Norwegian University of Life Sciences
Faculty of Veterinary Medicine
Department of Companion Animal Clinical Sciences

Philosophiae Doctor (PhD)
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Something in the way you move: Studies of movement asymmetry in young Standardbred trotters

Studier av bevegelsesasymmetri hos unge varmblodstravere

Anne Selvén Kallerud

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That a horse takes pleasure in swift movement, may be shown conclusively. As soon as he has got his liberty, he sets off at a trot or gallop, never at a walking pace; so natural and instinctive a pleasure does this action afford him, if he is not forced to perform it to excess; since it is true of horse and man alike that nothing is pleasant if carried to excess.

Xenophon, ca. 350 BCE, *On Horsemanship*

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Table of Contents

All photographs in this thesis were taken by the thesis author, unless otherwise stated.

1 Abbreviations

a: Acceleration

COM: Centre of mass

CPG: Central pattern generator

F: Force

GRF: Ground reaction force

HDmax: Difference in maximum position of the head

HDmin: Difference in minimum position of the head

IMU: Inertial measurement unit

LF: Left forelimb

LH: Left hindlimb

m: Mass

PDmax: Difference in maximum position of the pelvis

PDmin: Difference in minimum position of the pelvis

RF: Right forelimb

RH: Right hindlimb

2 List of papers

I. **Objectively measured movement asymmetry in yearling Standardbred trotters**
Anne S. Kallerud*, Cathrine T. Fjordbakk, Eli H. S. Hendrickson, Emma Persson-Sjödin, Marie Hammarberg, Marie Rhodin, Elin Hernlund
Equine Vet J. 2020;00:1-10. https://doi.org/10.1111/evj.13302

II. **Non-banked curved tracks influence movement symmetry in two-year-old Standardbred trotters**
Anne S. Kallerud*, Elin Hernlund, Anna Byström, Emma Persson-Sjödin, Marie Rhodin, Eli H. S. Hendrickson, Cathrine T. Fjordbakk
Equine Vet J. 2021;00:1-10. https://doi.org/10.1111/evj.13409

III. **A longitudinal study of movement asymmetry and indicators of orthopaedic health in young Standardbred trotters**
Anne S. Kallerud*, Cathrine T. Fjordbakk, Elin Hernlund, Eli H. S. Hendrickson, Marie Rhodin
Manuscript

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3 Summary

Lameness is a major welfare issue in athletic horses. Traditional lameness evaluation is based on subjectively assessing whether the horse shows asymmetrical movement, and this can be challenging. Sensor-based systems that accurately quantify equine movement asymmetry are now available. However, knowledge is lacking regarding the biological and clinical relevance of measured movement asymmetry. This is especially true for specific types of horses, such as the Standardbred trotter.

We conducted a prospective, longitudinal study to look at movement asymmetry in young Standardbred trotters. The main areas of interest were the prevalence and magnitude of movement asymmetry at the initiation of training (paper I), any changes seen in asymmetry with increasing age and increasing training (paper III), as well as under different training circumstances (paper II). We were also interested in reporting the occurrence of orthopaedic veterinary interventions during the study period. Finally, we wanted to look at the number of horses that completed a qualification race, as well as how many went on to participate in regular races before the end of their three-year-old season.

Standardbred trotters were recruited as yearlings, just as they were starting their training. The study period was two years, until the end of the three-year-old season. Movement asymmetry was measured utilising an inertial measurement unit (IMU) system during both in-hand trotting and during driven exercise. Data was collected approximately every third month at 13 different training yards; 114 yearlings were recruited to the study. Study drop-out was substantial during the study period, as many horses changed trainers or were taken out of training for different reasons, including lameness.

Our main findings were:

- During the first months of training, a high proportion (94%) of Standardbred yearlings showed movement asymmetries. Most horses showed mild

asymmetry. There was considerable variability (i.e. uncertainty) in the data, mainly due to the behaviour of inexperienced, fresh young horses. When asymmetry data from in-hand trials were compared to trials when the yearlings were driven on the track, there was no overall difference in asymmetry. However, substantial individual variation was observed, and some horses showed one asymmetry pattern in-hand and another altogether when driven on the track. This illustrates the importance of assessing the Standardbred on the track as well as in-hand during clinical lameness evaluation.

- In two-year-old Standardbreds, trotting through a curve during driven exercise induced systematic changes in measured movement asymmetry. These changes did not entirely correspond to previously described changes in asymmetry for horses lunged in circles. The changes seen in our Standardbreds were overall small. When collecting IMU asymmetry data under similar circumstances (large diameter trotting track, non-banked turns and jogging speed) for clinical lameness evaluations, there is little need to differentiate between data from the straight part of the track and data from the curved part of the track.

- During the first two years of training, movement asymmetry in our cohort of Standardbred trotters was substantial, ranging from mild to severe in magnitude. Most horses showed mild or moderate movement asymmetry. There was some evidence of an increase in asymmetry magnitude over time for hindlimb parameters, however, these results need to be interpreted with care due to the large number of horses dropping out during the study period. The most frequent orthopaedic veterinary intervention was therapeutic joint injections, which were more common for three-year-old horses in our cohort. Despite this, completion rates for qualification races were high (> 70%) and the percentage of study horses that entered regular races (64%) is above the national average for this age group.

Our results contribute to the knowledge base of objectively measured movement asymmetry in young Standardbred trotters. Suggested future research should focus on the possible causal relationship between the magnitude of measured movement asymmetry and the development of clinical lameness. Further knowledge of the relationship between these two entities could potentially lead to earlier detection of clinical lameness.

4 Norsk sammendrag

Halthet er en betydelig utfordring for sportshester. Tradisjonelt baserer halthetsbedømmelse seg på en subjektiv vurdering av om hesten viser asymmetriske bevegelser. Dette kan være vanskelig å bedømme. Sensor-baserte systemer som med stor grad av nøyaktighet måler bevegelsesasymmetri hos hester er nå tilgjengelig. Vi mangler derimot kunnskap om den biologiske og kliniske relevansen av målt bevegelsesasymmetri. Dette gjelder særlig for enkelte typer hester, slik som varmblodstravere.

Dette doktorgradsarbeidet tar utgangspunkt i en større prospektiv, longitudinell studie for å se på bevegelsesasymmetri hos unge varmblodstravere. Av særlig interesse for oss var å se på forekomsten og graden av bevegelsesasymmetri ved starten av treningskarrieren (studie 1), og å undersøke hvordan asymmetri endrer seg med økende alder og grad av trening (studie 3), samt under ulike treningsforhold (studie 2). Forekomsten av ortopediske veterinærbehandlinger i løpet av studieperioden var også av interesse. Endelig undersøkte vi hvor mange hester som gjennomførte prøveløp før utgangen av treårssesongen, og hvor mange som også startet i ordinære travløp i denne perioden.

Varmblodstravere ble rekruttert som åringer, rett etter at de var satt i trening. Studieperioden var to år, fram til slutten av treårssesongen. Bevegelsesasymmetri ble målt ved hjelp av et «inertial measurement unit» (IMU) system. Hestene ble målt både ved mønstring for hånd og under kjøring. Vi samlet inn data fra 13 ulike treningsstaller omtrent hver tredje måned, og studien omfattet 114 åringer. Et betydelig antall hester falt fra i løpet av studieperioden. Årsaken til dette var at mange hester byttet trener eller ble tatt ut av trening av ulike årsaker, inkludert halthet.

Våre hovedfunn var:

- I løpet av de første månedene hestene var i trening målte vi asymmetriske bevegelsesmønstre hos en stor andel (94%) av åringene. De fleste hestene hadde mild asymmetri. Det var betydelig variasjon (dvs. usikkerhet) knyttet til disse resultatene, hovedsakelig på grunn av atferden til de uerfarne, spreke unghestene. Sammenligning av asymmetridata fra mønstring for hånd med data fra kjøring på travbanen viste ingen endring i asymmetri på gruppenivå. Den individuelle variasjonen var derimot markert. Enkelte hester hadde én type asymmetrimønster når de ble travet for hånd, og et helt annet mønster når de ble kjørt på banen. Dette illustrerer hvor viktig det er å vurdere travhester under kjøring i tillegg til for hånd ved kliniske halthetsundersøkelser.

- Når toårige varmblodstravere ble kjørt gjennom en sving på travbanen oppsto det målbare, systematiske endringer i bevegelsesasymmetri. De endringene vi fant samsvarer bare delvis med tidligere beskrevne endringer i bevegelsesasymmetri hos hester som longeres i sirkel. Endringene vi så hos våre travhester var imidlertid små. Når en anvender et IMU-system ved kliniske halthetsundersøkelser under lignende omstendigheter som i vår studie (travbane med stor diameter, ikke doserte svinger og joggetempo) er det derfor ikke nødvendig å skille mellom data fra langsiden og data fra svingen.

- I løpet av de første to årene med trening observerte vi betydelig bevegelsesasymmetri hos våre travhester. De fleste hestene viste mild til moderat bevegelsesasymmetri, og en mindre andel hester hadde moderat til kraftig asymmetri. Det var tegn til en viss økning i graden av bakbensasymmetri over tid på gruppenivå, men disse resultatene må tolkes med forsiktighet fordi et stort antall hester forsvant fra studiedeltagelse. Bruk av terapeutiske leddbehandlinger var den hyppigst forekommende ortopediske veterinærbehandlingen i løpet av studietiden, vanligst forekommende hos treårige travere i vår studie. Til tross for dette fullførte en høy andel av hestene godkjente prøveløp (> 70%). Av hestene i studien deltok

64% i ordinære løp. Dette er en høyere prosentandel enn det nasjonale gjennomsnittet for denne aldersgruppen.

Resultatene fra våre studier bidrar til økt kunnskap om objektive målinger av bevegelsesasymmetri hos unge varmblodstravere. Forslag til framtidig forskning knytter seg særlig til den mulige årsakssammenhengen mellom graden av målt bevegelsesasymmetri og utviklingen av klinisk halthet. Ytterligere kunnskap om denne sammenhengen kan forhåpentligvis føre til tidligere oppdagelse av klinisk halthet.

5 Introduction

5.1 General introduction

The object aimed at is the prevention of disease. It is an old but true saying, that "an ounce of prevention is worth a pound of cure;" and it is more convenient and less expensive.

Dadd, 1850,

The advocate of veterinary reform and outlines of anatomy and physiology of the horse[51]

The theme for this thesis is movement asymmetry in the Standardbred trotter: What is the prevalence of movement asymmetry, how does movement asymmetry change under different training circumstances and with increased age and training of the horse, and why does it matter?

Summarised, the background for this thesis is that lameness is a highly prevalent welfare issue in horses and diagnosing lameness correctly can be challenging for the equine veterinarian. Traditional lameness evaluation is primarily based on visual recognition of a (presumed pathological) asymmetric movement pattern as the horse shifts body weight to unload the painful structure(s). Through research and technological development, we can now accurately quantify even slight movement asymmetry, unrecognisable to the human eye. However, asymmetry may be caused by non-pathological, individual variances in locomotion, and knowledge is lacking about the relationship between measured movement asymmetry and clinically evident lameness. Although the scientific body of knowledge in this area is growing fast, research into the realm of trotting racehorses, such as the Standardbred trotter, is scarce. This is a population of horses where high demands are placed at an early age to train and race at near maximum capacity. We know that lameness is prevalent in these horses, and musculoskeletal injuries are commonly career-ending issues. Can we use data on movement asymmetry to predict, perhaps even prevent, clinical lameness? In order to reach this potential ultimate future goal, we must know more about movement asymmetry in the Standardbred: What is the prevalence of movement asymmetry and how does movement asymmetry change under different training circumstances and with increased age and training of the horse? The studies in this thesis investigate some of these aspects through collection of asymmetry data from a cohort of Standardbred trotters. Data collection commenced as the horses were yearlings and at the starting point of their racehorse training, and concluded two years later, at the end of their three-year-old season.

Historically, there has been a keen interest in the horse's locomotor system, especially the orthopaedic health of the horse. The following chapter looks at lameness in the horse, including **how non-lame and lame horses move**.

5.2 Introduction to lameness in the horse

> *The idea of a good horse with poor legs is a misnomer; the legs are the essence of the horse, and every other part of the equine machine is of only subservient and tributary importance.*

Liautard, 1888,
Lameness of Horses and Diseases of the Locomotory Apparatus[150]

The term **lameness** originally described a "weakness of limbs" (from the Old English *lama*, German *lahm*[250]) and in modern usage describes a clinical sign that results in a gait abnormality.[214] This can be due to pain (e.g. injury, inflammation), or a mechanical defect associated with the musculoskeletal system, causing the horse to limp.[214] Lameness is therefore by definition not a disease, it is a clinical sign of an abnormal condition, the way a fever is a sign of illness. The soundness of horse limbs has been subject to great interest since ancient times. One of the earliest sources describing riding horses, written by the Greek historian Xenophon (c. 430-350 BCE), advices the prospective horse buyer to first look at the feet.[266] The importance of equine orthopaedic health is understandable; arguably, the horse is of interest to humans primarily due to its locomotor apparatus. Although there is some controversy as to both the exact origin of the horse and its earliest domestication,[88,96] the horse appeared in cave art more than 30,000 years ago,[244] while the earliest archaeological evidence of horse husbandry (including the use of bits and harness) dates from Asian steppe dwellings approx. 5500 years ago.[179] The use of the horse for **transportation** drastically increased the mobility of humans and shaped the course of human history through accelerated migration and trade[135] as well as warfare.[97] As the horse lost its importance as a means of transportation in most parts of the world during the 20th century, its popularity as a **recreational animal** in various ridden and driven disciplines has increased. As has been pointed out,[251] the demands on the horse may have changed, but not necessarily decreased: Historically, the horse needed a functioning locomotor system, while the successful modern equine athlete is in need of a superior locomotor system.[251] Lameness not only curbs the use of the sport horse, affecting training progression and often leading to economic losses for the horse owner, it also impacts horse welfare. Overwhelming evidence shows that lameness is the most reported sign of illness as well as the primary cause of days lost from training. This is true for the general sport horse population,[186] including dressage horses,[168] showjumpers,[70] event horses,[225] western performance horses,[119] and working military horses.[202] Multiple epidemiological studies show equally high occurrence of lameness in Thoroughbred racehorses,[12,64,151,174,204] as well as in Standardbred harness racehorses.[19,59,89,233,246]

It follows that lameness makes up a significant part of the caseload for many equine veterinarians.[153] So how can we **recognise lameness** and locate its cause? In the following, lameness is discussed as a sign of pain originating from the musculoskeletal system of the horse, excluding neurological or mechanical deficits that may lead to gait abnormalities. Traditionally, veterinarians assess horses presented as lame by methodical **clinical evaluation**. After obtaining a history from the owner/trainer/rider of the horse regarding the presenting complaint, a thorough examination of the horse's musculoskeletal system follows. Briefly, the veterinarian visually assesses the horse's conformation and posture, palpates relevant musculoskeletal structures, investigates the presence of foot pain by the use of hoof testers and evaluates the locomotion of the horse at a walk and trot in-hand, possibly also assessing locomotion during circling or lunging and/or during ridden or driven exercise, and on different surfaces. The veterinarian may also perform flexion tests of the limbs to evaluate the range of motion of the joints and to potentially aggravate pain in certain areas of the limb, attempting to narrow down the anatomical location of the painful structure. To localise the anatomical source of the pain diagnostic analgesia is often required, using local anaesthetic to reduce or remove the pain from a specific area of the horse's body and then re-assessing the horse for a reduction in lameness. Once an area of pain has been localised, diagnostic imaging of the area is warranted. Imaging modalities such as digital radiography and ultrasonography are common in veterinary medicine, and computer tomography (CT), magnetic resonance imaging (MRI) and scintigraphy are now available to an increasing number of veterinarians and horses. Accurately localising the cause of lameness is a prerequisite for reaching a correct diagnosis and initiating the appropriate treatment.

To reach a correct diagnosis, the **lame limb(s) of the horse need to be identified**. Traditionally, lameness has been divided into supporting limb lameness (pain during weight-bearing on the limb)[216] and swinging limb lameness (affecting how the horse carries the limb)[216] or a mix of these. Supporting limb lameness or mixed lameness are the most common.[216] Biomechanically, lameness can be divided into impact-type and push-off-type lameness,[124] relating more to the functional use of the locomotor system.

Lameness evaluation is commonly performed with the horse **trotting**, as the trot is regarded as the most useful gait for detecting asymmetric movement.[216] Gait can be defined as a repetitively performed interlimb coordination pattern,[40] and is often divided into symmetrical and asymmetrical gaits.[104] Symmetrical gaits, such as the walk, trot and pace, have footfalls that are evenly spaced in time,[104] as opposed to asymmetrical gaits such as the canter. The trot is a two-beat, diagonal gait,[104] with footfalls as described by Muybridge in his book *Animals in Motion* (1902)[170];

> "a system of progress in which each pair of diagonal feet are alternately lifted with more or less synchronism, thrust forward, and again placed on the ground; the body of the animal making a transit, without support, twice during each stride."[170]

Gaits with suspension phases, such as the trot and the pace, are costly in effort but have the advantage that two limbs work together to propel the horse forward, while at the same time providing the horse with adequate stability and cushioning.[106] Since the trot is a symmetrical gait it makes asymmetrical movement easier to spot, and the velocity of the horse and suspension phases result in higher concussion of the limbs, increasing the signs of supporting limb lameness.[42] As the trotting gait is central to assessing the lame horse, understanding **how non-lame horses move at the trot** is essential.

5.2.1 How non-lame horses move

Coordinated limb movement is regulated by **central pattern generators (CPGs)** that are established during development.[94,95] A CPG is a collection of neurons that can generate a coordinated rhythmic output without external feedback.[142] In all vertebrates locomotor CPGs are controlled by specific locomotor command regions located in the brainstem, while the CPGs themselves are located in the ventral spinal cord.[94,137] Per limb, a separate spinal CPG network control the standard muscle activation patterns for that limb (coordinated activation of flexor and extensor muscles).[94,95] Interaction of the different limb CPGs enable interlimb coordination, resulting in specific gait patterns such as the alternating diagonal pattern of the trot.[94] A trotting stride consists of two phases, the stance phase (limbs on the ground) and the swing phase (limbs in the air), usually with two periods of suspension per stride. The stance phase can be divided into impact, mid-stance, and breakover/push-off. A stride is the "unit" of the gait; one stride is equal to one complete repetition of the gait pattern.[40] In **figure 1** the left forelimb-right hindlimb is in the swing phase and the opposite diagonal (right forelimb-left hindlimb) is in the stance phase.

***Figure 1**. A dressage horse trotting.*

While at first glance the diagonal limb pairs seem to move in synchrony, we can see that the left hindlimb is already pushing off the ground, while the right forelimb is still fully on the ground. The diagonal footfalls of the trot are not always synchronous, instead either a hind- or a forelimb may move in advance of its diagonal counterpart.[45,63] This is termed **diagonal dissociation or advanced placement,**[63] and is most easily seen during slow-motion video analysis. Dissociation of the trot was commented upon already at the time of the earliest motion picture analyses of the horse in the late 1800s.[170] As the hoofs contact the ground, if the hindlimb contacts the ground before the forelimb it is called positive diagonal dissociation[43] or hind-first dissociation[107] (**figure 2**), and if the forelimb contacts the ground before the hindlimb it is named negative diagonal dissociation[43] or fore-first dissociation.[107]

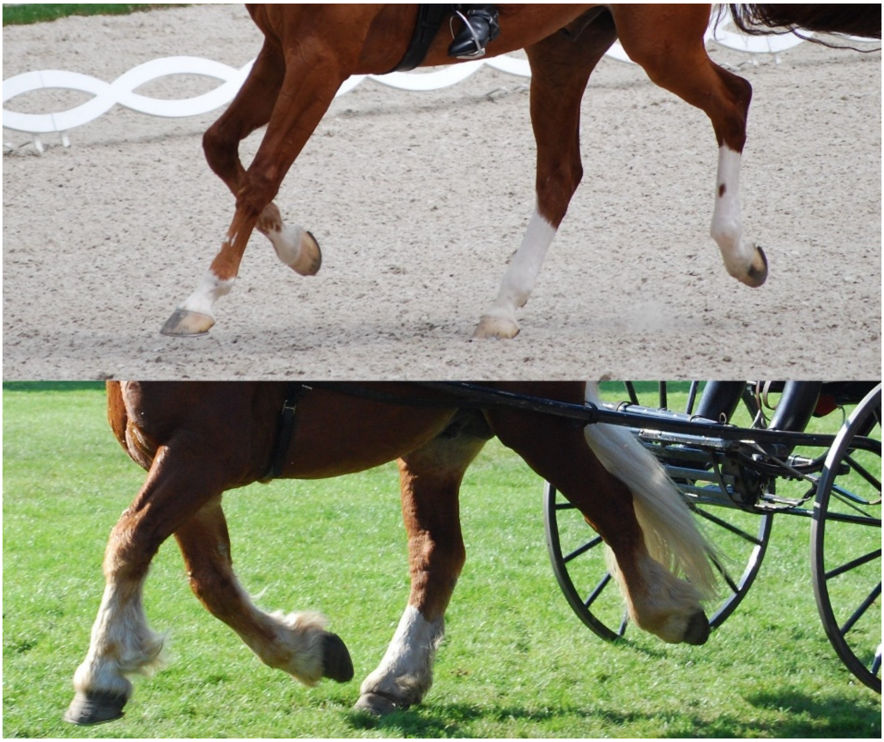

Figure 2*. Horses showing positive diagonal, or hind-first, dissociation during trot.*

Hind-first placement is regarded as a desirable trait for dressage horses,[110] while racing trotters reportedly frequently display fore-first placement.[63,170]

One reason for this variation in footfalls may be that it allows the horse to maintain trunk stability while partially decreasing mechanical energy losses.[107,108] When the horse moves, a **ground reaction force (GRF)** is created during the stance phase.[46] As the hoofs push against the ground, the ground offers a resisting force of equal magnitude.[46] This interaction follows Newton's third law of motion, which states that for every action (force) there is an equal and opposite reaction. The magnitude and direction of the GRF determines the resulting speed and direction of movement of the horse's body.[46] This interaction follows Newton's second law of motion, which states that the net force (F, vector sum of all forces) is the product of an object's mass (m) times its acceleration (a).

Shifting of body weight is commonly defined by describing shifting of the body **centre of mass (COM)**. The horse has a relatively high COM due to its long, light limbs, with the mean position of the COM in a squarely standing horse approx. at the level of the 13th thoracic vertebra, or lowest point of the back, and approx. 2 cm below the level of the hip joint.[28] In a horse standing with the head and neck in a neutral position, the weight distribution of the total body weight is 58% on the forelimbs, and 42% on the hindlimbs.[41] Therefore, the COM is closer to the forelimbs than the hindlimbs. During locomotion and the creation of GRFs, the redirection of the COM is associated with mechanical energy loss in all legged creatures.[108,218] This interaction is explained through the concept of **collisional mechanics**, as described by Lee et al.[144]:

> "In steady speed locomotion, the limbs act primarily as struts that divert the path of the CoM in a collision-like interaction with the supporting substrate. Dynamic collisions, such as two balls colliding, exert forces abruptly, whereas the compliant legs of animals distribute forces over the duration of a step and over multiple steps within a stride."[144]

Horses with a hind-first placement in the trot had reduced collisional losses compared to horses with synchronous placement at the same trotting speed.[107] Fore-first placement may aid the Standardbred trotter in trotting at greater speed. As the forelimb contacts the ground, the hindlimb continues to travel forward until ground contact is made.[42] The further forward the hindlimb is able to travel before meeting the ground, the greater is the increase in over-tracking, i.e. the hind hoof landing in front of the same side (ipsilateral) front hoof.[42] Increased over-tracking greatly contributes to increased stride length during high-speed trot.[42]

That the horse is "born to run" makes it apt for racing. The horse has been characterised by Hildebrand as "perhaps the most efficient running machine ever evolved; probably no other vertebrate has so many structural adaptations for untiring progress on the ground."[103] A few central **adaptations for economising locomotion and conserving energy** will be briefly described in the following. While these strategies are not limited to the horse, they are very well developed in this species. During gaits without suspension phases, such as the walk, the body and its COM is vaulted up and over each limb during the stance phase[36,40]; this concept is called inverted pendulum mechanics.[36] Conversely, during gaits with a phase of suspension, such as the trot and gallop, the COM travels downwards during the stance phase because the body weight of the animal compresses its joints and supporting structures.[40] The distal limb and its joints are supported primarily by more or less elastic tendons and ligaments (suspensory ligament, superficial and deep digital flexor tendons and their accessory ligaments). During stance phase, elastic soft tissue stretches, and energy is stored; energy is released as the body weight passes forward over the limb.[5,40] Thus, tendons act as springs,[5,182,263] and this **spring mass mechanism** reduces the amount of work left to the musculature.[5] Horses' joints act mainly as hinges, which enables movement forwards and backwards in a sagittal plane, but restricts limb adduction and abduction.[105] This reduces energetic cost by **decreasing the need for stabilising tissue** to prevent unwanted sideways motion as well as dislocation.[105] Most of the horse's force-generating muscle mass is located proximally, on the upper limb close to the trunk.[182] In the evolution of the long limbs of the horse, the lower limb segment lengthened and underwent a reduction in digits.[227] Consequently, the equine limb becomes progressively lighter from proximal to distal. The **cost of moving the distal limb is reduced,**[105] as exemplified by the analogy of a person swinging a hammer[105]; if the hammer is held by its heavier head, it takes little effort to swing the light handle in an arc; however, if the hammer is held by the handle it takes more effort to swing the head in the same arc.[105]

Figure 3a-c: *Standardbreds showing the diagonal footfalls of the trot at* ***a)*** *warm-up trot,* ***b)*** *high-speed trot, with a marked phase of suspension, and* ***c)*** *a Standardbred pacer showing the ipsilateral (same side) footfalls of the pace, during a suspension phase. The pacer is fitted with hobbles that limits the limbs to moving in an ipsilateral fashion.*

During high-speed trot the trotting racehorse pushes off the ground with a higher vertical velocity,[42] **increasing the suspension phase** and thereby covering more ground (**figure 3b**). In Standardbreds trotting at a speed of 12 m/s (43 km/h), the swing phases accounted for 75% of the total stride duration, leaving the diagonal limb pairs on the ground for only 25% of a total stride.[62] The same horses reached a maximum stride length of over 6 metres per stride.[62] Hoyt & Taylor[114] showed that oxygen consumption is a curvilinear function of speed, resulting in a U-shaped relationship between cost of transportation (the metabolic cost of moving a given distance[240]) and speed. In ponies trotting freely, their "preferred" speed coincided with the speed at which the cost of transportation was at a minimum.[114] With increasing speed, the ponies transitioned to a gallop, leading to the hypothesis that horses **change gait at speeds that minimise the energetic cost of movement**. In contrast, Farley & Taylor[76] showed that ponies changed from a trot to a gallop while the energetic cost of galloping was still higher than trotting; the gait change occurred **when musculoskeletal forces reached a certain level.**[76] In the same ponies, peak vertical GRF increased with increasing trotting speed and fell by an average of 14% after the transition to gallop.[76] In another study[217] the same two ponies, as well as two dogs, were running on a treadmill after being surgically equipped with strain gauges in the radius and tibia; one pony also wore a special shoe fitted with force transducers.[217] Maximum strain magnitude as well as peak forces increased with increasing trotting speed and decreased when switching to canter; the maximum strain magnitude as well as peak force decreased by up to 42% when switching to the faster gait.[217] It is suggested that the musculoskeletal system has certain "safety margins" or thresholds that serve to protect the animal from injury; **one of these protective features is the changing of gaits**[76,217] – an undesired option when racing Standardbred trotters, where the horse staying in the trot is a prerequisite for racing success.

The trot is a naturally occurring gait in all horse breeds, while the pace is only common in certain breeds.[104] The Standardbred breed contains both Standardbred trotters and Standardbred pacers.[165] The **pace** is a two-beat gait where the limb pairs do not move as diagonal pairs, instead the fore- and hindlimb on the same side move together, making it a laterally symmetrical (ipsilateral) gait[104] (**figure 3c**). Recent genetic studies have shown that a mutation in the **DMRT3 "gait keeper" gene** alters the locomotor pattern in horses and is obligatory for "gaitedness".[8,116] Gaited horses are horses that can perform other gaits in addition to the three naturally occurring gaits of walk, trot and canter/gallop,[8] such as the pace. The North American Standardbred is fixed for the DMRT3 mutation, meaning that all North American Standardbreds express the gene mutation.[8,201] The Scandinavian Standardbred has a lower mutation prevalence, probably due to the influence of French trotter lineage which have a lower frequency of the mutation.[8,201]

The DMRT3 mutation not only facilitates certain gaits in horses, it may also promote the ability to trot or pace at high speed as well as inhibit the transition from trot or pace to gallop.[8] The DMRT3 gene mutation is strongly linked to trotting performance in Standardbreds, as reported in a study by Jäderkvist et al.[116]; "horses homozygous for the mutant A allele are faster, they have a cleaner trot, they earn more money, and they win more races". Whether this gene mutation also influences movement asymmetry is not known. The overall frequency of the A allele in Standardbreds is 98%,[116] however, not all Standardbreds pace. Alternative genetic variations have been detected that are highly associated with pacing,[159] and these may shed further light on the occurrence and heritability of the pacing gait in Standardbreds. In Europe only trotters are raced,[241] while pacing races are popular in some parts of the world such as North America, Australia and New Zealand.[241]

Some locomotor adaptations in non-lame horses have been described so far in this chapter. When describing and analysing locomotion, we can use kinetic or kinematic methods. **Kinetics** is the study of how forces act on a body and how these forces produce changes in movement.[212] Forces are divided into internal forces, external forces, and torques. Bone strain and tendon forces are internal forces, while external forces are forces between an object (i.e. hoof) and a substrate (i.e. ground surface), such as the GRF. **Kinematics** describe the resulting movement of objects. Kinematic data encompass temporal (stride duration, limb coordination patterns),[47] linear (stride length, distance between limb placements, flight paths of body parts)[47] and angular (rotational movement)[47] variables that describe the trajectories of body segments during motion. Although forces (kinetics) dictate movement (kinematics), since we cannot see forces, conventional lameness assessment is based on visual (kinematic) changes in movement. However, forces can be measured, and gives us the basis for understanding how certain changes in movement occur.

One measurable kinetic variable is the GRF. To explain the three-dimensional GRF vector, it is often divided into its three force components; **vertical GRF, longitudinal GRF and transverse GRF.**[109] The vertical GRF is directed upward (vertically) and represents the anti-gravity support function of the limb,[47] projecting the horse's body upward into the aerial phase.[44] The longitudinal GRF delivers acceleration and deceleration[47]; during early stance phase the longitudinal GRF brakes the horse as the hoof reaches the ground,[47] while during late stance phase it acts as a propulsive (push-off) force.[47] The transverse GRF concerns sideways or turning movement,[47] and when the horse is moving in a straight line, its magnitude is small, increasing when the horse turns.[47] In sum, the GRF is an approximate measure of distal limb loading.[267] The vertical GRF has the largest magnitude of the three GRF components.[46] In a trotting horse, after impact of the hoof on the ground vertical GRFs are higher in the forelimb than the diagonal hindlimb.[109] This is in agreement with the COM of the horse being closer to the forelimbs than the hindlimbs. During trot, the vertical GRF is at its maximum during diagonal mid-stance,[109] concurring with the COM reaching its lowest position[109]; peak vertical GRF coincides with maximal forelimb fetlock extension in all gaits.[163] The COM reaches its highest point, on average, just before the suspension phase.[109] Vertical displacement of the head and trunk displays a **sinusoidal (wavelike) pattern**[109] as the horse's body and COM moves up and down with the rhythmical stance and swing phases of the trotting strides. During one complete trotting stride, the body of the horse moves up and down twice, tracing an even, double sinusoidal pattern. In non-lame horses at the trot, GRFs are symmetrical between the left and right diagonal limb pairs.[109]

5.2.2 How lame horses move

Horses that are lame due to pain are asymmetric movers, since they try to shift a portion of their bodyweight away from the painful structure(s). **Asymmetry** can refer to many different aspects of movement, however, in this context asymmetry is used to describe a discrepancy in movement between the two “halves” of a trotting stride; e.g. asymmetric trot would mean that the horse moves differently when using one diagonal limb pair than when using the other. While asymmetry is inherently associated with lameness, asymmetric movement does not always mean that lameness is present. This conundrum will be further explored in chapter 5.4.

Transient lameness can be induced in non-lame horses using different techniques, for example by applying pressure to the sole of the hoof to induce hoof pain[29,30,57,87,132,221] or injection of substances into a joint to induce joint pain.[53,140] Studies using **induced lameness** models allow us to study locomotor changes in horses that were previously non-lame, and that, due to the study intervention, have pain arising from the same anatomical location. Therefore, locomotor changes seen in horses with induced lameness can be reliably considered lameness-induced changes, and not, for example, an individual gait variation. While horses in general show a low level of individual variation during consecutive strides, there is substantial gait variation between individual horses.[20,30,62] Both kinetic and kinematic studies have shown that horses use multiple adaptations to reduce limb loading in a lame limb. Kinematic variables are described by vectors such as displacement, velocity and acceleration.[212] In this context, displacement is defined as a change in the position of an object[212]; velocity describes the rate of change of displacement with respect to time[212] (or how fast an object is moving and in which direction), and acceleration is the rate of change of velocity with respect to time[212] (or how fast an object's velocity changes with time).

Lame horses adjust **speed and limb timing.** Overall, lame horses have decreased velocity over ground, taking slower, shorter strides.[57] However, stride parameters are dependent on horse velocity, and so descriptions of lame limb adaptations may vary when velocity is changed. When exercised on a treadmill, velocity is controlled, and lame horses adapt by taking shorter, but quicker strides, **increasing their stride frequency** and thereby decreasing stride duration.[259,260] This results in a reduction in limb loading (vertical impulse) per stride. Within the stride, **stance duration is increased** in horses with mild to moderate lameness, leaving the limb in contact with the ground for a longer time.[32,259] While this might at first seem counterintuitive, since the horse wants to avoid putting weight on the lame limb, extending the stance duration leads to a reduction in peak vertical forces by reducing the rate of loading.[259,260] Since the lame horse has a shorter stride duration but increased stance duration, it follows that the **swing phase of the stride is shortened.**[32,259,260] Changes in stride duration and swing phase are often larger in forelimb lame horses than in horses with hindlimb lameness.[32,259] The **suspension phase** in forelimb lame horses is shorter for the lame limb diagonal, with less or close to no shortening for the sound diagonal,[32,259] reflecting reduced propulsion during the stance phase (push-off) of the lame limb with increasing lameness.[259] Relative to stride duration, this means that the **transition time from the lame diagonal to the sound diagonal** is shortened, and correspondingly extended when transitioning from the sound to the lame diagonal.[259,260] Suspension phase changes lead to changes in **diagonal dissociation** in forelimb lame horses; during both sound and lame diagonals, earlier placement of the forelimbs (increased fore-first placement) has been reported.[32,221] In hindlimb lame horses, the opposite has been reported, with increased hind-first placement in the sound diagonal.[260] However, in hindlimb lame horses changes in temporal parameters such as suspension phases and diagonal dissociation are not consistently seen,[32] perhaps due to more effective load damping in the hind limb (greater tarsal flexion)[26] and the hindlimbs carrying less body weight compared to the forelimbs.[26] In general, changes in temporal stride parameters are valuable for understanding lameness. However, they are highly dependent on degree of lameness with many variables showing no difference between non-lame horses and horses with subtle or mild lameness, limiting their usefulness as lameness indicators.[32]

Looking at changes in the **vertical displacement of the horse's head and trunk** is the simplest and most employed strategy for assessing lameness-induced changes in movement.[18,30,125,216] In the lame horse, there is a reduction in vertical velocity, acceleration and displacement of both head and trunk[30] during the stance phase of the lame diagonal, but not during the sound diagonal.[30] This is mirrored in the vertical displacement amplitude of the horse's COM,[24] which is also reduced during lame limb stance phase and slightly increased during the stance phase of the sound diagonal.[24] The symmetrical, sinusoidal pattern of vertical displacement described in the sound trotting horse becomes asymmetrical in the lame horse, due to the described discrepancies in vertical vectors between the diagonal limb pairs.[24]

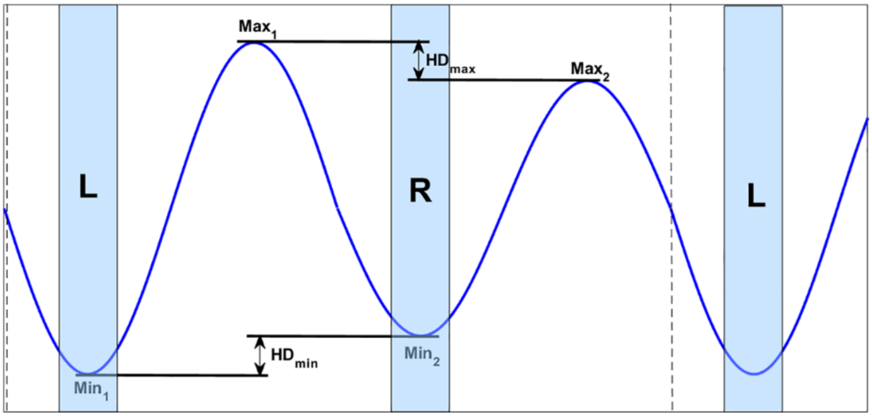

***Figure 4**. Illustration of change in vertical displacement amplitude (blue line) of the head in a horse with right forelimb lameness. Blue bars indicate approx. timing of left (L) and right (R) forelimb midstance. During sound limb (L) stance, the limb is fully weight-bearing and head displacement is greater than during lame limb (R) stance, where displacement amplitude is reduced due to lesser weight-bearing. HDmin and HDmax show the calculated difference in head displacement between the diagonal limb pair stride phases. Figure published in Rhodin et al. (2017).[206] Creative commons license (CC BY).*

During forelimb lameness, reduction in vertical acceleration and displacement of the head is well described[30,132,258] (**figure 4**), as is the reduction in displacement amplitude (less up-and-down movement) of the tubera sacrale (the highest point of the pelvis) of a lame hindlimb.[30] Studies of severely forelimb lame horses, as reviewed in Back & Clayton,[26] have reported that the horse may avoid lifting the head altogether (or even lift the head slightly on limb impact), thereby reducing the two cycles seen in the sinusoidal pattern per stride to a single cycle per stride. The horse's head and long neck act as a lever, and asymmetric head and neck movement plays a major role in the redistribution of weight in lame horses.[29,30,247]

For the purposes of subjective lameness examination, the above changes in vertical acceleration and displacement of the head and trunk correspond to the commonly used term "**head nod**" onto the sound forelimb in a forelimb lame horse and are correlated to the terms "**pelvic/hip hike**" or "**pelvic/hip drop**" for describing hindlimb lameness. Confusion exists regarding the two latter terms in clinical practice, as summarised by May & Wyn-Jones,[158] due to inconsistencies in the descriptions of how to identify hindlimb lameness. What has been shown is that, in addition to the described change in the position of the tubera sacrale, there is an increase in vertical displacement amplitude of the tuber coxae (point of the hip) of the lame limb compared to the sound limb[158]; the tuber coxae of the lame limb "moves more" than the tuber coxae of the sound limb.

