Vertical movement asymmetries in 3-year-old SWB horses and their associations with scores in Young Horse Tests

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Abstract

To improve equine performance and welfare, many attempts have been made to investigate associations between performance, longevity, orthopaedic health, conformation and talent. Causal relationships between these qualities supported by strong scientific evidence are lacking. This is partly due to absence of objective, accurate and repeatable metrics. The Swedish Warmblood is a sport horse bred for performance and to improve performance so called “young horse tests” (YHT) are arranged each year. They provide insight to the young horse population’s conformation and talent. Linear profiling is a recently introduced method thought to increase objectivity and measurability for visual assessment of conformation, gait, jumping and behavioural qualities in the young horse tests.

Increased objectivity is also achieved in gait assessment research through kinematic tools. Such tools, offering objective measurements of vertical movement asymmetry of the head and pelvis, have proven useful in detection of subtle lameness in the horse. Recent studies using these tools have shown a high prevalence of vertical movement asymmetries in horses considered sound, including foals. The aim of this study was to investigate possible associations between scores in the YHT and the degree of vertical movement asymmetry in 3-year-old Swedish Warmblood horses using an objective gait analysis tool. Additionally, possible differences in vertical movement asymmetry between horses bred for different equestrian disciplines were investigated.

A total of 116 three-year-old Swedish Warmblood horses were recruited to the study at five YHT events. The horses were recorded at the trot on a flat surface using a smart phone gait analysis application. Each horse was assigned to either of the categories jumping, dressage, all-round or thoroughbred, based on their pedigree. Scores from the YHT were retrieved from the Swedish Warmblood Association (SWB) and transformed into 18 factors. From the four asymmetry values retrieved from the motion measurements, three mean asymmetry values per trial were calculated for each individual: forelimb asymmetry, hindlimb asymmetry and total asymmetry. The total asymmetry, i.e. sum of all asymmetry values, was significantly ($p < 0.01$) lower in horses bred for dressage than in horses bred for show jumping. Correlation coefficients between asymmetry values and YHT score factors were calculated using Pearson’s method. Seventeen significant ($|r| \geq 0.20$) correlations were found and subsequently used to construct linear models. In these models, fourteen YHT score factors significantly ($p \leq 0.05$) explained their respective asymmetry value. These factors consisted of one jumping factor, three conformational factors and ten gait related factors. The coefficient of determination was generally low (adjusted $r^2 < 0.10$).

Overall, what is considered to be good gaits in walk and trot seems to be associated with a lower degree of vertical movement asymmetry. There are however some limitations to the study. The study population is small (n = 116), and potentially skewed in the sense that it likely includes the best developed 3-year-old SWB horses. Also because of novel data handling, the practical implications can’t be fully determined. The results do all the same raise interesting questions about human conception of subtle gait asymmetries and the importance of vertical movement symmetry to performance in the Swedish Warmblood and should be further investigated.

Keywords orthopaedic health, objective gait assessment, conformation, linear profiling, movement asymmetry, artificial intelligence, computer vision, Swedish Warmblood

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Abbreviations

Atot	Total asymmetry (HDmin + HDmax + PDmin + PDmax)
Atot.c	Total asymmetry, centred
EBV	Estimated Breeding Value
HDmax	Head difference maximum
HDmin	Head difference minimum
Htot	Sum of forelimb asymmetry (HDmin + HDmax)
Htot.c	Sum of forelimb asymmetry, centred
KWPN	Royal Dutch Warmblood Studbook
PDmax	Pelvis difference maximum
PDmin	Pelvis difference minimum
Ptot	Sum of hindlimb asymmetry (PDmin + PDmax)
Ptot.c	Sum of hindlimb asymmetry, centred
ROM	Range of Motion
RHQT	Riding Horse Quality Test
SWB	Swedish Warmblood Association
WFFS	Warmblood Fragile Foal Syndrome
YHT	Young Horse Test

1. Introduction

1.1 General introduction

Different conformation, gait and jumping characteristics are by tradition believed to predict horse's potential for performance and soundness. To improve equine performance and welfare many attempts have been made to investigate the associations between performance, longevity, orthopaedic health, conformation and talent in the horse (Braam *et al*. 2011; Ducro *et al*. 2007, 2009; Holmström &. Philipsson 1993; Jönsson *et al*. 2014a; Jönsson *et al*. 2014b; Magnusson & Thafvelin 1990; Wallin *et al*. 2001). Causal relationships between these qualities supported by strong scientific evidence are lacking. Unsettled definitions, difficulties in quantification, confounding factors and complex interactions make the search for causal relationships challenging.

