Pfau your comments have been invaluable and always on point. Thank you for interesting discussions and advice. Even though from all the way over on the British Isles, your wonderful sense of humour has graced my inbox and made many days brighter.

I also want to thank all the **horse owners** and **horses** that took part in the studies included in this thesis. Thank you for letting me measure your horses' movement and for trotting up those extra times. Special thanks to the **Swedish Horse Guards Society**, the **National Equestrian Center at Strömsholm**, **Färingsö Riding School** and **Uppsala Yrkesgymnasium Jälla** and all the wonderful staff who helped me out at each of these facilities.

Elin Hernlund, for being my idol. Thank you for being so supportive, for all wonderful discussions, teaching collaborations and invaluable advice about all aspects of life. **Katrina Ask** my one and only roomie! I don't know how I managed to cope before I had you to laugh, joke, grumble and share 'biskvier' with. You have done an excellent job as room manager but now it's time for me to take over! **Ellinor Spörndly-Nees** for being the most caring and supportive person ever. You are the dissertation expert, life advice provider and generally just awesome. **Agneta Egenvall** for sharing you statistical brilliance, contributing with your point of view and for fun times and discussions. **Claudia von Brömssen** for excellent statistical advice. **Laurie Tyrrell** and **Mark Nannerman** at the Equinosis team for excellent help and support with the Lameness Locator systems. The **Qualisys team** for excellent support and especially **Christoffer Roepstorff** for all help, collaboration and for being so positive!

Past and present members of Maries all star Equine Biomechanics team: **Johan Lundblad**, **Camilla Frisk**, **Anna Byström**, **Britt Coles, Sara Weidenblad, Marie Hammarberg** it is, and has been, an absolute pleasure working with you!

Thanks to the Zürich team including **Mike Weishaupt**, **Lea Ramseier** and **Thomas Wiestner** among others and to **Lars Roepstorff** for collecting the data used in Paper III.

The international equine biomechanics PhD students and up and coming superstars: **Anne Selvén Kallerud, Filipe Serra-Bragança, Aagje Hardeman** for all collaborations, journal clubs and fun times. Also **Line Greve** for data and collaboration on Paper IV.

Siri Morén and **Camilla Ahrenbring** who collected part of the data for Paper I and the splendid veterinary students who has helped me since **Camilla Fredriksson**, **Amanda Landstedt**, **Tobias Wrangberg**, **Lisa Marie Andersson, Lina Bogren.**

All the amazing past and present PhD students who I have encountered along the way **Linda Andersson**, **Malin Connysson**, **Carl Ekstrand**, **Sanna Truelsen Lindåse, Maria Löfgren, Josefin Söder, Anna Sjöblom, Maja Wiklund, Lisa Johansson, Lena-Marie Tamminen, Amy Barstow, Marie Eisersiö, Birgitta Staaf-Larsson, Madeleine Högberg, Denise Söderros, Hadrien Gourlé, Emelie Torsson, Gunilla Ström Hallenberg, Torun Wallgren, Hanna Palmqvist, Ida Hallberg, Suvi Mäkeläinen, Daniel Bergman** and many more for interesting discussions during courses, fika and fun PhD-council times.

A big thanks to all my amazing teaching colleagues at AFB. The level of your skill was known to me already as a veterinary student, but the awe has since just increased. A special mention to **Lisa Persson, Sören Johansson** and **Richard Ferm** for making Clinical Anatomy such a joy to teach each year.

And of course **everyone at AFB** where the special "röda-soffan-fika-feeling" is all encompassing. Special thanks to **Maria Trollsås** for organisational help with things big and small.

I have also not forgotten the amazing people at my "first" department, special mention to: **Kia Nostell**, **Anna Berg, Malin Hagberg-Gustavsson, Mia Rihimäki, Sussi Petersson, Elin Svonni**

En icke obetydlig del av de senaste åren har spenderats på hästkliniken och där förtjänar pol-gänget **Christine Jonsson**, **Wendela Warnbrant, Mike Woolford, Moa Alkarp, Jenny Myrin, Åsa Näsbom** tack för ert stöd under

mina första stapplande ortopedi steg och för att ni gör POL till en så mysig plats. **Malin Santesson** och **Lena Brask** för allt ni lärt mig och alla frågor ni besvarat. **Tina, Sara** och **Cia** för ert stöd, er humor och alla hästar ni debiterat åt mig när det gått dåligt tidsmässigt…igen. **Henrik x2** som löser alla hovproblem, **Bild** för att ni är så grymma och **Fredrik Tinmark** för gott samarbete kring Q-horse.