The **relationship between production of force and acceleration** is defined by the formula derived from Newton's second law of motion:

$$F = m * a$$

where F = sum of forces acting on an object, m = mass of an object and a = acceleration of the object. As the mass of the horse is constant (per horse), force = acceleration. Vertical acceleration translates to force; even without measuring force we can deduce that if vertical acceleration is reduced during lame limb stance phase, the force (loading) acting on this particular limb is reduced during stance as well. Kinetic studies confirm this observation: During the stance phase, force amplitudes are reduced in the lame limb.[49,259] Earlier in this chapter we discussed that the COM of the horse reaches its lowest level at midstance, coinciding with peak vertical GRF and maximal **forelimb fetlock extension** in the sound horse.[109,163] Conversely, as the acceleration decreases, fetlock extension (as well as coffin joint flexion) is reduced in the lame limb at mid-stance in both fore- and hindlimb lameness,[31,49] with (small) compensatory increases in the same joints of the other, sound limbs.[31] In a model of induced superficial flexor tendon tendinitis, a decrease in fetlock hyperextension of 11° corresponded to a decrease of 27% in peak vertical force.[49] A contrasting adaptation has been seen in proximal joints; joint flexion increased with increasing lameness, more so in the tarsal joint than in the shoulder joint.[31] While reduced movement of the distal joints indicate reduced limb loading, the **increase in flexion of the proximal joints** (mainly shoulder and tarsal joints) is believed to be an extensor-muscle controlled “soft braking” mechanism, reducing the peak vertical force during hoof impact.[31]

In forelimb lame horses, reduction in the downward acceleration of the head onto the lame limb leads to **weight shifting along the longitudinal axis of the horse**[259] (here from the front to the back), along with the COM being shifted caudally,[24] increasing the weight carried by the diagonal hindlimb by approx. 6% during moderate lameness.[259] During the sound diagonal, loading is increased in the contralateral (sound) forelimb while loading is decreased in the diagonal hindlimb.[259] This is due to a combination of the vertical downwards head nod and the higher horizontal braking forces in the sound forelimb,[259] creating a downward momentum of the trunk that creates the described changes.[259] For example, a horse with left forelimb lameness would a) during the stance of the lame diagonal (left fore-right hind), shift weight from the left lame forelimb towards the right hindlimb, and b) during the sound diagonal stance, increase weightbearing on the right forelimb, causing less weightbearing in the left hindlimb. In hindlimb lame horses, the diagonal forelimb has an increase in weightbearing of approx. 3%.[260] During the sound diagonal stance, loading is increased in the diagonal hindlimb by approx. 2%.[260]

In summary, we know that the horse during steady-state trot **adjusts loading of the lame limb through the following adaptations**[259,260]**:**

1) increasing stride frequency; redistributing the total vertical impulse across more strides by increasing the number of strides used for a given distance,

2) increasing stance duration; reducing peak loading and the rate of loading by leaving the hoof longer on the ground,

3) redistributing load from the lame diagonal to the sound diagonal; shortening transition time from the lame to the sound diagonal pair and shortening the suspension phase of the lame diagonal, and

4) redistributing load from the lame limb to the sound limb within the diagonal limb pair; weight shifted along the longitudinal axis of the horse unloads weight from the lame limb while increasing loading in the diagonal sound limb.

Together, these adaptations cause a reduction in peak vertical forces of the lame limb. In horses with induced forelimb lameness, a peak vertical force reduction of 4% in horses with subtle lameness, increasing to 9% in mild lameness and 24% in moderate lameness, has been reported.[259]

The weight shifting patterns seen within the diagonal limb pairs lays the foundation for the compensatory patterns that may be seen in lame horses. **Compensatory lameness** occurs when a lameness is mimicked in a sound limb due to primary lameness in a different limb. For **primarily hindlimb lame horses**, lameness may be mimicked in the ipsilateral forelimb.[136,242,260] Horses with moderate hindlimb lameness may show a distinct head nod during stance phase of the lame diagonal pair (as the horse shifts weight forward onto the sound forelimb, away from the lame hindlimb).[242] For a horse with left hindlimb lameness, the increased downwards head nod during right forelimb stance gives the impression of left forelimb lameness (decreased weightbearing). For **primarily forelimb lame horses,** the pattern is more complex. There is evidence of lameness being mimicked chiefly in the diagonal (contralateral) hindlimb,[31,156,242] but also to a certain degree in the ipsilateral hindlimb[259] or in both hindlimbs.[136] Although most studies on compensatory lameness have been performed in horses with induced lameness,[31,136,259,260] results from horses with naturally occurring lameness show the same patterns.[156,242] When suspecting compensatory lameness, the idea of the horse having true **lameness of multiple limbs** should be entertained. Diagnostic analgesia should help provide answers, however, recent investigations into asymmetric changes in the **withers** show promise of aiding in locating primary lameness.[192,207] **Bilateral lameness** is another challenge, due to the lack of distinct asymmetric movements when trotting in a straight line.[25] In clinical practice, circling the horse, either during lunging or while ridden, is commonly used to induce more asymmetric movement.

When on a **curved path**, the horse must produce an inwardly directed GRF during the stance phase, resulting in centripetal acceleration.[112] Horses being lunged in a circle lean inward,[48,112] and body lean increases with decreasing circle radius as well as increasing speed.[198] On the circle, systematic changes in movement symmetry have been investigated.[22,37,211,231,248,48,92,93,112,191,198,208,209] While there are some discrepancies between studies utilising different measurement systems and between surfaces (hard versus soft surface), some frequently occurring patterns have been identified. One recurrent finding in lunged and ridden horses is that measured asymmetry on the circle may **mimic or increase inside hindlimb lameness.**[198,208,209,231] This occurs as the pelvis drops to a lower minimum position during the stance phase of the outside hindlimb and movement of the inside tuber coxae increases,[198] possibly due to the horse having to flex the inside hindlimb more and/or lift it higher in order to facilitate ground clearing during the swing phase.[198] **Inside forelimb lameness may be mimicked or increased** on the circle through a mild downward head nod during the outside forelimb stance phase.[191,231] However, in some horses an **outside forelimb asymmetry** is seen,[209] and in some horses with induced forelimb lameness, lameness was greatest with the lame limb on the outside of the circle.[208] Although certain patterns are common, horse-specific adaptations play a role, as some horses do not show the same amount of body lean or asymmetric pattern/asymmetry magnitude when going in opposite directions (left versus right circle).[22,209,231]

While the trotting gait is evidently suitable for lameness detection, and much knowledge has been gained on how the horse moves both when sound and lame and under different conditions, the veterinarians' primary task of identifying the correct lame limb is not necessarily solved. Throughout studies of subjective veterinary lameness examinations, **veterinarians show low to moderate agreement as to which limb is lame.**[86,99,126,145,229] Agreement is highest in horses with moderate or severe lameness and in forelimb lame horses, and lowest when assessing horses with only mild lameness, or horses with hindlimb lameness. Increased experience can improve scores[9,99,228] but not consistently.[229] In a study using animated sound and lame horses, determining if a horse was lame or sound had a higher success rate than assigning the lameness to a specific limb.[229] More surprisingly, in the same study sound horses (being animated, these horses showed perfect symmetry of movement) were often classified as hindlimb lame by experienced veterinarians.[229] **Bias** is inherent to subjective assessment, which may cause disagreement between veterinarians, but also affect the individual veterinarian's ability to correctly evaluate the presence of or change in lameness. "Expectation bias" has been reported: Just knowing that diagnostic analgesia had been performed in a horse influenced clinical assessment of the horse's lameness in one study.[9]

Bias and differing experience may partly explain differences in assessing lameness. Another aspect is the **difference in observational techniques** such as which anatomical landmarks are used for assessment of asymmetry. While there is widespread agreement that looking at the movement of the head is the most useful to recognise (and measure) forelimb lameness,[18,183,216] there are different, and partially conflicting, descriptions of what to look for to identify hindlimb lameness.[158,216] The two principal strategies for observing and/or measuring hindlimb lameness are a) movement of the tubera sacrale/whole pelvis,[30,139,242] and b) movement of the tubera coxae.[158,197] These methods are not in opposition but may explain some of the discrepancy between subjective lameness evaluations. For example, the **conformation** of a horse may influence one parameter more than another. A recent study showed that in horses with an artificially created **discrepancy in limb length**, objective measurements of asymmetry of the tubera sacrale were increased, while measurements of the tubera coxae were unaffected.[245] On the other hand, assessment of tubera coxae movement and symmetry may be complicated by existing anatomical asymmetry (e.g. in horses with previous tuber coxae fractures[215]), or due to existing asymmetrical tubera coxae movement in clinically non-lame horses.[30] In addition, differing knowledge and interpretation of compensatory lameness patterns may contribute to disagreement.

Another aspect when it comes to investigating the basis for low inter-rater agreement for lameness, as well as to why low-grade and hindlimb lameness are more difficult to assess than forelimb lameness, the **limits of human perception** have been proposed as a critical factor. Firstly, there are boundaries for how fast the eye can see, especially for events that require a cognitive interpretation.[113] Secondly, there is a visual threshold for asymmetry detection. This was exemplified in a study where veterinarians and veterinary students were asked to watch two moving squares on a computer screen, the squares being simulations based on tuber coxae marker data from real horses.[180] A 25% difference in the vertical movement amplitude between the two objects was needed for visual detection of asymmetric movement.[180] The above features shed light on the difficulties of picking up low-grade lameness, where a low degree of asymmetry is combined with a comparatively high velocity of the horse. In sum, the temporal resolution of our eyes may be too low to detect smaller or inconsistent asymmetries in the movement of the horse.

Limitations of human vision is nothing new; as we'll see in the next chapter, it was the starting point of what may be called the first **revolution in gait analysis**.

5.3 Equine locomotion research

> *In the spring of the year 1872, while the author was directing the photographic surveys of the United States Government on the Pacific Coast, there was revived in the city of San Francisco a controversy in regard to animal locomotion, which we may infer, on the authority Plato, was warmly argued by the ancient Egyptians, and which probably had its origin in the studio of the primitive artist when he submitted to a group of critical friends his first etching of a mammoth crushing through the forest, or of a reindeer grazing on the plains.*
>
> *In this modern instance, the principal subject of dispute was the possibility of a horse, while trotting – even at the height of his speed – having all four of his feet, at any portion of his stride, simultaneously free from contact with the ground.*

Muybridge, 1902,
Animals in Motion[170]

In the above quote the British-born **Eadweard Muybridge** (1830-1904) sums up a historical dispute, namely that of human vision being unable to correctly distinguish the footfalls of animals at higher speeds (in addition he recounts what sounds like one of the world's earliest peer reviews). The dispute concerning footfalls was finally resolved by Muybridge in the 1870s and 80s. Through a novel set-up, **sequential photographs** were obtained by stringing threads across a straight track; the horse on the track would break the strings as it moved forward, tripping the camera shutters of the multiple cameras lined up along the track.[171,223] Muybridge's images (**figure 5**) showed that there are indeed **suspension phases** during fast trot, as well as during the gallop. The venture was initially backed by the railroad magnate and former governor of California, Leland Stanford, and carried out on his stock farm in Palo Alto, California (later the site of the Stanford University).[178,223]

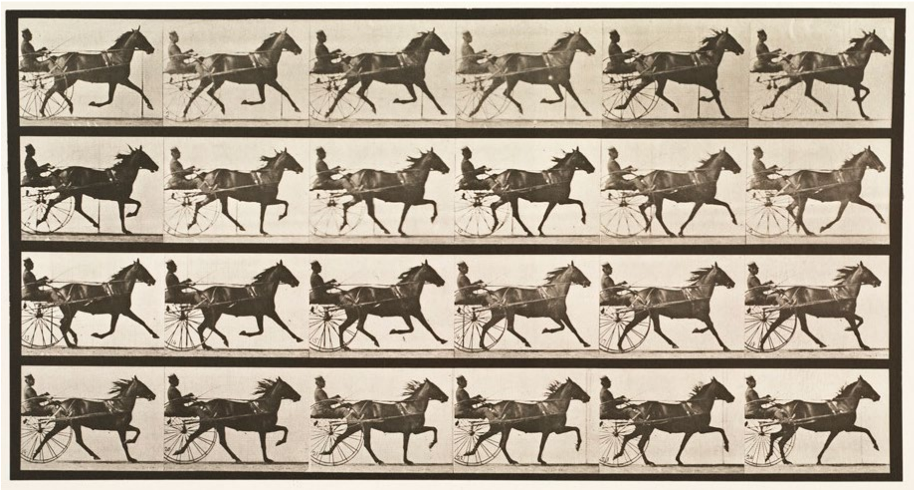

***Figure 5**. Trotter mare "Lizzie M"; note the negative diagonal, or fore-first, dissociation of the trot. Plate 609 from Muybridge: Animal locomotion: an electro-photographic investigation of consecutive phases of animal movements (1872-1885).*[169] *Creative commons license, courtesy of Boston Public Library.*[169]

Although there were some interruptions along the way, most notably due to Muybridge being trialled for the murder of his wife's lover,[223,251] these serial images were later to be animated through Muybridge's invention of the "zoopraxiscope", producing some of the world's first ever motion pictures.[7]

Muybridge was not the first to contribute to the knowledge of animal locomotion (for an historical overview, see chapter 1 in Back & Clayton[251]), and although he became perhaps the most famous, he was not the only one that investigated animal movement at the time. His contemporary, the French **Étienne-Jules Marey** (1830-1904) developed his own ingenious way of **recording footfalls** of both humans and animals (**figure 6**) and reached many of the same conclusions as Muybridge. In Marey's own (translated) words[157]:

> "The following method has been employed in this research: indiarubber balls stuffed with hair are fixed under the hoofs of the horse, and kept in position by calkins which screw into the metal of the shoe. Each of these balls is in connection with a long indiarubber tube which is fastened to the horse's legs

by flannel binders. These tubes communicate with the recording apparatus. The latter is provided with a tracing needle, and held in the hand of the rider (…) The pressure of the feet upon the ground compresses the balls with which they are provided, and forces the contained air into the recording tambours."[157]

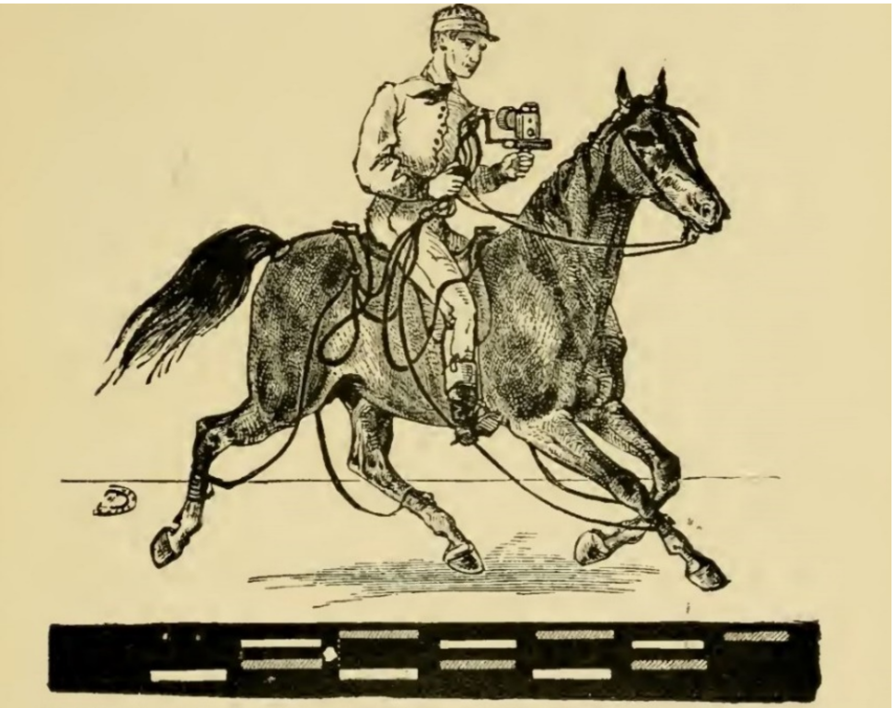
FIG. 7.—Horse at a *full trot*. The point indicated on the chart corresponds to the position of the horse represented in the figure.

Figure 6. *Illustration of Marey's pneumatic device to determine limb placement. Note the chart at the bottom of the image, showing the diagonal footfalls of the trot, and the point indicating that the horse is in a phase of suspension on the image. From Marey: Movement (1895).*[157] *Courtesy of the Biodiversity Heritage Library/Webster Family Library of Veterinary Medicine (copyright expired).*

Despite these breakthroughs in knowledge of both animal movement and photographic development, activity on the animal locomotion front quieted down in the following decades. In 1965, professor of zoology Milton Hildebrand stated that:

> "It is remarkable, however, that in spite of the advent of the motion picture camera (…) the study by Muybridge remained for 70 years the only significant contribution to the analysis of quadrupedal gaits."[104]

Hildebrand himself published multiple noteworthy studies on gait classification and the motion of animals, including horses.[103–106]

Made possible by the emergence of the computer and further technological advances in cinematography, Swedish researchers published a series of landmark studies[52,61–63,83–85] during the 1970s and 80s using a labour-intensive **high-speed cinematographic technique**. Presenting research on the stride characteristics of Standardbred trotters and the adverse effects of not adequately **banking the turns** (making the outer edge of the track higher than the inner edge) of harness racing tracks, these studies became the basis for modern harness track design in many countries and contributed to improving the orthopaedic health of Standardbred racehorses. When one Australian harness racing track increased the banking on turns from 4.8° to 5.7°, it was associated with a 22% decrease in injury and lameness rate.[75]

Further developments within kinematic studies with a combination of **marker-based motion analysis** and the use of accelerometers formed the basis for many studies, including central studies on lameness, referred to in the previous chapter.[30–32] Additional development and refinement has led to commercially available **optical motion capture** systems[101,111] that can collect a large and differing amount of data based on marker placement; infra-red cameras track the position of reflective markers that are attached directly onto the horse. However, proper set-up is crucial as data accuracy is dependent on multiple factors, such as the amount of cameras available.[71] In the 1980s the use of stationary **force plates** to investigate kinetic movement had also begun.[164,166] While the force plate is still considered the "gold standard" for lameness detection, as it directly measures the GRFs, it is mostly used for research purposes due to the more permanent and considerable set-up, in addition to an often time-consuming data collection process. For example, as the horse must hit the force plate with only one limb at a time, acquiring sufficient valid strides can be challenging. **Pressure plates** measure primarily vertical force through the summation of weight-bearing sensors.[177] A stand-alone portable pressure plate for clinical use has been investigated,[176] and differences in postural balance and pressure redistribution between limbs in sound and lame ponies has been described by the use of a pressure plate.[200] An **instrumented treadmill** has been built at the University of Zürich in Switzerland that combines direct measurement of forces with the ability to collect data from all four limbs over consecutive strides.[257] Key studies relating to compensatory load redistribution in lame horses have been carried out on the force-measuring treadmill.[259,260] Another option for directly measuring forces is the use of a **force shoe**.[38] Most of the above-mentioned systems have a shared downside in that while useful for research, they are not readily available for widespread, daily clinical use either due to considerable set-up, time spent collecting data and/or cost.

A game-changer in recent years has been the application of **horse-mounted sensor-based technology**. Sensors in the form of accelerometers have been investigated for use in gait evaluation[15,16,133,134,258]; as the sensors are mounted directly on the horse and data can be transferred to a portable computer, data can be collected from horses during a visit at their home yard and during normal exercise, including on the harness racetrack.[14] Current commercial systems often utilise **inertial measurement units (IMUs)** that contain accelerometers, magnetometers and gyroscopes.[20,127,199] For the first time, portable, affordable objective measurement systems are available to assist the veterinarian during lameness examinations either in the clinic or in the field. Studies show that IMU-based systems can reliably detect gait events[175,219,232] and quantify changes in asymmetry,[127,128,133,139,194,205] and that they outperform veterinarians for detection of lameness.[131,160] Most IMU systems base their computation of movement asymmetry primarily on the measurement of vertical acceleration. As discussed in detail in chapter 5.2, reliable systematic changes in the vertical acceleration of the head and trunk manifest in the lame horse. Changes in acceleration accurately depict changes in the vertical forces acting on the limbs due to the formula of $F = m*a$. Vertical acceleration values are mathematically translated into vertical displacement within the IMU-based systems software, which gives us our quantification of asymmetry.[129,130] A **limitation** of IMU-based systems is that due to accumulated integration errors when calculating displacement, they are influenced by sensor drift.[20] Methods to limit drift have been reported.[20]

So, it seems that we now have available technology that can aid veterinarians when needed in correctly establishing which limb is lame during a lameness examination. However, with new technology comes **new challenges**, some of which will be highlighted in the following chapter.

5.4 Controversies and knowledge gaps

> *The buyer inquires "is the horse sound?" the seller replies "warranted sound," and makes himself responsible for it by giving a written certificate. As the word sound forms such an important part of the contract, we might expect that its meaning would be well defined, and clearly understood in the same sense by both parties. But no such thing; on the contrary, not two out of an hundred attach the same meaning to it.*

Stewart, 1834,
Advice to Purchasers of Horses[235]

With the introduction of objective measurement systems that can determine even the slightest asymmetric movement, undetectable by subjective evaluation, other considerations arise. Being able to measure such small abnormalities invites the question of **what "normal" asymmetry is**. In horses, as in all biological beings, to expect perfect symmetry of movement would be unreasonable. Physiologic, or "normal", left-right differences during movement, expressed as preferential usage of one side of the body, exists in horses in the form of **laterality**.[77,149,161,162,262] Laterality in humans is well known,[147,188] the most common example being right-handed versus left-handed people. Laterality is suggested to be congenital, arising in the cerebral cortex; for a review see Byström et al.[34] To the author's knowledge there are no studies on the link between movement asymmetry due to laterality and movement asymmetry due to lameness. It is unknown to what extent this "functional asymmetry" is detected during objective asymmetry measurements, and it may therefore be considered a confounder when measuring asymmetric movement to assess potential lameness. In the words of equine locomotor research legend Dr. Buchner: "Each sound horse shows asymmetries provided that it is recorded accurately enough."[27]

One possible solution to separating normal from abnormal asymmetry is the development of **thresholds**, based on clinical data from lame horses. One such set of thresholds for acceptable fore- and hindlimb asymmetry are established for a commercially available system.[72] However, controversy in interpretation of the IMU measurements exist, demonstrated by the fact that a large proportion (>70%) of sport horses in regular training and considered free from lameness by their owners score above these asymmetry thresholds.[206] Similar results of above-threshold asymmetry are documented for other "owner-sound" Warmblood riding horses,[191,209] polo ponies in training[193] and Thoroughbred racehorses.[192]

Figure 7 exemplifies the situation; we have a large amount of horses, often in full training and with no complaint from the owner or trainer of orthopaedic issues, that when measured by an objective IMU system show considerable asymmetry. Perhaps the thresholds are too strict, at least for some types of horses; "relaxed" thresholds for Thoroughbred racehorses, based on agreement between visual assessment of asymmetric movement and objectively collected data, have been proposed.[196]

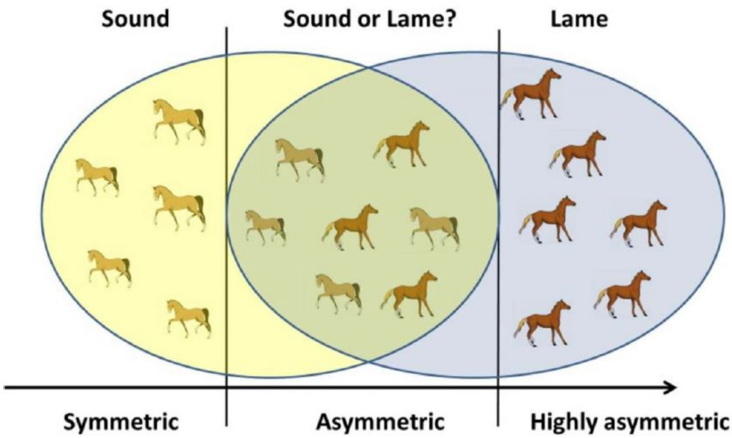

Figure 7*. Illustration of a central challenge in objectively measured asymmetry; how to separate asymmetry due to biological variation from asymmetry due to orthopaedic pain? Illustration by Marie Rhodin used with permission.*

Although further discussion on appropriate thresholds is warranted, the fact remains that while we can play with sensitivity and specificity by adjusting thresholds, e.g. by increasing the proportion of horses defined as asymmetrical (or lame) by lowering the threshold and vice versa, the overall presence of asymmetry in the measured population is the same and we still do not know the biological importance it carries.

In the recent past, multiple opinions on the implications of the quickly expanding use of objective asymmetry data have been voiced.[66,90,195] There is an ongoing, thriving debate within the equine veterinary community on **what constitutes lameness** and, simplified, should this be determined by man or machine?[2,3,17,65,252,255,256] Although emphasis has been placed on the fact that objective measurement systems are to be considered an aid to the veterinarian, and not a replacement of neither veterinarian nor a thorough clinical examination, warnings of **overreliance on technology** have been made.[17] Knowledge of the limitations of any technology used is vital for appropriate employment, and one important aspect of most objective asymmetry data is that is relies heavily on only one or a few measured variables, i.e. vertical acceleration. While the variable(s) may be accurate, the concern is that clinical assessment encompasses many factors that may be missed as they are not readily measured during objective data collection.[66]

When debating the implementation of novel appliances, it may be enlightening to reflect upon similar instances in other fields. One such instance is the debate that arose within the medical field with the **introduction of the thermometer** in 1717.[224] While not universally embraced at first, in time the usefulness of the thermometer prevailed (even though it took roughly 100 years), especially after a large amount of patient data had been collected.[224] The history of the thermometer includes some early misunderstandings; one was that having to rely on using a thermometer suggested incompetence on part of the doctor,[224] another the wrongful belief (of the patient) that the thermometer could tell where the illness was located, when it was only an aid to the doctor to determine if an elevated temperature was present in the patient.[224] More recently, hospital practice of hastily employing **newly available, very accurate and advanced CT imaging** when evaluating patients for pulmonary embolisms[261] lead to some thought-provoking findings. With increased use of sensitive CT scans, more pulmonary emboli were found, however, only a minimal reduction in deaths from pulmonary embolisms was recorded.[261] Instead, the authors of the study discuss that many patients may have undergone unnecessary procedures and treatment for embolisms that were likely not clinically significant.[261]

In the horse, we have established that knowledge is lacking regarding the biological variance and potential clinical significance of movement asymmetry. While we are keen to avoid over-diagnosing lameness based on "too accurate" measurements of asymmetry, we are also aware of the limitations of subjective lameness assessment, as well as the high prevalence of lameness in the horse population, and lameness manifesting itself as asymmetric movement. The magnitude of measured asymmetry in presumed sound horses is comparable to that in horses with induced lameness[208] and horses with clinical lameness that responded to diagnostic analgesia.[155,156] Comprehensive subjective lameness examinations of presumed sound horses found a large proportion of these to be lame,[67,68] suggesting that high prevalence of asymmetrical movement, and lameness, is not purely a "too-accurately measured" issue.

Two main knowledge gaps have thus been identified:

One is the difficulty in **discriminating between pain-induced and physiologic asymmetry**. Different options are available for further investigating this issue. The most definitive way of confirming pain-induced asymmetry/lameness would be by abolishing it, using diagnostic analgesia. While this is standard for lameness examinations in the individual horse, it does not lend itself as a tool for screening of a large amount of horses, both due to time and cost restrictions as well as the risk of rare, but serious consequences of invasive techniques such as intra-articular injections.[143,234] A less invasive method is to provide the horse with oral analgesia, as done in one study[189]; asymmetric horses were recruited, and in a crossover design received either a commonly used non-steroidal anti-inflammatory drug (the NSAID Meloxicam) or placebo. In this group of horses, there was no reduction in asymmetry after treatment. Whether this is due to the horses only displaying asymmetry due to biological variation, or whether the asymmetry was pain-induced but non-responsive to the specific medication used is unknown.[189] A different way of assessing the clinical relevance of asymmetry would be to follow a larger group of horses over time, to assess changes in asymmetry over time and any possible association between presence and magnitude of asymmetry and occurring lameness.

This leads us to the second knowledge gap; the **undefined relationship between presence of asymmetry and the development of lameness**. There is a paucity of longitudinal studies looking at the development of asymmetry. One study found that vertical displacement asymmetry increased during intensified training periods in a group of 16 Swedish Standardbred trotters followed over 2½ years.[210] In studies of Thoroughbred racehorses in Germany and the UK, an increase in the incidence of lameness/injury coincided with the beginning of the more intensive training/racing season in the spring.[151,204] Despite the major advances made within veterinary medicine in the last decades, both concerning knowledge of lameness mechanisms and the availability of imaging modalities and treatment options, epidemiological studies of Thoroughbred racehorses show that there is little change in the proportion of training days lost due to injuries of the musculoskeletal system.[64] By increasing our knowledge of the relationship between asymmetry and lameness, perhaps there is a possibility of detecting impending lameness by keeping track of developments in asymmetry over time?

There has been an increase in the amount of objective data collected and analysed from riding horses[191,193,206,209] and Thoroughbred racehorses,[192,196,220] however, there is a marked **lack of objectively measured asymmetry data** concerning Standardbred trotters. The **Standardbred trotter** can be particularly challenging to assess for lameness, as lameness seen at trot in-hand may not correlate to lameness during training on the track,[165] and the observed degree of lameness may vary with trotting speed.[165] Since Standardbreds race, and often train, on oval tracks, an additional element comes into play when evaluating locomotion in Standardbreds. On the oval track turns must be navigated, and as discussed earlier, systematic changes in asymmetry are introduced when horses travel on a circular path. All these characteristics should make the Standardbred an obvious candidate for employing the help of objective measurement systems. It also elucidates the need for further knowledge of prevalent locomotor asymmetry in the Standardbred, as well as how factors such as navigating turns on the track and differing speed affects asymmetry. These queries are made perhaps even more pertinent by the fact that **harness racehorses demand the utmost of their locomotor systems**, as we will see in the following chapter.

5.5 Harness racing and the Standardbred racehorse

> *When, in May, 1788, the gray horse Messenger dashed down the gangway of a ship from England, lying at the foot of Market street wharf, in Philadelphia, the history of the American trotting horse began*.

Coates, 1901,
A Short History of the American Trotting and Pacing Horse[50]

The horse has a long history as man's sporting companion, including as a harness racehorse. Chariot racing (**figure 8**) was present at the ancient Olympic games from 680 BCE,[115] where "the four-horse chariot race was the most popular, prestigious and long-lasting event on the equestrian programme"[115] with a race length of "12 times around the track, covering about 14,000 m".[115]

Figure 8*. The earliest form of organised harness racing? Demonstration of chariot racing at the Celle State Stud, Germany (2009).*

Modern day horse racing can be grouped based on horse breed, gait, and distance raced. The most common non-harness racing disciplines are:

- Endurance racing with primarily Arabian-type horses allowing varying gaits and speed, with race distances up to 160 km in a single day[78]
- Thoroughbred racing at a gallop with typical distances of 1000-2800+ m (flat racing)[21] or 3200-6400+ m (jumps racing)[21]
- Quarter Horse racing at a gallop with distances of approx. 200 to 800 m[91]; the breed is named after the traditional 400 metre or quarter of a mile races.[91]

Harness racing is conducted at a trot or pace with the driver in a light-weight cart (sulky) behind the horse. During training a heavier training cart is often used (**figure 9**). Some trotting or pacing races are conducted with a rider instead of a driver (monté races).

Figure 9. *Standardbred trotters during training on the racetrack.*

Horses used for modern-day harness racing are either warmblood-type horses such as the Standardbred, French or Russian trotter or mixes of these,[165,241] or cold-blooded-types such as the Norwegian-Swedish cold-blooded trotter or Finnhorse/Finnish cold-blooded trotter.[74] While Standardbred racing is common in many parts of the world, such as North America, Australia, New Zealand, Russia, and many European countries including Scandinavia and Finland, racing with cold-blooded breeds is popular primarily in the Nordic countries of Norway, Sweden and Finland. The European Standardbred is a mix of American bloodlines, crossed to a differing degree with European bloodlines, mainly French trotters.[241]

The **Standardbred breed** was developed in North America during the 1800s, however, it was an imported British Thoroughbred stallion that prompted the development of the Standardbred harness racehorse.[50,165] Arriving in Pennsylvania in 1788, the stallion Messenger produced offspring that were considered good trotters.[165] One of Messenger's descendants, Hambletonian 10, is considered the foundation sire of the breed.[165] The ensuing popularity of harness racing may be due not only to the increased quality of trotting horses, but also owing to a historical event. In a 1901 book by Coates,[50] the author writes about Messenger:

> "Had it not been that a few years after his arrival the Pennsylvania Legislature passed a law prohibiting racing, thus compelling those owning fine horses to keep them for road purposes, in all probability his progeny would have been trained to gallop instead of trot."[50]

Registration in the breed stud book was reserved for those horses that could trot or pace a US mile in the standard time of 2½ min or less, hence the name Standardbred.[165] The Hambletonian Stakes, named after the founding stallion, has been run since 1926; it is open only for three-year-old Standardbred trotters and has a purse of $1.2 million (per 2020), making it the world's most lucrative harness race.[98]

Common **race distances** for harness races are 1640 metres (sprinter races) up to 3140 metres (stayer races).[1] Many races in Scandinavia have a middle distance of 2140 metres, while the 1-mile race (1609 m) is most common in North American Standardbred racing.[165] In Europe speed records are noted as kilometre-speed; i.e. the holder of the current Norwegian record time of 1.09,4 for horses 5 years and older (set by the horse Cokstile in May 2020[54]) trotted 1 km in 1 min 9,4 s (giving an average trotting speed of 52 km/h). Racing speeds are steadily increasing, as demonstrated in a study from 2001 by Árnason, who compiled race time data from 44 372 Swedish Standardbreds born 1976-1994.[10] Based on the improvements in racing speed seen in these generations, Árnason predicted that a racing time record km-speed of 1.08 min would be achieved by 2050.[10] Speed development seems to be faster than predicted; one current Swedish record time was set by the horse Commander Crowe in 2011, with a km-speed of 1.08,9 min,[237] and in 2017 the horse Propulsion set another record of 1.08,1 min[237] – just one millisecond away from Árnason's predicted 2050 speed record. Intense genetic selection may be one reason for this rapid development,[10] improvements in management, track surfaces and track banking another.

Standardbreds usually start racing as two- or three-year-olds.[165,241] There is ongoing debate about possible adverse effects of **early racing** both for Thoroughbreds and Standardbreds. Many races for two-year-olds in Europe and North America offer substantial prize money and provides opportunity for a quick return on the investment it is to own a racehorse. The **annual cost of owning a racehorse** differs between countries, discipline and trainer, however, a 2015 ownership cost survey by the UK organisation Racehorse Owners Association (ROA) presented average annual costs of £ 22 595 (Norwegian krone (NOK) 266 262) for a Thoroughbred racehorse running on the flat and £ 16 325 (NOK 192 376) for a Thoroughbred jumps horse.[203] Annual costs say nothing of the original investment of buying a (promising) horse, or additional costs such as veterinary treatment. To the author's knowledge, there are no similar official estimates for Standardbred trotters in Scandinavia, however, personal knowledge gathered throughout this study would give an estimate of annual costs starting at NOK 120 000-160 000 for a horse in professional training. The popularity of co-ownership of horses or owner syndicates (Norwegian: andelslag) is therefore understandable, as is the desire for the horse owner to enter the horse in races at an early age.

5.6 The Standardbred trotter in Norway and Sweden

> *Trabrennen haben in Norwegen schon in ältester Zeit als rationeller Sport stattgefunden. Wenn die Bauern im Winter an Feiertagen von der Kirche nach Hause fuhren, pflegten sie stets die Schnelligkeit ihrer Rasse auf dem Eise der Fjorde zu erproben. Hierdurch wurde eine rege Nachfrage nach schnellfüssigen Trabern wachgerufen und dies führte wiederum zur Anlage von Trabbahnen in Kristiania, Drammen und an vielen anderen Orten, wo grössere Flüsse und Seen es ermöglichen, diesem Sport im Winter ohne nennenswerte Kosten zu huldigen.*
>
> *[Trotting races have been held in Norway as a rational sport since ancient times. As the farmers returned home from church on holidays, they persistently tested the speed of their horses on the ice of the fjords. Through this a keen demand for fast trotters was awakened, and this led to the construction of trotting racetracks in Kristiania, Drammen and many other places where larger rivers and lakes make it possible to pay homage to the sport in winter without mentionable cost.]*

Wrangel, 1909,
Die Rassen des Pferdes[264]
[Thesis author's unofficial translation]

Harness racing has a long history in both Norway and Sweden, originally using the local cold-blooded breeds for racing until the Standardbred was introduced. In **Norway**, the first official harness race was held in 1832,[23] and races were primarily held on iced-over lakes and fjords until the first land track was developed near Oslo (Slependen) in the 1870s.[23] In 1875 the Norwegian Trotting Association was formed, and in 1928 Bjerke racetrack in Oslo was established.[23] Today, there are 11 official harness racing tracks in Norway, with Bjerke still the main national track.[23] In **Sweden**, the timeline is similar; the precursor to the Swedish Trotting Association was founded in 1900.[238] Racing on ice was common in Sweden as well, and in 1907 races on ice were held in 45 different locations.[238] The first over ground track, Jägersro, was opened in 1907 and is still operational today.[238] In 1903, Wången, a stud farm for the preservation of the North-Swedish draft horse was founded, staying in business until 1996, when the facility was repurposed as an educational centre for horse racing.[238] Today, there are 33 official harness racetracks distributed across Sweden.[238]

Harness racing is a larger sport in Sweden than in Norway, reflected in the numbers of foals born per year, number of horses participating in races and number of races held per year. This is illustrated in **tables 1-5**; all data is from the 2019 annual report of the European trotting union (UET).[243] All numbers relate to warmblood (Standardbred) horses, other breeds such as the Norwegian-Swedish cold-blooded trotter and the Russian Orlow-trotter are excluded. There is a negative numerical trend for almost all variables, except for prizemoney per race and horse. However, this may just reflect the fact that prizemoney is distributed across fewer races held as well as a lower number of horses participating in races.

	2015	**2016**	**2017**	**2018**	**2019**	**2015-2019 in %**
Sweden	2 733	2 705	2 734	2 750	2 750	0,6
Norway	741	485	572	547	491	-33,7
Total (UET)*	20 809	19 935	20 070	19 475	19 503	-6,3

**Total (UET) = numbers for all UET countries.*

***Table 1**. Number of Standardbred foals born per year, 2015-2019.*

	2015	**2016**	**2017**	**2018**	**2019**	**2015-2019 in %**
Sweden	7 950	7 851	7 649	7 438	7 382	-7,1
Norway	2 504	2 303	2 224	3 815	1 916	-23,5
Total (UET)*	46 824	46 353	45 052	45 153	42 677	-8,9

**Total (UET) = numbers for all UET countries.*

***Table 2**. Number of races per year.*

	2015	2016	2017	2018	2019	2015-2019 in %
Sweden	11 508	11 114	10 499	10 270	10 220	-11,2
Norway	3 387	3 077	3 048	4 564	2 498	-26,3
Total (UET)*	58 557	58 897	56 141	56 204	53 050	-9,4

**Total (UET) = numbers for all UET countries.*

***Table 3**. Number of horses participating in races, 2015-2019.*

	2015	2016	2017	2018	2019	2015-2019 in %	Total prizemoney 2019
Sweden	8 862	9 317	9 256	11 000	10 744	21,2	79 313 647
Norway	6 153	6 433	7 141	6 259	6 725	9,3	12 886 699
Total (UET)*	NA	NA	NA	NA	NA	NA	406 614 359

**Total (UET) = numbers for all UET countries.*

***Table 4**. Evolution of prizemoney (in Euro) per race, 2015-2019, as well as total amount of prizemoney awarded in 2019. NA = Not available.*

	2015	2016	2017	2018	2019	2015-2019 in %
Sweden	6 122	6 582	6 743	7 966	7 761	26,8
Norway	4 549	4 815	5 211	5 232	5 158	13,4

***Table 5**. Evolution of prizemoney (in Euro) per horse, 2015-2019.*

In both Norway and Sweden there is a similar racing system for Standardbred trotters. For young horses, there are two types of races available prior to starting in regular (official tote) races. The first type is a **voluntary preparation race** (Norway: mønstringsløp, Sweden: premielopp) where the horses need to finish the race within a set time interval. Horses can participate in preparation races from May 1st (Norway[55]) or March 1st (Sweden[236]) of their two-year-old year. For horses born 2016, the time interval was 1.24,0 – 1.35,0 (min/km) in 2018 in Norway, tightening to 1.24,0 – 1.32,0 for horses participating late in the year.[55] These races are only open to two-year-olds and are arranged to prepare the horses for later regular races as well as to encourage early training and non-competitive racing. There is prizemoney awarded to those who complete such races (e.g. 20 000 SEK for Swedish horses in 2020[236]). For horses where the owner/trainer has high expectations, there is the option to forfeit this money and instead register the horse in an arrangement (Norway: premiesjansen, Sweden: premiechansen) that gives much higher prizemoney in later selected age group races should the horse qualify for these. The second type of pre-race is a **mandatory qualification race** (Norway: prøveløp, Sweden: kvalificeringslopp) which all horses need to complete before being allowed to enter regular races. These races do not have a set time interval and are held to make sure the horses are in racing condition and are adequately prepared to enter competitive races. Two-year-old horses can enter these races starting on July 1st in both Norway and Sweden.[55,236] There is some prizemoney awarded for these races as well. Regular races for two-year-old horses are allowed in both countries if two-year-olds only compete against other horses of the same age. However, while two-year-old races are arranged regularly after July 1st each year in Sweden, such races are not usually held in Norway, and there are none planned for the near future according to the race plan for 2017-2022.[56]

6 Study objectives and results

6.1 Aims of the thesis

The overall aim of this thesis is to provide further evidence-based knowledge of asymmetric movement in Standardbred trotters. Aspects of prevalence, distribution, magnitude, and development of vertical movement asymmetry in Standardbred trotters was investigated through studies with these specific aims:

1. To quantify the prevalence and magnitude of objectively measured vertical movement asymmetry in yearling Standardbred trotters both in-hand and during driven exercise (paper I).