The Swedish Warmblood is bred for performance. To improve performance and conformation qualities, so called "young horse tests" (YHT) are arranged each year, and since rate of participation is decent (around 40% of eligible three-year-olds) they provide insight to the young horse population. Linear profiling, a method of describing characteristics on a scale between two biological extremes, has added a new dimension to the tests and hopes are it will facilitate research through increased objectivity.

Increased objectivity is also achieved in gait assessment research through kinematic tools. Such tools, offering objective measurements of vertical movement asymmetry of the head and pelvis, have proven useful in detection of subtle lameness in the horse, but studies have shown a large proportion of owner-sound horses displaying asymmetries above lameness thresholds (Leclerq *et al*. 2023; Persson-Sjodin *et al*. 2019; Pfau *et al*. 2016; Rhodin *et al*. 2016, 2017), complicating interpretation of measurements. Recent studies also revealed similar levels of movement asymmetries in foals (Zetterberg *et al*. 2023) and one-year-old Standardbred trotters in the beginning of their training (Kallerud *et al*. 2021).

1.2 Aims of the study

The aim of this study was to investigate possible associations between scores in the YHT and degree of vertical movement asymmetry in three-year-old Swedish Warmblood horses using an objective gait analysis tool. We also wanted to investigate possible differences in vertical movement asymmetry between horses bred for different equestrian disciplines.

2. Literature Review

2.1 The Swedish Warmblood

The Swedish warmblood originates from cavalry horses (Graaf 2004). Historically these were mostly of Swedish landrace type but Russian, oriental, Anglo-Norman, English thoroughbred and above all Hanoverian horses have been used to improve their quality. Following great Swedish equestrian success in the 1924 Olympic games, voices were raised to include a breeding objective for horses suited for competition in the breeding goal for the Swedish warmblood. Hence the formation of the first Swedish breeding association for warm-blooded horses, later called the Swedish Warmblood Association (SWB), in 1928. The SWB studbook is open, meaning horses of different warmblood ancestry that correspond to the SWB breeding objective can be added to the studbook (SWB 2023b).

Ablondi *et al*. (2019b) compared the SWB horse to the Exmoor pony, a breed not intended for sport performance, to describe what genetically signifies the SWB breed. Results confirmed there has been a selection for performance in equestrian sports within the SWB breed, as the worst performing SWB horse was genetically superior in equestrian sports to the best performing Exmoor pony. This agrees well with the findings of Viklund *et al*. (2010), who demonstrated that the genetic progress for the main equestrian disciplines in the SWB, dressage and show jumping, has increased substantially from the mid 1980s. Analysis of high-density genotype information by Ablondi *et al*. (2019a) has confirmed a tendency of division of the SWB breed into two populations specialized in dressage and show jumping, respectively. Ablondi *et al*. (2019b) showed genes known to be related to fertility, behavior and physical abilities seem to have been targeted in the selection of animals for breeding within the SWB horse. Selection was evident in regions known to be involved in nervous system functionality and muscle contraction and development.

2.1.1 Achieving the breeding objective

The current overall breeding objective for the SWB horse stated by the SWB is to produce a "Noble, correct and durable warmblood horse that through performance-oriented temperament, rideability, good movement and/or jumping ability is internationally competitive" (SWB 2021). The breeding objective is specified further for conformation, dressage, show jumping, eventing, health and durability and temperament respectively. According to the breeding plan, this is achieved through working towards a genetic gain as big as possible, taking biological and ethical aspects into consideration (SWB 2021). An essential practice is the systematic evaluation of mares, stallions and young horses which together with competition results and relatives' performances constitutes the foundation of their individual estimated breeding values (EBVs). The EBVs indicate how the individual is expected to pass down different traits to its offspring. This can be used by breeders to make educated decisions when planning parent combinations.

2.1.2 Assessment of the young Swedish Warmblood: Young Horse Tests and Riding Horse Quality Tests

The wide assessment of young Swedish Warmblood horses began in 1973 when the riding horse quality test (RHQT) was introduced for four-year-old horses (Viklund *et al*. 2011). An additional test, the young horse test (YHT), was established in 1999 for three-year-old horses to facilitate an earlier selection of talented horses for sport or breeding, as well as to encourage handling of the young horse. In 2018, about 40% of the eligible Swedish Warmblood horses participated in YHTs (Viklund & Eriksson 2018). Gait and show jumping scores from evaluations of young horses have in multiple warmblood studbooks been shown indicative of future competition performance in dressage and show jumping, respectively, proving the relevance of these tests to breeders (Ducro *et al*. 2007; Viklund *et al*. 2010).