Inte alls att förglömma **alla andra på Hästkliniken** för att ni gjort det så roligt att jobba nere hos er på somrar och jourer. **Lena Ström, Ylva Hedberg-Alm, Linda Perttula, Sara Larsdotter-Davy, Tamas Toth** och **Miloz Grabski** förtjänar extra tack för alla frågor ni besvarat, inte sällan mitt i natten. Alla andra nuvarande och tidigare på UDS, ingen nämnd ingen glömd, ni är fantastiska att jobba med. Hästarna har tur som har er när de har oturen att bli sjuka!

Sabrina Skov-Hansen den danska superkirurgen jag lärde känna nästan samtidigt som jag började denna PhD resa, och som därmed kan beskyllas för mycket. Jag vet med säkerhet att jag ej överlevt dessa år utan dig. Kära stutis vännerna: **Elin Holmroos** som jag känt sedan FU26 och beundrar för din magiska järnvilja, **Sofie Ericzén** från min första basgrupp som gjorde nationerna osäkra med mig och **Oskar Maxon** som jag känt sedan du var väldigt ung och haft så mycket episka upptåg med, ni var under utbildningen högst ansvariga för min överlevnad och abstinensen hålls numer som tur i schack av regelbundna spelkvällar. **Katarina Högberg von Schultz** som bor för långt bort men vars värme, glädje och träningspepp når hit ändå. Ni tillförde också **Josef**, **Fredrik** och **Matte** som nu frivilligt eller ofrivilligt är inkluderade i vännersektionen :)
Emma Odelros som är min bästa livlina när fölen kommer och som tog initiativ till den viktigaste dagen på veckan, sushiiii/bonde onsdag, hur hade detta gått om inte allt mellan himmel och jord kunnat avklaras med gänget som utöver många redan nämnda ovan också inkluderat **Anna Eidnert-Eriksson** och **Marij Tijssen** (yes, you 'slided in on a shrimp sandwich' into the Swedish section). **Bröms** för att du tar hand om Olle när jag måste jobba och **Olga Svensson** som peppar till träning

Amanda Dahlgren hårdrocksblomman i norr, du bor för långt borta (och **Per** med) men är nära i hjärtat. Tack för att du alltid finns där!
Alla andra fantastiska vänner från den episka tiden på Nordvik: **Caroline Westerlund**, **Emma Karlsson, Tove Göransson, Jenny Ögren, Lina Melin,** och ovärderliga vänner från barndomen **Muckas** och **Camilla Larsson.** Jag hoppas få fortsätta ha er alla i mitt liv!

Tack **Per Jonsson** och **Helena Vestin** som visade mig som veterinärstudent hur fantastiskt det är med ortopedi och **Ann** och **Peter** för att ni låtit mig och dansken komma och rida era fina hästar.

Släkten är värst men också bäst! Moster **Lena**, **Julia**, **Patrik** och fina **Mormor**, ni bor lite långt borta men är nära i hjärtat. **Morfar** som ej finns hos oss längre och vars upptåg jag saknar. **Lotta**, **Magnus** och **Björn**, ni hamnar också här i egenskap av numera adopterad släkt. Tack för att ni finns!

Jag kommer aldrig att förstå det där intresset för ekonomi **Bror** men nu har du ju ändå **Malin** och genom henne lite mer vettiga intressen i form av världens gulligaste katt. Vi är rätt olika men jag är ändå glad att omtänksamma, snälla du är just min bror.

Mamma och **Pappa,** vad som än händer kommer jag aldrig kunna skylla några av mina problem på en dålig barndom. Tack för att ni finns och för att ni är dom bästa föräldrar man kan ha!
Tack för nattsagor och vaggvisor, för alla utflykter i skogen och fjällen, för alla mil i bil (Danmark är ju exempelvis ett tämligen litet land :)), för en förebild i löpningen (kan pappa så kan väl jag springa maraton), för att ni lät mig tjata mig till en hund (även om du nog är värsta hundgalningen nu mamma), lät mig tjata mig till att få börja rida och för att ni alltid stöttat mig i allt!

Olle jag är inte säker på att du visste vad du gav dig in på när vi träffades på den där vårbalen, men jag är så glad att jag fann just dig! Du finns alltid där och stöttar, ger mig ett perspektiv som sträcker sig längre än veterinärbubblan och ser till att jag har popcorn att livnära mig på när dagen varit tuff. Jag hoppas få fortsätta vandra, springa och bara mysa i soffan med dig många år framöver. Jag älskar dig!

Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2020:12

This thesis investigates the clinical significance and interpretation of vertical movement asymmetries in riding horses under different circumstances. Pain medication proved ineffective in reducing movement asymmetries in riding horses in training while 'rising trot' induced movement asymmetries. The challenging discrimination between true forelimb lameness and compensatory head movement asymmetry could be facilitated by concurrent evaluation of withers movement symmetry.

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Online publication of thesis summary: http://pub.epsilon.slu.se/

ISSN 1652-6880
ISBN (print version) 978-91-7760- 542-3
ISBN (electronic version) 978-91-7760-543-0