2. To investigate differences in objectively measured vertical movement asymmetry between straight and curved track sections of non-banked oval trotting tracks in Standardbred trotters (paper II).

3. To describe the changes in objectively measured vertical movement asymmetry and the occurrence of treatment for lameness in a cohort of Standardbred trotters over two years, from yearling until three-year-old (paper III).

6.2 Research questions and hypotheses

Based on the aims, these specific research questions and hypotheses were formed:

1. What is the prevalence of vertical movement asymmetry in yearling Standardbred trotters, and does asymmetry distribution and magnitude differ between in-hand and driven trot?
   Our hypothesis was that asymmetry scores would be higher when evaluating horses in-hand versus driven, since the horses are constrained by the harness and pulling a sulky during driven exercise (paper I).

2. Does trotting through a non-banked curve on an oval racetrack at low speed influence vertical movement asymmetry?
   Our hypothesis was that trotting through curves would induce a consistent change in asymmetry patterns, as previously seen in riding horses being lunged on a circle (paper II).

3. In our cohort of young Standardbred trotters, how does asymmetry change with age and training? What is the occurrence of treatment for lameness during this period?
   Our hypothesis was that asymmetry would increase with increased training due to accumulated strain on the musculoskeletal system (paper III).

6.3 Summary of results

Reported results in this section contains an overview of included horses per paper (**figure 10**), summaries of papers I-III (**tables 6-8**) and additional, unpublished results concerning the influence of overcheck use on movement asymmetry. Summaries of papers contain only the main characteristics and results of each study; for more details see the individual papers.

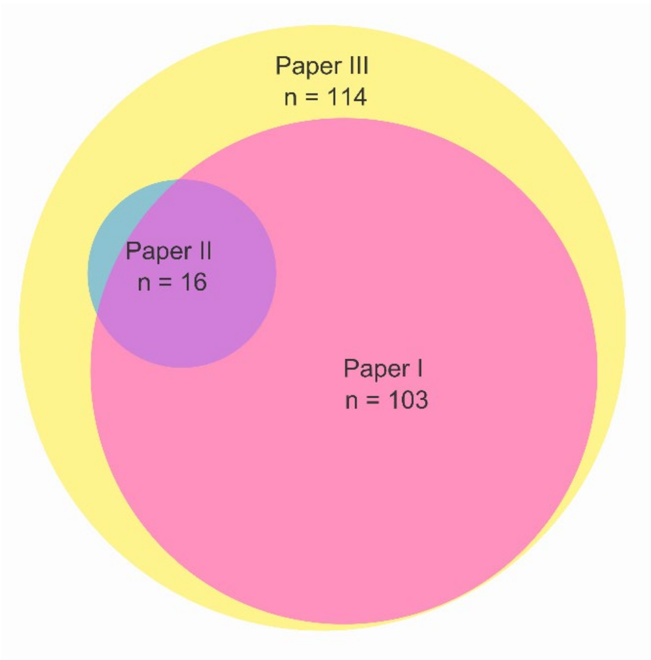

Figure 10*. Diagram of included horses per paper. Paper I (pink circle) included 103 horses as yearlings; paper II (blue circle) included 16 horses as two-year-olds; and in paper III (yellow circle) all 114 horses initially recruited for this project were included. These horses were included when they were starting their training as yearlings and were followed until the end of their two- or three-year-old season.*

For the studies contained in this thesis, a **commercially available IMU system**, Equinosis Q with Lameness Locator software (LL), was used to objectively measure movement asymmetry in the form of vertical displacement. The system records movement (acceleration) in the direction of the accelerometer (IMU sensor) and calculates vertical displacement from vertical acceleration using its own local reference frame, not a global reference frame. In other words, the IMU system used in our study does not calculate position relative to the ground but compares the two halves of a trotting stride, comparing the right forelimb to the left forelimb and similarly for the hindlimbs.[133] The IMU system software also contains a size-correcting algorithm that normalises the asymmetry parameter value. This ensures that, for example, a mild lameness in a small Shetland pony would have a comparable asymmetry in millimetres to a mild lameness in a massive Shire horse, even though their raw vertical displacement values ("up-and-down" movement) would differ greatly while trotting. Software asymmetry calculations result in four asymmetry parameters: head minimum (HDmin) and head maximum (HDmax) difference, and pelvis minimum (PDmin) and pelvis maximum (PDmax) difference. Asymmetric head movement reflects forelimb asymmetry, while asymmetric pelvic movement reflects hindlimb asymmetry. HDmin difference is calculated as the minimum head height during right forelimb stance minus the minimum head height during left forelimb stance, while the HDmax difference is calculated as the maximum head height before right forelimb weight-bearing minus the maximum head height before left forelimb weight-bearing.[127] The same principle is used for the movement of the pelvis to calculate PDmin and PDmax. A parameter value of 0 mm indicates perfect symmetry, with no difference between the two halves of a stride.

Paper	Research question & study design	Hypothesis	Materials & methods	Statistics	Main limitations	Key findings
I	What is the prevalence of movement asymmetry in yearling Standardbred trotters, and does asymmetry distribution and magnitude differ between in-hand and driven trot? Cross-sectional, observational study.	Asymmetry scores would be higher when evaluating horses in-hand versus driven, since the horses are constrained by the harness and pulling a sulky during driven exercise.	103 horses from 13 trainers. All were Standardbred trotter yearlings born in 2016/2017, broken to harness, within the first six months of driven exercise and assessed as fit-to-train by the trainer. Data collected with Lameness Locator in-hand and while driven on the track.	Descriptive statistics and mixed models. Model building: Fixed effects: trial mode, with the levels: in-hand or track trial, in-hand trial pre- or post-track trial, straight or oval track), sex (male or female), height at the withers, height difference between the withers and pelvis. Random effect: Horse nested within trainer. Outcome: Asymmetry scores for fore- and hindlimbs (head and pelvis scores).	High data variability, which was reflected in large standard deviations, mainly due to a lack of horse compliance. This is a potential source of uncertainty for both visual and objective assessment of movement asymmetry in these horses.	1) Overall, 91 of 103 (88%) horses were defined as asymmetric, using previously determined thresholds. 2) 14 of 71 horses (20%) switched the side (limb) of asymmetry between in-hand and track trials. 3) No significant group-level difference in asymmetry between in-hand and track trials.

***Table 6**. Summary of paper I.*

Paper	Research question & study design	Hypothesis	Materials & methods	Statistics	Main limitations	Key findings
II	Does trotting through a non-banked curve on the oval racetrack at low speed influence movement symmetry? Cross-sectional, observational study.	Trotting through curves would induce a consistent change in symmetry patterns, as previously seen in riding horses lunged on a circle.	16 two-year-old Standardbred trotters from four trainers. Data collected with Lameness Locator on oval trotting tracks. Strides collected were divided into strides on the straight part of the track and strides during the curved (turning) part of the track.	Descriptive statistics and mixed models. Model building: Fixed effects: track segment (straight or curve), stride duration, as well as two-way interactions of these. Random effect: Horse. Outcome: Asymmetry scores for fore- and hindlimbs (head and pelvis scores) on the straight versus on the curve.	Horses were evaluated going in one direction only on the track (clockwise). Horses were measured on non-banked curves, jogging at relatively low speed; results are only valid under these circumstances, not for fast/racing trot or on banked tracks.	1) Significant systematic differences in asymmetry between straight and curved track segments were found; not identical to lunged horses. 2) Curve-induced changes were an increase in outside forelimb impact and push-off asymmetry and an increase in outside hindlimb impact asymmetry. 3) Effect sizes were small, indicating minor importance for clinical decision-making when assessing trotters on the straight versus curved part of the track.

***Table 7**. Summary of paper II.*

Paper	Research question & study design	Hypothesis	Materials & methods	Statistics	Main limitations	Key findings
III	In our cohort of young Standardbred trotters, how does asymmetry change with age and training? What is the occurrence of treatment for lameness during this period? Longitudinal, observational study.	Asymmetry magnitude would increase with increased training due to accumulated strain on the musculoskeletal system.	114 yearlings recruited from 13 different trainers. Movement asymmetry data was collected every third month for two years with the Lameness Locator during driven exercise. Information on veterinary treatments was collected. Movement asymmetry was classified based on published thresholds for the sensor system used.	Descriptive statistics. Due to substantial study drop-out and frequent joint injections no statistical analysis to test associations between measured asymmetry and development of clinical lameness were made.	The number of study drop-outs during the study period was substantial.	1) At all data collection visits, almost all horses were categorised as asymmetric. 2) Therapeutic joint injections were frequent, with the first horses receiving treatment in the spring as two-year-olds; almost all horses remaining to study completion received joint treatment. 3) Despite the above results, most horses completed their qualification race and went on to race in regular tote races by the end of their three-year-old season.

***Table 8**. Summary of paper III.*

6.4 Overcheck use (unpublished data)

During work on paper II, comparing straight track segments to curved track segments, nine horses fitted with overchecks during data collection were also evaluated during oval track exercise. The function of an overcheck (**figure 11**) is primarily to act as a support to the horse at the end of training intervals or races, allowing the tired, front-end heavy horse to lean on the overcheck bit. It may also be used to have more control over difficult horses or horses that bear down on the bit excessively.

Figure 11. *Horse fitted with an overcheck, which runs from a separate bit (check bit), over the poll of the horse and attaches to the top of the harness surcingle.*

However, there was a slight difference in baseline asymmetry for the group of horses with overcheck and the group of horses without overcheck (**figure 12**). Since data was collected from horses either fitted with an overcheck or not (no cross-over design), any potential effect of overcheck use between these two groups of horses could not be differentiated from the effect of different baseline asymmetries.

Therefore, horses with overcheck were excluded from analysis in paper II. However, data from the overcheck group was further examined to explore possible effects of overcheck on movement asymmetry parameters. When overcheck use was included in the statistical model detailed in paper II, there was a significant effect of overcheck when compared to horses without overcheck. In the following summary of results mainly significant results are described.

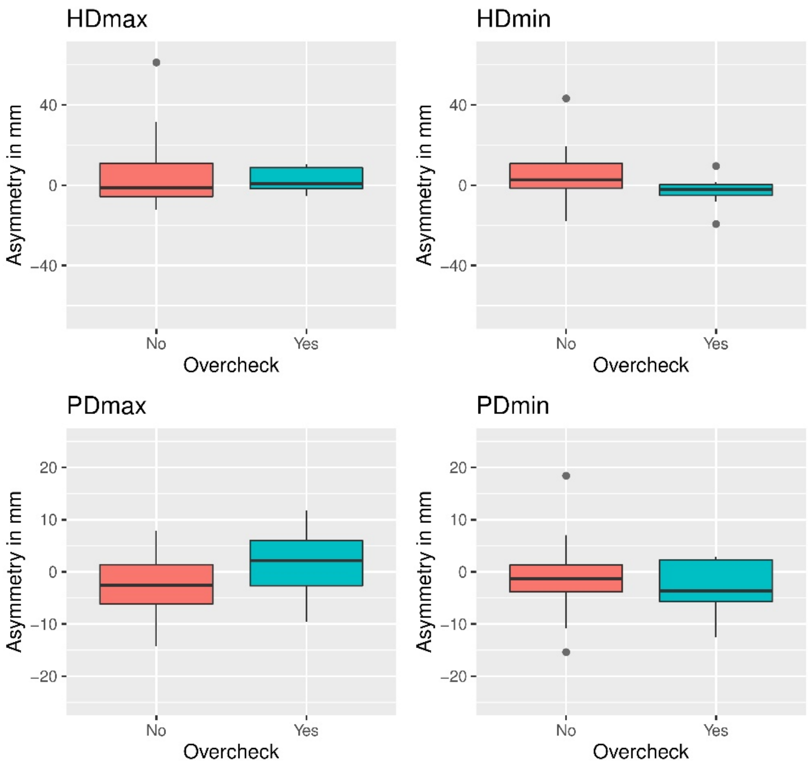

Figure 12. *Boxplot showing group differences in asymmetry scores for 25 two-year-old Standardbred trotters. Data is from the straight part of the oval track only. Horses without overcheck n = 16, horses with overcheck n = 9.*

For HDmax there was a significant three-way interaction between track segment (straight versus curve), stride duration and the use of an overcheck; $P < 0.001$ (**figure 13**). The slope value shows the change in symmetry in mm per 1 second (s) change in stride duration, e.g. a value of 19.7 mm per s corresponds to a change in symmetry of 1.97 mm per 100 ms change in stride duration (e.g. a change in stride duration from 0.5 to 0.6 s). For horses without overcheck ($n = 16$) there was a negative linear relationship between stride duration and asymmetry during curves (slope: -49.3 mm per s, SE 9.2, 95% CI -67.3 to -31.3) suggesting a lesser height reached by the head after outside forelimb push-off in the curve with increasing stride duration. In the post-hoc pairwise comparison the effect of the curve for horses without overcheck was -2.2 mm ($P < 0.001$, 95% CI -1.6 to -2.7) compared to straight track.

In horses wearing an overcheck ($n = 9$) this effect was not found. Instead, there was a positive, but not quite significant, linear relationship between stride duration and asymmetry during curved track segments (slope: 17.6 mm per s, SE 9.4, 95% CI -0.7 to 35.9). On the straight track segment all horses had a positive linear relationship, significant only for horses with overcheck (horses with overcheck: slope 19.7 mm per s, SE 9.3, 95% CI 1.4 to 37.9; horses without overcheck: slope 6.0 mm per s, SE 9.0, 95% CI -11.6 to 23.6). For horses wearing an overcheck, this suggests a slight increase in HDmax asymmetry with increasing stride duration on the straight part of the track.

For HDmin there were significant two-way interactions between track segment and overcheck use as well as between track segment and stride duration (both $P < 0.001$; data not shown). On the curve, a negative linear relationship (slope -21.8 mm per s, SE 7.1, 95% CI -35.6 to -8.0) was found between stride duration and HDmin asymmetry, indicating a lesser downward nod on the outer forelimb with an increasing stride duration. On the straight, a positive linear relationship (slope 17.9 mm per s, SE 7.0, 95% CI 4.3 to 31.5) was found between HDmin asymmetry and stride duration. In the post-hoc pairwise comparison, for horses without overcheck the effect of curve on HDmin asymmetry compared to straight track was -1.8 mm ($P < 0.001$, 95% CI -1.2 to -2.4). For horses with overcheck the effect of the curve was the

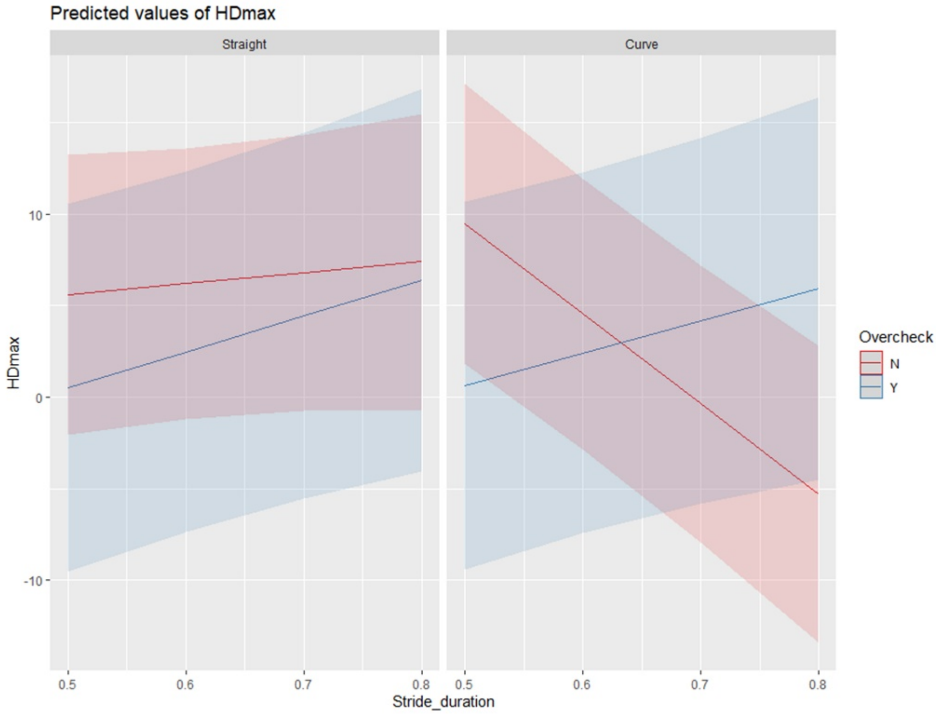

Figure 13. *Three-way interaction plot for track segment, stride duration and overcheck use for HDmax, showing the difference between horses with and without overcheck when navigating a curve. Slopes: With overcheck, straight track: 19.7 mm per s (SE 9.3, 95% CI 1.4 to 37.9); with overcheck, curved track: 17.6 mm per s (SE 9.4, 95% CI -0.7 to 35.9); without overcheck, straight: 6.0 mm per s (SE 9.0, 95% CI -11.6 to 23.6), without overcheck, curve: -49.3 mm per s (SE 9.2, 95% CI -67.3 to -31.3). Overcheck: N = No overcheck, Y = Overcheck.*

opposite and smaller, with 0.7 mm compared to the straight track segments (P = 0.04, 95% CI 0.1 to 1.4).

For PDmax the same two-way interactions as for HDmin were significant (track segment and overcheck use, track segment and stride duration; both P < 0.001; data not shown). For stride duration, there was a positive linear relationship with PDmax asymmetry for both curved segments (slope 32.4 mm per s, SE 3.1, 95% CI 26.4 to

38.4) and straight segments (slope 21.0 mm per s, SE 3.0, 95% CI 15.0 to 26.9). Post-hoc pairwise comparisons for horses with overcheck showed an estimated difference of -1.1 mm ($P < 0.001$, 95% CI -0.8 to -1.4) on the curve compared to the straight, indicating a decreased upward motion of the pelvis after outer hindlimb push-off. For PDmin there was no significant effect of overcheck use.

In the above model, overcheck use was significant during the curved part of the track for the parameters HDmin and PDmax. The parameter HDmin in horses without overcheck showed an increased downward nod on the inner forelimb (mimicking outside forelimb impact asymmetry), in accordance with findings in lunged horses.[209] Horses with overcheck on the other hand had the opposite result, mimicking an inside forelimb impact asymmetry during the curve, albeit to a lesser degree with less than a millimetre difference in asymmetry between the straight and curved track segments. For PDmax measurements, horses with overcheck had a decrease in the upward motion of the pelvis on the outside hindlimb after push-off, corresponding to findings in lunged riding horses.[209]

We cannot conclude whether these findings are due to the overcheck restricting the downward vertical movement of the horses' head, or because the horses with overchecks differed in their strategy for navigating the curve. Horses fitted with an overcheck by their trainer might have had training-related issues warranting overcheck use, potentially confounding our results. However, overcheck use does seem to affect measurements of movement asymmetry to some degree and warrants further investigation.

7 Discussion

7.1 Methodological considerations

7.1.1 Study design

The overarching study design was a prospective, longitudinal single-cohort study, as detailed in paper III. Data from specific time points were extracted for analysis to answer the specific research questions in papers I and II, thus taking the shape of cross-sectional studies.

Our longitudinal study was observational, with no interventions from the side of the investigators. It was a **single-cohort study**; ideally, there would have been two groups, with one group exposed to training and one control group that was not exposed to training. However, finding a suitable control group for data collection of movement asymmetry in a breed bred specifically for racing, means that most, if not all, Standardbreds not in training would be unsuitable, i.e. injured or otherwise not fit for the purpose of this study. One solution would have been to own two groups of Standardbreds ourselves, where we as investigators could control the exposure to training. In the 1980s, Drevemo et al.[60] had a control group of untrained Standardbred colts that were compared to trained Standardbred colts, although there were only 10 horses in total. Ringmark et al.[210] followed 16 Standardbred colts for 2½ years. These colts had been retained for study purposes. In co-operation with the educational horse racing centre of Wången training could be controlled; one group of horses enjoyed a reduced training load, while the other group of horses were in regular training and acted as a control group. However, breeding or buying horses for study purposes is usually prohibited by cost and feasibility, especially if a larger sample size is desired. For our study purpose, asking horse owners to keep horses out of training for years in order to form a control group would have been unlikely to succeed.

The lack of a suitable control group is one aspect that makes it difficult to ascertain what changes in asymmetry could be attributed specifically to training towards a career in racing. Another aspect is that during the first years of training, starting as yearlings, the horses are in a period of major **developmental growth** which could affect measurements of movement asymmetry. Such developmental growth would occur in a control group of horses of the same age as well. However, observing systematic changes in asymmetry between two such groups at certain points in time could potentially point towards whether the asymmetry would be associated with developmental changes as opposed to training-induced asymmetry. One advantage of a prospective cohort study is that since the exposure or cause occurs before the outcome of interest, causality can potentially be established, as opposed to retrospective studies that can be used to look at associations but not to assign causality.

The underlying **intention of this longitudinal study** was to look at associations between measurements of asymmetric movement and the incidence of clinical lameness. As discussed earlier in this thesis, two of the current major knowledge gaps when it comes to interpreting movement asymmetry in horses are a) how to discriminate between pain-induced and normal asymmetry (biological variation) and b) how to further define the relationship between asymmetry magnitude and the development of lameness. Increased knowledge in these areas may aid in detecting lameness as early as possible and perhaps even detecting issues prior to the horse becoming visibly (subjectively) lame. During the two years of data collection for our study, two main limitations became apparent that affected the possibilities to further define the relationship between movement asymmetry and clinical lameness through the current longitudinal study.

The first was the substantial **loss of horses to data collection** experienced during the study period. This is a known challenge when it comes to longitudinal studies. The rate of horse "turn-over", as witnessed through the frequency of trainer and/or owner change, as well as lameness and training issues resulting in horses being restricted from regular training, was considerable. Logistically, it was not possible to collect data from horses that changed trainers, even though many of the horses that dropped out of the study were still in active training elsewhere. Another challenge was a phenomenon resembling “study fatigue”, causing two of the trainers to prematurely withdraw from the study, although they were fully informed of the planned study period when recruited to the study.

The other main limitation is one not uncommon to observational studies, namely the **lack of control** of what happens to the study subjects. In our study we wanted to follow a cohort of horses in training over time. We recruited professional trainers for participation, both to ensure that horses included would be subjected to a regular training schedule as well as to be able to measure as many horses as possible at each training yard (as most amateur trainers have only a few horses in training at any given time). Due to this, we could not interfere with the training schedule or veterinary interventions of the participating horses. In our case, veterinary treatment in the form of therapeutic joint injections clouded our ability to relate data on movement asymmetry to the development of clinical lameness. For instance, it was not unusual for some horses to have had multiple limbs and/or joints injected within the three-month time interval between two visits. This makes it difficult to assess any previously measured asymmetry in one or more limbs to a change in asymmetry seen after the treatment(s). Since we know that lameness is common in racehorses, it could be anticipated that veterinary interventions would be common. However, the amount of therapeutic joint injections observed in this cohort of very young horses was unexpected. **Shortening the time interval** between data collections could potentially have made it easier to relate measured movement asymmetry to the occurrence of lameness.

Other external influences that may affect our movement asymmetry data also have to be considered. One such factor specific to Standardbreds is the use of an **overcheck**, as described earlier. Overcheck use was at the discretion of the trainer. Overcheck length was not standardised as it was individually fitted to the horse, depending on the conformation of the horse. The overcheck is usually fitted so that there is no effect of it when the horse keeps its head in a neutral position, the overcheck only coming into effect when the horse lowers its head. Overchecks used during racing are often shortened for the duration of the race. During data collection for our study, overchecks were in all cases described by the trainer as “long” or “long-moderate”. During our data collection, “long” overchecks were primarily used on the yearlings, both to get the horses used to this piece of tack but also as a security measure, i.e. to discourage the horse from pulling its head down between its front legs and potentially buck or otherwise misbehave. “Long-moderate” overchecks were mainly employed when the horses were older and during high-speed (interval) training. Overcheck use varied greatly between trainers. Some used overchecks regularly while others felt that the horses should be able to “carry themselves” without help during training.

Another consideration is the **day-to-day variability** of movement asymmetry that may exist. In one study where movement asymmetry was measured repeatedly in Thoroughbred racehorses (using a different IMU system to the one in our study), absolute differences in asymmetry ranging from median daily differences of 4 to 7 mm and median weekly differences from 4 to 8 mm were reported.[220] Daily or weekly variations in movement may especially play a role in racehorses or other equine athletes, as it must be assumed that these horses experience phenomena such as post-training/race muscle stiffness and/or fatigue, as well as other body “aches and pains” on a regular basis. Depending on when movement asymmetry data is collected, e.g. on the day following a race or following a day of rest, this is likely to affect the data collected to an unknown degree. In the same study,[220] the authors point out that methodological variation may occur related to the **re-instrumentation** of the horses on different days. Correct placement of the IMU sensors are of great importance to ensure that the collected data is valid; challenges specific to data collection in our study will be discussed below (see section 7.1.3 Data collection).

7.1.2 Sample selection and sample size

Our cohort consisted of horses from a **convenience sample** of training yards. One disadvantage of not having a more randomly selected group is the possibility of the study results having a lower external validity due to the risk of introducing **systematic bias**. In our study, a "subject sampling bias" has been introduced. By opting to only include professional training yards, the horse material is to a certain extent "pre-selected" both by the trainer who decides to take the horse into training and by the horse owner(s) who have decided on spending money on putting the horse into professional training. Our cohort is therefore likely to consist of "high quality" horses with a good or superior genetic background that are presumed to possess the ability to race successfully. This belief has been strengthened by the higher than average proportion of horses in our cohort to compete in regular tote races (see paper III). Several cohort horses also participated in elite races during the study period and appeared in ranking lists of the most successful young Standardbred trotters in Norway or Sweden. Training and other management factors such as pressure to compete in races may also differ for horses in professional training versus those in amateur training. This may have influenced some of our results for the longitudinal part of the study (paper III), such as the frequency of therapeutic joint injections, although this is pure speculation on the part of the thesis author. Regarding the results presented for the longitudinal part (paper III), although the **internal validity** of our study is affected by the amount of study drop-outs, results can be considered valid for young Standardbreds in professional training. The **external validity** of the same may be limited, as results may differ for horses in amateur training as well as for older horses that are no longer affected by musculoskeletal growth.

Sample size calculations are generally necessary to ensure valid study data. As summarized by Lenth,[148] the sample size of the study

> "must be "big enough" that an effect of such magnitude as to be of scientific significance will also be statistically significant. It is just as important,

however, that the study not be "too big", where an effect of little scientific importance is nevertheless statistically detectable."[148]

Where existing data on a subject is scarce, adequate sample size may be problematic to calculate. To generate data, a pilot study can be conducted, or the sample size calculation can be based on data from existing studies in adjacent fields. In the case of Standardbred trotters, no published data was available for sample size calculation, however, published data from in-hand trials of owner-sound Warmblood riding horses[206] using the same IMU system as for the Standardbred trotters was available. A post-hoc sample size calculation was carried out during the study period. To estimate a sample mean with a desired precision, in this case to estimate mean asymmetry in young Standardbred trotters, the below formula was used. It is based on equation 2.5 in Dohoo et al.: *Veterinary Epidemiologic Research.*[58]

Formula: $n = \frac{Z_\alpha^2 \sigma^2}{L^2}$

Where:
n = sample size
Z_α= 1.96 (when α = 0.05). Z_α is the (1-α/2) percentile of a standard normal distribution.
σ^2= *a priori* estimate of the population variance: Estimated range that would encompass 95% of the values and assume that range is equal to 4σ.

- ➔ Based on published data in riding horses, we would expect asymmetry values for most horses to be within 0-30 mm.
- ➔ 30 mm/4 = 7.5 mm. σ = 7.5; σ^2 = $\mathbf{56.25^2}$.

L = The precision of the estimate, equal to half the desired length of a confidence interval (CI, equals range of values within which we expect the true population mean to lie with a certain probability).

- ➔ Desired CI: If expecting 95% of horses to be within 0-30 mm; half the desired length of CI = 15 mm.

Calculation:

$$n = \frac{Z_{\alpha}^{2}\sigma^{2}}{L^{2}} = \frac{(1.96\ x\ 1.96)(56.25\ x\ 56.25)}{(15\ x\ 15)} = \frac{(3.8416)(3\ 164.0625)}{225} = \frac{12\ 155.0625}{225} = 54.0225 \approx \mathbf{54}$$

The estimated sample size is 54 horses. Considering the risk of loss of horses to data collection during longitudinal studies, recruiting more horses than the required sample size may be of value. In our study, although we recruited over 100 horses, only 22 horses remained at the last data collection visit.

Although **loss of study subjects** should always be as small as possible, for cohort studies acceptable rates for subjects dropping out of a study rely greatly on the reason for doing so. In one study with simulated intervention data, when observations were missing at random, up to 60% loss to follow-up could be tolerated before important bias was introduced.[141] On the other hand, if observations were not missing at random, i.e. the probability of being lost to follow-up depended on the outcome,[141] serious bias (here for odds ratio calculations) was introduced at much lower levels of loss to follow-up.[141] In our cohort of Standardbred horses, some loss to data collection is likely related to the outcome. For example, horses removed from training due to "lack of talent" or persistent training issues may have underlying orthopaedic pathology, which could be associated with movement asymmetry. One of the most frequent reasons for study drop-out in our cohort was the horse changing trainer; the exact reasons for this were largely unknown. If related to, for example, the owner "randomly" selling the horse and thus the horse changes trainer, this could be considered independent from the outcome of interest. If, however, the owner moved the horse due to a perceived poor performance of the horse, this may be related to movement asymmetry and/or the orthopaedic health of the horse.

7.1.3 Data collection

Data was collected with the earlier described LL system. In addition to objectively quantifying movement asymmetry in our cohort, an added benefit to using an objective system during a longitudinal study is the elimination of observer bias. Observer bias is defined as "gradual, systematic changes over a period of time by a particular observer in his or her application of criteria for recording or scoring observations."[6]

The main challenge during data collection was the use of the LL system during trials on the trotting track. This pertained mainly to instrumentation, where sensor placement collided with trotting harness placement, and ensuring a consistent wireless connection between the horse-mounted IMU sensors and the system software running on a separate tablet.

Marker or sensor misplacement has been shown to induce small but significant errors in calculated asymmetry parameters.[222] For the LL system, IMU sensors are placed on the poll, pelvis (tubera sacrale) and right forelimb, with an optional sensor on the withers (**figure 14**). To obtain accurate data, the poll, withers, and pelvis sensors need to be placed on the midline of the horse. The LL system software uses the vertical axis data to calculate vertical displacement asymmetry.[133] While some measurement error is to be expected when placing a sensor on a live animal, if the vertical axis of the accelerometer is not vertical, the measured vertical acceleration will be less than the true vertical acceleration.[133] Unintentional backward and forward movement of the sensor will add to the vertical acceleration signal.[133]

The **withers sensor** was added to the system set-up; although not necessary for the calculation of the main asymmetry parameters (HD/PD min/max), it may provide information as to the location of a primary lameness if a compensatory lameness pattern is present. For track trials in our Standardbreds, secure attachment of the withers sensor almost invariably failed once the horse started sweating. Data from the withers sensor was not analysed in this study.

Figure 14. *Instrumentation for data collection. The yellow arrows show the correct placement of the poll, pelvis, and right forelimb sensors. The grey arrow shows the optional withers sensor. The blue arrow shows a pastern wrap without a sensor, that was placed on the left forelimb during the first data collection trials (visit 1) to avoid any induced asymmetric movement from yearlings unaccustomed to wearing protective limb wear. The red arrow points to the electrode belt that measured heart rate during driven trials (heart rate data was not used in the studies in this thesis).*

Data from the **pastern sensor** is used to determine the stride rate and timing of stance and swing phases.[127] If the sensor turns 180 degrees to the back of the pastern then opposite limbs (right instead of left and vice versa) are recorded as asymmetric. During exercise on the track at faster speeds the pastern sensor wrap was prone to rotating, especially when the horse started sweating, despite additional tape used to secure the wrap (**figure 15**).

Figure 15. *Pastern sensor wraps and additional tape. Only the right forelimb pastern wrap contains a sensor.*

Figure 16. *Correct placement of the pelvis sensor on the midline of the horse.*

Correct placement of the **pelvis sensor** on the midline (**figure 16**) proved difficult, as the back strap of the harness interfered with sensor placement. The biggest issue was during higher speeds, where the pelvis sensor was pulled down to one side by the harness, causing the sensor to tilt (**figure 17**) and frequently lose its secure attachment to the midline of the horse. During higher speeds, many Standardbreds land with the hind hooves outside of the front hooves, called "passing gaited".[165] Standardbreds who are "in-line gaited" land with the hind hooves in line with the front hooves.[165] Passing gaited horses seem to have an increase in the yaw or side-to-side movement of the hindquarters, and less "up-and-down" movement, as seen on camera during data collection. This "wagging" movement seemed to displace the pelvis sensor much more than at a slow/jogging trot, where additional taping was enough for secure attachment. For the current study, data collected from high-speed trials could not be analysed mainly due to this issue. Recently, the LL system developer has manufactured a special "harness pelvic cradle" for the pelvis sensor to avoid this issue when measuring harness racehorses.

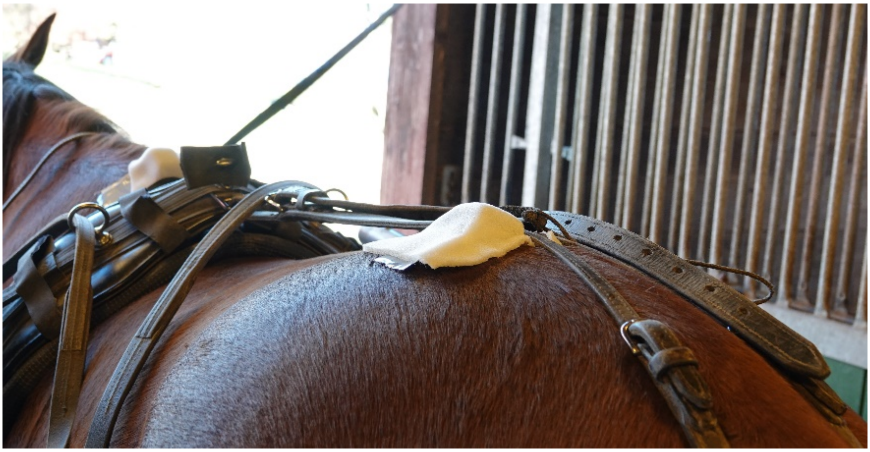

Figure 17. *The pelvis sensor is pulled down (to the right) by the harness.*

The other main issue was the horse-mounted sensors falling outside of the Bluetooth range of the software system tablet when the Standardbreds were exercised on the track. One solution to this issue is to follow the horse in a vehicle (**figure 18a**) as was done during some data collection visits during this study. This does however require a suitable vehicle, an additional person to drive the vehicle, and a horse that is not affected by being chased by a vehicle (although this seemed true for most Standardbreds, who in general showed an unflappable demeanour).

Figure 18a. *Driving after the horse on a training track in winter.*

Figure 18b. *Collecting data from the horse in 18a. Tablet running the system software; the USB Bluetooth antenna (red) is fitted with an enforcer/extended range antenna (black).*

Another option is to fit the driver of the horse with a backpack and have the software tablet follow the horse around the track. This worked best when the Bluetooth antenna was attached to the side of the driver's helmet and connected to the tablet via an extension cord (**figure 19**). The downside to this arrangement is the loss of control over starting and stopping a data collection trial, as well as that any technical difficulties with the data collection will go unnoticed until the horse is halted, and the tablet taken out of the backpack.

Figure 19. *The driver carries a backpack with the tablet running the LL system software. To ensure continuous Bluetooth connection to the sensors, the Bluetooth antennae is taped to the driver's helmet and connected to the tablet via an extension cord.*

A bit into the first year of data collection, a helmet camera was added to the data collection protocol (**figure 20**). This was a valuable addition, as it enabled both a better assessment of the pelvis sensor placement and attachment (or lack thereof) as well as giving an informative view of how the horse moved during exercise.

Figure 20. *View from the helmet camera during high-speed training on the track.*

One last consideration when it comes to data collection is regarding the information collected from the trainers. At every visit the trainers were asked about events pertaining to individual horses during the three months since the last visit, such as veterinary treatments. There were differences in how trainers kept records, ranging from digitalised records for each horse to simple memory. Whenever relying on memory for collection of study data, **recall accuracy and memory decay** needs to be considered. In a study of injury incidence in American farmers, recall periods of more than two months were likely to significantly underestimate injury rates.[117] In the present study, if memory decay was present it could have affected the reported frequency of veterinary treatments related to lameness, leading to potential underestimation of these occurrences in our longitudinal results.

7.2 Movement asymmetry and lameness in Standardbred trotters

The Presence of Lameness, regarded simply as a bare fact to be determined, might by many persons be supposed to be a matter uncreative of doubt or difficulty; and yet too frequently does it happen that the horse one person, one veterinary surgeon even, calls lame, another will declare to be sound.

Percivall, 1849,
Lameness in the Horse[187]

Two main themes present themselves through the results of the papers in this thesis. They are a) the prevalence of asymmetry in young Standardbred trotters and b) the orthopaedic health of young Standardbred trotters.

Asymmetry & gait variability

During all data collection visits, most trotters were classed as **asymmetric** when implementing thresholds as defined in papers I and III. One question that quickly arises is whether we are looking at lame or non-lame horses when faced with data showing asymmetric movement. This question is perhaps most pressing for data presented in paper I, where horses had only recently been introduced to training, and thus, should not have been subjected to any substantial musculoskeletal overload or strain. An important caveat when interpreting our data is the lack of a thorough orthopaedic examination, combined with the fact that horses with possible low-grade lameness were not excluded. However, in paper I, we aimed to describe the prevalence of movement asymmetry in young Standardbreds as they were starting their training career. Therefore, we included a representative cohort of young Standardbred trotters that were in full regular training, as this represents the real-life situation for these occupational horses. The same way a horse can be considered "fit-to-compete" in equitation disciplines without being non-lame if it were to undergo a complete orthopaedic evaluation, our horses were considered "fit-to-train" by the person who had the full responsibility for the daily health assessment of these horses (the trainer), and thereby also the welfare of the horses.