In both the RHQT and YHT the horses are subjectively assessed by trained judges in relation to the breeding objectives. They are assigned evaluating scores from 1 to 10 for a number of traits, where 10 is closest to the breeding objective (SWB 2021). In the YHT all horses are assessed as both jumping and dressage talents (SWB 2023c), while in the RHQT they can be assessed as either dressage talents, jumping talents or both (SWB 2023a). At first the tests included a veterinary examination that led to individual health scores, but the examination was excluded from the tests in 2006 (Bonow *et al.* n.d.).

To achieve increased objectivity and measurability in the evaluations and facilitate further identification of desirable traits within the SWB horse a linear scoring system was introduced in addition to the traditional evaluating scores in 2013 (SWB 2014). Linear profiling is a method that has been used successfully in breeding programs in other species (Duensing *et al*. 2014). It has had an increasing importance in European warmblood studbooks, elevating the quality of phenotype documentation (Duensing *et al*. 2014) as it has in the SWB studbook as well (Viklund & Eriksson 2018). The design of this scoring system differs from the traditional in that the linear traits are scored on a 9-step scale from one biological extreme to the other with population mean in the middle and no defined optimum. These scores are assigned by the same team of judges that give the evaluating scores and a detailed description of the system used within the SWB can be found on the SWB website (SWB 2014). The number of scored traits depends on the type of breeding evaluation event i.e., the age of the horse. In the YHT here are a total of 50 traits; 20 conformation traits, 16 gait traits, 13 jumping traits and one behavioural trait (SWB 2014).

Nazari-Ghadikolaei *et al*. (2023) performed factor analysis on both the linearly scored traits and the evaluated traits used in YHT and concluded this could be useful in future research. Factor analysis is a method used to reduce the amount of observed and correlated variables to a lesser number of underlying factors. In the study in question there were 18 factors, consisting of 14 factors from linearly scored traits and four from evaluating traits. The variance explained by the factors ranged from 2% to 83%. The best explained traits were those related to size, proportions, show jumping and a few gait traits whilst the lowest percentage of variance explained was for several leg conformation traits, walk suppleness and backline conformation.

2.2 Associations between orthopaedic health, performance, longevity, conformation, gait quality and show jumping technique in the Swedish Warmblood

The SWB breeding objective is focused on longevity and performance in competition. What is assessed in the YHT and RHQT can be summarized as conformation, gait quality and show jumping technique. Orthopaedic health is arguably the link between desired and assessed qualities, being a prerequisite for performance and longevity and believed to be a consequence partly of conformation (Magnusson & Thafvelin 1990; Holmström & Philipsson 1993; Jönsson *et al.* 2014b).

Figure 1. Orthopaedic health as the link between assessed and desired qualities in the SWB horse.

Unsettled definitions, difficulties in quantification, confounding factors and complex interactions between all these qualities make the search for causal relationships challenging. Generally positive associations between conformation, health, performance and longevity have been reported in the SWB horse using data from RHQT (Jönsson *et al*. 2014a). Performance in the SWB horse is most commonly measured as accumulated points from official competition. Very few studies of longevity of the SWB horse in relation to abovementioned qualities have been performed using true longevity as life span in years (Wallin *et al*. 2001), probably due to unavailability of information on survival. Instead, the longevity measure most commonly used is a type of "functional longevity", defined as years in competition (Braam *et al*. 2011; Jönsson *et al*. 2014a). Conformation, gait quality and show jumping technique are all qualities that the SWB define in their manuals for evaluations (SWB 2014).

Orthopaedic health can be defined in different ways. One useful definition is from a study in which most trainers agreed health could be defined as lack of injuries negatively influencing training and racing (Magnusson & Thafvelin 1990). The authors also emphasized that the border between sound and unsound is floating.

Training effect is a confounder of interest discussed by (Braam *et al*. 2011). They reported that SWB horses with success, defined as placings, in more than one discipline by the age of six had significantly more years in competition than all other competing horses, possibly indicating a positive association between performance and longevity. The authors suggest the increased number of years in competition could be a positive effect of an all-round training of the young horse, but also acknowledge the confounding effect of talent; a horse perceived as talented is more likely to get advantages in training and consequently enter competition at an earlier age, resulting in more results in competition.

In addition, there may be numerous confounders that are still unknown. Recently Ablondi *et al*. (2022) presented findings of a positive effect of the warmblood fragile foal syndrome (WFFS) allele, otherwise known to cause a lethal condition in equine foetuses and foals when inherited from both parents, on a number of gait traits in the SWB horse including elasticity, primarily dressage horses. The authors suggest selection for carriership of the WFFS allele within the SWB breed might be a result of impaired collagen structure enabling the carriers to a more extreme locomotion pattern.