The main limitation of the data presented in paper I was the high stride-by-stride variability, expressed as **high standard deviations** per trial measurement. In one published article where the clinical thresholds used in papers I and III were applied to detect lameness,[160] one criteria was that the standard deviation was below the respective asymmetry parameter mean. The LL system guidelines stipulate that the standard deviation should be below or close to the parameter mean.[72] In paper I of this thesis, trial standard deviations were categorised into levels of variability based on the distance from the trial parameter mean. Hardly any trials were in the "low variability" group, defined as a standard deviation value less than 50% of the trial parameter mean (e.g. a standard deviation of 5 mm or less for a trial parameter mean, e.g. HDmin, of 10 mm). Most trials had standard deviations of more than 150% of the mean parameter value, reflecting a variability in gait both seen and measured. One possible interpretation of this is that these yearlings are mostly sound. In a lame horse, the expectation would be that at least one asymmetry parameter mean would be a high number, reflecting the consistent gait unevenness introduced by weight-shifting off one or more painful structure(s). Hence, the standard deviation should be below the high parameter mean, since the horse is not showing much stride-by-stride variability and since the parameter mean is elevated. Conversely, horses classified as symmetrical (below threshold) would often be expected to have a standard deviation value above that of the parameter mean, since the parameter mean is close to 0. In paper I, many of the horses had parameter means above threshold where the standard deviation values were higher than the parameter means. These horses often had a boisterous nature (although our study lacked a control group, we did at times have an out of control group) and would only barely be convinced to trot-up in-hand in a straight line.

Different types of asymmetric movement in young Standardbred horses have been observed in other studies and differing underlying causes have been discussed. Comparing published studies is complicated by the fact that both measurement techniques and outcome parameters differ between most studies in this breed. A study by Leleu et al.[146] looked at the effect of age on movement asymmetry in 143 clinically sound French Standardbred trotters in training, measured on a track at three different speeds. The movement pattern of two- and three-year-old horses were more asymmetrical than older horses at slow (8.5 m/s) and medium (10 m/s) speeds. Vertical displacement asymmetry (as measured by an accelerometer placed on the sternum of the horse) was one of only two variables not dependent on speed but only age, being higher in two-year-old horses compared to older horses across all speeds. The authors discuss that the increased asymmetry in younger horses may be due to immaturity of gait and lack of coordination. Conversely, Drevemo et al.[60] hypothesised that asymmetries in the locomotion patterns of younger Standardbreds are an expression of congenital laterality or sidedness. In their study, ten Standardbred colts, trained to trot on a treadmill, were assessed by the use of high-speed cinematography at eight, 12 and 18 months of age at a trotting speed of 4 m/s. Five colts were subjected to regular and controlled training, while the remaining five colts functioned as an untrained control group. Asymmetries were present in the form of differences between the diagonal limb pairs within a stride, resulting in different diagonal lengths within a stride as well as different degrees of diagonal dissociation within a stride. These asymmetries were most pronounced at 18 months, and the group of trained colts were more asymmetrical than the control group. Vertical displacement asymmetry was not measured in this study.

Subjectively, some yearlings in our cohort displayed consistent asymmetrical movement. While this could be due to either movement incoordination at this young age or laterality, an underlying pathological process could not be ruled out. Indeed, at the following data collection points, the majority of these horses continued to show asymmetrical movement, and therapeutic joint injections were administered to the first horses in the cohort already in the spring of their two-year-old year, only months after the initial data collection.

<u>Change in asymmetry over time</u>

During the entire study period of two years, most horses were classified as asymmetric at each visit. **Asymmetry magnitude** ranged from mild to severe, with most horses showing mild to moderate asymmetry. In paper III, an increase in hindlimb asymmetry was seen over time, most evident for the parameter PDmin. Hindlimb lameness is noted to be more common than forelimb lameness in Standardbred trotters, often attributed to the horse having to pull a draft load.[120,121,165] The forelimb parameter HDmax decreased over time. Subjectively, this parameter seemed to be the most influenced by the horses' behaviour, i.e. unsteady head carriage and head tossing. One possible interpretation of the decrease in HDmax is that the horses were better behaved as they matured. However, we need to interpret these data with care, both due to the variation in the number of included horses per data collection visit, as well as the confounding effect of therapeutic joint injections received by the cohort horses during the study period.

The presence of a low number of severely asymmetric horses in full training was constant. These horses were, in the author's opinion, clearly lame. Sometimes, the veterinarian and the trainer both **recognise movement asymmetry of one or more limbs but interpret it differently**. The veterinarian might be biased to see asymmetry primarily as a sign of lameness, as recognition of lameness forms a large part of the veterinarians' work and training. The trainer on the other hand might be biased towards thinking the horse has a training-related issue when it moves asymmetrically, e.g. due to differing muscle strength or growth issues. The most certain way of deciding what the cause of the asymmetrical movement is would be to commence a full orthopaedic work-up including diagnostic analgesia. Another, less invasive method, may be to collect objective movement data again at a later date, assuming that lameness-induced asymmetry would be consistently present or even worsen, while more arbitrary causes such as training-related asymmetry should change, ideally improve, between the two data collections. However, keeping a lame horse in training could be detrimental to both the site of injury, as well as the welfare of the horse.

Prevalence of lameness

Older published studies of subjective evaluations of lameness in Standardbred trotters show that there was an overall (very) high prevalence of **lameness in Standardbreds**. Dolvik et al.[59] reported the prevalence of lameness in 265 randomly selected three-year-old Standardbred trotters in Norway to be almost 70%. Lameness examination in the study included clinical inspection, palpation and evaluation at the walk and trot, as well as flexion tests of both proximal and distal limbs. Horses in regular training as well as untrained horses and horses with reduced training were included, however, there were only small differences in lameness prevalence between the groups. Magnusson et al.[154] looked at the orthopaedic health status of 500 four-year-old Standardbred horses in Sweden. Over 99% of the horses had signs of injury when palpated by a veterinarian, however, in this study the horses were not assessed for lameness during movement. The author states that

> "77 per cent of the Standardbred trotters studied had signs of injuries serious enough to be noticed, for instance at examination for soundness, and often temporarily seen coinciding with lameness."[154]

More recently, Vigre et al.[246] looked at 265 Standardbred trotters in training with professional trainers over a five-month period: 26% (69 of 265) of the horses experienced at least one event of interrupted optimal training related to lameness. In a study on middle carpal joint pathology by Skiöldebrand et al.,[226] 28 Standardbred trotters were followed over two years, from the initiation of training. During the study period, 22 horses were (impermanently) lame from the middle carpal joints.[226] Bertuglia et al.[19] reported 429 injuries in 356 Standardbred trotters during 8961 months at risk.

The reportedly high prevalence of lameness in the Standardbred trotter is an important welfare issue. With such a high prevalence of lameness comes the risk of lame trotters participating in races. Some veterinarians even consider this a fact of the sport: "Some overnight and stakes horses are chronically lame but race weekly, although lame horses race slower, and horses drop in class as lameness progresses", as described by Mitchell et al.[165] The authors go on to say that:

> "STBs have unusual resiliency and race rather well with chronic lameness, but lameness does not resolve with speed (…) Signs of lameness become less visually apparent when horses go fast."[165]

Trotting speed

Trotting speed influences the outcome of both subjective and objective lameness evaluations[230] and affect locomotor variables.[146] Any speed preference of the horse also plays a part; an individual "optimal" trotting speed could be established in horses on the treadmill.[185] During optimal speed the gait variation, as expressed by standard deviation, was small while movement asymmetry was at its maximum.[185] In sound Standardbred trotters exercised at increasing speeds on a treadmill, van Weeren et al.[253] reported a more uniform gait at higher speeds when looking at temporal and linear gait characteristics.

In our longitudinal study, speed was not controlled but recorded during track exercise. Mean speed for driven exercise trials per data collection visit are listed in paper III and show a slight increase in speed from yearling age. Mean jogging (warm-up) speeds per visit were relatively stable, centred around 6 m/s. When looking at movement asymmetry on the straight versus curved part of the track (paper II), there was close to no difference in mean speed between straight track and curved track trials. Nevertheless, when stride duration was included in the statistical model as a proxy for speed, there were strong interactions between stride duration and most asymmetry parameters.

In Standardbred racing, all horses are inspected on the track by the **track veterinarian** prior to starting in a race. Horses pass the track veterinarian at a speed comparable to racing speed, while performing a "test start" with the horse accelerating from moderate to high speed. This is to ensure that horses competing in a race are "fit-to-compete". This is the only official soundness check for horses competing in trotting events, precluding the track veterinarian from routinely evaluating horses at slower speeds pre-race. In a study by Peham et al.,[184] increased speed in moderately forelimb lame horses trotting on a treadmill caused an increase in lameness as expressed by an increased difference in vertical head motion between left and right forelimb stance.[184] However, in the same study the range of vertical head motion decreased with increasing speed in 15 of 16 horses.[184] In a study looking at sound to mildly lame horses by Starke et al.,[230] "more horses were subjectively declared sound at higher speeds"[230] when trotting in a straight line, while straight line objective asymmetry data did not consistently change with increased speed.[230] These studies therefore recommend that horses should be trotted at slow speeds during subjective lameness examinations, in order for the veterinarian to be able to observe (especially low-grade) lameness.[184,230]

For Standardbred trotters, this assessment at slower speed should still be conducted with the horse driven. The reason for this is the complicating feature that Standardbreds may show differences in movement between in-hand trot and driven exercise. In paper I, 20% of the yearlings "switched" which limb was responsible for the asymmetry between in-hand and driven trials. This characteristic is pointed out in veterinary textbooks as well, stating that "correlation between lameness seen in hand and that at racing speed is often poor".[121] Rather than being caused only by differences in speed, other potential reasons include pulling a cart and differences in surface.[165] In addition to the challenge of subjectively determining lameness at high speed, harness racehorses may show less lameness at pre-race inspections than what their orthopaedic health would suggest, due to additional factors such as adrenaline and a "competitive mind-set".

Racing mentality & performance parameters

As in all elite sports, performance is determined not only by the physical traits of the athlete but to a large degree by the athlete's mentality. In human athletes, **higher pain thresholds** have been recorded compared to non-athletes.[81,190] To the author's knowledge there are no studies on this in horses, but both personal experience and anecdotal evidence makes it clear that this is also the case in equine athletes. One example is by Dr. Adams in an older edition of Adams' *Lameness in Horses*, when discussing performance in horses:

> "Another factor is that called "heart". This could be properly termed "desire", and some horses definitely have more of a sense of competition than others. This desire often permits a horse that is suffering pain from certain types of lameness to compete successfully and win."[4]

***Figure 21**. Data collection from Standardbred trotters on the track.*

Since breeding of performance horses is based on pairing horses that have performed well, we may be selecting not only for speed and stamina but also for a certain competitive mentality when breeding athletic horses. Further, horses in hard training are likely acclimatised to endure a certain level of pain. We might consider a sound horse (however that may be defined) a prerequisite for good performance, and lameness is often an underlying cause of poor performance in racehorses.[69,167] There seems, however, to be substantial individual differences as to the relationship between orthopaedic health and race performance. An even more explicit opinion can be found in one of the most widely used veterinary orthopaedic textbooks, *Diagnosis and Management of Lameness in the Horse,* where Dr. Ross states that:

> "Part of the art of the lameness examination is separating those horses capable of performing with moderate pain at a high level from those that cannot do so."[214]

Barrey et al.[14] were some of the first to use accelerometers to measure symmetry on the track when they looked at 24 French Standardbred trotters in the mid-1990s. Accelerometers were placed on the sternum of the horses prior to a standardised locomotor test on the track. There was no significant association between symmetry/regularity of the trot and performance, however, the authors comment that "orthopaedic troubles" probably limited performance in one group of horses.[14]

To determine success or not after an intervention in racehorses, e.g. a surgical procedure, the number of starts in races, placings or money earned per start or accumulated prizemoney is often compared to the horse's track record prior to the intervention. These are useful **outcome parameters** in studies assessing a horse's ability to perform well, provided the researcher also considers variables such as the availability of races, the level of competition in the race and the differences in prize money between countries or even regions within a country. However, if we concede for now that horses racing successfully may be lame, this means that racing performance may not be useful as a parameter for determining orthopaedic health. For racehorses, this is an important distinction, as **racing performance is often used to assess the effects of early training and racing**.

Early training and racing

There is convincing evidence that a certain amount of training is needed at a young age to stimulate and strengthen the musculoskeletal system to withstand the strains of training and racing.[79,80,123,254] At the same time, multiple studies confirm that most musculoskeletal injuries and breakdowns are due to repeated, cyclic loading; in other words, the locomotor system becomes overloaded and over time cannot keep up with the demands placed on it.[13,173,181,226] Thus, there is debate as to the amount of training and racing a young horse should be subjected to.[213] One approach to evaluating the effect of early training and/or racing in Standardbreds is to look at their racing careers.[138,239] One large-scale retrospective study that looked at the effect of early training and racing in Standardbreds in New Zealand included all 3032 horses born in a year; of these 1018 (33.6%) registered with a trainer and 272 (9%) raced as two-year-olds.[239] This study concluded that:

> "Horses that first raced as 2-year-olds had a longer racing career and more race starts than those that that did not race as 2-year-olds ($p<0.001$); this was also true when starts in the 2-year-olds were omitted from analyses".[239]

The authors state that this study "is the first time that early training and not just racing has been shown to have a positive effect on career length."[239] The authors make no claims as to the orthopaedic health of these horses, although the reader may be inclined to consider increased career length as a sign of good health. Using retrospective studies to infer causality is questionable. One phenomenon that should be considered is that of the so-called "healthy worker effect", or in this case, the "healthy horse effect".

The **"healthy worker effect"** has been defined as a

> "special type of selection bias, typically seen in observational studies of occupational exposures with improper choice of comparison group (usually general population)."[39]

As retold in Fox & Collier (1976),[82] William Ogle is credited with first reporting this effect in 1885 while calculating the death rates in different industries in England and Wales for the years 1871-80. One of Ogle's observations was that

> "some occupations may repel, while others attract, the unfit at the age of starting work, and, conversely, some occupations may be of necessity recruited from men of supernormal physical condition."[82]

In other words, some occupations, e.g. those requiring strenuous physical work, were held by those workers who were in good physical shape. Since these workers were healthier than those in other occupations, death rates might be lower even though the work took more of a toll on the worker. Therefore, this selection bias should prevent us from using lower death rates in occupations with, for example, heavy manual labour to argue that heavy manual labour leads to a healthier or longer life. When we retrospectively look at racing careers for horses and determine that those who train and race at an early age have longer careers or earn more money, are we detecting a real (protective?) benefit of starting horses early, or are we just selectively looking at those horses who were able to withstand a rigorous training and racing schedule? Are these horses our "men of supernormal physical condition"?

In the study by Bertuglia et al.[19] racing intensity was identified as a protective predictor of risk in Standardbred racehorses, i.e. horses that raced frequently were at a lesser risk of injury. However, the authors discuss that the variable "racing intensity" may be a representation of the "healthy horse" effect, since non-injured horses are able to race more frequently than injured horses.

Veterinary orthopaedic interventions

In our longitudinal study, many horses that were in full training where nevertheless often subjected to **therapeutic joint injections**. There was great variation among the trainers as to both the use of and interpretation of needing joint injections. Some trainers assessed this as regular "maintenance" of the horses, while others classified horses needing joint injections as lame and in need of rest. Whenever animals form part of the human economy, animal welfare must be given the utmost consideration. In the case of racehorses, economic considerations relate to the livelihood of the trainer, the profit for the owner(s) and the winnings of the betting public. It therefore stands to reason that racehorses need even stricter surveillance of their welfare by non-invested parties. It is outside the scope of this thesis to discuss the ethical use of animals for sporting purposes. It is however worth noting that in recent years there has been increased attention of a "social licence" framework to assess the legitimacy of sporting industries[102] and the question of when the use of animals for sporting purposes becomes abuse.[35] In May 2020, well-recognised trainer of Standardbred trotters Roger Walmann gave an interview[118] on his opinion of the current state of the trotting sport:

> "Det är inte någon tvekan om att hästarna i dag går fortare än vad de orkar. Det hade varit roligt att se hur mycket mediciner det går åt till att spruta hästarna i dag jämfört med för 15 år sedan. Det har blivit en helt annan sport (…) Det handlar bara om att vinna travlopp, kosta vad det kosta vill. (…) Jag lovar till hundra procent att det här inte går längre. Folk kommer att reagera. Det är inte möjligt att fortsätta så här."[118]
>
> ["There is no doubt that the horses today are going faster than what they can cope with. It would be interesting to look at the amount of medication used for joint injections today compared to 15 years ago. It's become a completely different sport (…) It's all about winning races, no matter the cost. (…) I promise, one hundred percent, that this cannot go on. People will react. It's not possible to go on like this."]
>
> [Thesis author's unofficial translation]

At this point in time, we **do not have any conclusive evidence** as to the relationship between the presence and magnitude of measured movement asymmetry and the development of clinical lameness in young Standardbreds. However, our longitudinal data documented that movement asymmetry was present in most horses during the first two years of training. We also documented the use of frequent therapeutic joint injections, which can realistically be interpreted as treatment for perceived lameness in this cohort of horses. Having gained much knowledge in recent years as to the shortcomings of subjective lameness detection in horses, further investigation into the use of objective asymmetry data to detect lameness as early as possible is strongly warranted. The use of defined thresholds to classify a horse as lame or not is appealing and could lend itself to "screening" of horses to determine lameness. There is however much (justified) debate as to where that threshold should lie; one reason may be that the amount of collected asymmetry data is too scarce and only available for certain types of horses under certain circumstances. Perhaps, in these early days of objective asymmetry measurements, the individual horse must set the bar for what is “normal” or not. By establishing a baseline movement asymmetry pattern for an individual horse, and regularly obtaining movement asymmetry data, small changes that are atypical for the individual horse could be detected and action in the form of an orthopaedic check-up exam could be taken.

Today, taking a horse’s **temperature** in the morning is routine at most, if not all, training yards. If the temperature is elevated, the veterinarian may be called out to assess the situation, prior to the horse showing signs of extensive disease, and while relatively minor measures may be enough to prevent further illness. Purportedly, it took a century of use and data collection before the fever thermometer was generally accepted in the medical community as a highly valuable tool for aiding the doctor in his work.[224] With any luck, it won’t take that long before the veterinary community has further explored and established evidence-based practices for the use of objective movement asymmetry data in Standardbred trotters.

8 Conclusions and future research

Technology won't replace vets. . .but vets who use technology logically and carefully will replace those who don't.

Dr. Derek Knottenbelt, 2017, quote from "Using the past to make the future better"; Plenary opening lecture, 56th British Equine Veterinary Association (BEVA) Congress, 2017, in Liverpool, UK.

<u>The three main results from this thesis were:</u>

- During all data collection visits, most horses were classified as asymmetrical movers. In those horses who remained in training and were available for data collection, therapeutic joint injections were common. Establishing causality between measured asymmetry magnitude and orthopaedic pain was not possible with our current dataset.

  Suggestions for future research:
  <u>Aim:</u> To further determine the clinical relevance of measured movement asymmetry; to determine if it is possible to define a significant change/increase in asymmetry that precedes the onset of visible lameness.

  - Conduct a study to further establish the day-to-day and/or weekly physiological variation in asymmetry in Standardbred horses. Suggested set-up: Included horses would be deemed sound as per a full subjective lameness examination including flexion tests as well as defined as symmetrical after objective movement asymmetry measurements. Thereafter daily asymmetry data collected at set times, e.g. in the morning prior to turn-out or exercise. Data collected on 10-14 consecutive days.

- Conduct a prospective, longitudinal study with shorter time intervals between asymmetry data collections at training yard(s) where, in general, horse turn-over is low; possibly even incorporate daily data collection through future tools aimed at everyday training monitoring.
- More extensive orthopaedic lameness examinations, including diagnostic anaesthesia and/or systemic analgesic tests, could be performed regularly in a cohort where asymmetry data is collected; asymmetry data should be collected at the time of orthopaedic examinations as well.
- A study based on collaborative efforts from racehorse veterinarians to increase the evidence base for objective data in these horses. For example, relate measured asymmetry to the results of diagnostic anaesthesia during lameness exams, look at specific asymmetry patterns and possible correlations to specific confirmed diagnoses.

❖ When applying clinically used thresholds, most young Standardbred trotters were classified as asymmetric from the beginning of training as yearlings. The range of asymmetry was large, with most horses having mild asymmetrical movement. Standard deviations were often high, especially during the first data collections in very young horses, indicating large stride-to-stride variability during data collection.

Suggestions for future research:

Aim: To further determine how to interpret movement asymmetry trials with high standard deviations, i.e. how do we interpret data with high variability when this is all that is available, e.g. in young, unhandled racehorses?

- To know if the measured asymmetries were mainly due to the behaviour of young horses, unaccustomed to trotting up in-hand, we could perform a study where young horses are being trained to trot in-hand, concurrently collecting asymmetry data.

- Combine asymmetry data collection with orthopaedic lameness examinations including flexion tests and, if warranted, diagnostic analgesia.

❖ When exercising on a non-banked curved track at jogging speed, in a clockwise direction, specific changes in measured asymmetry were induced, mimicking mild outside fore- and hindlimb asymmetry.

Suggestions for future research:

Aim: To determine if the changes seen in movement asymmetry are the same going in both directions; the influence of banking track turns, and the effect of speed when driving on banked tracks.

- Conduct a study where movement asymmetry is measured going in both clockwise and anti-clockwise directions through non-banked track turns.
- Cross-over study where the horses are driven at moderate speed through both non-banked and banked turns; track selection would be important to ensure that the turn radius is similar for non-banked and banked turns – most larger/official racetracks have banked turns on the inner part of the track and an outer part (larger radius) where the track is not banked.
- Conduct a study where movement asymmetry is measured during trotting through a banked curve at different (increasing) speeds to determine the effect of speed on asymmetry parameters.
- Conduct a cross-over study where Standardbreds are trained to be lunged, in order to investigate whether differences seen between lunged horses and Standardbreds driven on a curved track are primarily due to pulling a sulky and driver. Speed and circle radius would ideally be the same during lunging and driving.

Additional results and observations were:

- Some horses showed different asymmetrical movement during in-hand and during driven exercise. This is especially relevant for lameness evaluations in Standardbreds, since these are often conducted with the horse trotting in-hand.

  Suggestions for future research:

  Aim: To determine the occurrence of "switching" of the limb(s) responsible for the measured asymmetry.

  - Conduct a study where data is collected in-hand as well as during (standardised) driven exercise and preferably during all exercise phases; warm-up, high-speed/interval training, and cool-down.
  - Based on the above data; determine whether any patterns can be discerned, e.g. a systematic change from forelimb to hindlimb lameness between the in-hand and driven trot.
  - One hypothesis could be that the change in asymmetry is due to the horse having to pull a cart/sulky and driver. The potential effect of pulling a cart and driver could be further investigated using pressure wagons; these are training carts in common use for Standardbred training, where the wheels are braked to a set level, controlled by the driver. The relationship between measured asymmetry and increasing pressure (weight to be pulled) could be clarified.

- Most horses in our study had in-hand data collected either prior to or after driven exercise. Subjectively, some horses "warm-out" of their asymmetrical movement while some horses become more asymmetrical with exercise.

  Suggestions for future research:

Aim: To determine whether there are systematic changes in measured asymmetry pre and post exercise; whether there is a change in asymmetry after intense exercise.

- Conduct a study where data is collected in-hand before and after driven exercise: preferably before and after light exercise as well as before and after high-speed training.

- There is some preliminary evidence that use of an overcheck systematically affects measured asymmetry.

Suggestions for future research:

Aim: To determine the use of an overcheck on asymmetry parameters.

- Conduct a cross-over study of overcheck use during driven exercise; data should be collected from both straight and curved track segments. Include different overcheck fits, i.e. long, moderate, and short length. Standardisation of overcheck length may not be feasible, as it is contingent on horse conformation.

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10 Appendices

10.1 Review of irrelevant literature

This part is not terribly important. It is however, in the author's opinion, quite interesting, and will hopefully be of enjoyment to those who have made it this far. This section contains a few bits and pieces that I have stumbled upon during the past 3½ years relating to equine locomotion and/or Standardbred trotters.

- Someone who really has dug deep into the effect of history on equine locomotion are Linford et al.,[152] who assessed the influence of buried archaeology on equine locomotion; a correlation was found between archaeological remains and gait alteration.

- A different type of gait alteration in humans is described in Butler & Dominy's paper on the biomechanical properties of Monty Python's Silly Walks; "If silly walking can be defined as deviations from typical walking, then silliness can be quantified using two-dimensional video-based motion analysis."[33]

- Erickson's tale of "horse-whims, teamboats, treadwheels and treadmills" details the history of such things as the equine treadmill, a staple of later locomotor research; one type of treadmill machinery was even used to race horses on stage in the 1890s.[73]

- The first documented photo finish in a horse race was in 1881.[122] The famous photographer Muybridge wrote in a letter to the editor of *Nature* in 1882 that: "I venture to predict, in the near future that no race of any importance will be undertaken without the assistance of photography to determine the winner of what might otherwise be a so-called 'dead-heat'."[122]

- Some participants in trotting races are not even horses. The elk “Stolta”, raised by humans after her mother was killed by the train, was trained to work in the Swedish forest.[100] In 1907 she became famous after participating in a trotting race in the Swedish town of Falun – rumour has it she won the race.[100]

- The term sulky for a light-weight wagon has been around for a long time, perhaps so termed as it is the perfect vehicle to sulk in; that could be one interpretation of this entry in Walrond’s *The Encyclopaedia of Driving*[249]:

  > “Sulky: A low single-seat vehicle which is built of tubular steel and has two small pneumatic-tyred wheels. It is used for trotting and pacing races. Early Sulkies were built with a single seat on a high framework above large wheels. They were so named because of the solitary confinement of the driver”.[249]

  This vehicle is not to be confused with the “Suicide Gig”: “A type of Cocking Cart which had a groom's seat about 3 feet higher than the driver's seat”.[249]

- Some trotting horses have more of a legacy than others. The Swedish Standardbred Big Noon was the king of the trotting sport around the time of the second World War. Born in 1936, he was the first Swedish Standardbred to trot a kilometre in less than 1.20 min.[172] In 1942, Big Noon travelled to a war-occupied Oslo in Norway to compete in a race at Bjerke trotting track. Despite galloping and thus losing much ground at the start of the race, Big Noon won the race to massive cheers.[172] The spectator record of 24 000 has to this day not been surpassed at Bjerke.[172] When Big Noon was euthanised in 1964, his death was mentioned in *The New York Times*: “He was 28 years old, the equivalent of about 110 years in human life.”[11]

I’d like to end this thesis with my favourite horse trainer quote from this project:

“**Horses don’t think much, but they observe everything.**”

10.2 Author resumé

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Sept. 2017 – April 2021	PhD candidate, Norwegian University of Life Sciences (NMBU), Faculty of Veterinary Medicine, Dep. of Companion Animal Clinical Sciences, Equine Section, Oslo, Norway
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Nov. 2009 – Sept. 2012	*During studies assisted with the training of dressage horses, Dressurausbildung Graubohm, Hannover, Germany*

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Jan. 2007 – May 2007	Classes in philosophy, ethics, and public law, University of Oslo (UiO)
July – Dec. 2006	Groom for dressage rider Ann Katrin Linsenhoff, Schafhof Reitanlage & Gestüt, Kronberg, Germany
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11 Papers I-III

Paper I

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GENERAL ARTICLE

Equine Veterinary Journal WILEY

Objectively measured movement asymmetry in yearling Standardbred trotters

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Abstract

Background: Lameness evaluation of Standardbred trotters can be challenging due to discrepancies in observed movement asymmetry between in-hand and track exercise, and between different trotting speeds. There are few studies on objective measurement of movement in Standardbreds, and little knowledge regarding biological variation and clinical significance of measured movement asymmetry in this breed.

Objectives: To quantify the prevalence and magnitude of objectively measured movement asymmetry in young Standardbred trotters, and identify associations with trainer, sex, height, track type and in-hand measurement prior to or after track trials.

Study design: Cross-sectional, observational study.

Methods: A total of 114 Standardbred yearlings were evaluated with a wireless inertial sensor system during trot in-hand and when driven on a track. After exclusions relating to lameness or technical difficulties, 103 horses were included in the study; 77 were evaluated in-hand and on the track, 24 only in-hand and 2 only on the track.

Results: Front and/or hindlimb parameters were above asymmetry thresholds previously established for other breeds during in-hand trials for 94 (93%) horses and during track trials for 74 (94%) horses. Most horses showed mild asymmetry. A minority of horses (20%) switched side of the asymmetry for one or more parameters between in-hand and track trials. Mixed model analyses revealed no significant effects of trial mode (in-hand or track trial, in-hand trial pre- or post-track trial, straight or oval track), trainer or horse height. Females had a significant but small reduction in asymmetry in one front limb parameter (HD_{max}) compared with males (1.7 mm, 95% CI 0.18-3.28, $P = .03$).

Main limitations: High data variability, reflected in large trial standard deviations, relating mainly to a lack of horse compliance.

Conclusions: A high proportion of Standardbred yearlings showed movement asymmetries. There was no group-level effect between in-hand and track trials, however, considerable individual variation was observed.

KEYWORDS
horse, lameness, harness racing, IMU, locomotion

1 | INTRODUCTION

Traditionally, lameness evaluation relies on visually recognising movement asymmetry during walking and trotting in-hand. However, subjective lameness evaluation may be unreliable[1,2] and veterinarians may also show bias when evaluating response to diagnostic analgesia.[3] Subjective assessment of movement irregularities can be particularly challenging in the Standardbred trotter. Reasons for this, as suggested by veterinarians experienced in working with Standardbreds,[4] include that lameness seen at trot in-hand may not correlate with lameness during training, and that the observed degree of lameness may vary with trotting speed. With these challenges of subjective lameness evaluation in mind, developing and refining more reliable, objective methods for equine lameness evaluation continues.

Objective measurement of movement asymmetry is possible with wireless technology using inertial measurement unit (IMU) sensors. Threshold criteria for movement asymmetry exist for a commercially available IMU system, and relate closely to between-trial repeatability.[5] However, difficulties remain regarding interpretation of the clinical relevance of IMU measurements in sports horses[6] and knowledge is lacking for the Standardbred trotter.

The aim of the current study was to describe the prevalence and magnitude of motion asymmetry in young Standardbred trotters beginning their training, evaluated both in-hand and during driven exercise. Our hypothesis was that asymmetry scores would be higher when evaluating horses in-hand vs driven, as trotting-up in-hand would allow the animals to move more freely vs when exercised within the constraints of a harness and sulky. Additionally, we aimed to investigate potential associations between movement asymmetry and trainer, sex, height, track type and measuring in-hand asymmetry prior to or after track trials.

2 | MATERIALS AND METHODS

2.1 | Study design and cohort description

Fifteen trainers were contacted regarding study participation. Twelve agreed to participate. One additional trainer was recruited based on advertisement of the study. Training yard-level inclusion criteria were location (proximity to Oslo, Norway or Stockholm, Sweden), a licensed professional trainer in charge and willingness to participate in the study over time. One additional trainer in southern Sweden was included despite not fulfilling the proximity criteria due to the large number of horses available at the yard.

Horse-level recruitment criteria were breed, age and training level; only Standardbred trotter yearlings that were broken to harness and within the first 6 months of driven exercise were recruited. At each yard, all horses available that fitted the recruitment criteria and were currently in regular training were evaluated. The horses were assessed by their trainer as fit to train, meaning that the trainer had not observed any lameness, or other issues likely to reduce or interrupt training. Horses were excluded if they paced instead of trotted during trials, or there was veterinarian-observed subjective lameness of >2/5 degrees according to the American Association of Equine Practitioners (AAEP) scale (0-5) during the in-hand trial.

2.2 | Clinical examination and measurements of movement asymmetry

All horses underwent a general physical examination and measurement of height at the withers and pelvis at their training yards or local racetrack, performed by one of the authors (A.S.K., E.H.S.H. or M.H.). The horses were evaluated at the trot driven on a track and in-hand (either before or after driven exercise) with a sensor-based objective movement analysis system (Lameness Locator® by Equinosis® LLC). The horses were trotted in-hand in a straight line by their regular handler or one of the investigators (A.S.K., E.H.S.H., M.R. or E.H.) on a firm ground surface, consisting of either gravel, asphalt, packed dirt or hard packed snow/ice, and as even and level as circumstances allowed. The handler was positioned on the left-hand side of the horse and instructed to trot the horse as straight as possible and without interfering with its head carriage. During in-hand trials, the horse was subjectively assessed for lameness by one veterinarian (A.S.K. or E.H.S.H.). For track trials, the horses were exercised by their usual driver, with their regular tack and according to their planned schedule. All tracks were dirt tracks with a surface of packed dirt/sand, mixed with snow during the winter months. A GPS device (Polar M450, Polar Electro) worn by the driver registered speed, distance and route of the trial. Data from both in-hand and track trials were subjectively deemed valid when the horse completed a trial with acceptable straightness and regularity. One in-hand trial and one track trial per horse were used for analysis. As the horses followed their individual scheduled training, the distance trotted per training session varied. For horses exercised over longer distances (>2 km), more than one track trial was collected. If a horse had more than one valid trial, the first trial was used. Default settings (2017 software v1.2r) were used for trial stride selection; preferred stride selection was ≥25 steps.

The movement analysis system sensors were mounted on the poll, pelvis and right front pastern of the horse according to the manufacturers' directions.[7] The pelvis sensor was fastened with extra strong double-sided adhesive tape (Teppeteip, Clas Ohlson) and standard-issue duct tape and covered with additional adhesive tape (Snøgg Animal Polster, Norgesplaster AS) for track trials to prevent loosening. The pastern wrap was secured with elastic tape (Norbind, Norgesplaster AS) to prevent rotation during exercise. The IMU sensors consisted of a tri-axial accelerometer, gyroscope and magnetometer that recorded the vertical acceleration of the head and torso and the angular velocity of the right front limb at 200 Hz with 8-bit digital resolution. A computer tablet with appropriate software received wireless data transmission from the sensors via Bluetooth technology. For trials on oval tracks, the IMU system tablet was placed in a small backpack worn by the driver to ensure continuous connection between the horse-mounted sensors and the receiving computer tablet.

2.3 | Data processing

Software data output consisted of four parameter values for each trial calculated from the mean difference in head minimum (HD_{min}) and head maximum (HD_{max}) positions between the right and left diagonal of each trotting stride, and the mean difference in pelvis minimum (PD_{min}) and pelvis maximum (PD_{max}) positions between the right and left diagonal of each trotting stride.[5] A vector sum ($\sqrt{(HD_{max}^2 + HD_{min}^2)}$) of the mean HD_{max} and HD_{min} values was calculated. Detailed descriptions of the data processing can be found elsewhere.[5,6]

2.4 | Data analysis

2.4.1 | Descriptive data calculations

Criteria for movement asymmetry were based on recommendations for clinical use by the IMU system provider[7] and correspond to published confidence intervals for repeatability of measurements with the system in a variety of non-Standardbred breeds.[5] The asymmetry threshold for the front limb vector sum was 8.5 mm, for front limb HD_{min} and HD_{max} was ±6 mm and for hindlimb PD_{min} and PD_{max} was ±3 mm; values below these thresholds were defined as symmetric. Furthermore, asymmetry was divided into severity categories based on the amplitude of asymmetry in millimetres. Category intervals were based on an increase in millimetre asymmetry by adding the threshold value (8.5, 6 or 3 mm) to each progressing category. The resulting categories were "mild" (vector sum asymmetry 8.5-17 mm/front limb asymmetry 6-12 mm/hind limb asymmetry 3-6 mm), "mild-moderate" (17-25.5 mm/12-18 cm/6-9 mm), "moderate" (25.5-34 mm/18-24 mm/9-12 mm), "moderate-severe" (34-42.5 mm/24-30 mm/12-15 mm) and "severe" (>42.5 mm/>30 mm/>15 mm). Combined scores were created where the horse was classified as either front or hindlimb asymmetric if one front or hindlimb parameter (HD_{min} or HD_{max}, PD_{min} or PD_{max}) was above its respective threshold. Where relevant, horses were included in both front and hind asymmetry categories. For horses with bilateral asymmetry in either the front or the hindlimbs, each horse's combined severity score within the front or hindlimb category was based on the limb with the highest asymmetry score.

Horses which had been successfully measured both in-hand and driven and which had asymmetry identified in the in-hand trial were assigned to one of three categories: Same limb asymmetry present during both in-hand and track trials; limb asymmetry absent in the track trial or limb asymmetry changed during the track trial (left to right or vice versa).

For each limb parameter (HD_{min}, HD_{max}, PD_{min} and PD_{max}), a standard deviation (SD) was reported in the software data output, giving a measure of variability of the strides collected in the trial. Trial SD magnitude is categorised based on distance from the trial mean, where a SD value less than or close to the parameter mean indicates a fairly consistent trial.[7] In our study, SD categories were made based on the distance of the SD value from the respective asymmetry parameter mean. The three SD magnitude categories were (a) trials with an SD of more than 120% of its respective mean (high variability); (b) trials with SD between 50% and 120% of mean (moderate variability) and (c) trials with SD below 50% of mean (low variability). These categories correspond to the levels of evidence (weak, moderate and strong) presented in the IMU system output data (AIDE statement).

2.4.2 | Model building

Movement asymmetry data were analysed using open software (R, version 3.6.1, The R Foundation for Statistical Computing). Mixed models were created using the two-sided lmer function in the lme4 package. Four models were created, where each outcome variable was the absolute values of one of the four asymmetry parameters HD_{min}, HD_{max}, PD_{min} and PD_{max}. In all models, fixed effects were trial mode (with the levels: in-hand or track trial, in-hand trial pre- or post-track trial, straight or oval track), sex (male or female), height at the withers and height difference between the withers and pelvis. Trial speed and surface were not included in the model as these were considered similar for all horses. Horse nested within trainer was entered as a random effect (random intercept) in all models. Normality of residuals was checked using q-q plots and homoscedasticity by plotting the residuals against the fitted values. Evaluation of statistical significance was made using type II *P*-values generated by a Wald *F* test with Kenward-Roger approximated *df* using the ANOVA function in the car package. Post-hoc pairwise comparisons were performed using the lsmeans function with Satterthwaite approximated *df* in the lsmeans package. The level of significance was defined as $P \le .05$.

3 | RESULTS

3.1 | Study population and measurements

A total of 114 horses were recruited to the study, with a median of 5 horses per trainer (range 1-29 horses). Age in months at the time of measurement was 17.8 ± 1.5, 17.5 (mean ± SD, median). Four horses had been broken for harness within the past 3-6 months, all other horses within 3 months of measurement. A flowchart illustrating the distribution of horses and trials, reasons for exclusion and the number of successful in-hand and track trials is presented in Figure 1. Incomplete data were due to technical issues where the trial for unknown reasons could not be analysed by the system software.

A total of 180 trials from 103 horses were included; 56 males (55 stallions, 1 gelding) and 47 females. Median height at the withers was

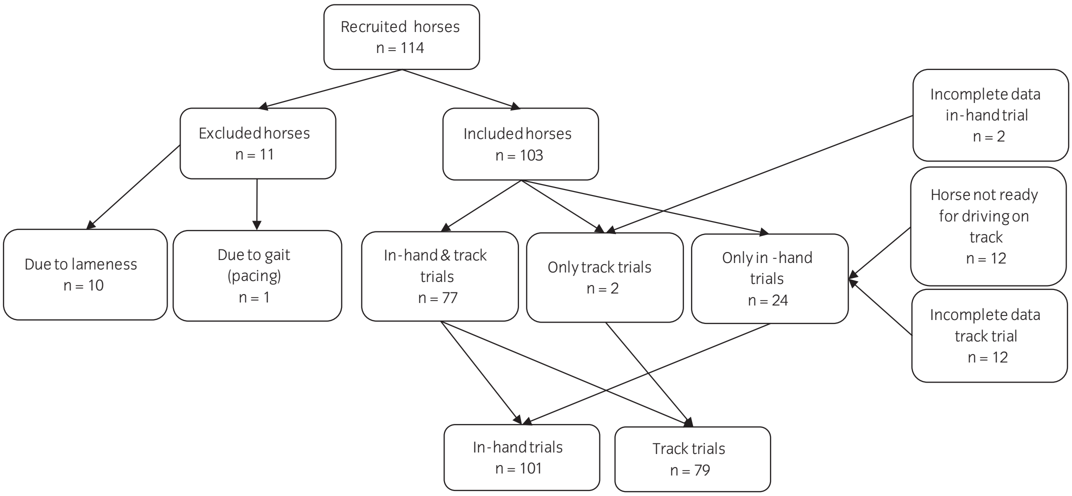

FIGURE 1 Flowchart of number of horses and trials in the study

153 cm (range 139-165 cm), median height at the pelvis was 157 cm (range 145-166 cm) and the median height difference between the withers and pelvis was 4 cm (range 1-9 cm). Data on height were missing for one horse.

Gait was evaluated in-hand before (n = 44) or after (n = 45) driven exercise. For in-hand trials, 37 ± 13.9 strides (mean ± SD) were evaluated, whereas 302 ± 276.2 strides were evaluated for driven trials. In-hand, 20 horses had trials where stride selection was below 25 strides per trial for front and/or hindlimbs. For these horses a minimum of 18 strides were evaluated. Speed in track trials was 5.0 ± 0.6 m/s (18.1 ± 2.3 km/h); speed data were missing for five horses. Horses were driven either on straight (n = 30) or oval (n = 49) tracks. On oval tracks, 30 horses were driven clockwise and 19 anticlockwise. Tracks were either not banked or the horses were driven on a nonbanked part of the track.

3.2 | Descriptive statistics

Of the 103 horses included for analysis, 91 (88%) horses were defined as having asymmetry using the manufacturer-recommended thresholds. None of the 77 horses with both in-hand and track trials were found to be below recommended thresholds for all parameters in both trials. Values for one or more front or hindlimb parameters were above thresholds for 94 of 101 horses (93%) evaluated in-hand. In 79 horses that had data collected during track exercise, 74 horses (94%) had one or more front or hindlimb parameter values defined as above the recommended thresholds. In total, during 180 in-hand and track trials, one or more parameters were above thresholds in 166 trials (92%). For one trial, all standard deviations were lower than their respective parameter mean values (HD_{min}, HD_{max}, PD_{min} and PD_{max}). For all other symmetric and asymmetric trials, at least one asymmetry parameter had a SD greater than its respective mean. An overview of the horses exceeding the recommended thresholds for front and/or hindlimb parameters and in-hand and on the track is detailed in Table 1.

During in-hand trials, contralateral forelimb and hindlimb asymmetry was recorded in 22 horses, and ipsilateral asymmetry in 18 horses. For track trials, 12 horses had contralateral fore and hindlimb asymmetry and 14 horses had ipsilateral asymmetry. An overview of the distribution of asymmetry severity is presented in Figure 2 and distribution of asymmetry categories for individual limbs is presented in Figure S1. In the 71 horses measured both in-hand and driven which had asymmetry in-hand, 14 (20%) horses switched the side of the asymmetry in at least one front or hindlimb parameter between the trials (Figure 3). The remaining 57 horses had asymmetry of the same limb(s) during both trials. Table 2 shows the increase or decrease in asymmetry of horses with same limb asymmetry between in-hand and track trials.

3.3 | Effects of trainer, sex, height and trial mode

For the HD_{min} and PD_{min} models, the residuals deviated from normality and a square root transformation rendered reasonably normally distributed residuals. Females had significantly lower HD_{max} than males (mean difference 1.7 mm, 95% CI 0.18-3.28, P = .03) but other asymmetry parameters were not associated significantly with sex. There were no significant associations between trainer, trial mode (in-hand or track trial, in-hand trial pre- or post-track trial, straight or oval track), height at the withers and height difference between withers and pelvis and asymmetry parameters HD_{min}, HD_{max}, PD_{min} and PD_{max}.

4 | DISCUSSION

Our data demonstrate that a large proportion of Standardbred yearlings in regular training display asymmetry at the trot both when

TABLE 1 Trials with one or more parameters exceeding the asymmetry threshold

Parameter, side of asymmetry	Number of trials with asymmetric parameter	Asymmetry mean (mm)	Range of asymmetry mean (mm)	SD mean (mm)	Number of trials with high variability	Number of trials with moderate variability	Number of trials with low variability
In-hand							
HD_{min}, right	25, 27%	14.2	6.3 to 30.0	22.5	19	6	0
HD_{min}, left	23, 24%	−13.6	−6.1 to −27.9	20.6	11	11	1
HD_{max}, right	21, 22%	11.6	6.1 to 21.8	14.4	10	11	0
HD_{max}, left	17, 18%	−11.6	−6.9 to −16.3	18.1	11	6	0
VS, right	24, 26%	18.1	9.6 to 34.8	N/A	N/A	N/A	N/A
VS, left	26, 28%	−16.2	−9.6 to −28.8	N/A	N/A	N/A	N/A
PD_{min}, right	23, 24%	5.9	3.2 to 11.9	7.3	13	10	0
PD_{min}, left	25, 27%	−6.0	−3.3 to −10.4	9.0	14	11	0
PD_{max}, right	30, 32%	5.2	3.0 to 10.4	6.8	14	14	2
PD_{max}, left	27, 29%	−4.9	−3.1 to −11.4	6.6	12	15	0
Track							
HD_{min}, right	22, 30%	10.2	6.0 to 19.8	13.4	10	12	0
HD_{min}, left	12, 16%	−10.0	−6.2 to −17.9	14.6	7	5	0
HD_{max}, right	24, 32%	11.7	6.4 to 20.2	12.6	10	12	2
HD_{max}, left	17, 23%	−10.4	−6.1 to −15.6	15.7	12	5	0
VS, right	31, 42%	13.4	8.5 to 20.5	N/A	N/A	N/A	N/A
VS, left	18, 24%	−13.8	−9.1 to −21.8	N/A	N/A	N/A	N/A
PD_{min}, right	23, 31%	7.4	3.1 to 27.5	7.8	10	11	2
PD_{min}, left	18, 24%	−7.1	−3.1 to −11.2	6.4	5	11	2
PD_{max}, right	18, 24%	5.1	3.2 to 13.0	4.8	6	11	1
PD_{max}, left	23, 31%	−5.9	−3.1 to −11.2	6.3	9	14	0

Note: Data from asymmetric in-hand trials (n = 94) and asymmetric track trials (n = 74) from 103 horses. Left limb side asymmetry = negative values and right limb side asymmetry = positive values.

Abbreviations: HD_{min}/HD_{max}, difference in head minimum/maximum positions between right and left portions of the stride; VS, Vector sum of mean values of HDmin and HDmax; PD_{min}/PD_{max}, difference in pelvis minimum/maximum positions between right and left portions of the stride; SD, standard deviation; NA, not applicable; Trials with high variability, SD > 120% of parameter mean; Trials with moderate variability, SD > 50% and <120% of parameter mean; Trials with low variability, SD < 50% of parameter mean.

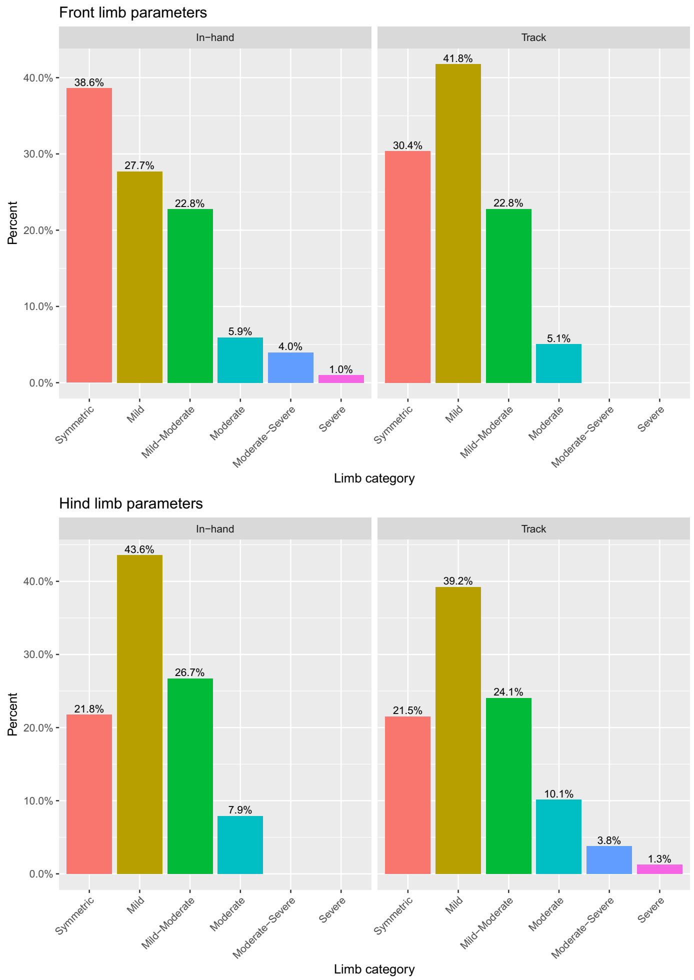

FIGURE 2 Distribution of limb asymmetry categories for combined front or hindlimb parameters. Horses; n = 103, in-hand trials; n = 101, track trials; n = 79. Asymmetry in mm per category for front limb/hindlimb: Symmetric: 0-6/0-3/, mild: 6-12/3-6, mild-moderate: 12-18/6-9, moderate: 18-24/9-12, moderate-severe: 24-30/12-15, and severe: >30/>15

evaluated in-hand and when driven on the track. Our hypothesis that horses would trot more symmetrically when exercised within the constraints of a harness and sulky was not supported by the data we collected. Although no associations between exercise mode and asymmetry parameters were found at the group level, our descriptive data show that evaluating young Standardbreds both in-hand and on the track reveals individual differences in the magnitude of asymmetry and sometimes the side of the asymmetry between the in-hand and track trials.

The large SDs demonstrate substantial within-trial variability, representing a potential source of uncertainty for both visual and objective assessment of movement asymmetry in this population of young horses, also accounting for the main limitation of our study. One of the biggest challenges we encountered in data collection was acquiring acceptable trot-ups in-hand from excitable yearlings. Although this affects our data, it also reflects the clinical reality faced by equine practitioners. We specifically chose to investigate this age group as the results from this study may serve as reference values for expected movement asymmetry in yearling Standardbred trotters. The yearlings were evaluated at the initiation of training to minimise the likelihood that they had accrued training-related injuries. It is not clear whether we are measuring widespread hitherto undetected subclinical, pain-mediated disease or whether the asymmetry documented in this group of young horses represents biological variation which might be different across breeds and disciplines.

In general, horses experiencing unvarying orthopaedic pain show consistent movement asymmetry of the same limb(s) due to offloading of the affected structures through changes in loading and force production.[8] Horses which were subjectively lame at recruitment were excluded. The yearlings found to be asymmetrical in the current study did not undergo further orthopaedic or neurological examination; therefore, we cannot draw any conclusions as to if or to what extent musculoskeletal or neurological disease and/or pain caused

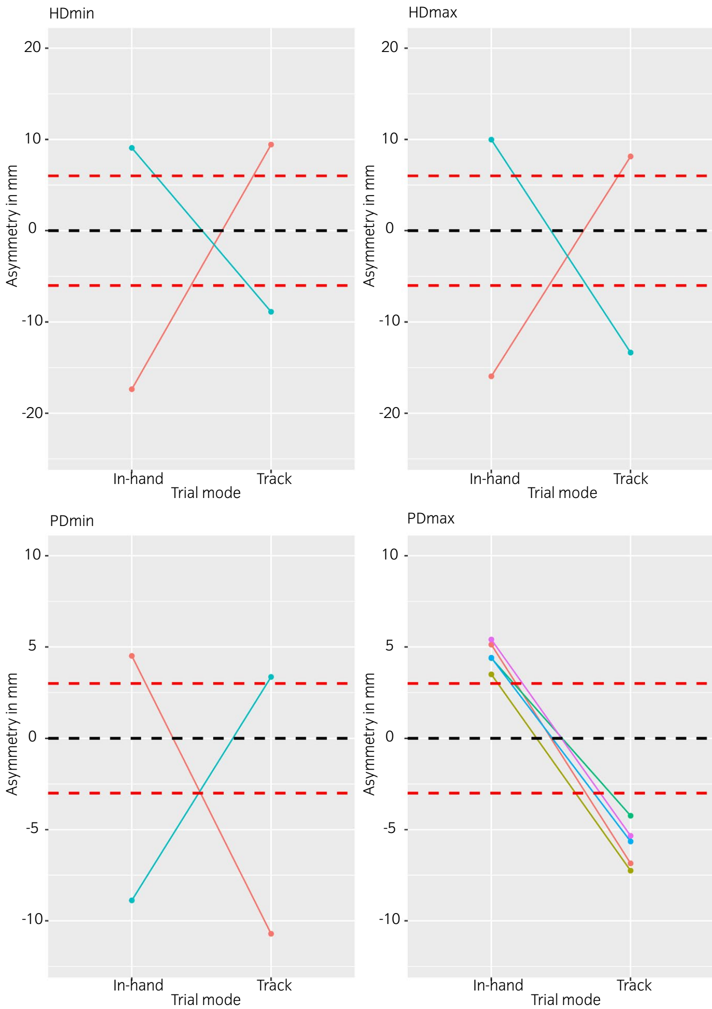

FIGURE 3 Horses (n = 14) that switched sides of limb asymmetry between in-hand and track trials. Each colour in the line plot represents an individual horse. Left limb side asymmetry = negative values and right limb side asymmetry = positive values. Red stippled line denotes the asymmetry threshold for the parameter (HD_{min}/HD_{max} 6 mm, PD_{min}/PD_{max} 3 mm). VS, vector sum of mean values of HD_{min} and HD_{max}; HD_{min}/HD_{max}, difference in head minimum/maximum positions between right and left portions of the stride; PD_{min}/PD_{max}, difference in pelvis minimum/maximum positions between right and left portions of the stride. Data for VS not shown (n = 3)

the measured asymmetry. The data collected and presented here are aimed at describing the prevalence and magnitude of movement asymmetry in young Standardbreds in training, and not its underlying causes. One might argue that it is improbable that almost all yearlings in a cohort could be affected by orthopaedic pain, especially at such an early age and prior to any substantial training. The young age of the horses in this study may influence the measurements. Varying degrees of locomotor incoordination and inconsistent asymmetric movement were observed during subjective assessment of the horses. As in young children,[9] stabilisation of movement frequency and pattern might increase with maturation and increased neuromuscular control in young horses. The horses in this study were not specifically assessed regarding potential ataxia relating to neurological disease. Although the incidence of clinical signs related to cervical vertebral disease is higher in young horses,[10] Standardbreds are less likely to be affected than other breeds such as Thoroughbreds.[10,11]

Horses were included in this study on a presumption of being ‘fit to train’, implying ‘soundness’. It is debatable whether ‘soundness’ as assessed by non-veterinary professionals is an appropriate criterion for selecting nonlame horses.[12] Keeping in mind that ‘sound’ horses are not necessarily expected to be perfectly symmetrical, our cohort nevertheless show mean asymmetries close to those from horses with induced lameness[13] and horses with clinical lameness that responded to diagnostic analgesia.[14,15] In our study, objective asymmetry data were collected from all yearlings that fulfilled the recruitment criteria at the respective training yards, avoiding any intentional selection bias, for example, by the trainer selecting horses that were suspected to have a locomotor issue. The yearlings had recently been introduced to harness and light training pulling a driver and sulky. This adjustment may influence the locomotion pattern, however, it does not seem to represent a systematic effect, as horse asymmetry either

TABLE 2 Increase or decrease in limb asymmetry from in-hand to track trials

Parameter, side of asymmetry	In hand trial: No. of horses with values above recommended thresholds in-hand	Track trial: No. of horses with values above recommended thresholds in hand and during track exercise with an increase in asymmetry from in-hand to track trial	No. of horses with values above recommended thresholds in hand and during track exercise with a decrease in asymmetry from in-hand to track trial	No. of horses with increased values in hand which decreased to below recommended thresholds during track trial
HD_{min}, right	19	3	4	12
HD_{min}, left	15	3	4	8
HD_{max}, right	17	8	3	6
HD_{max}, left	11	1	2	8
VS, right	16	5	6	5
VS, left	16	5	5	6
PD_{min}, right	19	7	4	8
PD_{min}, left	18	6	4	8
PD_{max}, right	19	7	3	9
PD_{max}, left	18	7	2	9

Note: Change in asymmetry of horses (n = 57) that were classified as asymmetrical based on recommended thresholds for each parameter during in-hand trials and did not switch the side of asymmetry between in-hand and track trial.

Abbreviations: HD_{min}/HD_{max}, difference in head minimum/maximum positions between right and left portions of the stride; PD_{min}/PD_{max}, difference in pelvis minimum/maximum positions between right and left portions of the stride; VS, vector sum of mean values of HD_{min} and HD_{max}.

increased or decreased when driving on the track. Consideration should also be given to the effect of the handler of the horse during in-hand trials. Handlers as well as drivers of the horses differed between the yards, and this could potentially influence the measurements. Although a firm surface footing was available for in-hand trials at all yards, material composition was not identical, and weather conditions influenced the firmness of both in-hand and track surfaces. This may have influenced the collected gait data. The material composition and maintenance routines of the trotting tracks in this study were in all cases similar. The focus on compacting the material to create a solid substrate that will allow both horse and sulky to move easily over the surface make these types of tracks less variable between each other than many other horse sport surfaces.[16]

Movement asymmetries in Standardbreds were studied in the early 1980s by use of a novel high-speed cinematographic technique.[17–21] In one study[21] asymmetries in the locomotion patterns of younger Standardbreds were proposed to be a further manifestation of congenital laterality or sidedness. It is not currently known whether movement asymmetry increases, decreases or stabilises with age and training. In 16 Swedish Standardbred trotter yearlings followed over 2.5 years, vertical displacement asymmetry increased during intensified training periods.[22] Alternatively, in a group of French Standardbred horses, younger horses were more asymmetrical across various parameters than older horses.[23] However, without unexercised control groups, it is not possible to differentiate an effect of age from the effect of training in horses. In young horses, the effect of growth on locomotion patterns must also be considered. In our study, neither height at the withers nor the individual height difference between withers and pelvis, calculated as a potential proxy measure of intensity of growth or growth spurts, were significantly associated with asymmetry variables.

Our data are similar to those of Rhodin et al,[6] where 72.5% of 222 'owner-sound' Warmblood riding horses of different ages had at least one asymmetry parameter above the same asymmetry thresholds applied in our study. Although the magnitude of mean asymmetries of the riding horses matched well with the Standardbreds in our study, the trials in the cited study were included for analysis only if the standard deviation value was below that of its respective trial mean. Objective studies of movement asymmetry have included 'owner-sound' Warmblood riding horses,[6,24,25] polo ponies in training[26] and Thoroughbreds.[27] A shared finding in these studies is that most horses in regular exercise perceived by their owners/riders/trainers as sound show substantial asymmetries during in-hand straight line trot.

We found no associations between asymmetry variables and in-hand vs track trials or straight vs oval tracks. However, as there was large individual variation between in-hand and track trials and the possible influence of young age on the results, future studies looking at associations between track design and gait in an older cohort of horses would be interesting. The significant effect of sex on the HD_{max} parameter was small and with relatively wide confidence intervals and it is of questionable biological significance. Further studies are needed to replicate this finding, and if so, determine what clinical importance it may have.

In the current study, we used the predetermined, manufacturer-recommended thresholds to define and describe the distribution and magnitude of asymmetry. As has been pointed out by others,[27] the value in applying thresholds may not lie in making a dichotomous assessment of whether a horse is 'diseased' or not, as this can only be decided by a complete clinical evaluation; rather, thresholds might aid in removing clinical bias. It could be argued that it would be better not to apply thresholds to describe the findings in our study to avoid 'mislabelling' or misinterpreting the health status of these horses. However, thresholds allow for easier comparison of the changes in asymmetry between in-hand and track measurements and are also in common use with the measurement system applied in this study for both clinical and research purposes.

Our study adds to the scientific knowledge base on movement asymmetries in horses, and specifically young Standardbred trotters. Movement asymmetry was prevalent in our cohort of Standardbred trotter yearlings, with considerable individual variation between trials. Within-trial variability was high, influencing the reliability of the data. Future studies with a longitudinal design are required to provide information on changes in asymmetry over time and to explore potential associations between measured movement asymmetry and the development of clinical lameness.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST

No competing interests have been declared.

AUTHOR CONTRIBUTIONS

M. Rhodin and E. Hernlund designed the study and A. Kallerud, E. Hendrickson, M. Hammarberg, M. Rhodin and E. Hernlund collected the data. A. Kallerud, E. Persson-Sjodin and E. Hernlund performed data analysis and statistics. A. Kallerud and C. Fjordbakk wrote the manuscript. All authors contributed to data interpretation and revising the manuscript, as well as read and approved the final manuscript.

ETHICAL ANIMAL RESEARCH

The study was approved by the ethics committee at the Faculty of Veterinary Medicine, Norwegian University of Life Sciences (approval number 14/04723-47).

OWNER INFORMED CONSENT

A signed consent form was obtained from trainers of all horses included in the study.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publo n/10.1111/evj.13302.

DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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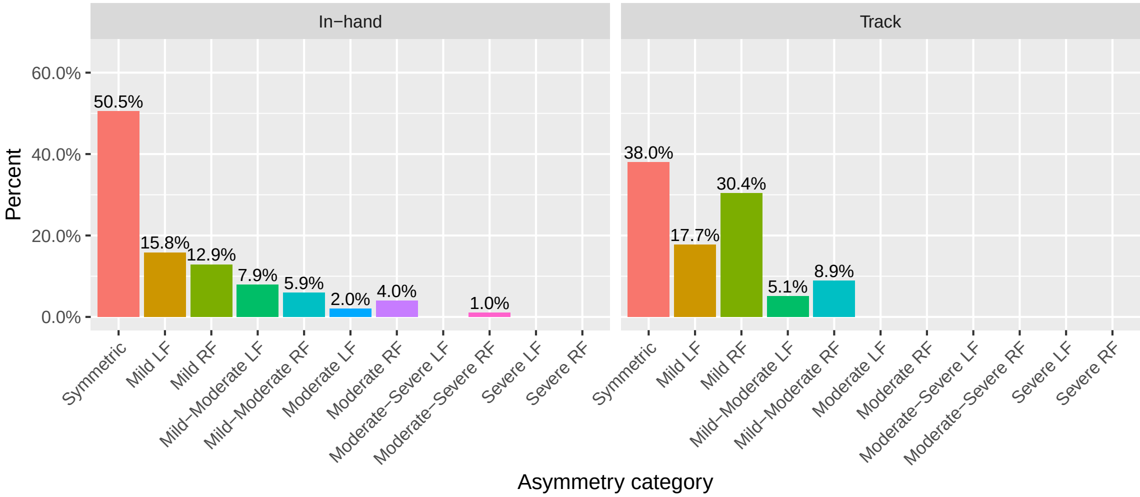
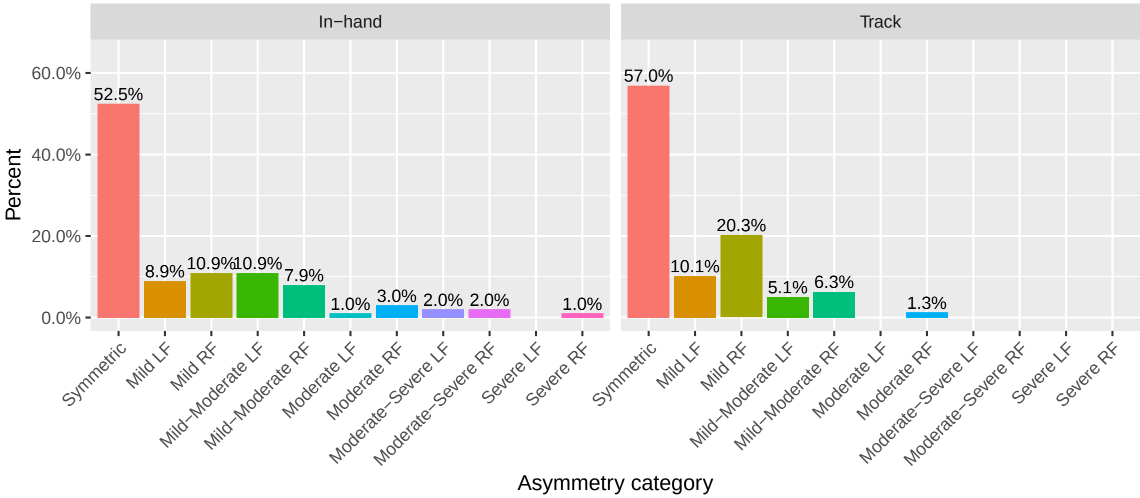
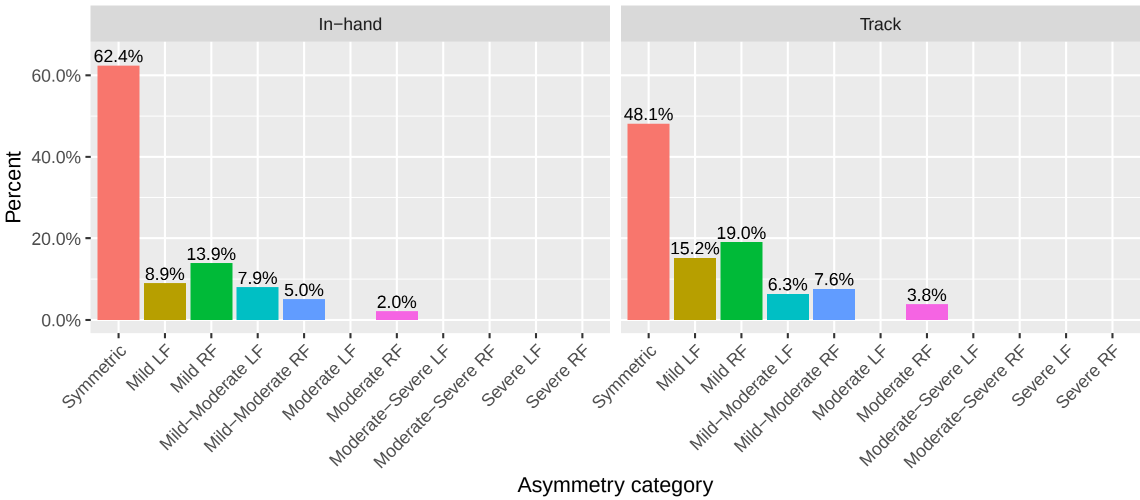
Figure S1: Vector sum values

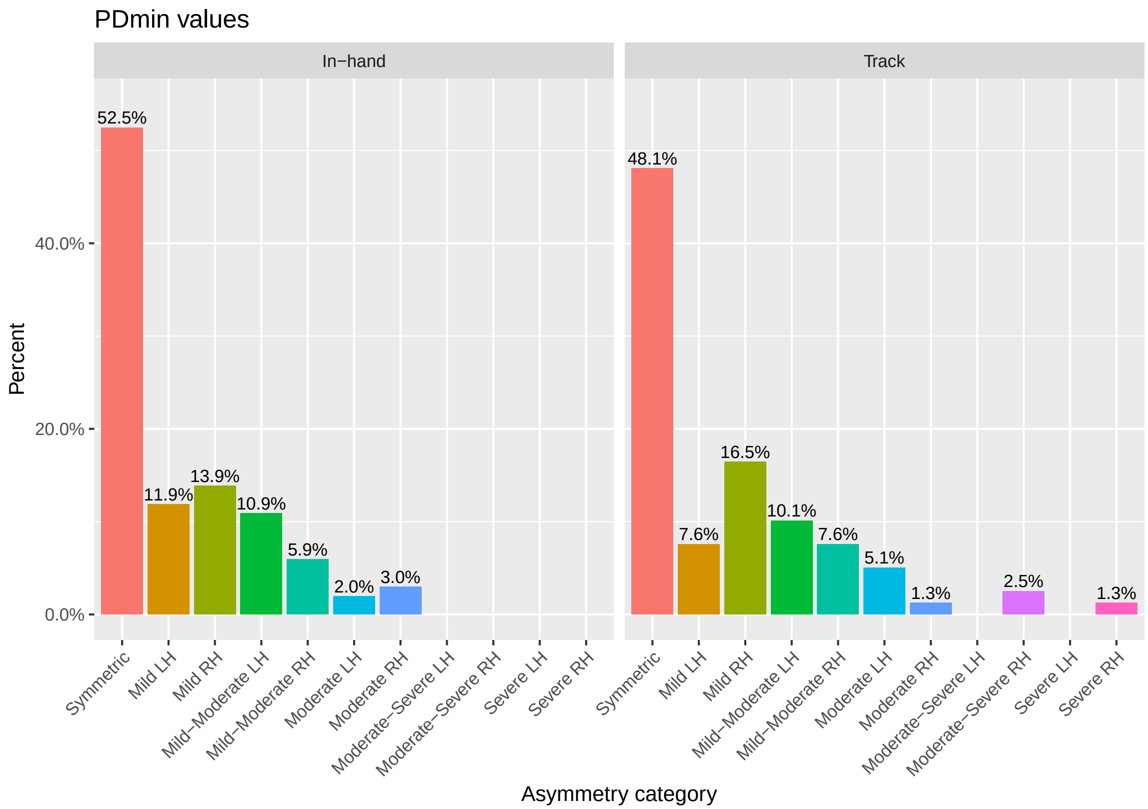


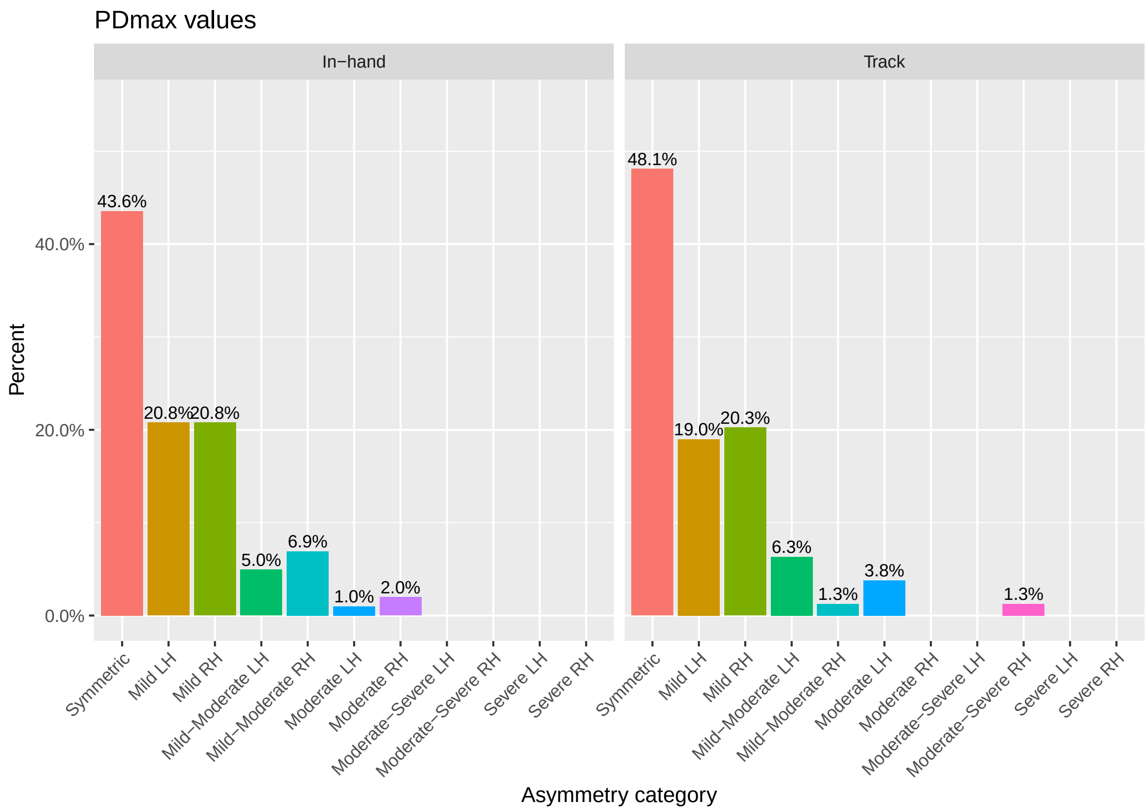
HDmin values



HDmax values




PDmin values
In−hand
Track
Percent
0.0%
20.0%
40.0%
52.5%
11.9%
13.9%
10.9%
5.9%
2.0%
3.0%
48.1%
7.6%
16.5%
10.1%
7.6%
5.1%
1.3%
2.5%
1.3%
Symmetric
Mild LH
Mild RH
Mild−Moderate LH
Mild−Moderate RH
Moderate LH
Moderate RH
Moderate−Severe LH
Moderate−Severe RH
Severe LH
Severe RH
Asymmetry category


PDmax values
In−hand
Track
Percent
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20.0%
40.0%
43.6%
20.8%
20.8%
5.0%
6.9%
1.0%
2.0%
48.1%
19.0%
20.3%
6.3%
1.3%
3.8%
1.3%
Symmetric
Mild LH
Mild RH
Mild−Moderate LH
Mild−Moderate RH
Moderate LH
Moderate RH
Moderate−Severe LH
Moderate−Severe RH
Severe LH
Severe RH
Asymmetry category

Figure S1: Distribution of limb asymmetry parameters for all horses.
Horses; n = 103, in-hand trials; n = 101, track trials; n = 79. LF = Left front limb, LH = Left hind limb, RF = Right front limb, RH = Right hindlimb. Asymmetry in mm per category for VS/HDmin or HDmax/PDmin or PDmax: Symmetric: 0-8.5/0-6/0-3, mild: 8.5-17/6-12/3-6, mild-moderate: 17-25.5/12-18/6-9, moderate: 25.5-34/18-24/9-12, moderate-severe: 34-42.5/24-30/12-15, severe: >42.5/>30/>15. VS = Vector sum of mean values of HDmin and HDmax, HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride, PDmin/PDmax = difference in pelvis minimum/ maximum positions between right and left portions of the stride.

Table S1: Results of mixed model ANOVA analysis.

Analysis of Deviance Table: Type II Wald F tests with Kenward-Roger degrees of freedom

	HDmin				**HDmax**				**PDmin**				**PDmax**			
Predictors	***F***	***Df***	***Df.res***	***Pr(>F)***	***F***	***Df***	***Df.res***	***Pr(>F)***	***F***	***Df***	***Df.res***	***Pr(>F)***	***F***	***Df***	***Df.res***	***Pr(>F)***
Mode	1.82	3	89.44	0.15	0.68	3	100.76	0.57	2.14	3	76.47	0.10	0.33	3	81.01	0.80
Sex	0.21	1	92.09	0.64	4.82	1	91.02	**0.03***	0.62	1	94.88	0.43	0.60	1	95.12	0.44
Height at withers	2.06	1	94.77	0.15	0.02	1	96.62	0.90	0.01	1	79.06	0.92	3.60	1	82.41	0.06
Height difference withers - sacrum	0.19	1	95.03	0.66	2.82	1	94.93	0.10	0.71	1	94.54	0.40	0.44	1	95.16	0.51

Number of observations: 180
Number of horses: 103
Number of groups: 13

***Post hoc test results for effect of sex of horse on HDmax: In females, overall HDmax asymmetry is reduced by 1.7 mm. Pairwise comparison, degrees-of-freedom method: Satterthwaite**

Estimate	**SE**	**Df**	**t-ratio**	**p-value**	**95% CI**
1.73	0.78	90	2.22	0.03	0.18, 3.28

Paper II

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GENERAL ARTICLE

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Non-banked curved tracks influence movement symmetry in two-year-old Standardbred trotters

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Abstract

Background: Little is known regarding how trotting through curves affects locomotion symmetry in Standardbred trotters.

Objectives: To investigate differences in objectively measured Standardbred trotter vertical motion symmetry between straight and non-banked, curved sections of oval trotting tracks during exercise warm-up, using a wireless inertial measurement unit (IMU) system.

Study design: Cross-sectional, observational study.

Methods: Sixteen horses were included. Mixed models were used to assess associations between symmetry, track segment (straight vs curve) and stride duration.

Results: Significant results for forelimb parameters were dependent on interactions between track segments and stride duration. At mean stride duration (0.611 second), during the curved track segment horses showed a lower maximum vertical position of the head after push-off of the outside forelimb (estimate −2.3 mm, $P < 0.0001$, 95% CI −1.7 to −2.9) and higher minimum vertical position of the head during stance of the outside forelimb (estimate −1.8 mm, $P < 0.0001$, 95% CI −1.2 to −2.5) compared to straight track, mimicking outside forelimb impact and push-off asymmetry during track curves. For hindlimb parameters, during the curve there was a decreased downward motion of the pelvis during outer hindlimb stance (estimate−0.7 mm, $P < 0.0001$, 95% CI −0.4 to −1.0), mimicking outside hindlimb impact asymmetry.

Main limitations: Horses were evaluated going in one direction only on the track (clockwise).

Conclusions: Systematic differences between straight and curved track segments were found but did not fully correspond to previously described findings for horses lunged in circles. Effect sizes were overall small. Data in our study were collected from horses trotting on 1000 m tracks with curve radii of 80-85 m. On non-banked tracks of this size, collecting IMU symmetry data at jogging speeds without distinguishing between straight and curved parts is unlikely to adversely affect clinical decision-making.

KEYWORDS
horse, asymmetry, circle, IMU, turn

1 | INTRODUCTION

Standardbred trotters are raced and often trained on oval tracks and therefore regularly trot through curves. Evaluating trotters (and pacers) during oval track exercise is recommended in several veterinary textbooks as a valuable routine part of the lameness work-up.[1,2] Assessing movement asymmetries in horses on a circle is challenging[3]; during lungeing horses cope with the circular track in a way that induces known vertical motion asymmetries of the head and pelvis, such as a reduced upward push of the outer hindlimb with a concurrent smaller descent on the inner hindlimb.[4,5] In a model of induced lameness, moving on a circle influenced both the pattern and the magnitude of vertical movement symmetry parameters obtained using a horse-mounted inertial measurement unit (IMU) system.[6] IMU systems have the capacity to accurately describe (a)symmetric locomotion[7] and are increasing in popularity amongst equine veterinarians as an aid in lameness examinations. However, while there are multiple studies[4–6,8–12] describing the effect of circling on objectively measured locomotion symmetry in riding horses, little knowledge exists regarding the effect of curves on locomotion symmetry in Standardbred trotters. A deeper understanding of how curves, as well as the use of common harness tack such as an overcheck, affect the normal motion pattern is of importance for subjective gait evaluation as well as for clinicians incorporating objective symmetry measurements during track exercise as part of their routine lameness work-up in this breed.

The aims of our study were to (a) describe the difference in objectively determined vertical movement symmetry of the head and pelvis in Standardbred trotters while trotting at jogging speed on the straight vs the curved part of a non-banked oval track, and (b) to explore the effect of stride duration on the degree of symmetry in these horses. Our hypothesis was that trotting through curves would induce a consistent change in symmetry patterns, as previously seen in riding horses being lunged.