2.2.1 Performance and longevity

Braam *et al*. (2011) found number of years in competition to be a representative measure of potential for both longevity and performance in the SWB horse. The genetic correlations between performance in competition and RHQT traits on one hand and longevity on the other were highest for jumping traits, whereas the correlations were considerably lower for dressage traits. This is supported by findings by Bonow *et al*. (n.d.) where show jumping traits in YHT had a positive linear relationship with future competition results, whilst gait traits had a curvilinear relationship with performance in dressage competition indicating an intermediate optimum. Interestingly, Wallin *et al*. (2001) demonstrated opposite trends for scores in RHQT and longevity measured as life span in years. The relationship between jumping ability in RHQT and risk ratio for early culling was curvilinear, indicating that show jumping horses with intermediate talent had the greatest chance of long-term survival. On the contrary, a higher overall gait score was associated with greater longevity, corresponding well to later findings about movement in trot by Jönsson *et al*. (2014a).

It can be hypothesized this positive gait-longevity trend could change with breeding progress. Ablondi *et al*. (2022) concluded that the WFFS allele had a favorable effect on several performance traits, especially those related to movement in dressage bred horses. They had a more elastic trot with a longer stride and a hindlimb position more under the body. Assuming these horses have an impaired collagen structure and extreme locomotion, it is reasonable to question if they will have a greater longevity.

Associations were also seen between walk traits, health and longevity. The same type of qualities that would be favorable in trot; hindlimb activity, overreach, free shoulder movements and good rhythm; were also in walk positively correlated with locomotion score based off SWB RHQT veterinary examination (Jönsson *et al*. 2014b) and longevity (Jönsson *et al*. 2014a). Similarly, stiff movement and small overreach in walk were qualities negatively associated with the locomotion score (Jönsson *et al*. 2014b) just like in trot (Jönsson *et al*. 2014a). The WFFS carriers' walk was also found to have a more even cadence and a longer stride (Ablondi *et al*. 2022). For dressage bred horses the rhythm in canter was more even than non-carriers, a relationship that was inverted for show jumping bred horses.

2.2.2 The influence of conformation

Most studies investigating the relationship between conformation and performance in the SWB horse have used data from the subjective conformation assessments in the RHQT or YHT. Jönsson *et al*. (2014a) concluded that noble body type, intermediate size, slightly sloping shoulder, well positioned neck, long croup and well-developed withers were genetically associated with increased longevity and lifetime performance in the SWB horse. The most negative associations were found for small horses with short limbs, deep thorax and steep shoulder angle. Toed-in forelimb deviation, offset knees and narrow at the carpus were also negatively associated with lifetime performance, as in lifetime accumulated points, and longevity, as in years in competition. The optimum height at withers for health resembled that for increased longevity. When studying Dutch Warmbloods (KWPN) Ducro *et al*. (2009) found that horses performing at elite level in dressage and show jumping to a larger extent were of what is considered better conformation than horses performing at lower levels.

Ablondi *et al.* (2022) described significant differences in conformation between carriers of the WFFS allele and non-carriers. This together with the evidence of selection for this allele in dressage horses could be regarded as indirect evidence that the associated conformation traits are advantageous to dressage performance. The dressage bred carriers had longer bodies, necks and loins, as well as a more arched necks, lower withers, shorter croup and forelimbs more over the knee than non-carrier dressage-bred horses. The show jumping bred carriers had longer loins and a more sloping croup than their corresponding non carriers.

In an effort to increase objectivity when comparing conformation and performance, Holmström & Philipsson (1993) attempted measuring bone axis lengths and joint angles using both direct measurements on the horses' bodies and measurements obtained from photographs. They observed several significant associations between measurements, gait and show jumping scores in the RHQT and subsequent competetion results. Lesser slope of the femur length axis, smaller hip joint angle, height at withers, length of femur and length of humerus were all positively associated with the total gait score. Twenty three percent of the variation in the evaluating gait score and 3% of the ridden show jumping score could be explained by objective conformational measures. To the author's knowledge this approach of objective measurement has not been repeated in studies of the SWB horse.

Jönsson *et al*. (2014b) reported that all overall conformation scores in young SWB horses were significantly positively associated with the orthopaedic health score and concluded that what is generally considered to be good conformation by the judges is associated with a good health status. Wallin *et al*. (2001) observed that orthopaedic health had a greater influence on longevity than did conformation judged at RHQT. However, the risk ratio of early culling was almost twice as high for the horse attaining the worst total conformation score compared to the best scoring horse, and authors observed a clear trend between the risk ratio from low to high total conformation score. The same trend was seen with the evaluated leg conformation trait; horses scoring six or lower had a higher risk for early culling than those scoring seven and above.

In the model by Jönsson *et al*. (2014a) conformation explained 28% and 15% of the orthopaedic health score and the locomotion score, respectively. Significant relationships have also been demonstrated between conformation and orthopaedic health in previous studies. Magnusson & Thafvelin (1990) studied associations between conformation and health in Swedish 4-year-old Standardbred trotters and found that 11% of the variation in orthopaedic status was explained by conformation, corresponding to 7% in a later study of SWB horses at RHQT by Holmström & Philipsson (1993).