2 | MATERIALS AND METHODS

2.1 | Study design and data collection

Standardbred trotters in their second year of training (ie approximately 2 years of age) were recruited to the study; these horses were enrolled in a larger, ongoing longitudinal study. Data on locomotion symmetry from their first training season as well as detailed information on cohort recruitment have been reported previously.[13] Data collection for the current study was conducted within the time period May – October 2018 at three training yards in Norway and Sweden. Included horses were in regular training which entailed oval track trotting exercise. Movement symmetry data was collected using an IMU system (Lameness Locator® by Equinosis LLC) as described below.

On the day of data collection, one of the investigators (A.S.K.) performed a general physical examination of all horses prior to exercise and measured the height at the withers and at the tubera sacrale (pelvis height). The horses wore their regular trotting harness and additional gear such as boots as per the trainers' preference. None of the included horses wore an overcheck, limb hobbles, head poles or side poles. Horses were instrumented with IMUs on the poll, pelvis and right front pastern as previously described.[14] To reduce interference from the back strap of the harness as well as to prevent sensor loosening during exercise, the pelvis sensor was fastened with extra strong double-sided adhesive tape (Teppeteip, Clas Ohlson) and standard-issue duct tape, then covered with additional adhesive tape (Snøgg Animal Polster, Norgesplaster AS). To prevent rotation of the neoprene pastern wrap, two rounds of elastic, adhesive cloth tape (Norbind, Norgesplaster AS) was applied to secure the wrap to the limb of the horse.

The IMU sensors each contain an accelerometer, gyroscope and magnetometer, and record the vertical acceleration of the head and torso and the angular velocity of the right front limb, sampling at 200 Hz with 8-bit digital resolution. Bluetooth technology provided wireless data transmission between the IMU sensors and a computer tablet running the proprietary system software. During data collection, the driver of the horse carried a small backpack with the receiving tablet to ensure continuous connection to the horse-mounted sensors. The driver also wore a GPS device (Polar M450, Polar Electro) that registered speed, distance and route of the training session.

IMU data were collected as horses were driven at a trot around the non-banked part (ie the flat, outer part) of the oval tracks at their regular warm-up speed in a clockwise direction of travel. Horses were evaluated on the track at their respective yards. All tracks were regularly maintained packed dirt tracks. Information on track length and curve radius was either collected from official sources,[15] from the trainer, or determined from the GPS data collected during trials. For the latter, curve radius (r) was calculated by the formula $r = \frac{circumference}{2\pi}$ where circumference was defined as 2x the GPS recorded curve distance. A representative exercise trial was defined as trotting through a minimum of one complete round of the oval track, resulting in data from a minimum of two straight long sides and two curves. As exercise distance and number of trials collected per horse varied between horses and trainers, the first representative trial collected for each horse was used for data analysis. Only one day of data collection was performed per horse.

2.2 | Data processing

The IMU system measures acceleration along the vertical axis of the IMU sensor. Using a double integration process the system software then calculates the minimum and maximum head and pelvic height differences between the right and left sides for every stride in the trial.[14] This results in four symmetry parameters; head minimum (HDmin) and head maximum (HDmax) difference, and pelvis minimum (PDmin) and pelvis maximum (PDmax) difference, describing the right-left step symmetry of the horse in millimetres (mm). For example, the HDmin difference is calculated as the minimum head height during right forelimb stance minus the minimum head height during left forelimb stance, while the HDmax difference is calculated as the maximum head height before right forelimb weight-bearing minus the maximum head height before left forelimb weight-bearing. The same principle is used for the movement of the pelvis to calculate PDmin and PDmax. A parameter value of 0 mm indicates perfect symmetry, with no difference in symmetry between the two halves of a stride. As defined by the system software, asymmetries indicating a right limb asymmetry were recorded as positive values, whereas asymmetries indicating a left limb asymmetry were recorded as negative values. Further descriptions of parameter calculations have been published elsewhere.[14]

Default settings (Lameness Locator® 2017 software v1.2r) were used for stride selection from each trial. Raw data for the selected strides was exported from the system software and processed in MATLAB (Release 2019a, The MathWorks Inc).[16] A custom-written MATLAB-script was used to plot the Y- and X- components of the pelvis sensor magnetometer as well as pelvic sensor yaw-data. To determine when the horse was travelling in a straight line and when the horse was going through a curve a visual inspection of these components was performed, focusing on whether the data tracings were horizontal or sloping, indicating a constant or changing direction of motion. Consistent segments with good agreement between yaw- and magnetometer data were extracted for use. No thresholds were used for stride selection. An example of the stride selection process is provided in Figure S1. Outlier removal for head parameters was performed, where each stride value was compared to the average value of all strides using Mahalanobis distance; strides where the parameter value exceeded three standard deviations from the mean (for the respective parameter) were removed. Trials were excluded from data analysis when technical difficulties with the IMU system such as sensor loosening during exercise or incomplete data acquisition resulted in inadequate data recordings. For descriptive results symmetry means, standard deviations, medians and ranges were calculated. Horse symmetry was further classified based on published thresholds for asymmetry in Thoroughbred racehorses.[17] These suggested thresholds are based on data from a study utilising a different system than the one used in the current study; comparison of these two systems show existing but small differences in symmetry value magnitude.[18] Horses were classified as asymmetric if they had one or more mean parameter values above ±14.5 mm (HDmin, HDmax) or ±7.5 mm (PDmin, PDmax) on the straight part of the track. Furthermore, asymmetric horses were divided into categories depending on which parameter was above threshold value, as well as which limb was affected; eg a horse with a mean HDmin value more positive than 14.5 mm would be classified as having right forelimb asymmetry for the HDmin parameter; conversely, a horse with a mean PDmin value more negative than −7.5 mm would be classified as being left hindlimb asymmetric for the PDmin parameter etc.

2.3 | Model building

Data were analysed using R open software (Version 4.0.06, The R Foundation for Statistical Computing).[19] Two-tailed hypothesis testing was performed by creating mixed models using the lmer function in the lme4 package. To evaluate the effect of the curve on vertical movement symmetry, four models with each symmetry parameter defined as outcome, were created using stride level data where signs were kept (negative indicating left and positive indicating right). The entered fixed effects were track segment (straight or curve) and stride duration, as well as two-way interactions of these. Stride duration was included as a proxy for speed (increase in stride duration corresponding to a decrease in speed). Horse was entered as a random effect to adjust for clustering. For all models, normality of residuals was checked using q-q plots and homoscedasticity by plotting the residuals against the fitted values. Evaluation of statistical significance was made using type III p-values generated by a Wald F-test with Satterthwaite approximated *df* using the ANOVA function in base R. The level of significance was defined as $P < 0.05$. Full models were reduced to contain only significant main effects and interactions. Post-hoc pairwise comparisons were performed using the emmeans function and simple slopes for interactions were calculated using the emtrends function from the emmeans package with Kenward-Roger approximated *df*. Estimated marginal means were computed at stride duration grand mean, across all horses, trials and selected strides. P-values were adjusted by Tukey's method.

3 | RESULTS

3.1 | Descriptive findings

Trials from 38 horses were evaluated and 16 horses were included for analysis. Included horses were trained by four different trainers, two of which were based in Norway and two in Sweden. The median number of horses per trainer was three (range 1-9; two trainers had only 1 horse included, two trainers had 5 and 9 horses, respectively). The horses were trained on three different tracks; two training tracks and one official racing track. All tracks were 1000 m in length. The curve radius for training track A was approximately 80 m (length of curve = approximately 250 m), and for training track B and the official racing track approximately 85 m (length of curve = approximately 270 m). A flowchart of the number of included and excluded horses, reasons for exclusion and the number of horses exercised on the different tracks is presented in Figure 1.

Included horses comprised nine males (four stallions, five geldings) and seven mares. Median height at the withers was 160 cm (range 154-167 cm) and median height at the pelvis was 160 cm (range 155-166 cm). Data on height was missing for two horses. Median age was 28.0 months (range 23.4-29.9 months). Mean speed during the trials was 5.7 ± 0.7 m/s (mean ± SD). Mean stride duration in seconds ± SD was 0.611 ± 0.031 (straight track segments: 0.611 ± 0.032; curved track segments: 0.612 ± 0.031). A mean of 152 ± 70 strides was evaluated per horse (straight track segments: 143 ± 71 strides, curved track segments: 161 ± 70 strides). A median of three separate straight parts and three separate curved parts (range 2 – 5 for both track segments) of the track were analysed per

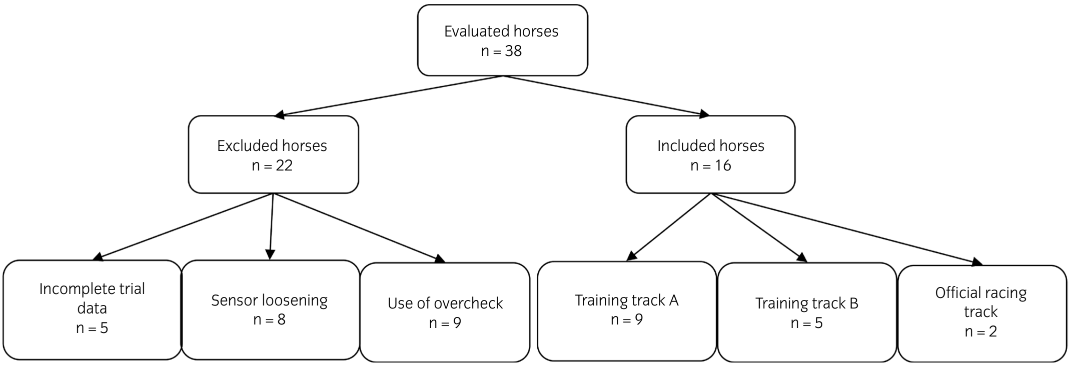

FIGURE 1 Flowchart of included/excluded horses and distribution of tracks

horse. Descriptive data for straight track segments are detailed in Table 1. Individual changes in symmetry values between straight and curved track segments are illustrated in Figure 2.

For individual horse parameter means for straight and curved track segments see Data S1. When implementing threshold values, seven horses were classified as symmetric and nine horses as asymmetric; six of the asymmetric horses had mean values above threshold for only one parameter. The remaining three horses had either contralateral asymmetry, ipsilateral asymmetry or asymmetry in one limb only but was above threshold for two parameters in the same limb. More details on the distribution of limb asymmetry is provided in Table S1 and Figure S2.

3.2 | Model results

Residuals were normally distributed in all models, and untransformed data were used. The four models demonstrated significant effects on fore- and hindlimb symmetry parameters as outlined below; estimated marginal means and pairwise comparisons are presented in Table 2 and full ANOVA results are listed in Data S2. Interaction plots for all parameters with significant interactions (HDmax, HDmin, PDmax) are illustrated in Figure 3.

3.2.1 | Forelimb parameters

For HDmax there was a significant two-way interaction between track segment (straight vs curve) and stride duration ($P < 0.001$). In the post-hoc pairwise comparison (Table 2), at group mean stride duration (0.611 second), the effect of the curve compared to the straight track was −2.3 mm ($P < 0.001$, 95% CI −1.7 to −2.9), indicating a relatively lower maximum vertical position of the head after push-off of the outside forelimb during curves. There was a negative linear relationship between stride duration and symmetry during curves (slope: −49.3 mm per s, SE 9.5, 95% CI −67.9 to −30.7) suggesting a lesser height reached by the head after outside forelimb push-off in the curve with increasing stride duration. The slope value demonstrates the change in symmetry in mm per 1 second change in stride duration; −49.3 mm per second corresponds to a change in symmetry of −4.93 mm per 100 ms change in stride duration (eg a change in stride duration from 0.5 to 0.6 second). On the straight track segment there was a positive but non-significant linear relationship between stride duration and symmetry (slope 6.0 mm per s [0.6 mm per 100 ms], SE 9.3, 95% CI −12.2 to 24.1).

For HDmin there was a significant two-way interaction between track segment and stride duration ($P < 0.001$). In the post-hoc pairwise comparison, at group mean stride duration (0.611 second), the effect of the curve compared to the straight track was −1.8 mm ($P < 0.001$, 95% CI −1.2 to −2.5), indicating a relatively higher minimum vertical position of the head during stance of the outside forelimb during curves. During the curve, a negative linear relationship (slope −39.6 mm per s (−3.96 mm per 100 ms), SE 10.5, 95% CI −60.1 to −19.1) was found between stride duration and HDmin symmetry, indicating a lesser downward motion of the head during outer forelimb stance phase with increasing stride duration. On the straight, a positive but non-significant linear relationship (slope 2.3 mm per s (0.23 mm per 100 ms), SE 10.2, 95% CI −17.8 to 22.3) was found between HDmin symmetry and stride duration.

3.2.2 | Hindlimb parameters

For PDmax the same two-way interaction as for the forelimb parameters was significant in the main ANOVA output (track segment and stride duration, $P = 0.003$), however, in the post-hoc analysis no significant difference was detected in symmetry between curved and straight track segments (for post-hoc analysis values see Table 2). For stride duration, there was a positive linear relationship with PDmax symmetry for both curved segments (slope 29.1 mm per s (2.91 mm per 100 ms), SE 4.1, 95% CI 21.1 to 37.1) and straight segments (slope 17.2 mm per s (1.72 mm per 100 ms), SE 4.0, 95% CI 9.3 to 25.0), suggesting an increase in the upward vertical movement of the pelvis after outer hindlimb push-off with increasing stride

TABLE 1 Mean, SD, median and range of symmetry for all 16 horses

Parameter	Side of asymmetry	Number of horses	Mean	SD	Median	Range
HDmax	All trials	16	6.2	NA	−1.4	−12.1 to 61.1
	Left	8	−6.5	2.7	−5.7	−3.3 to −12.1
	Right	8	18.8	19.7	12.9	0.6 to 61.1
HDmin	All trials	16	5.1	NA	2.7	−17.8 to 43.2
	Left	5	−8.2	6.5	−8.4	−0.7 to −17.8
	Right	11	11.2	12.3	8.2	0.2 to 43.2
PDmax	All trials	16	−2.8	NA	−2.6	−14.2 to 7.9
	Left	11	−5.9	4.4	−5.4	−0.6 to −14.2
	Right	5	4.0	2.6	3.2	0.8 to 7.9
PDmin	All trials	16	−1.2	NA	−1.3	−15.4 to 18.4
	Left	11	−4.7	4.7	−2.9	−0.8 to −15.5
	Right	5	6.5	7.0	4.2	1.0 to 18.4

Note: Trial values (in mm) from the straight part of the track. Side of asymmetry: Left = parameter mean <0 mm; right=parameter mean >0 mm.

Abbreviations: HDmin/HDmax, difference in head minimum/maximum positions between right and left portions of the stride; PDmin/PDmax, difference in pelvis minimum/maximum positions between right and left portions of the stride; NA, not applicable; SD, standard deviation.

duration, with a steeper slope for the curved track segment than the straight.

For PDmin there was no significant interaction between track segment and stride duration; of the two main effects track segment was significant ($P < 0.001$) whilst stride duration was not ($P = 0.9$). In the post-hoc pairwise comparison the effect of curve compared to straight track was −0.7 mm ($P < 0.001$, 95% CI −0.4 to −1.0), indicating a decreased downward motion of the pelvis during outer hindlimb stance on the curved track.

4 | DISCUSSION

Our cohort of two-year-old Standardbred trotters showed significant systematic differences in movement symmetry between trotting exercise on straight vs non-banked curved parts of an oval track, however, these differences are only in partial agreement with changes seen in lunged horses. Our hypothesis is therefore only partially supported by our findings. Horses being lunged on a 6-10 m diameter circle lean inward[8,9] and body lean increases with decreasing circle radius as well as increasing speed.[11] Starke et al. reported that inside forelimb lameness may be mimicked on the circle through a mild downward head nod during the outside forelimb stance phase,[5] representing a HDmin-type (impact) asymmetry of the inner forelimb. However, in a larger sample of lunged horses, Rhodin et al. reported that the majority of horses had a curve-induced increased downward nod during inside forelimb stance (mimicking outside forelimb impact asymmetry),[4] while a lesser number of horses in the same study showed an opposite pattern, with apparent inside forelimb impact asymmetry on the lunge.[4] Some of the discrepancy of the reported results for the effect of circling on forelimb symmetry may stem from different measurement systems being used, where Starke et al. utilised a system that corrects for the tilting of the sensor in relation to the true, global vertical through the gravitational acceleration, while the system being used in the study by Rhodin et al. and in the current study does not.[18] In our Standardbreds navigating curves, for the parameter HDmin there was a decreased downward motion of the head during outer forelimb stance (mimicking outside forelimb impact asymmetry), in accordance with findings in lunged horses.[4] For HDmax, during curves the Standardbreds in our study showed a decrease in push-off on the outside forelimb, while a decrease in inside forelimb push-off has been reported in lunged riding horses.[4]

One recurrent finding in lunged and ridden horses is that measured asymmetry when travelling on a circular path may mimic inside hindlimb lameness.[4–6,11] This occurs as the pelvis drops to a lower minimum position during the stance phase of the outside hindlimb and movement of the inside tuber coxae increases,[11] possibly due to the horse having to flex the inside hindlimb more and/or lift it higher in order to facilitate ground clearing during the swing phase of the inside hindlimb,[11] mimicking a PDmin-type (impact) asymmetry of the inner hindlimb. In our study, the opposite was found, with PDmin asymmetry manifesting in the outer hindlimb; there was a reduced downward vertical movement of the pelvis during the outer hindlimb stance phase, mimicking an outside hindlimb impact asymmetry during the curve. For PDmax measurements, a decrease in the upward motion of the pelvis on the outside hindlimb after push-off has been reported in lunged riding horses,[4] mimicking outside hindlimb push-off lameness. In our study, there were no significant differences in PDmax symmetry detected during post-hoc analysis between curved and straight track segments. In our study, there are highly significant differences between straight and curved track segments for most parameters, however, the effect sizes are overall small.

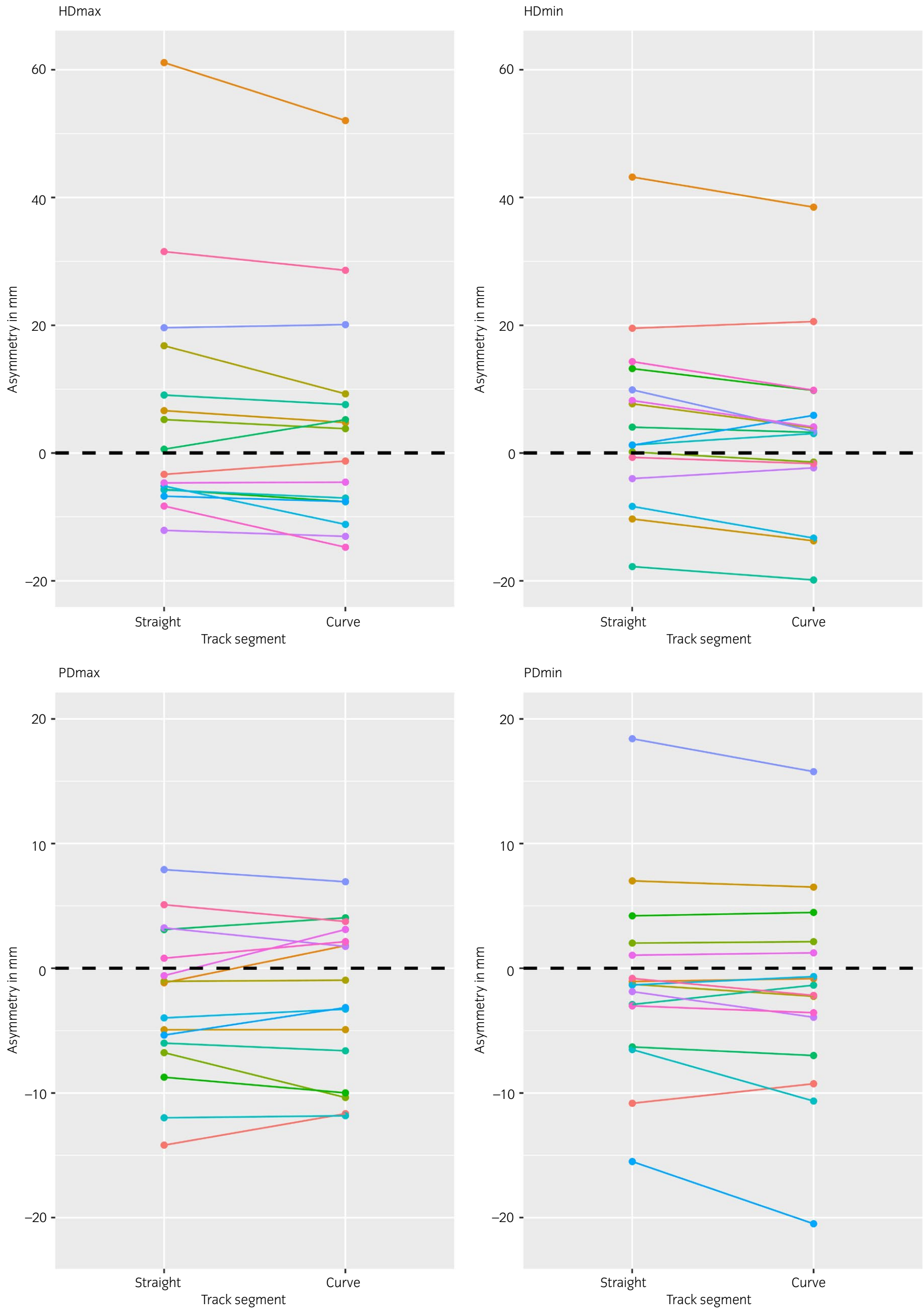

FIGURE 2 Line plot of symmetry values on straight and curved track segments. Data for all horses, n = 16. Each colour in the line plot represents an individual horse. Black stippled line at 0 mm elucidates the dividing line between left (negative values) and right (positive values) side asymmetry for the parameter. HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride, PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride.

TABLE 2 Estimated marginal means and contrasts from post-hoc analysis

Model	Track segment	Estimate	SE	*df*	95% CI	t-ratio	*P*-value
Estimated marginal means							
HDmax	Straight	6.27	4.5	15	−3.3 to 15.9	1.39	0.2
	Curve	3.99	4.5	15	−6.6 to 13.6	0.89	0.4
HDmin	Straight	4.98	3.54	15	−2.6 to 12.5	1.41	0.2
	Curve	3.14	3.54	15	−4.4 to 10.7	0.89	0.4
PDmax	Straight	−2.76	1.5	15	−6.0 to 0.4	−1.84	0.09
	Curve	−2.52	1.5	15	−5.7 to 0.7	−1.68	0.1
PDmin	Straight	−1.09	1.9	15	−5.2 to 3.0	−0.57	0.6
	Curve	−1.78	1.9	15	−5.8 to 2.3	−0.94	0.4
Contrasts							
HDmax	Straight - curve	2.28	0.29	4,874	1.7 to 2.9	7.78	**<0.001**
HDmin	Straight - curve	1.84	0.32	4,875	1.2 to 2.5	5.69	**<0.001**
PDmax	Straight - curve	−0.24	0.13	5,107	−0.5 to 0.01	−1.86	0.06
PDmin	Straight - curve	0.69	0.14	5,108	0.4 to 1.0	4.98	**<0.001**

Note: Data from all 16 horses.

Abbreviations: HDmin/HDmax, difference in head minimum/maximum positions between right and left portions of the stride; PDmin/PDmax, difference in pelvis minimum/maximum positions between right and left portions of the stride; SE, standard error; *df*, degrees of freedom; 95% CI, 95% confidence interval.

Bold font is used when $P<0.05$.

There are several differences between riding horses being lunged and Standardbreds trotting on an oval track, such as the much wider curve radius of a trotting track; increased trotting speed of Standardbreds on the track; as well as the unknown effect of how pulling a sulky and driver may constrain the horses' ability to adapt to a curved path. In our study the horses were not driven by the same driver but exercised with their usual driver in the sulky. Different drivers may drive their horses slightly differently through the track curve, eg by positioning the horse's head more towards the inside or outside during the curved track, which may have influenced our measurements. In horses being lunged there are conflicting reports on whether there is a systematic influence of curve direction on symmetry[9,10] or not,[4,5,8] or whether this is due to the presence of lameness.[20] Horse-specific adaptations may cause differences in symmetry when lungeing in opposite directions.[4,5,10] In our study the horses travelled only in a clockwise direction on the track, as per the trainers' customary warm-up routine, therefore we could not investigate any potential effect of curve direction. Additionally, we cannot rule out that some of the more asymmetric horses in our study were experiencing orthopaedic pain, which may have influenced how they navigated the curved track segments.

In riding horses lunged on a 10 m circle, inward body lean was greater on a flat surface than on a banked surface.[8] In the 1970s, Dalin et al.[21] looked at Standardbreds trotting through curves as part of a collection of studies that lead to revised guidelines for the degree of banking of trotting track curves.[22,23] Sound two- and three-year old Standardbreds trotting at lower speeds (7.6 m/s) on two mildly banked (3.5 vs 4.5 degrees) oval tracks had symmetric movement through curves as judged by hoof landing patterns, diagonal patterns, extremity adduction and inward inclination as evaluated by high-speed cinematography.[21] With increased speed (13.3 m/s) there were significant contralateral (diagonal) differences for most parameters including increased inward body lean as well as a swinging or drifting of the hindquarters to the outside of the track while travelling through the curve.[21] This suggests that speed may be of greater importance than the curve radius itself for some curve-induced asymmetries, as centripetal acceleration is calculated by dividing velocity squared by the radius: $a_c = \frac{v^2}{r}$. Another aspect particular to horses exercising on oval tracks, when comparing these with horses ridden or lunged in circles, is that while the radius of an oval trotting track can be varied slightly by driving the horse along the outside or inside boundaries of the track, it is relatively constant and unchangeable. For the Standardbred trotter exercising on an oval track, speed rather than radius may be the more influencing factor. Once speed increases, banking is a key factor for Standardbred locomotion when navigating the curve. How trotting through banked track curves at greater speeds affects objectively measured symmetry parameters remains to be studied. In our study, changes in most symmetry parameters were coupled to stride duration. Stride duration was included as a proxy for speed, assuming that an increase in stride duration would mean a decrease in speed. However, stride duration by itself is not identical to speed of the horse as velocity is influenced by stride length in addition to stride frequency. Mean stride duration was almost the same for both straight and curved track segments in our study, however, the significant interactions of symmetry parameters, stride duration and track segment warrant further investigation.

In summary, we identified systematic curve-induced asymmetries in our Standardbred cohort. This is of importance both for subjective gait evaluation as well as for clinicians using this type

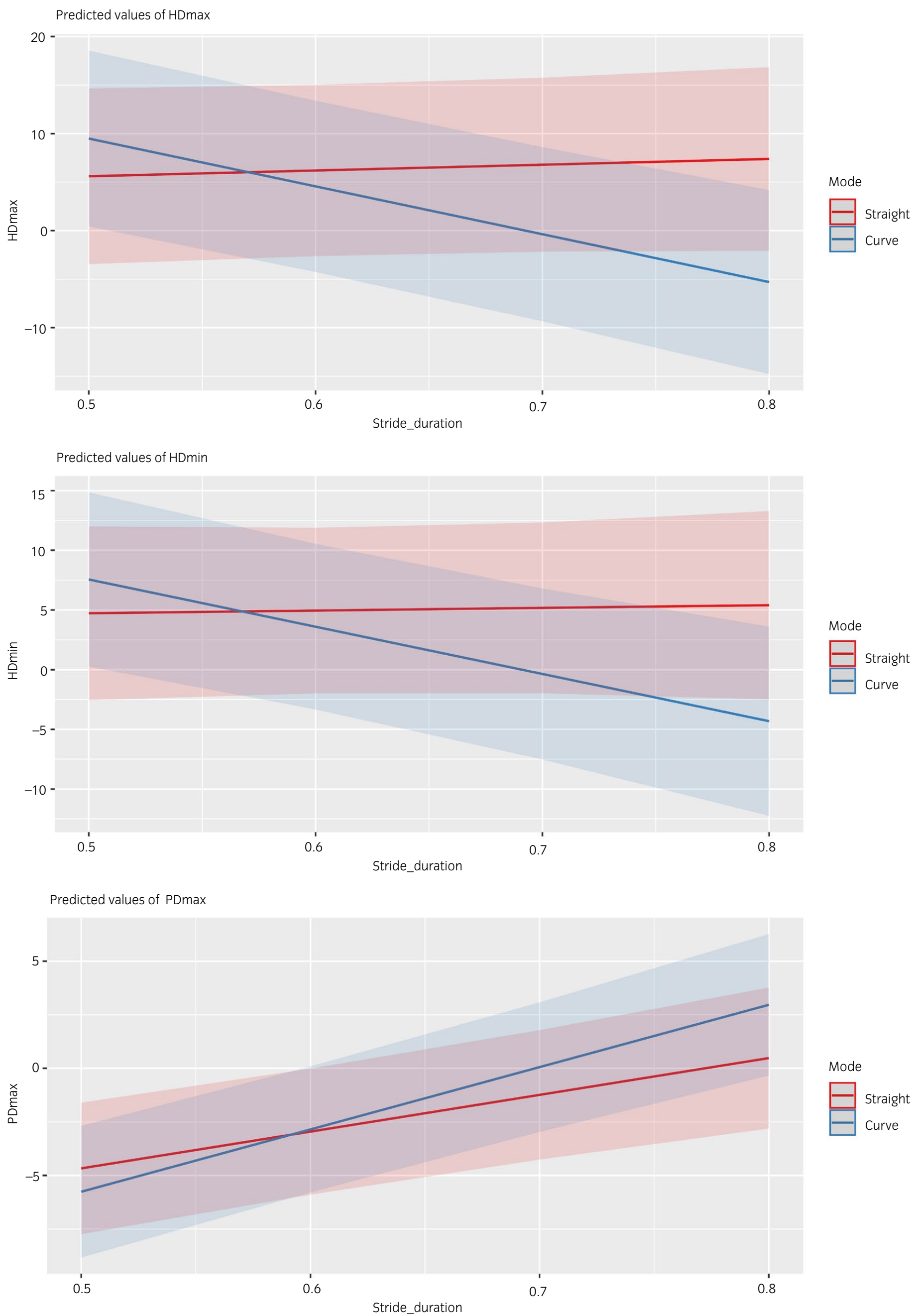

FIGURE 3 Two-way interaction plots for track segment and stride duration. Data for all horses, n = 16. Slope values: HDmax; curve: −49.3 mm per s, SE 9.5, 95% CI −67.9 to −30.7, straight: 6.0 mm per s, SE 9.3, 95% CI −12.2 to 24.1, HDmin; curve: −39.6 mm per s (−3.96 mm per 100 ms), SE 10.5, 95% CI −60.1 to −19.1, straight: 2.3 mm per s, SE 10.2, 95% CI −17.8 to 22.3, PDmax; curve: 29.1 mm per s, SE 4.1, 95% CI 21.1 to 37.1, straight: 17.2 mm per s, SE 4.0, 95% CI 9.3 to 25.0. PDmin not included as no significant interaction for this parameter. HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride, PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride

of IMU systems to evaluate Standardbred horses on the track. In our relatively small cohort of horses with a wide range of existing asymmetries, with data collected from horses trotting on 1000 m tracks with curve radii of 80-85 m, effect sizes were small; under these conditions, collecting IMU symmetry data at jogging speeds without distinguishing between straight and curved parts of a non-banked track is unlikely to adversely affect clinical decision-making.

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CONFLICT OF INTERESTS

No competing interests have been declared.

AUTHOR CONTRIBUTIONS

M. Rhodin, E. Hernlund and E. H. S. Hendrickson conceptualised the study and A. S. Kallerud collected the data. A. Byström developed the data analysis MATLAB scripts. A. Byström, E. Hernlund, A. S. Kallerud and E. Persson-Sjodin performed data analysis and statistics. A. S. Kallerud, C. T. Fjordbakk and E. Hernlund wrote the manuscript. All authors contributed to data interpretation and revising the manuscript, as well as read and approved the final manuscript. A. S. Kallerud had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

ETHICAL ANIMAL RESEARCH

The study was approved by the ethics committee at the Faculty of Veterinary Medicine, Norwegian University of Life Sciences (approval number 14/04723-47).

INFORMED CONSENT

A signed consent form was obtained from trainers of all horses included in the study.

DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

PEER REVIEW

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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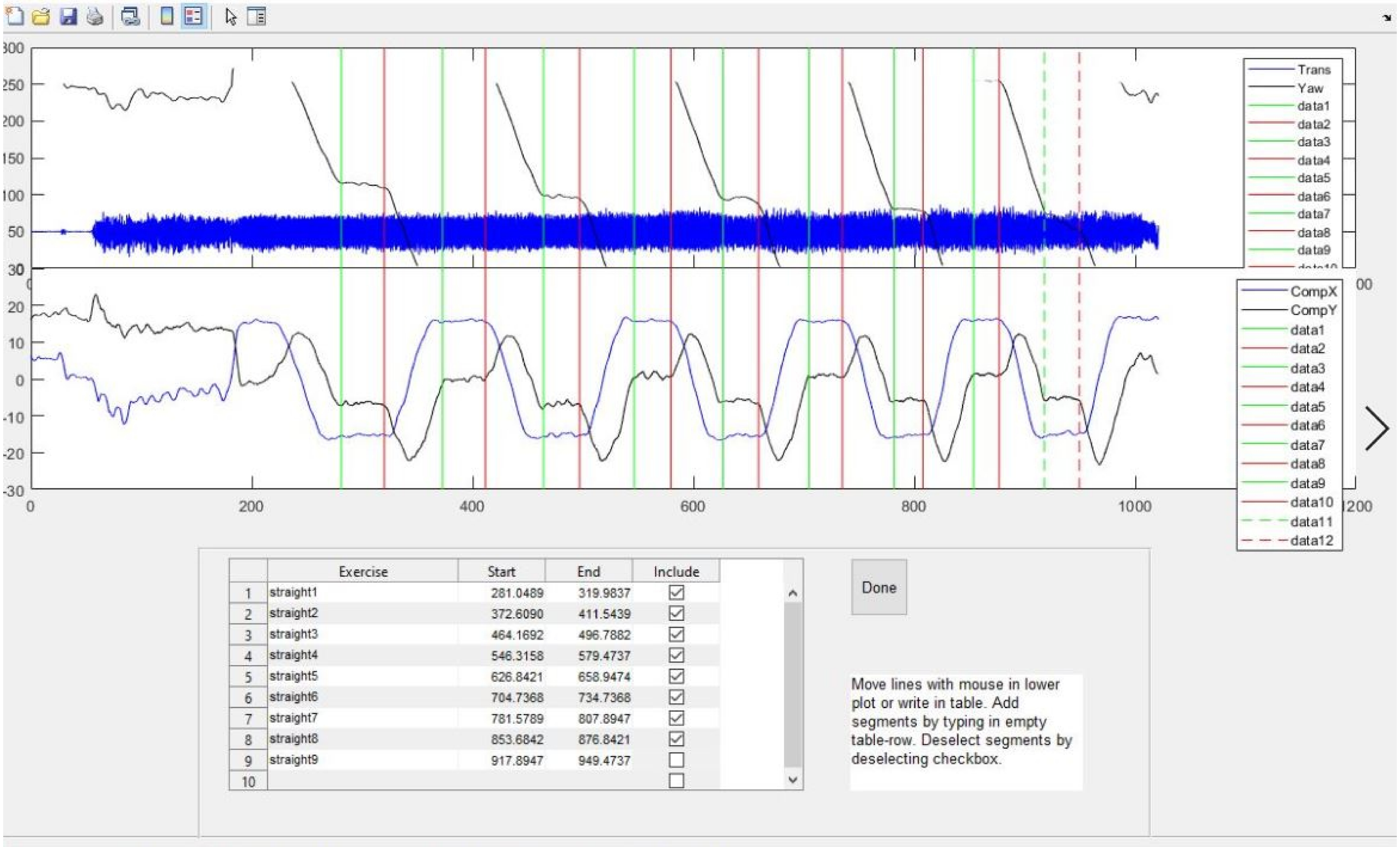
Figure S1: Example of stride selection in MATLAB. The selection of track segments (straight vs. curve) had no threshold values and was not automated but based on visual comparison (and agreement of) pelvic sensor yaw data (upper part of graph) and magnetometer data (lower part of graph). The green line indicates the beginning of the straight track part and the red line the end of the straight segment/ beginning of curved segment, or in other words: Horizonal data tracings show that the horse is moving in a constant direction/straight line, sloping tracings show that the horse is moving in a changing direction/turning.



	Exercise	Start	End	Include
1	straight1	281.0489	319.9837	☑
2	straight2	372.6090	411.5439	☑
3	straight3	464.1692	496.7882	☑
4	straight4	546.3158	579.4737	☑
5	straight5	626.8421	658.9474	☑
6	straight6	704.7368	734.7368	☑
7	straight7	781.5789	807.8947	☑
8	straight8	853.6842	876.8421	☑
9	straight9	917.8947	949.4737	☐
10				☐

Figure S2: Distribution of asymmetric limbs (boxplot).

Boxplot of asymmetrical horses, n = 9. RF = Right forelimb, LF = Left forelimb, RH = Right hindlimb, LH = Left hindlimb.

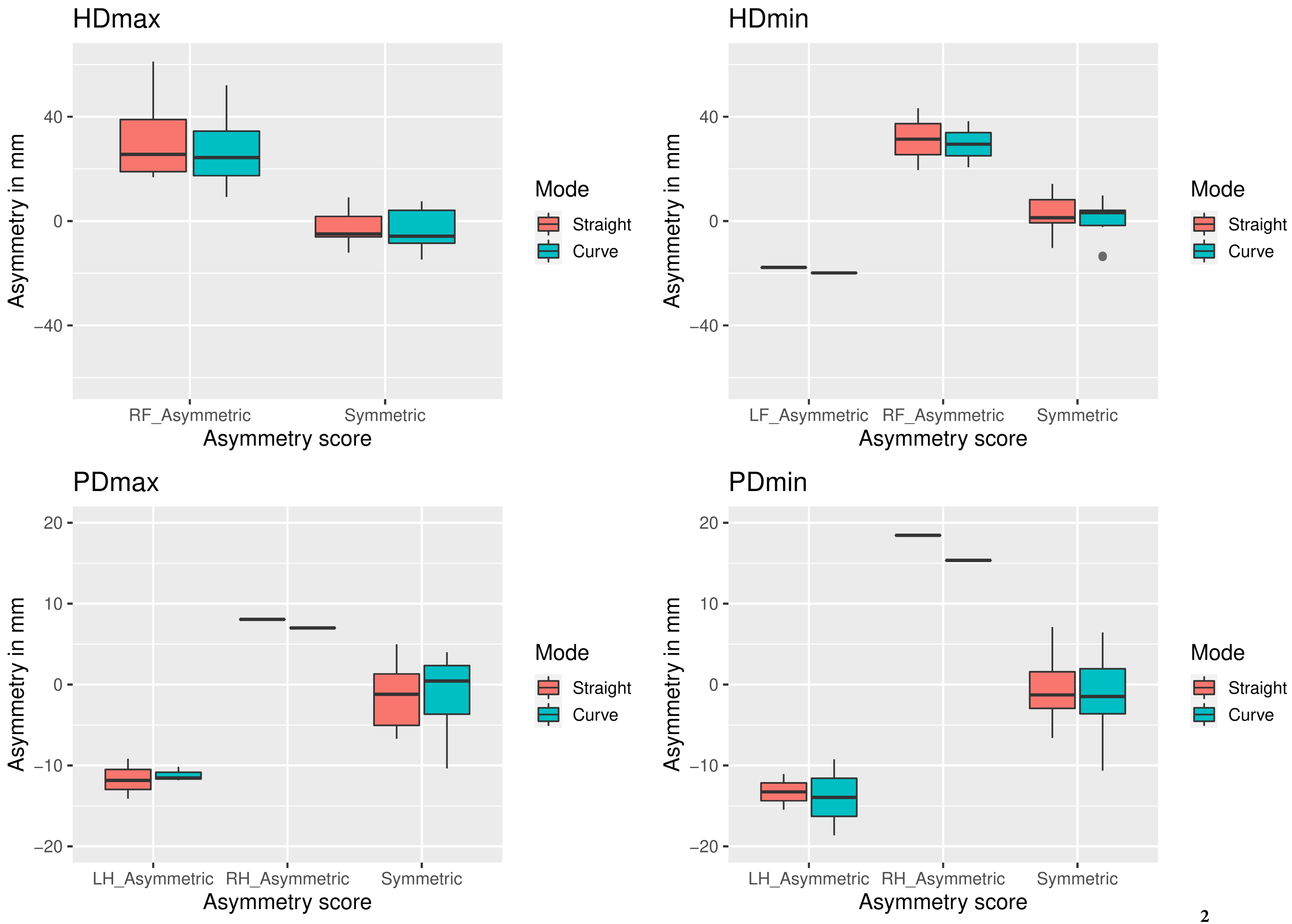
HDmax: LF asymmetric n = 0; RF asymmetric n = 4, symmetric n = 5.