The type of association between conformation traits and orthopaedic health seems to differ between traits. One trait that seems to have a centered optimum is height at withers. This has been shown for Standardbred trotters (Magnusson & Thafvelin 1990) and for SWB horses (Jönsson *et al*. 2014b). The same type of curvilinear trend is seen for hock angles in SWB horses (Jönsson *et al*. 2014b; Viklund & Eriksson 2018) and Standardbred trotters (Magnusson & Thafvelin 1990).

On the contrary, some traits seem to have a linear correlation with orthopaedic health. For example, a slightly sloping shoulder, or in other words a small angle between the length axis of the shoulder blade and the horizontal plane, has proven to be beneficial for different measures of orthopaedic health (Magnusson & Thafvelin 1990; Holmström & Philipsson 1993; Jönsson *et al*. 2014b) and a steep sloping shoulder was shown to negatively influence health scores (Jönsson *et al*. 2014b). A well-positioned, long neck has also been associated with better health status in young horses whereas a broad-based neck was negatively correlated with the locomotion score (Jönsson *et al*. 2014b). In the same study, long lines were beneficial for orthopaedic health score and short back was the trait with the greatest negative influence on most health traits.

Correctness of legs is often focused upon when studying the influence of conformation on orthopaedic health. Biomechanical reasoning that conformational limb deviations result in unphysiological impact and wear on tissues in the limb that lead to injury is widely adopted (Baxter *et al*. 2020). It is a complex matter, partly demonstrated by a considerably lower heritability than other evaluating traits in the SWB horse (Viklund & Eriksson 2018). Heritabilities in mentioned study were higher in linearly scored limb conformation traits, proving usefulness of the more detailed linear evaluation. Jönsson *et al*. (2014b) observed the best health status in RHQT veterinary examinations in horses without major limb deviations. The limb deviations that demonstrated the highest negative effect on the health status was toed-in or toed-out, small or large hock angle and stiff pasterns. Magnusson & Thafvelin (1990) also observed a positive relationship between long limbs and soundness in young standardbred trotters, and Jönsson *et al*. (2014b) found a negative genetic correlation between short limbs and RHQT veterinary locomotion score. In addition, Magnusson & Thafvelin (1990) concluded that fetlock angle was one of the conformational variables that explained orthopaedic status the most, while Jönsson *et al*. (2014b) observed that stiff or weak pasterns negatively influenced the locomotion score in RHQT. The later observation is interesting in the light of findings by Ducro *et al*. (2009), who observed a lower risk for early retirement in KWPN horses with upright pasterns. The main observation in the later study was the negative influence of uneven feet on number of years in competition.

2.2.3 Orthopaedic health

Results from studies of SWB horses, performed on data from YHT and RHQT but using different methods, indicate that findings in veterinary examinations of young horses can be associated with their future longevity (Wallin *et al*. 2001; Jönsson *et al*. 2014a). These authors agreed on the importance of early health recordings in young sport horses and their predictive value for longevity. In the study by Jönsson *et al*. (2014a), based on results from 8,000 horses, there was also a significantly lower OR for competition later in life for horses with positive flexion tests compared with no reaction. These horses also had a slightly (0.4 years) lower longevity, measured as years in competition.

Jönsson *et al*. (2014b) found movement in trot to be genetically positively associated with orthopaedic and, specifically, locomotion health scores in the SWB horse. Good rhythm, ground covering, limb energy and free shoulder movements were favorable traits. Meanwhile, stiff or irregular movements, small overreach and movement close to the ground were all negatively associated with health scores and in another study of the same population, longevity measured as years in competition (Jönsson *et al*. 2014a).

2.3 Lameness and movement asymmetry

Locomotor problems is the most common group of diagnoses in Swedish equine veterinary practice (Penell *et al*. 2005; Egenvall *et al*. 2006), as well as the most common cause of death or euthanasia (Egenvall *et al*. 2006). Locomotor problems can involve any anatomical region of the axial segments or the limb and can occur in multiple limbs concurrently (Baxter *et al*. 2020). Most horses with locomotor problems will display lameness (Baxter *et al*. 2020).

Several definitions of lameness can be found in veterinary textbooks. Baxter *et al*. (2020) use the definition "Lameness is an indication of a structural or functional disorder in one or more limbs or the axial skeleton that is evident while the horse is standing or at movement."; Ross (2011) uses "Lameness is simply a clinical sign—a manifestation of the signs of inflammation, including pain, or a mechanical defect—that results in a gait abnormality characterized by limping". There are more, but overall lameness is viewed as a clinical manifestation of pathology or loss of function in the horse's locomotor system, leading to an altered pattern of movement.

There are various types of lameness (Baxter *et al*. 2020). In addition to identifying whether lameness is present and in what limb(s), the practitioner needs to consider the possibility of so-called compensatory lameness. That is when horses display lameness, or a change in locomotion pattern, in a forelimb due to primary lameness in a hindlimb, or vice versa. Compensatory lameness is not a result of pain in the compensating limb but rather of a change in weight distribution (Baxter et al. 2020) and reverse when the primary lameness disappears (Uhlir *et al*. 1997; Kelmer *et al*. 2005). Secondary lameness, on the contrary, is lameness in a limb due to excessive strain as a result of a primary lameness in a different limb (Baxter *et al*. 2020).

2.3.1 Assessing lameness and movement asymmetry

According to Baxter *et al*. (2020) a traditional lameness evaluation consists of several steps. The practitioner will usually begin with collecting clinical history and assess the horse through visual inspection and palpation at a standstill. The horse is also assessed in movement through visual inspection, most commonly on the straight in hand and on the lunge, in both walk and trot. Other aspects of the horse's locomotion pattern are assessed, but the most sensitive to detect lameness is the vertical movement asymmetry of the horse's midline; the poll in forelimb lameness and the pelvis in hindlimb lameness during trot.

However, subjective lameness evaluation has shown poor inter-observer agreement, especially in subtle lameness, sometimes with diagnostic accuracy at or below chance level (Keegan *et al*. 2010; Hammarberg *et al*. 2016; Starke & Oosterlinck 2019). In order to study horse locomotion and quantify lameness more objectively different methods of recording movement have been developed, measuring force (kinetics) or motion (kinematics) (Baxter *et al*. 2020). In response to pain a horse will shift its weight from the painful limb, generating a lesser ground reaction force. Kinetics is by many considered the gold standard since it directly demonstrates reduced ground reaction forces, but it is difficult to use in practice.

According to Baxter *et al*. (2020) vertical movement (kinetics) of the horse's midline is directly related to ground reaction forces in limb loading. Kinematic gait assessment tools have been directed toward tracing vertical displacement of the poll and pelvis to identify forelimb and hindlimb lameness, respectively, as these anatomical landmarks have been proven sensitive to lameness detection (Buchner *et al*. 1996).

The trot is a symmetrical gait and the stride is a full cycle of limb movement involving all four limbs (Barrey 1999). The step of each limb includes a stance phase and a swing phase. In one trot stride the axial segments of the horse move up and down twice, forming a sinusoidal curve with two maxima and two minima representing swing and stance phases, respectively (Buchner *et al*. 1996). Lame horses alter the amplitude of vertical displacement of their poll and pelvis (Buchner *et al*. 1996). In an impact type lameness, the horse will sink less on the lame limb during stance phase as compared to the sound, creating a difference between the two minima for the poll in a forelimb lameness (HDmin) or pelvis in a hindlimb lameness (PDmin) (Baxter *et al*. 2020). In a push-off type lameness the horse will reach a lower maxima after the push-off of the lame limb as compared to the sound limb, creating a difference between the two maxima for the poll in a forelimb lameness (HDmax) or pelvis in a hindlimb lameness (PDmax). Moreover, in addition to these types of asymmetries, horses can display mixed patterns where both the vertical minima and maxima are altered in relation to the lame limb.

During a gait evaluation recording, kinematic gait assessment tools record poll, sacrum and sometimes withers vertical displacement in individual strides (Baxter *et al*. 2020). When the recording is completed, mean values for HDmin, HDmax, PDmin and PDmax are usually reported with their respective standard deviations. Raw data that constitutes these variables will be affected by any other movement of the poll or pelvis such as stumbling or head shaking, and various filtering techniques are used in the different software to avoid that unwanted erroneous motion affects the interpretation of asymmetry data (Serra Bragança *et al*. 2020).

Recently a new gait asymmetry quantification system using computer vision built on deep neural networks has been launched. A study by Lawin *et al*. (2023) compared data recorded from the new system to that of a state-of-the-art system to validate the former. Authors concluded the new system, designed as an iPhone application, is reliable and relatively accurate.

2.3.2 Movement asymmetry and sidedness

In several studies, a considerable proportion (53% to 72.5%) of horses in training perceived as sound by their owners have displayed movement asymmetries above clinically used thresholds for lameness in straight line trot (Pfau *et al*. 2016; Rhodin *et al*. 2016, 2017). Persson-Sjodin *et al*. (2019) performed a study where “owner-sound” horses, some of which were above aforementioned lameness thresholds, were treated with meloxicam and the results showed treatment did not significantly affect the horses’ movement asymmetries. In conclusion, there is clearly an overlap in degree of movement asymmetry between horses perceived as sound and unsound. Additionally, the finding that some horses with movement asymmetries above clinical thresholds for lameness are neither perceived as lame by their owners, nor treatable with an analgesic anti-inflammatory drug commonly used for treatment of locomotion disorders, suggests that movement asymmetries of this magnitude are not always painful.