HDmin: LF asymmetric n = 1; RF asymmetric n = 2; symmetric n = 6.

PDmax: LH asymmetric n = 3; RH asymmetric n = 1, symmetric n = 5.

PDmin: LH asymmetric n = 2; RH asymmetric n = 1, symmetric n = 6.

HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride, PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride.



HDmax
HDmin
PDmax
PDmin
Asymmetry in mm
Asymmetry score
Mode
Straight
Curve
RF_Asymmetric
LF_Asymmetric
LH_Asymmetric
RH_Asymmetric
Symmetric

Table S1: Distribution of asymmetric limbs**.**

Horses classified as asymmetric: n = 9. RF = Right forelimb, LF = Left forelimb, RH = Right hindlimb, LH = Left hindlimb.

HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride, PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride.

Horse no.	Forelimb symmetry	Hindlimb symmetry
1	HDmax, RF asymmetric	Symmetric
2	HDmax, RF asymmetric	Symmetric
3	HDmin, LF asymmetric	Symmetric
4	Symmetric	PDmax, LH asymmetric
5	Symmetric	PDmax, LH asymmetric
6	Symmetric	PDmin, LH asymmetric
7	HDmax, RF asymmetric	PDmax & PDmin, RH asymmetric
8	HDmax & HDmin, RF asymmetric	Symmetric
9	HDmin, RF asymmetric	PDmax & PDmin, LH asymmetric

Data S1: Individual horse symmetry means and standard deviations

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Horse ID	HDmax_straig	HDmax_straigh	HDmin_strai	HDmin_str	PDmax_stra	PDmax_st	PDmin_strai	PDmin_straight_SD	No_straight_se	HDmax_curve	HDmax_c	HDmin_c	HDmin_cur	PDmax_cur	PDmax_(	PDmin_(	PDmin_curve_S	No_curve_segments
1	-3.35	6.45	19.53	6.28	-14.19	4.29	-10.83	4.51	4	-1.26	6.63	20.58	6.13	-11.66	3.10	-9.26	4.98	4
2	61.13	16.33	43.21	15.73	-1.17	3.06	-1.06	4.36	4	52.05	16.48	38.49	15.14	1.82	3.10	-0.83	3.86	4
3	6.63	7.21	-10.33	8.96	-4.93	3.20	7.01	3.84	3	4.77	8.16	-13.75	9.44	-4.92	3.18	6.51	3.53	3
4	16.80	8.50	7.71	9.26	-1.05	3.87	-1.28	3.78	4	8.89	8.19	3.79	9.87	-1.05	3.57	-2.46	3.47	3
5	5.23	8.54	0.17	9.23	-6.77	3.17	2.02	5.65	2	3.80	7.95	-1.43	11.26	-10.37	3.54	2.13	4.60	2
6	-5.71	10.12	13.21	7.14	-8.74	4.46	4.20	2.60	2	-7.63	8.04	9.80	5.73	-9.99	3.90	4.48	3.09	3
7	0.60	8.34	4.05	7.79	3.10	3.66	-6.31	4.07	2	5.21	7.83	3.22	6.06	4.05	5.80	-7.00	5.76	2
8	9.07	8.39	-17.79	13.48	-6.00	4.85	-2.91	3.59	2	7.58	7.79	-19.88	9.99	-6.62	4.93	-1.36	2.92	2
9	-5.79	4.43	1.26	4.38	-11.99	5.13	-6.52	4.97	3	-7.06	5.44	3.05	4.22	-11.83	8.09	-10.65	6.21	3
10	-5.18	6.49	-8.36	8.31	-3.98	3.73	-1.34	3.10	2	-11.18	8.23	-13.33	8.05	-3.28	4.35	-0.67	3.09	2
11	-6.62	8.83	1.14	8.57	-5.47	5.42	-15.39	6.61	2	-7.61	7.96	5.90	8.59	-3.15	3.98	-20.49	7.09	3
12	19.62	16.06	9.88	22.90	7.91	4.57	18.41	5.63	4	20.10	15.05	3.39	19.53	6.94	4.30	15.77	6.35	3
13	-12.11	8.83	-4.01	11.42	3.24	3.66	-1.87	3.99	4	-13.05	9.08	-2.33	9.74	1.75	3.80	-3.93	5.84	2
14	-4.68	22.61	8.21	21.12	-0.59	5.34	1.05	6.08	2	-4.57	14.02	4.09	16.70	3.11	4.14	1.24	4.60	2
15	-8.31	5.92	14.31	4.79	0.81	2.80	-3.02	2.73	3	-14.76	4.60	9.83	4.76	2.14	1.94	-3.57	2.93	2
16	31.54	7.41	-0.68	7.03	5.10	5.19	-0.81	5.51	5	28.61	7.25	-1.67	6.63	3.75	4.78	-2.18	4.43	5
Group mean:	**6.18**	**9.65**	**5.09**	**10.40**	**-2.79**	**4.15**	**-1.17**	**4.44**	**3.00**	**3.99**	**8.92**	**3.11**	**9.49**	**-2.46**	**4.16**	**-2.02**	**4.55**	**2.81**
								Median, straight segm	**3**								**Median, curve s**	**3**
Min. value	**-12.11**		**-17.79**		**-14.19**		**-15.39**		**2.00**	**-14.76**		**-19.88**		**-11.83**		**-20.49**		**2.00**
Max. value	**61.13**		**43.21**		**7.91**		**18.41**		**5.00**	**52.05**		**38.49**		**6.94**		**15.77**		**5.00**

Legend:
SD = standard deviation
All values are in millimeters
HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride
PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride

Data S2: Complete ANOVA output.

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ANOVA output - Type III Analysis of Variance Table with Satterthwaite's method

All horses, n = 16

HDmax

Fixed effects	*Sum Sq*	*Mean Sq*	*NumDF*	*DenDF*	*F value*	*Pr(>F)*	
Stride duration	718.1	718.1	1.0	4888.4	7.12	0.0076	**
Track segment	3067.4	3067.4	1.0	4874.6	30.43	0.0000	***
Stride duration:Track segment	3540.4	3540.4	1.0	4874.6	35.12	0.0000	***

HDmin

Fixed effects	*Sum Sq*	*Mean Sq*	*NumDF*	*DenDF*	*F value*	*Pr(>F)*	
Stride duration	534.5	534.5	1.0	4861.1	4.35	0.0371	*
Track segment	1742.1	1742.1	1.0	4875.2	14.18	0.0002	***
Stride duration:Track segment	2030.3	2030.3	1.0	4875.1	16.52	0.0000	***

PDmax

Fixed effects	*Sum Sq*	*Mean Sq*	*NumDF*	*DenDF*	*F value*	*Pr(>F)*	
Stride duration	876.6	876.6	1.0	5103.3	43.66	0.0000	***
Track segment	163.0	163.0	1.0	5106.8	8.12	0.0044	**
Stride duration:Track segment	174.6	174.6	1.0	5106.8	8.70	0.0032	**

PDmin

Fixed effects	*Sum Sq*	*Mean Sq*	*NumDF*	*DenDF*	*F value*	*Pr(>F)*	
Stride duration	0.8	0.8	1.0	5117.6	0.03	0.8550	
Track segment	593.3	593.3	1.0	5107.5	24.80	0.0000	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*'

HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride
PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride

Paper III

Manuscript title: A longitudinal study of movement asymmetry and indicators of orthopaedic health in young Standardbred trotters

Keywords: Horse, IMU, joint injection, orthopaedic health.

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Declarations

Authorship: MR, EH and EHSH conceptualised the study and ASK, EHSH, EH and MR collected the data. ASK performed the descriptive statistics. ASK, CTF and EH wrote the manuscript. All authors contributed to data interpretation and revising the manuscript, as well as read and approved the final manuscript. ASK had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Sources of Funding: Swedish-Norwegian Foundation for Equine Research (H1647178) and the Norwegian Research Council (272327).

Competing Interests: The authors declare that they have no competing interest.

Ethical Animal Research: The study was approved by the ethics committee at the Faculty of Veterinary Medicine, Norwegian University of Life Sciences (approval number 14/04723-47).

Owner informed consent: A signed consent form was obtained from trainers of all horses included in the study.

Acknowledgements: We thank veterinary student Andreas Gjerstad for excellent help with data collection, and the trainers and grooms of the horses for their participation and assistance.

Data Accessibility Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Summary

Background: Knowledge is lacking regarding the amount and magnitude of objectively measured movement asymmetry at different ages and training stages in Standardbred racehorses. Lameness in this breed is common, but little objective data is available on the orthopaedic health of Standardbred racehorses in training.

Objectives: To describe changes in objectively measured movement asymmetry in a cohort of Standardbred trotters followed over a two-year period (yearlings to three-year-olds); to register indicators of orthopaedic health such as joint treatments within this cohort; and to record the number of horses completing a qualification race within the end of their three-year-old year.

Study design: Prospective cohort study.

Methods: Standardbred yearlings (n = 114) were recruited from 13 trainers in Norway and Sweden. A horse trial was defined as data collected with a wireless inertial sensor system during driven trotting exercise; trials were collected approximately every three months for two years. Movement asymmetry was classified based on published thresholds for the sensor system used in this study. Horse trials were classified as asymmetric if they had one or more forelimb asymmetry parameters with absolute values above 6 mm and/or one or more hindlimb asymmetry parameters above 3 mm. Information on orthopaedic veterinary treatments and racing starts were recorded.

Results: Asymmetric movement was common, with only 18 of 375 trials categorised as symmetric. During the first year of training 58 horses had data collected consistently, while during the second year only 15 horses were available for regular data collection. Therapeutic joint injections were the most frequent orthopaedic veterinary treatment. Of the 15 horses in the second year of data collection, 14 horses received at least one therapeutic joint injection within the study period. The number of horses that completed a qualification race as a two- or three-year-old was 82 of 114 recruited horses (72%), and 46 of the 58 horses (79%) with consistent data collection during the first year.

Main limitations: The number of horses dropping out of the study during the two years of data collection was substantial.

Conclusions: During the study period, only 18 out of 375 trials were categorised as symmetric. Movement ranged from symmetrical to severely asymmetrical, although mild to moderate asymmetry was most frequent. Therapeutic joint treatments were common, more so in three-year-old horses than two-year-old horses. Despite this, race participation was high.

Introduction

In the Standardbred trotter, studies from the 1990s describe frequent pathological orthopaedic findings[1] and lameness.[2,3] More recent studies show that training-related injuries[4] and lameness[5,6] are still highly prevalent in Standardbred racehorses. In Thoroughbred racehorses, an increase in training intensity has been associated with an increase in lameness incidence,[7] and in one study horses suffering a catastrophic musculoskeletal injury were more likely to have shown signs of lameness prior to death compared to controls.[8] Other risk factors for musculoskeletal injuries include racing and training intensity,[9,10] trainer[11] and medical treatment.[4]

Since the introduction of systems using horse-mounted inertial measurement units (IMUs), objectively measured movement asymmetry data are increasingly used by both researchers and clinicians.[12] In a group of young Standardbred trotters, measurements of movement asymmetry over a 2½ year period showed variation on a group-level throughout the years, with peaks in asymmetry level coinciding with increased training in the spring as two- and three-year-olds.[13] When collecting objective movement asymmetry data from yearling Standardbreds at the very start of their training career, we found a high prevalence of movement asymmetry; 94% of horses had asymmetry parameters above previously reported thresholds, though there was considerable variability in the data.[14] The aim of the current study was to continue monitoring movement asymmetry in the horses in the aforementioned study by collecting asymmetry data in the same cohort of Standardbred trotters over two years. Additionally, we wanted to register the occurrence of therapeutic joint injections during the study period, as well as the number of horses that completed a qualification race before the end of their three-year-old season. Our hypothesis was that movement asymmetry would increase in magnitude as horses grew older, due to cumulative training loads.

Material & Methods

Study design and data collection

Standardbred trotter yearlings were recruited from a convenience sample of professional trainers of harness-racing horses. Briefly, 13 trainers agreed to study participation; ten trainers were located in Norway and three in Sweden. Detailed information on cohort recruitment for this longitudinal study as well as movement asymmetry data from the horses' early exercise as yearlings are found in Kallerud et al.[14]

After recruitment, included training yards were visited approximately every three months. Data collection was prospectively planned over two years (2017-2019), aiming to follow the horses from initiation of training (autumn of their yearling year) until the autumn of their three-year-old year. For all training yards, four visits per year was planned. In the following, visit 1 – 4 is referred to as Year 1 whereas visit 5 – 8 is referred to as Year 2. The study was designed as a closed cohort study, meaning that per training yard only those horses that were enrolled as yearlings had data collected at following visits. Inclusion criteria per visit was that enrolled horses had to be in regular training (i.e. not resting for any reason such as injuries/health problems, or due to tactical race preparation), and that horses were made available to the research team for data collection. Exclusion criteria per visit were technical difficulties with data collection as detailed below. In order to be included in data analysis per year, horses had to participate at a minimum of three data collection visits per year.

During training yard visits for data collection, one of the investigators performed a physical examination of the horses, including measuring the height at the withers and at the tubera sacrale (pelvis height). All horses wore their regular trotting harness and additional gear as per the trainers' preference. Movement asymmetry data was collected using an IMU system (Lameness Locator® by Equinosis LLC[a]) as described below. Horses were instrumented with IMUs on the poll, pelvis and right front pastern as previously described.[15] The pelvis sensor was fastened with extra strong double-sided adhesive tape (Teppeteip, Clas Ohlson[b]) and standard-issue duct tape, then covered with additional adhesive tape (Snøgg Animal Polster, Norgesplaster AS[c]) to reduce interference from the back strap of the harness as well as to prevent sensor loosening during exercise. Two rounds of elastic, adhesive cloth tape (Norbind, Norgesplaster AS[c]) was applied to prevent rotation of the neoprene pastern wrap containing the pastern IMU.

Horses were evaluated while driven on the training track at their respective yards or at the nearest racetrack to the yard. A trial was defined as data collected during steady-state trot, with the horse driven on either a straight or an oval trotting track. As exercise distance and number of trials collected per horse varied between visits, horses, and trainers, the first trial collected for each horse with the horse exercising at a regular trot at jogging (warm-up) speed per visit was used for data analysis.

The IMU sensors each contain accelerometers, gyroscopes and magnetometers, and record the vertical acceleration of the head and torso and the angular velocity of the right forelimb, sampling at 200 Hz with 8-bit digital resolution. Wireless data transmission between the IMU sensors and a computer tablet running the proprietary system software was attained via Bluetooth technology. Two methods were used for data collection on the track; either the driver of the horse carried a small backpack containing the receiving tablet while data was collected, or a car was driven alongside the horse(s) while one of the investigators controlled the tablet. For most trials, the driver of the horse wore a GPS clock device (Polar M450, Polar Electro[d]) that registered speed, distance and route of the training session with the horse wearing an accompanying Polar electrode belt around the trunk that measured heart rate. Heart rate data was collected but not used for this study.

Data processing and calculations

The IMU system measures acceleration along the vertical axis of the IMU sensor. The IMU system software calculates the minimum and maximum head and pelvic height differences between the right and left trotting diagonal of the horse for each stride in the trial using a double integration process.[16] Data output consists of four parameter mean values in millimetres (mm) that describe the movement symmetry of the horse; head minimum (HDmin) and head maximum (HDmax) difference, and pelvis minimum (PDmin) and pelvis maximum (PDmax) difference. Thus, the HDmin difference is the minimum head height during right forelimb stance minus the minimum head height during left forelimb stance, while the HDmax difference is the maximum head height before right forelimb weight-bearing minus the maximum head height before left forelimb weight-bearing. The same principle is used for the movement of the pelvis to calculate PDmin and PDmax. A parameter value of 0 mm indicates perfect symmetry, with no difference in symmetry between the two halves of a trotting stride. As defined by the system software, asymmetries indicating a right limb asymmetry were recorded as positive values, whereas asymmetries indicating a left limb asymmetry were recorded as negative values. A vector sum calculated as $\sqrt{}(HDmax^2 + HDmin^2)$ to describe forelimb symmetry is calculated by the system software. Further descriptions of parameter calculations have been published elsewhere.[16] For the purpose of the current study, a vector sum for the hindlimb was manually calculated using an equivalent formula: $\sqrt{}(PDmax^2 + PDmin^2)$. Vector sum was calculated to provide a general metric for movement asymmetry magnitude, without relating this directly to a specific limb associated with the asymmetry. For vector sum calculations, signed values were converted to absolute values.

Default settings (Lameness Locator® 2017 software v1.2r) were used for initial stride selection from each trial. Trials were excluded from data analysis when technical difficulties with the IMU system such as sensor loosening during exercise or incomplete data acquisition resulted in inadequate data recordings. For horses exercised on oval tracks, only strides from the straight part of the track were used for analysis. Stride selection was done using a software option based on IMU magnetometer data. This allows for strides from the straight part of the track to be manually selected; only strides from within horizontal magnometer data tracings, indicating a constant direction of motion (i.e. the horse is trotting in a straight line), were selected. An example of the stride selection process is provided in Supplementary Figure S1.
Movement asymmetry was classified based on published lameness detection thresholds for the IMU system used in this study.[15] Parameter trial mean values were used for classification, regardless of trial standard deviations. Horses were classified as asymmetric if they had one or more parameter absolute mean values above 6 mm (HDmin, HDmax) or 3 mm (PDmin, PDmax). Asymmetric horses were

divided into categories depending on which parameter vas above threshold value, as well as which limb was affected; e.g. a horse with a mean HDmin value more positive than 6 mm would be classified as having right forelimb HDmin asymmetry; conversely, a horse with a mean PDmin value more negative than -3 mm would be classified as having a left hindlimb PDmin asymmetry etc. Further, asymmetry was divided into severity categories based on the magnitude of asymmetry in millimetres. Category intervals were based on an increase in absolute millimetre asymmetry by adding the threshold value (6 or 3 mm) to each progressing category. The resulting categories were; "mild" (forelimb asymmetry 6-12 mm/hind limb asymmetry 3-6 mm), "mild-moderate" (12-18 cm/6-9 mm), "moderate" (18-24 mm/9-12 mm), "moderate-severe" (24-30 mm/12-15 mm) and "severe" (>30 mm/>15 mm). These categories correspond to the levels of asymmetry presented in the IMU system output data, except for the 'severe' category which was added to describe the results of the current study. Combined scores for forelimb (HDmin & HDmax) and hindlimb (PDmin & PDmax) asymmetry was calculated; the horse was classified as fore- and/or hindlimb asymmetric if one fore- or hindlimb parameter was above its respective threshold. Horses with both fore- and hindlimb asymmetry were included in both the fore- and hindlimb combined categories. For horses with bilateral asymmetry each horse's combined severity score within the fore- or hindlimb category was based on the limb with the highest asymmetry score.

At each visit, trainers were asked about the individual horses' training progress and about veterinary treatments since the last visit. Information on radiographic screening of fetlocks and hocks for osteochondrosis/osteochondrosis dissecans (OC/D) was gathered when available, either through information from yearling sales listings or directly from the owner or trainer of the horse. Race information was obtained from the websites of the official racing organisations.[17] The number of horses completing a qualification race by the end of their three-year-old year was registered. Where applicable, participation in regular (i.e. official tote) races after the completion of a qualification race was registered.

Results

A total of 114 Standardbred yearlings were recruited to the study, with a median of five horses per trainer (range 1 – 29 horses). Ninety-five yearlings were recruited in the autumn of 2017, and an additional 19 yearlings were recruited one year later from two of the training yards already enrolled in the study. While data was collected over two years (2017-2019), these 19 horses were only followed for one year (2018-2019).

The planned eight data collection visits per training yard were completed for 11 of the included yards. Two trainers withdrew from further study participation after six visits; data from Year 1 from these yards was still included in data analysis. A flowchart of recruited horses and reasons for study drop-out is presented in Figure 1; horses were categorised as study drop-outs when they left the training yard, if they were taken out of training, or if technical issues prevented sufficient data to be collected for the horse. Included yearlings comprised 63 males (62 stallions, 1 gelding) and 51 mares. Information on radiographic findings of OC/D was available for 82 horses; 10 horses had not had radiographs taken prior to or during the study period, while information was missing for 22 horses. Of the horses in which radiographic information was available, 55 horses had no abnormal findings reported, while OC/D was noted in 27 horses. Of these, 16 underwent surgery prior to or during the study period, 4 did not, while data was missing for 7 horses.

A total of 375 trials were included for analysis. When implementing threshold values, 18 trials were categorised as symmetric. Trial asymmetry category was based on the limb with the highest asymmetry magnitude within each trial, which gave the following number of trials per category: Mild asymmetry: 100 trials; mild-moderate asymmetry: 117 trials; moderate asymmetry: 69 trials; moderate-severe asymmetry: 36 trials; severe asymmetry: 35 trials. For all trials, the number of included fore- and hindlimb strides is listed in Table 1 and mean speed per visit is shown in Table 2. Overviews of the age and height of horses per visit are provided in Supplemental Tables S1 and S2. Details of the distribution and magnitude of HDmin, HDmax, PDmin and PDmax asymmetry presented per limb and per visit is provided in Supplementary Figure S2. Asymmetry parameter means, standard deviations, medians and ranges are summarised in Tables 3a and 3b.

For hindlimb parameters, an overall increase in asymmetry magnitude was seen over time as illustrated in Figure 2, where the proportion of horses in the moderate to severe asymmetry categories increased during the study period, peaking at visit 7. This finding was not as evident for forelimb parameters, where the proportion of horses falling into the symmetric or mildly symmetric categories was consistently higher than for the hindlimb parameters throughout the study. To further describe the change in asymmetry magnitude over time, group-level absolute mean values per visit for HDmin, HDmax, PDmin and PDmax are presented in Figure 3. Hindlimb parameters, particularly PDmin, showed an increase in magnitude over time, while HDmin was more constant and HDmax decreased.

A summary of all recorded orthopaedic veterinary treatments is detailed in Supplementary Table S3. A total of 128 therapeutic joint injections were recorded during the study period (Table 4). The first joint injections were administered between visits 2 and 3, i.e. in the spring as the horses were two years old. An increasing number of injections were recorded from visit 3 to visit 8; most injections were administered in forelimb joints, with 40% of all injections administered in the carpus. Of the 15 horses contributing data to at least six out of the eight data collection visits, 14 horses received at least one therapeutic joint treatment by the end of the study period.

The relationship between asymmetry means (vector sums) for fore- and hindlimbs during Year 1 and completion of a qualification race is shown in Figure 4 for the 58 horses participating in at least three out of the four data collection visits during Year 1. Forty-six of the 58 horses (79%) completed a qualification race by the end of their three-year-old year. For all 114 horses recruited to the study, 82 horses (72%) completed a qualification race; of these, 73 horses (64%) went on to compete in regular races within the end of their three-year-old year.

Discussion

Our study describes the development in objectively measured movement asymmetry in a cohort of Standardbred trotters from yearlings until the end of their three-year-old season. During most trials, most horses moved asymmetrically, ranging from mild or moderate asymmetry up to severe asymmetry as per the applied thresholds. Our hypothesis of increasing magnitude of asymmetry over time was partially supported; overall, hindlimb asymmetry increased from initiation of training, whereas this finding was not as evident for forelimb parameters. One interpretation of this discrepancy could be that forelimb lameness is more easily recognised than hindlimb lameness by subjective evaluation. This could potentially lead to more frequent use of therapeutic joint injections in forelimbs, as well as skewing the study drop-outs to represent more horses with subjectively recognised forelimb lameness. Contrary, the parameter with the most unambiguous increase in asymmetry magnitude over time was PDmin, which although representing an impact-type asymmetry, might not be as easily acknowledged by trainers and addressed as a health problem. However, as the number of horses included per visit varied, and the number of horses decreased markedly with time, these results need to be interpreted with care.

Therapeutic joint injections were frequent, with the first horses receiving treatment in the spring as two-year-olds. While most horses did not receive joint injections during Year 1 (as yearlings and two-year-olds), of the 15 horses followed for the entire study period, 14 were treated with intra-articular medication. Nevertheless, a high proportion of study horses completed qualification races by the end of their three-year-old year. For the 58 horses with consistently collected asymmetry data during Year 1, we could not identify any difference in observed asymmetry parameters between horses that raced and those that did not (Figure 4).

Only a minority of horses could be followed for the entire study period, representing the main limitation of our study. Reasons for this were that a substantial amount of horses were either sold or changed trainers throughout the study period, as well as several horses that were taken out of training or euthanised due to lameness issues. During Year 1, technical issues during data collection caused loss of data, whereas such problems were largely overcome when starting data collection in Year 2. This situation represents the steep learning curve that practical data collection often entails. In retrospect, certain technical issues could have been identified and addressed by conducting a pilot-experiment. At the end of Year 1, we opted to include a further 19 yearlings that were arriving for training at two of the training yards already enrolled in the study. This was due to the observed increasing rate of study drop-outs as well as the technical issues experienced during data collection. Although these additional yearlings could only be followed for one year until the study period ended, we deemed it useful to increase the amount of data collected for horses in their first year of training. During Year 2, two trainers ended study participation prematurely. Although all trainers were well-informed of the planned study period upon (voluntary) study enrolment, some participants experiencing study fatigue is inevitable and not surprising.

Our study shows that horses with asymmetric movement are in training and entering races. The high occurrence of orthopaedic veterinary treatments, especially the frequency of joint treatments, reveals that clinical lameness is an important issue even in the youngest of Standardbred trotters. Racing performance, such as number of races entered, race wins/placings and/or prizemoney earned, are commonly used as outcome parameters when assessing performance before and after interventions in studies concerning racehorses. Such outcome measures may accurately demonstrate the performance level of a Standardbred racehorse. If, however, orthopaedic health is to be investigated in Standardbreds, this may not be adequately addressed if only racing performance is assessed.

In our cohort, the number of joint injections increased during the three-year-old season. In a study of musculoskeletal injuries in Standardbreds, Bertuglia et al.[4] reported that the risk of a major musculoskeletal injury increased with veterinary treatments to solve gait problems and subtle lameness.[4] Furthermore, horses that received medical treatments had a 2.6-fold increased risk compared to others to sustain a musculoskeletal injury in the following 30 days, but not necessarily in the same location as the treatment.[4] Bertuglia et al. also reported that despite veterinary examinations twice weekly, horses with mild lameness may not have been referred to the veterinarian. Whether this is due to mild lameness going undetected by the trainer, or due to a trainer-assessment of a lower degree of asymmetric movement not warranting further consideration is unknown. An IMU system that objectively measures asymmetric movement could be used to pick up subjectively undetected asymmetric movement. Although definitive thresholds for what constitutes “normal” asymmetry are lacking, if movement asymmetry data is collected over time, an increase in individual horse’s movement asymmetry could potentially be useful as a trigger for further veterinary attention.

Throughout this study, to what extent asymmetric movement in a horse was considered a potential lameness issue or more of a training-related issue varied greatly between trainers. The same was true for the trainers’ management of potentially lame horses, i.e. when a horse was assessed to need veterinary attention and/or rest. This led to a bias regarding which horses were treated and how frequently joint injections were administered and makes it tricky to assess orthopaedic health in relation to orthopaedic veterinary treatment in this cohort. For example, the one horse that did not receive any joint injections during the entire study period showed substantial asymmetrical movement when assesses both objectively and subjectively. Our observations are corroborated by those of Vigre et al.,[5] who reported that the factor "trainer" affected the hazard of lameness, that the hazard of lameness in Standardbreds differed greatly between trainers and that their impression was "that the threshold for taking a horse out of optimal training varied between the participating trainers".[5]

Through this prospective, longitudinal study it would have been interesting to attempt to uncover any associations of movement asymmetry magnitude over time and the subsequent development of orthopaedic injuries; i.e. would horses with more asymmetric movement be more likely to suffer from orthopaedic pain? However, a combination of the substantial study drop-out as well as other contributing factors makes it difficult to construct a valid statistical analysis of this association with our current data. For instance, our asymmetry data could be collected close to or far away in time from the joint injections performed. As mentioned above, the trainers varied greatly in their management of potentially lame horses, excluding the occurrence of joint treatment as a suitable criterion for lameness. Further, the trainers were continuously updated on the measured asymmetry of their horses; some trainers used this information actively to determine which horses should receive veterinary attention, while others seemingly did not take this information into account. Commonly, multiple joints in multiple limbs were treated during one veterinary intervention, making the effect on our subsequently measured asymmetry difficult to determine. The cohort horses were treated by different veterinarians; veterinarians are likely to employ different treatment strategies for orthopaedic problems, leading to fewer or more joint injections for the same level of lameness and/or suspected diagnosis.

The goal of training a Standardbred trotter is for it to compete in races, however, many Standardbreds never race. For Standardbreds born in 2016 and registered as in training, the proportion that participated in at least one regular race as a three-year-old was 52% in Sweden,[18] and 46% in Norway.[19] The amount of horses born in 2016 that had raced in regular races as two-year-olds was 6.6% in Sweden.[20] As races for two-year-olds are not routinely held in Norway, there are no comparable data. As four-year-olds, the percentage of horses racing had risen to almost 57% (per 31.10.2020) in Norway,[19] for Sweden no preliminary statistics have been published for 2020 at this time. In our cohort, 64% of the recruited 114 horses competed in regular races as three-year-olds. This higher than average percentage is likely because of our selection of horses that are in professional training; these horses may be of both higher quality and receive a higher quality of training. They may also be under more intense pressure to race than the average Standardbred. Standardbred trotters in Norway and Sweden must complete a qualification race before they can participate in regular races. Data on national averages for the completion of qualification races are not published.

Ringmark et al.[13] followed 16 Swedish Standardbred trotters at one state-owned facility (Wången) over a period of 2½ years, from yearlings to three-year-olds. Movement asymmetry was measured 17 times per horse in this time period, with the same objective measurement system as used in our study. In this study, horses that qualified for races early in the season as three-year-olds showed less asymmetric forelimb movement, expressed as vector sum asymmetry, and had fewer joint injections performed than those who qualified later in the season.[13] Published results are for in-hand trials only. In our cohort there was no obvious difference between horses that completed a qualification race or not when looking at mean (vector sum) asymmetry for driven exercise during Year 1. In the present study, horses were not divided into early and late qualifiers as race participation was also dependent on multiple factors other than the individual horse, such as availability of races in the region and trainer preference and schedule.

In conclusion, our study shows that objectively measured movement asymmetry in young Standardbred trotters in training is substantial and ranges from mild to severe in magnitude. There is some evidence of an increase in asymmetry magnitude over time for hindlimb parameters, however, our results need to be interpreted with care due to the large number of horses dropping out during the study period. The most frequent orthopaedic veterinary intervention was therapeutic joint injections, which were most common for three-year-old horses in our cohort. Despite this, completion rates for qualification races as well as regular races were overall high.

Manufacturers' addresses

[a] Lameness Locator® by Equinosis LLC, Columbia, Missouri, USA

[b] Teppeteip, Clas Ohlson, Insjön, Sweden

[c] Snøgg Animal Polster, Norgesplaster AS, Vennesla, Norway

[d] Polar M450, Polar Electro, Kempele, Finland

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		Forelimb strides				Hindlimb strides			
Visit no	Number of horses	Mean	SD	Median	Range	Mean	SD	Median	Range
1	84	147	106	114	29 - 503	155	113	120	31 - 535
2	72	146	128	97	25 - 792	154	133	101	25 - 814
3	70	200	123	185	23 - 515	211	130	195	23 - 531
4	56	241	148	193	62 - 550	252	155	203	64 - 577
5	36	170	73	162	46 - 377	182	77	174	48 - 385
6	16	239	154	228	66 - 570	257	166	243	73 - 594
7	21	221	142	163	74 - 547	237	160	168	73 - 600
8	20	196	125	152	66 - 554	208	130	171	66 - 582

Table 1. Number of fore- and hindlimb strides included per visit

SD = standard deviation.

	Speed					
Visit no	Number of horses with data	Number of horses with missing data	Mean m/s	SD m/s	Mean km/h	SD km/h
1	77	7	5.0	0.6	18.2	2.3
2	70	2	5.7	0.6	20.5	2.1
3	65	5	5.7	0.8	20.6	3.0
4	53	3	6.0	0.9	21.4	3.1
5	33	3	6.0	0.8	21.5	2.9
6	16	0	6.3	0.7	22.5	2.6
7	21	0	6.1	0.8	21.8	3.0
8	20	0	5.9	0.7	21.2	2.3

Table 2. Mean trial speed per visit

SD = standard deviation.

		Asymmetry parameter									
		HDmin					HDmax				
Visit no	Side of asymmetry	Number of trials	Mean	SD	Median	Range	Number of trials	Mean	SD	Median	Range
1	Left	33	-8.6	9.9	-5.9	-51.3 to -0.5	41	-8.1	8.3	-6.1	-47.0 to -0.1
	Right	51	6.3	5.9	4.4	0.3 to 28.6	43	7.8	5.2	8.1	0.1 to 21.9
2	Left	31	-8.0	9.7	-5.5	-51.8 to -0.3	31	-11.7	13.1	-9.4	-65.5 to -1.2
	Right	41	8.6	6.7	6.8	0.3 to 25.6	41	7.1	7.8	4.7	0.1 to 32.2
3	Left	34	-8.4	7.8	-6.0	-31.4 to -0.2	27	-8.1	5.6	-7.3	-19.3 to -0.7
	Right	36	9.7	12.3	6.2	0.1 to 60.9	43	8.9	10.3	7.6	0.1 to 62.2
4	Left	29	-8.2	7.5	-5.6	-28.3 to -0.5	26	-5.9	4.8	-4.5	-16.4 to -0.2
	Right	27	10.0	8.4	8.6	0.1 to 42.1	30	9.5	11.6	6.5	0.4 to 58.4
5	Left	9	-12.1	11.2	-12.6	-37.6 to -1.5	14	-7.2	5.1	-7.1	-14.3 to -0.5
	Right	27	8.0	7.3	5.9	0.4 to 28.9	22	7.6	6.5	5.1	0.2 to 22.5
6	Left	12	-4.4	2.6	-4.2	-8.5 to -0.2	11	-6.2	3.9	-5.8	-12.5 to 0.0
	Right	4	6.6	5.5	6.0	0.8 to 13.5	5	16.3	20.5	6.8	5.6 to 52.8
7	Left	11	-11.2	17.8	-3.4	-58.3 to -0.7	9	-8.7	7.7	-4.8	-25.3 to 0.0
	Right	10	6.1	5.8	4.5	1.1 to 21.5	12	12.2	8.9	10.5	2.1 to 30.0
8	Left	13	-7.8	7.0	-5.2	-19.9 to -0.2	9	-4.8	4.9	-3.3	-15.6 to -0.1
	Right	7	7.2	6.6	5.1	0.7 to 18.7	11	6.8	3.9	7.1	1.7 to 12.3

Table 3a. Asymmetry parameter means, SD, medians and ranges for HDmin and HDmax

All values in mm. Side of asymmetry: Left = asymmetry parameter < 0 mm; right = asymmetry parameter > 0 mm. HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride. SD = standard deviation.

		Asymmetry parameter									
		PDmin					PDmax				
Visit no	Side of asymmetry	Number of trials	Mean	SD	Median	Range	Number of trials	Mean	SD	Median	Range
1	Left	42	-4.6	4.7	-3.1	-26.1 to 0.0	48	-3.9	2.7	-3.2	-10.5 to 0.0
	Right	42	5.0	4.9	3.6	0.3 to 29.0	36	3.2	2.5	2.9	0.2 to 10.7
2	Left	44	-4.3	4.1	-3.4	-24.0 to 0.0	39	-5.0	4.0	-3.2	-16.6 to -0.2
	Right	28	6.1	4.7	4.8	0.3 to 17.9	33	6.7	5.1	5.5	0.1 to 21.3
3	Left	39	-4.5	4.3	-3.2	-14.3 to 0.0	32	-5.4	4.1	-4.5	-15.3 to -0.4
	Right	31	5.8	8.7	2.8	0.3 to 48.0	38	3.9	3.6	2.6	0.3 to 14.6
4	Left	30	-5.4	4.5	-4.3	-19.1 to -0.1	28	-6.1	3.4	-5.8	-12.4 to -0.8
	Right	26	5.9	5.0	4.5	0.2 to 17.2	28	5.2	5.0	3.6	0.1 to 22.8
5	Left	16	-5.8	4.2	-5.7	-12.7 to 0.0	16	-7.8	4.8	-6.4	-16.5 to -1.5
	Right	20	5.3	3.4	4.3	0.3 to 14.2	20	5.6	3.7	5.4	0.3 to 16.3
6	Left	8	-5.0	4.7	-3.4	-14.9 to -0.6	12	-6.6	4.6	-6.2	-18.8 to -0.3
	Right	8	7.8	6.7	5.0	0.9 to 21.3	4	7.7	4.7	8.6	1.2 to 12.4
7	Left	9	-7.0	4.2	-7.8	-14.2 to -1.8	13	-6.3	4.9	-4.2	-17.0 to -0.9
	Right	12	8.5	4.5	8.0	1.5 to 16.7	8	4.5	3.2	4.4	0.9 to 9.3
8	Left	9	-4.4	3.6	-4.0	-9.8 to -0.8	14	-5.8	4.8	-4.9	-15.9 to -0.1
	Right	11	8.2	7.1	6.6	0.6 to 26.0	6	3.9	3.1	3.6	0.3 to 7.5

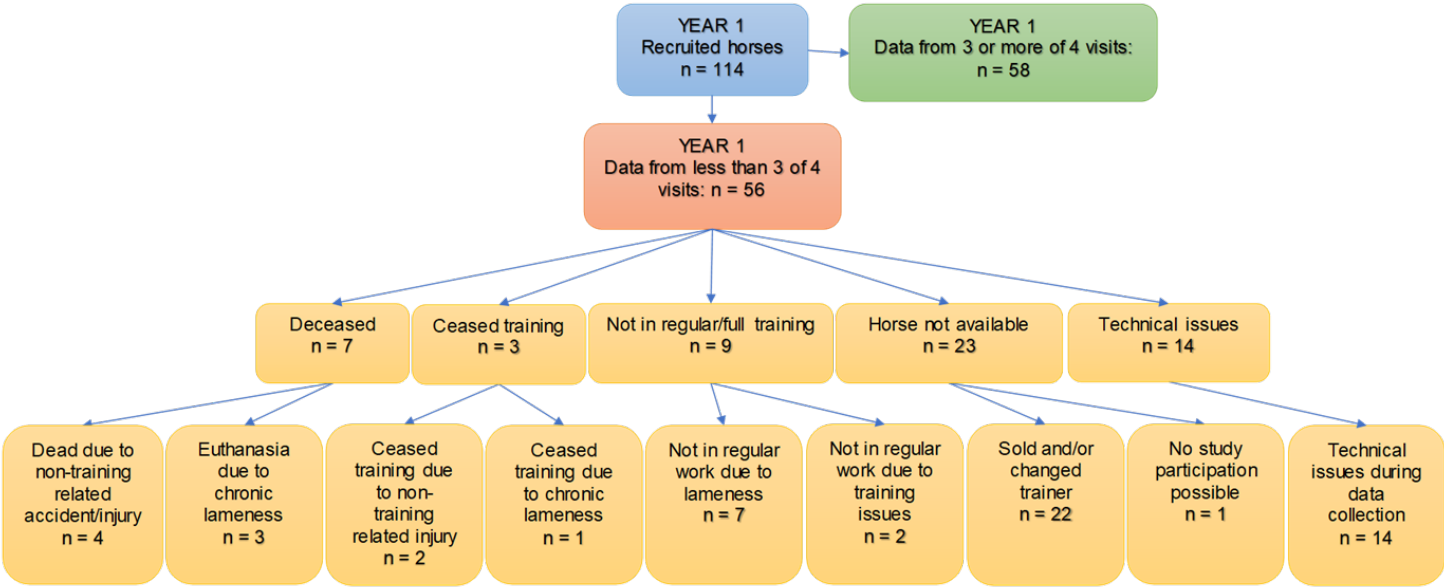
Table 3b. Asymmetry parameter means, SD, medians and ranges for PDmin and PDmax

All values in mm. Side of asymmetry: Left = asymmetry parameter < 0 mm; right = asymmetry parameter > 0 mm. PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride. SD = standard deviation.