Against the background of some of these results, van Weeren *et al*. (2017) raise questions in a consensus statement about how to define lameness versus absence of lameness, what role biological variation plays, and the adequacy of using clean cut-offs for lame or sound even on a population level. The authors strongly advice to discriminate between the term lameness, as in clinical manifestation of pathology, and movement asymmetry, as in subtle gait alterations. Not only is it according to the authors scientifically questionable to refer to subtle gait alterations as lameness, but it is also potentially harmful due to the strong association between lameness, reduced welfare and unfitness to compete.

The question about the aetiology(s) of these movement asymmetries remains unanswered but multiple theories are discussed amongst researchers in the field. Subsequent studies have demonstrated similar or even greater proportions of asymmetrical individuals amongst young horses, suggesting many of the vertical movement asymmetries seen in horses derives from something else than accumulated strain from training. Kallerud *et al*. (2021) studied yearling Standardbred trotters that had recently begun training and found forelimb or hindlimb movement asymmetry values to be above manufacturer lameness thresholds in 93% of trot in-hand-trials. Most of these horses displayed mild asymmetry with high inter-stride variability. When studying laterality in young warmblood horses, Leclercq *et al*. (2023) found 60-70% of included horses to display at least one asymmetry variable above manufacturer lameness thresholds.

When an effort was made to minimize the influence of acquired locomotor injuries by measuring vertical displacement of the poll and pelvis in clinically sound foals, there was still a high proportion of individuals reaching above the lameness thresholds (Zetterberg *et al*. 2023). The proportion for warmblood foals was however lower (45%) than that seen in adult horses in previous studies and that of the Standardbred foals in the same study (83%). Interestingly, the inter-stride variability was relatively high. There is evidence that horses with induced lameness have a relatively low inter-stride variability as compared to before induction of lameness (Serra Bragança et al. 2020). It has been hypothesized that this is a result of the horse trying to restrict its movement to reduce pain, whilst in a sound horse the variability will not lead to pain and external stimuli will influence the locomotion to a higher extent (Rhodin *et al*. 2017; Zetterberg *et al*. 2023). In the foal study, maybe the higher stride variability could be explained this way.

Other proposed aetiology theories on horse gait asymmetry is immaturity in the young horse (Kallerud *et al*. 2021; Zetterberg *et al*. 2023) and motor laterality (Rhodin *et al*. 2016, 2017; Persson-Sjodin *et al*. 2019; Baxter *et al*. 2020). Laterality can be defined as preference to use one side of the body, and motor laterality is a side preference specifically for motor tasks (Byström *et al*. 2020). Laterality has been described in a range of species and to some extent in horses. Motor laterality in the horse is previously documented (Van Heel *et al*. 2006, 2010; Lucidi *et al*. 2013) and proposed to have an impact on front foot evenness (Van Heel *et al*. 2006, 2010) and possibly predispose to future overload injuries (Van Heel *et al*. 2006, 2010). To the author's knowledge, individual vertical movement asymmetries have only been compared to motor laterality in the study by Leclercq *et al*. (2023), where no convincing associations were found between the two when a group of 40 horses were tested. Conclusive evidence of inherent laterality in horses, how it may vary between individuals and over time, not to mention the best way to test it or discriminate between laterality and lameness in a clinical setting, is currently lacking.

3. Material and Methods

3.1 Study design

A prospective, observational cross-sectional study was designed to investigate the degree of vertical movement asymmetry in three-year-old SWB horses and its potential associations with their scores in YHT.

3.2 Data collection

3.2.1 Locomotion data collection

For a total of five YHT events, four during the year of 2022 and one in 2023, on three different locations, owners and handlers of participating horses were asked to trot their horse for a recording with the Sleip app. Typically horses were recorded after completion of the whole test including gait and free jumping evaluation as well as riding test, but some horses were recorded before any of the tests, and some having completed all but the riding test. All participants signed a consent form agreeing to the terms of the study.

Each horse's identity was controlled comparing the official list of participants to both the number on their bridle and their name as written by the participant on the consent form. An iPhone 12 ProMax or an iPhone X GSM was set up on a tripod for recording. The different locations offered different settings but in all locations the setup was on a flat, hard but non-slippery surface with at least 30 meters of undisturbed footing ahead of the iPhone camera. There was a marking 35 meters ahead of the camera. All participants were instructed to trot the horse in hand back and forth to the marking twice, running a total of approximately 120 meters. Horses were not allowed to wear any equipment on their back, such as a saddle or a rug, for the recording.