		Treatment registered at visit no:								
Joint & limb:		1	2	3	4	5	6	7	8	Total number of injections
Carpus LF		NA	NA	1	1	4	5	6	8	25
Carpus RF		NA	NA	1	1	7	5	6	7	27
Fetlock joint LF		NA	NA		1	1		3	3	8
Fetlock joint RF		NA	NA		2	2			3	7
Coffin joint LF		NA	NA			1				1
Coffin joint RF		NA	NA			1		1		2
Hock LH		NA	NA	3				1	3	7
Hock RH		NA	NA	2	1	2			1	6
Stifle LH		NA	NA		2	4	2	4	2	14
Stifle RH		NA	NA	1	2	2	2	3	1	11
Fetlock joint LH		NA	NA		4	1		2	4	11
Fetlock joint RH		NA	NA			1	1	2	2	6
Coffin joint LH		NA	NA							0
Coffin joint RH		NA	NA							0
Unknown joint*	LF	NA	NA		1		2			3
	RF	NA	NA							
	LH	NA	NA							
	RH	NA	NA							
Total joints treated		NA	NA	8	15	26	17	28	34	128

Table 4. Overview over joint injection locations

Multiple injections considered representing one treatment course, were for the purpose of this study counted as one joint treatment. *Unknown joint: Information only available for which limb had been treated, not the specific joint. LF = left forelimb, RF = right forelimb, LH = Left hindlimb, RH = Right hindlimb. NA = Not applicable.


YEAR 1
Recruited horses
n = 114
YEAR 1
Data from 3 or more of 4 visits:
n = 58
YEAR 1
Data from less than 3 of 4
visits: n = 56
Deceased
n = 7
Ceased training
n = 3
Not in regular/full training
n = 9
Horse not available
n = 23
Technical issues
n = 14
Dead due to
non-training
related
accident/injury
n = 4
Euthanasia
due to
chronic
lameness
n = 3
Ceased
training due
to non-
training
related injury
n = 2
Ceased
training due
to chronic
lameness
n = 1
Not in regular
work due to
lameness
n = 7
Not in regular
work due to
training
issues
n = 2
Sold and/or
changed
trainer
n = 22
No study
participation
possible
n = 1
Technical
issues during
data
collection
n = 14

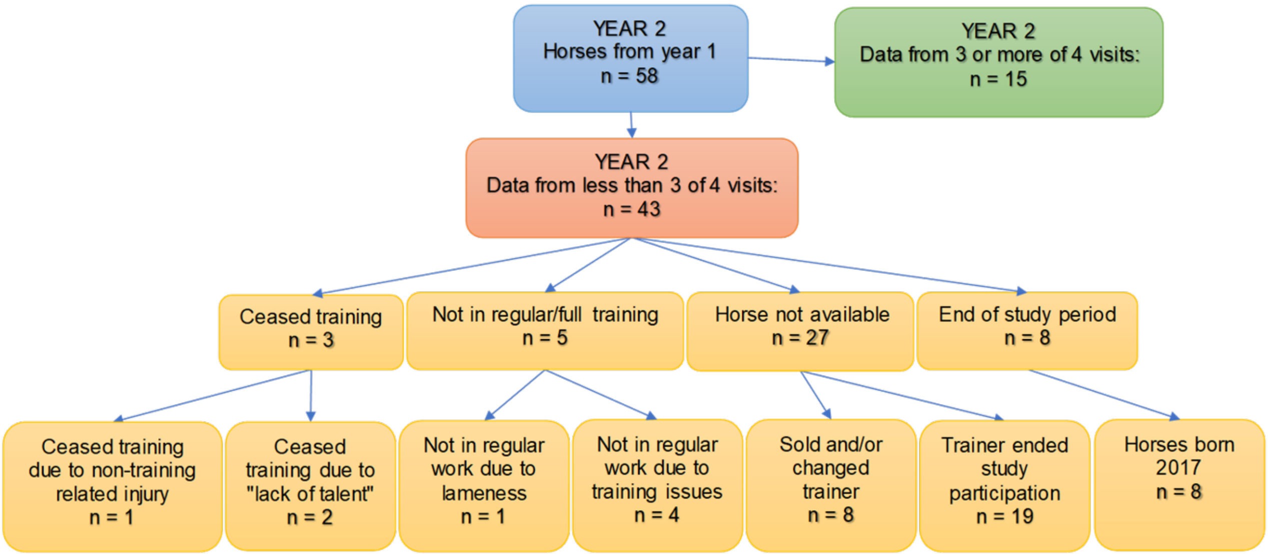
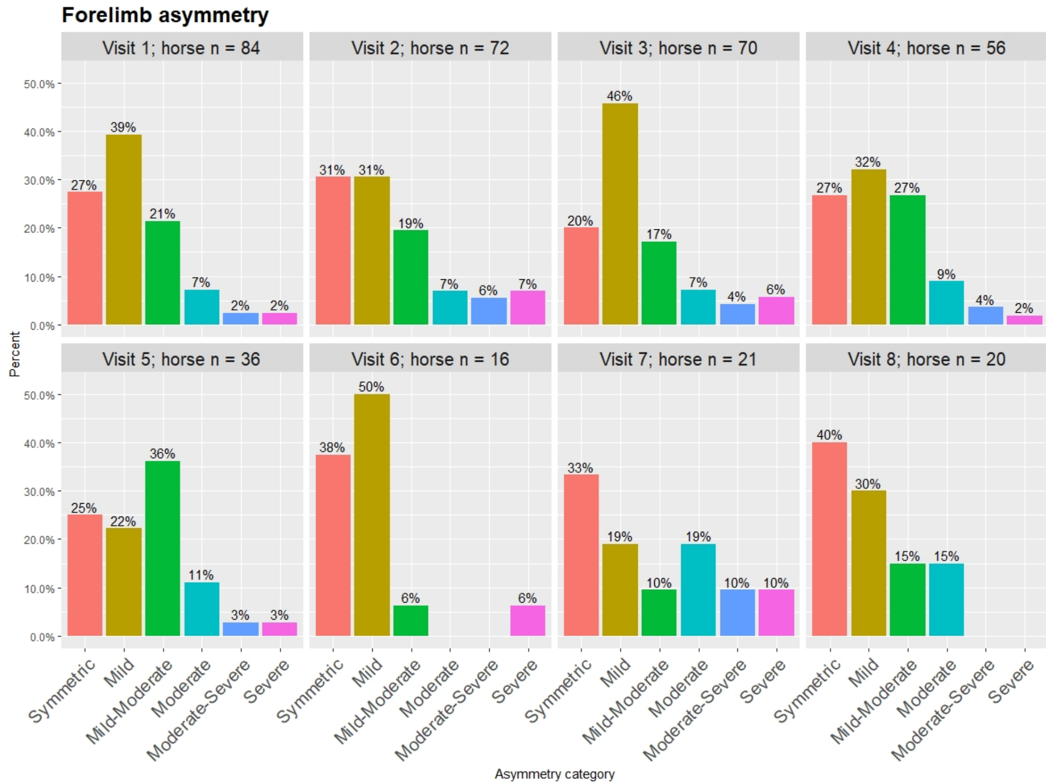


Figure 1. Flowcharts of recruited horses and reasons for study drop-out

Year 1 is defined as the first four visits (visit 1-4), from autumn as yearlings until autumns as two-year-olds, and Year 2 as the following four visits (visit 5-8) from winter as two-/three-year-olds until autumn as three-year-olds. Year 2: Of 19 yearlings born 2017, only eight participated until the end of the study period. The remaining 11 yearlings are included in Year 1 study drop-out categories (data from less than 3 of 4 visits).


Forelimb asymmetry
Visit 1; horse n = 84
Visit 2; horse n = 72
Visit 3; horse n = 70
Visit 4; horse n = 56
Visit 5; horse n = 36
Visit 6; horse n = 16
Visit 7; horse n = 21
Visit 8; horse n = 20
Percent
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Symmetric
Mild
Mild-Moderate
Moderate
Moderate-Severe
Severe
Asymmetry category

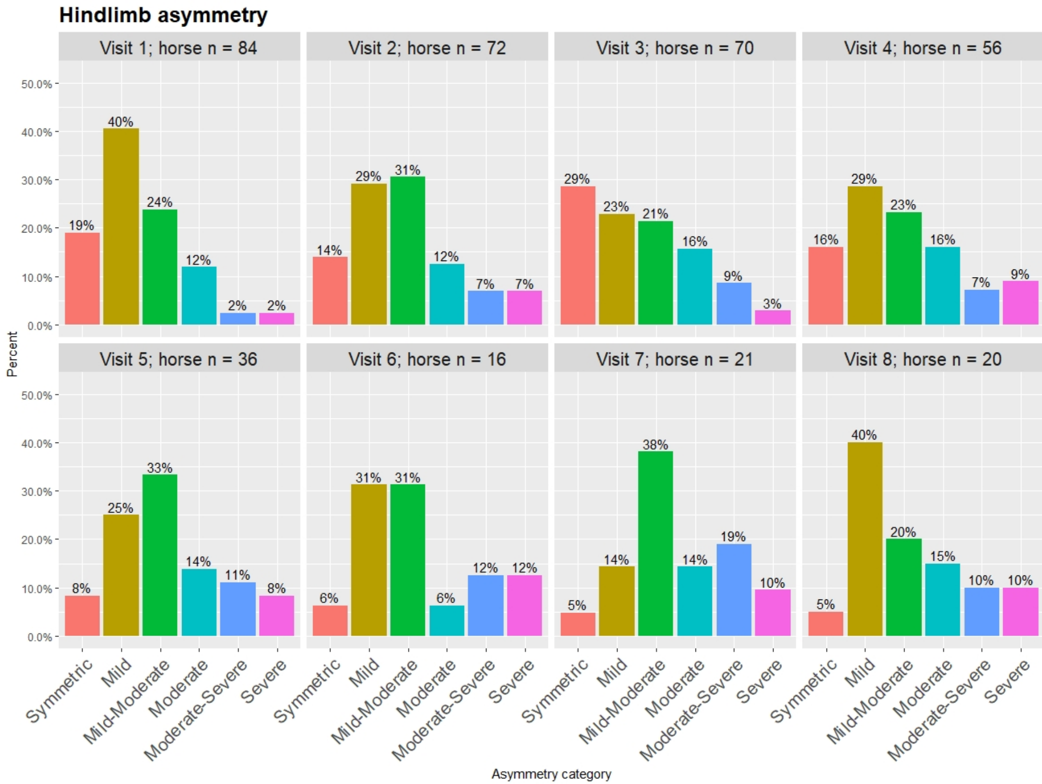


Figure 2. Distribution of limb asymmetry categories presented for combined left and right fore- or hindlimb parameters

Asymmetry in mm per category: Symmetric: Forelimb: 0-6/ Hindlimb: 0-3, mild: 6-12/3-6, mild-moderate: 12-18/6-9, moderate: 18-24/9-12, moderate-severe: 24-30/12-15, and severe: >30/>15.

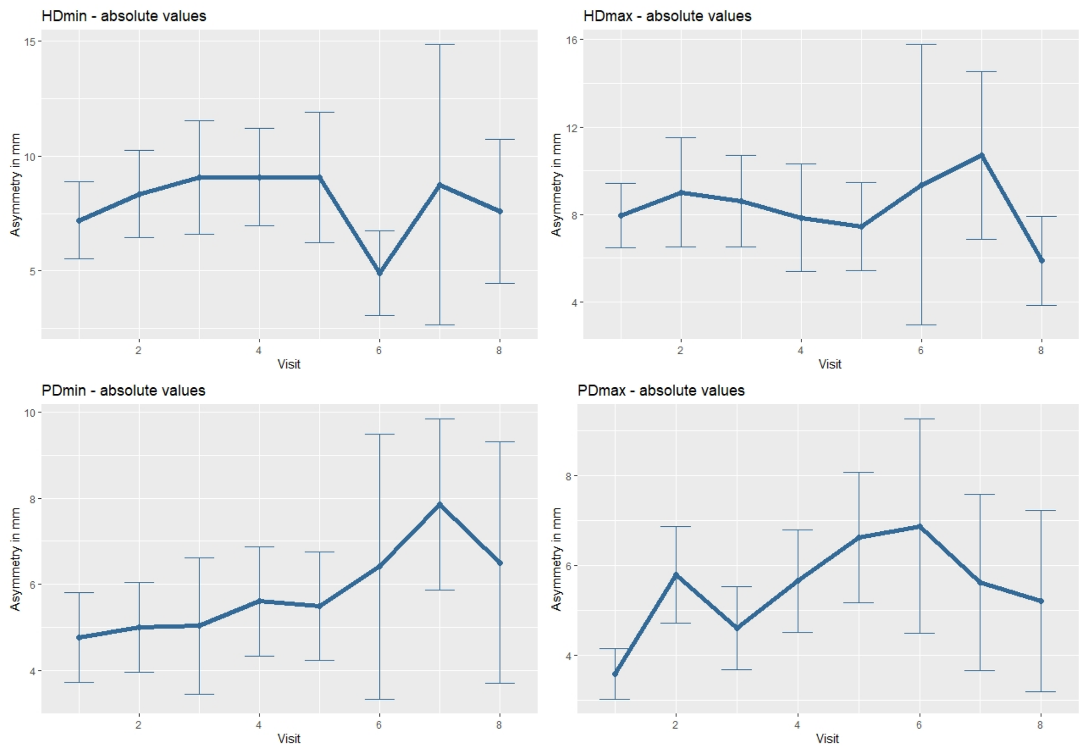


Figure 3. Mean asymmetry values for HDmin, HDmax, PDmin, PDmax per visit

Number of horses per visit (V); V1: 84, V2: 72, V3: 70, V4: 56, V5: 36, V6: 16, V7: 21, V8: 20. Error bars represent 95% confidence intervals. HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride. PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride.

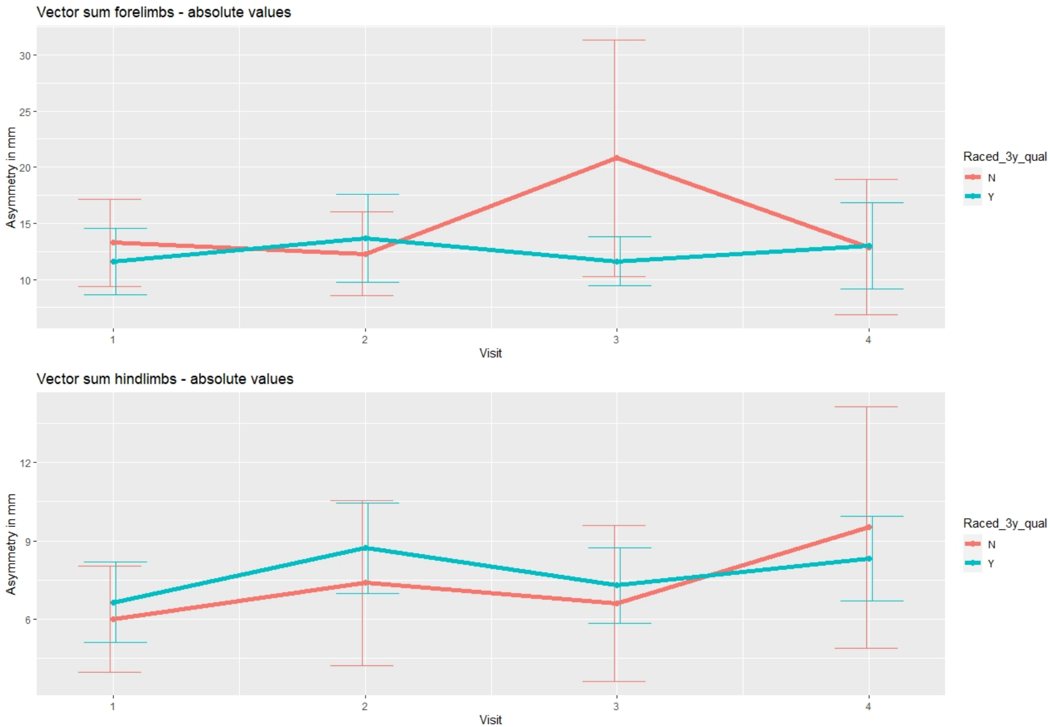


Figure 4. Asymmetry scores and completion of qualification race

Asymmetry means (vector sums) for 58 horses through visits 1-4. Error bars represent 95% confidence intervals. By the end of the year as three-year-olds: Horses completed qualification race n = 46, horses not completed qualification race = 12. Vector sum calculated as $\sqrt{(HDmax^2 + HDmin^2)}$ for forelimbs, and $\sqrt{(PDmax^2 + PDmin^2)}$ for hindlimbs. N = no, Y = yes.

		Age in months			
Visit no	Number of horses	Mean	SD	Median	Range
1	84	17.7	1.5	17.5	14.4 – 22.0
2	72	21.7	1.4	21.5	18.8 – 25.2
3	70	24.9	1.3	24.9	21.6 – 28.3
4	56	28.3	1.2	28.3	26.2 – 31.3
5	36	32.1	1.2	32.0	29.5 – 34.7
6	16	34.3	1.7	34.6	30.7 – 37.2
7	21	37.5	1.6	37.6	34.0 – 40.3
8	20	40.4	1.5	40.2	37.9 – 43.8

Supplementary Table S1. Age in months per visit

SD = standard deviation.

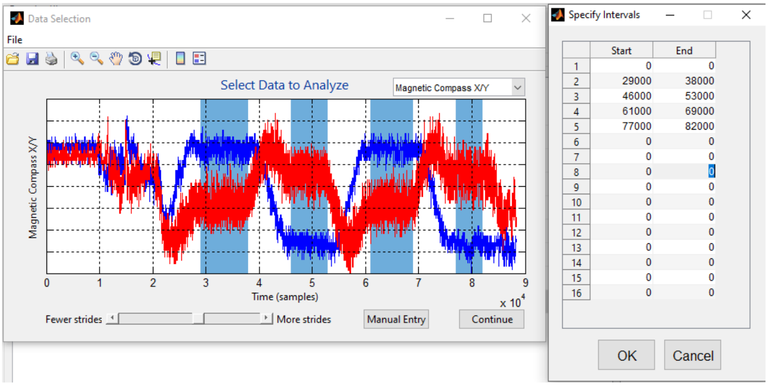
			Height in cm					
Visit no	Number of horses with data	Number of horses with missing data	Withers height: Mean	Withers height: SD	Pelvis height: Mean	Pelvis height: SD	Absolute difference withers – pelvis height: Mean	Absolute difference withers – pelvis height: SD
1	83	1	152.8	4.8	156.9	4.1	4.1	2.0
2	72	0	155.6	4.5	157.9	4.4	2.5	1.6
3	65	5	156.8	4.5	158.8	4.4	2.3	1.6
4	55	1	159.1	4.3	159.6	4.3	1.8	1.3
5	36	2	161.6	3.3	161.9	3.9	2.0	1.9
6	16	0	159.0	3.8	159.3	3.8	1.4	1.1
7	20	1	159.2	3.4	159.7	4.3	1.9	1.2
8	18	2	160.3	4.0	159.6	4.4	1.2	1.0

Supplementary Table S2. Height measured at the withers and pelvis per visit

SD = standard deviation. Absolute numbers are presented for the mean difference between withers and pelvis height; when height was measured, some horses were higher at the withers and some at the pelvis, giving a combination of values with either a positive or negative sign.

		Treatment registered at visit no.								
		1	2	3	4	5	6	7	8	Total
No. of horses available per visit		84	72	70	56	36	16	21	20	
No. of horses treated in a joint between visits		0	0	5	9	11	9	10	12	56
No. of horses that had joint injections for the first time		0	0	5	7	9	6	4	2	33
No. of limbs treated		0	0	8	12	23	14	24	27	108
No. of joints treated		0	0	8	15	26	17	28	34	128
No. of horses with joints in more than one limb treated per intervention		0	0	3	3	9	5	7	12	39
Other orthopaedic veterinary treatments	Plantar ligament pin firing	0	1	3	0	1	0	0	0	5
	Wound management	0	3	3	0	0	0	1	0	7
	Assessment/treatment for lameness without joint injection	0	4	0	6	1	0	0	1	12
	Arthroscopy (not OC/D related)	0	0	0	0	0	2	1	0	3
	Splint bone amputation due to fracture	0	1	0	0	0	0	0	0	1
	Carpal canal injections (bilateral)	0	0	0	1	1	0	0	0	2

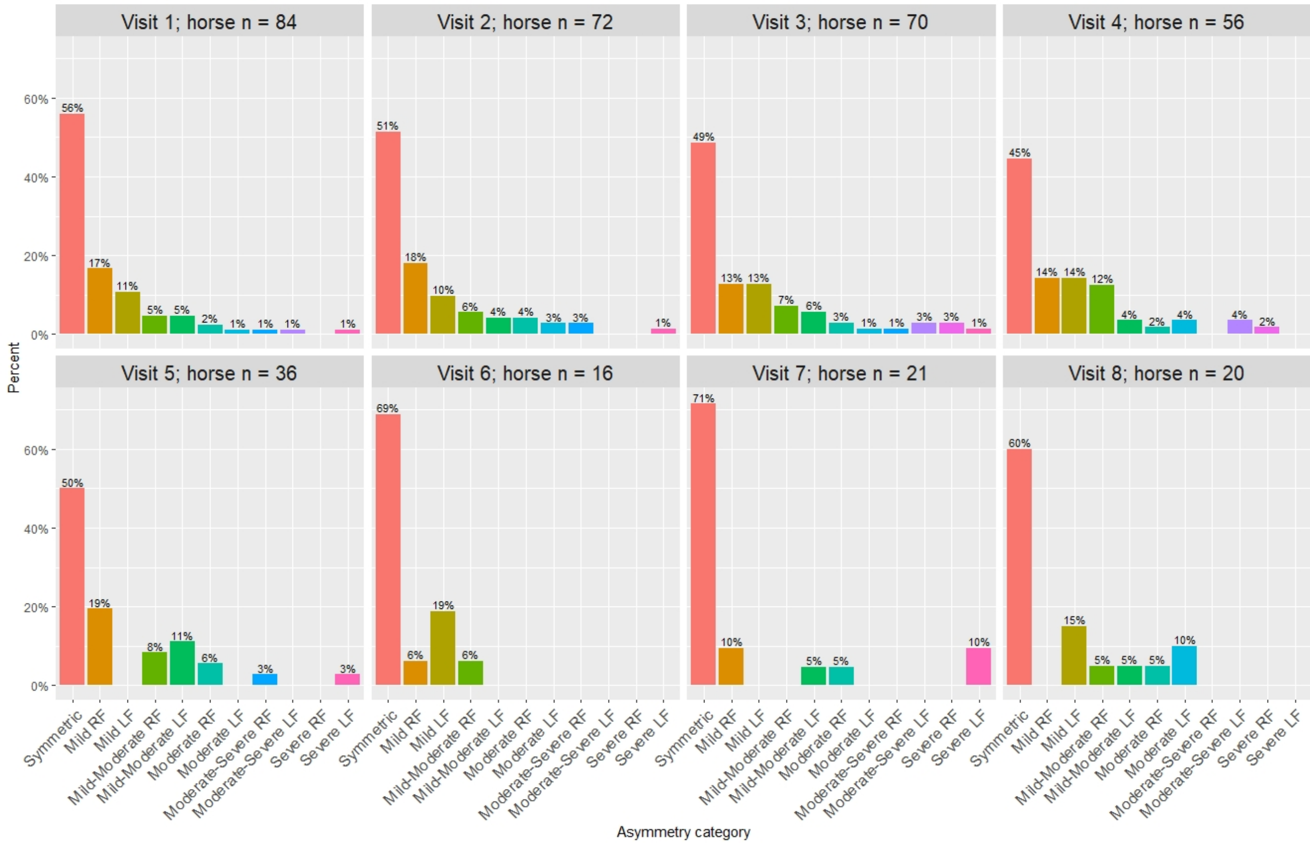
Supplementary Table S3. Overview over orthopaedic veterinary interventions

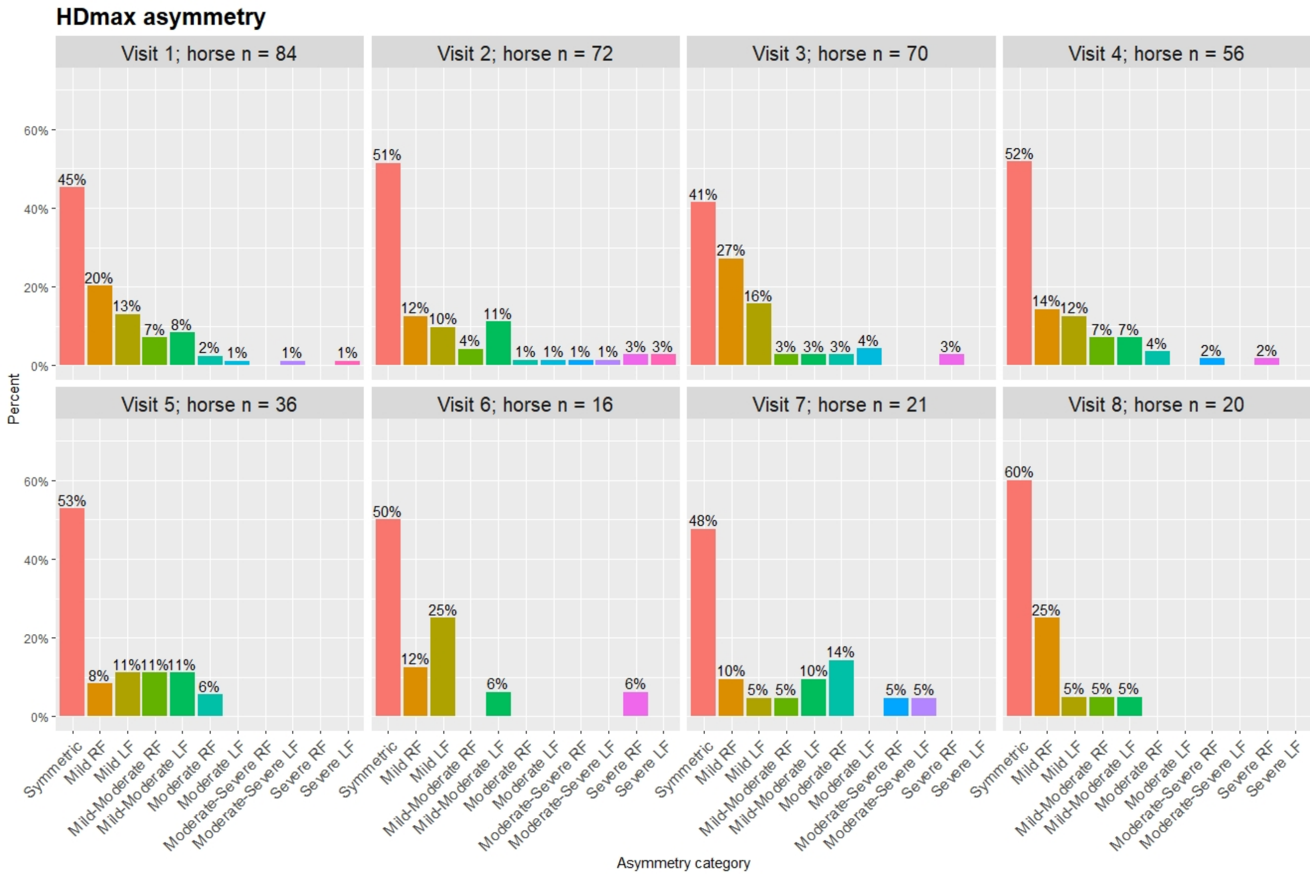


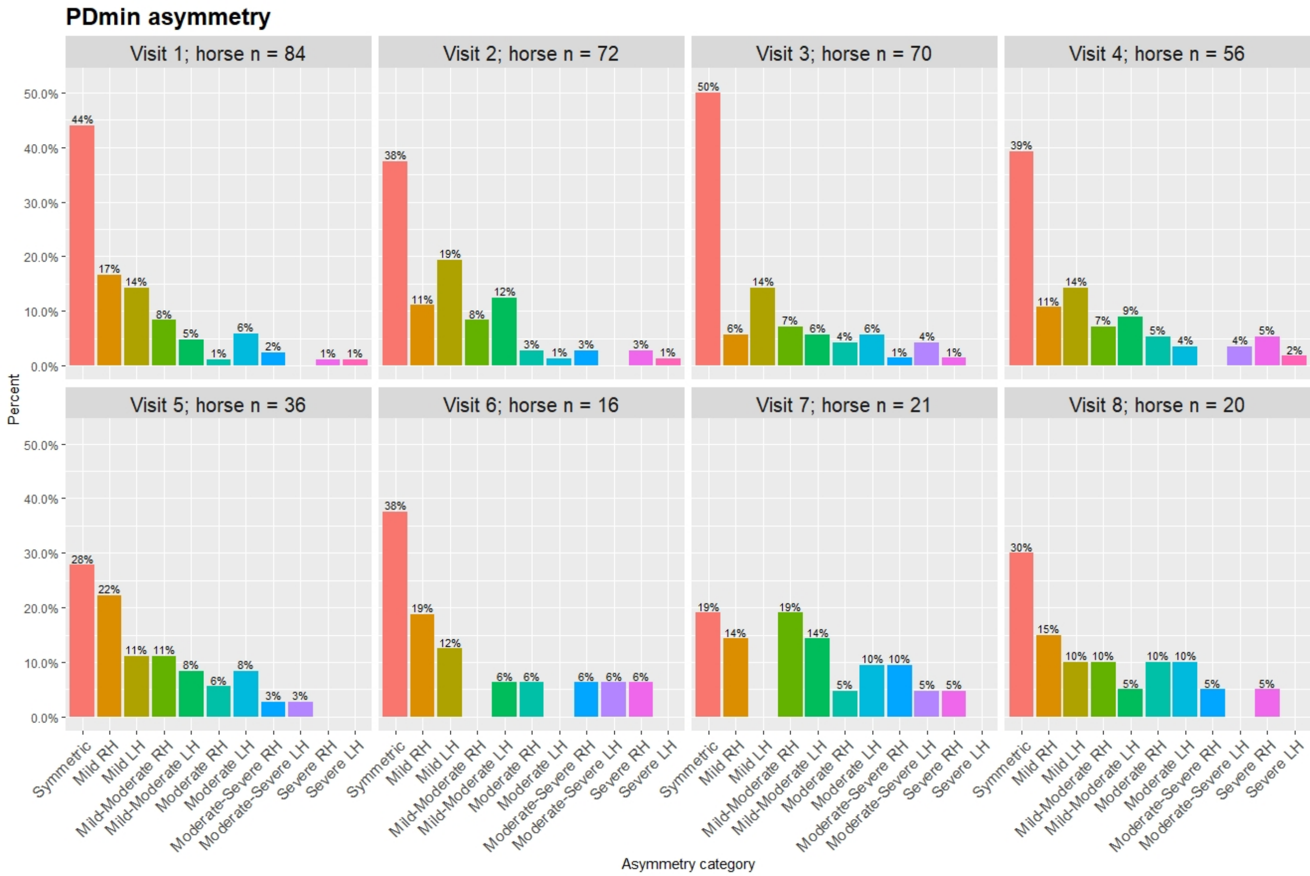
Supplementary Figure S1: Example of straight track stride selection

Example data from an oval trotting track trial. Horizonal magnetometer data tracings show that the horse is moving in a constant direction, i.e. along the straight long sides of the track; sloping tracings show that the horse is moving in a changing direction, i.e. trotting through a track curve.

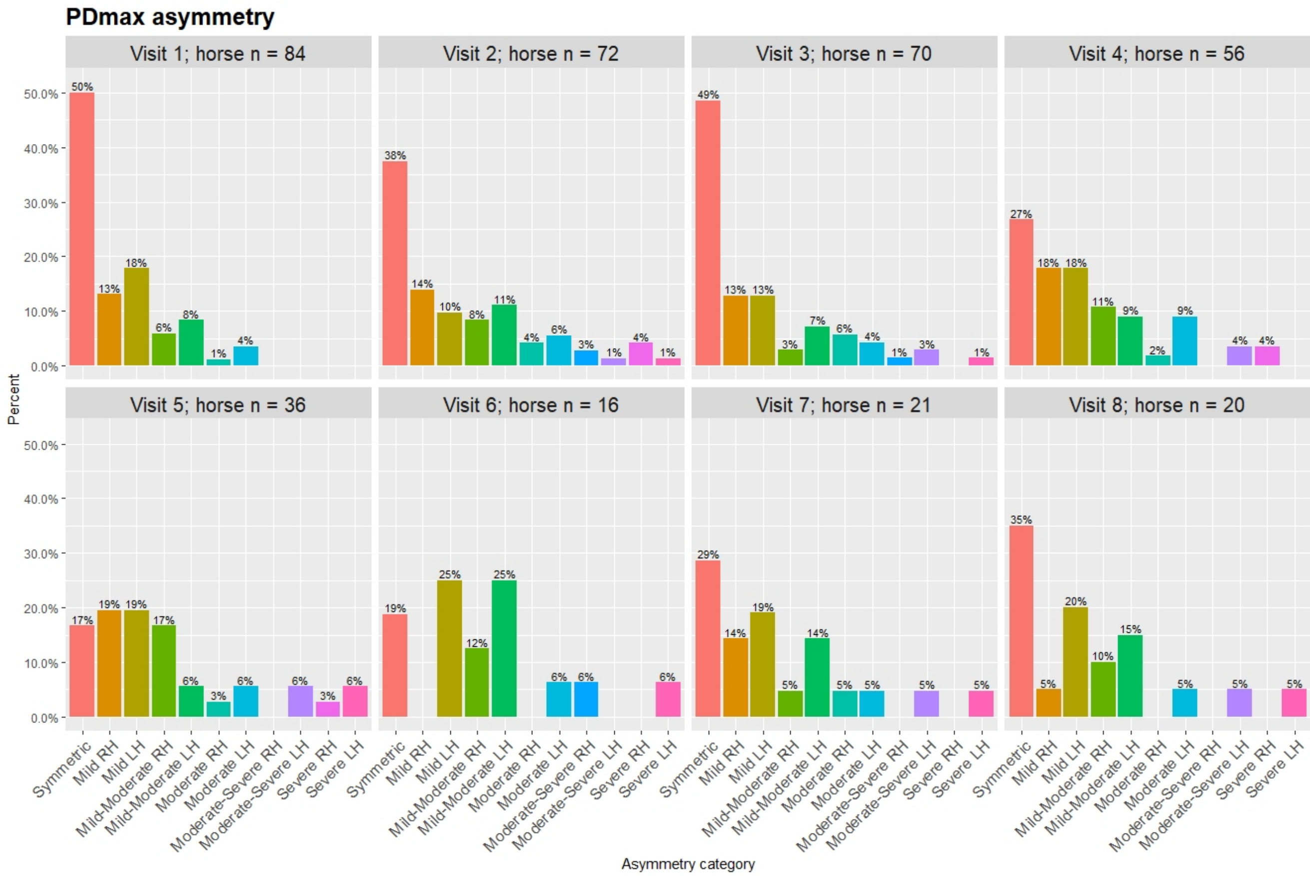
HDmin asymmetry




HDmax asymmetry
Visit 1; horse n = 84
Visit 2; horse n = 72
Visit 3; horse n = 70
Visit 4; horse n = 56
Visit 5; horse n = 36
Visit 6; horse n = 16
Visit 7; horse n = 21
Visit 8; horse n = 20
Percent
0%
20%
40%
60%
Symmetric
Mild RF
Mild LF
Mild-Moderate RF
Mild-Moderate LF
Moderate RF
Moderate LF
Moderate-Severe RF
Moderate-Severe LF
Severe RF
Severe LF
Asymmetry category



PDmin asymmetry
Visit 1; horse n = 84
Visit 2; horse n = 72
Visit 3; horse n = 70
Visit 4; horse n = 56
Visit 5; horse n = 36
Visit 6; horse n = 16
Visit 7; horse n = 21
Visit 8; horse n = 20
Percent
Asymmetry category
Symmetric
Mild RH
Mild LH
Mild-Moderate RH
Mild-Moderate LH
Moderate RH
Moderate LH
Moderate-Severe RH
Moderate-Severe LH
Severe RH
Severe LH


PDmax asymmetry
Visit 1; horse n = 84
Visit 2; horse n = 72
Visit 3; horse n = 70
Visit 4; horse n = 56
Visit 5; horse n = 36
Visit 6; horse n = 16
Visit 7; horse n = 21
Visit 8; horse n = 20
Percent
Asymmetry category
Symmetric
Mild RH
Mild LH
Mild-Moderate RH
Mild-Moderate LH
Moderate RH
Moderate LH
Moderate-Severe RH
Moderate-Severe LH
Severe RH
Severe LH

Supplementary Figure S2. Distribution and magnitude of asymmetry for HDmin, HDmax, PDmin, PDmax, presented for each limb

Asymmetry in mm per category: Symmetric: Forelimb 0-6/ Hindlimb 0-3, mild: 6-12/3-6, mild-moderate: 12-18/6-9, moderate: 18-24/9-12, moderate-severe: 24-30/12-15, severe: >30/>15. HDmin/HDmax = difference in head minimum/maximum positions between right and left portions of the stride. PDmin/PDmax = difference in pelvis minimum/maximum positions between right and left portions of the stride. LF = left forelimb, RF = right forelimb, LH = Left hindlimb, RH = Right hindlimb.

Lista Errata

Page	Line	Changed from	Changed to
3	22	movement	measurement
10	10	three-year-old-season	three-year-old season
10	14	how non-lame and lame horses move	**how non-lame and lame horses move**
13	23	”.	.”
19	6	metre	metres
25	8	terms	term
26	6	are	is
37	30	;	:
46	10	two- or three-year olds	two- or three-year-olds
54	2	Lameness Locator® by Equinosis LLC	Equinosis Q with Lameness Locator software
55	Table 6	14 trainers	13 trainers
55	Table 6	2016	2016/2017
67	16	rankings	ranking
79	1	has	have
79	13	Drevemo et al.	Drevemo et al.[60]
80	18	authors’	author’s
82	5	“.	.”
93	19	endure	ensure
124	24	the New York Times	*The New York Times*

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