3.2.2 Linear and evaluating scores

The identity of each horse was controlled through microchip reading as part of the event. The horses were evaluated in a YHT event, including measuring of height at withers, scoring of linear descriptive traits and evaluating traits. The horses were assessed for a total of 8 evaluating traits and 68 linear descriptive traits. Of the descriptive traits, 50 were on a 9-step scale from A-I, where E represents population average and A and I respectively represent biological extremes. Another 18 descriptive traits were assessed on a 2-step present/not present scale. The complete protocol can be found in Appendix 1. Of the 50 linear descriptive traits 13 were related to jumping, 16 to movement, 20 to conformation and one was a behavioral trait. The evaluating traits consisted of type, head-neck-body, correctness of legs, walk in hand, trot in hand, free canter, show jumping technique and temperament in jumping. These traits were scored on a scale from 1 (poor) to 10 (excellent) in relation to the breeding goal. The protocols were transcribed to an Excel sheet and scoring letters A-I exchanged with the numbers 1-9 to facilitate statistical analysis. An excel sheet with the scores and withers height from the horses included in the study was subsequently retrieved from the Swedish Warmblood Association.

3.2.3 Pedigree categorisation

Horses in the study were assigned to one of four categories J (jumping), D (dressage), AR (all-round) or Th (thoroughbred) based on their sire and grandsire. A horse was assigned to J (jumping) if both their sire and grandsire were considered to be show jumping talents, D (dressage) if both their sire and grandsire were considered to be dressage talents. A horse was assigned to the AR (all-round) category if it had a J sire and a D grandsire or vice versa. A horse was assigned to Th category if its sire and grandsire were English Thoroughbred or Arabian Thoroughbred. Anglo-Arabian Thoroughbreds were assigned to the AR category since they typically have intermediate breeding values for both dressage and show jumping. A horse with an AR category sire were assigned to D, J or AR category based on their grandsire.

The categorization of the sires and grandsires was done stepwise. If they had been approved in a Swedish Stallion Performance Test they would easily be assigned to a J or D category because since 2002 stallions have only been assessed for one of the two disciplines. Stallions lacking results from a Swedish Stallion Performance Test after the year of 2001 were evaluated based on their estimated breeding values. If such were not available, stallions would be categorized based on their own competition results if available, offspring competition results or pedigree. Stallions with either good EBVs or good performance in both dressage and show jumping were assigned to the AR category.

3.3 Data processing

Stride level data from all recordings were retrieved from the Sleip app. Exclusion criteria were set to exclude movement asymmetry values from data of potentially low quality. HDmin, HDmax, PDmin or PDmax values based on recordings with less than 20 strides (HDmin, HDmax) or 15 strides (PDmin, PDmax) were excluded because of too few strides. A factor of 0.25 (forelimb) and 0.4 (hindlimb) was used to make hind- and forelimb values comparable in magnitude. Absolute mean values for HDmin, HDmax, PDmin or PDmax of 0.5 or higher, with a standard deviation of more than 100% of the mean, were excluded from the results because of high variation.

Absolute HDmin and HDmax values were added to make a total forelimb asymmetry value, Htot. The same principle was applied to PDmin and PDmax to produce the second asymmetry value Ptot. The third and final asymmetry value Atot was the sum of Htot and Ptot, i.e. all asymmetry values. When values for Htot or Ptot were excluded because of low quality, the Atot was automatically excluded. However, if the forelimb value was excluded for a horse but the hindlimb value met the standard, the hindlimb value would be included or vice versa.

To increase statistical power the 50 9-step linear scores and 8 evaluating scores from YHT as well as the horse's withers height was transformed for each individual horse to 18 traits, henceforth referred to as "YHT score factors", using factor loadings from factor analysis by Nazari-Ghadikolaei *et al*. (2023). Factors and factor loadings can be found in Appendix 2.

3.4 Data analysis

Descriptive statistics were performed to visualize the study population.

One-way ANOVA was performed to determine differences in forelimb, hindlimb and total asymmetry for the subgroups dressage, show jumping and all-round bred horses. P-values were determined using student t-test corrected with the Bonferroni method.

Investigation of the possible associations between asymmetry values and YHT scores was done stepwise. First, a correlation matrix was computed for Htot, Ptot, Atot and the 18 YHT score factors using Pearson's correlation coefficient in RStudio. This allowed a first selection of variables of interest. Correlations with an absolute value ≥ 0.20 were considered as possibly significant and therefore chosen for regression analysis.

Second, the chosen sets of variables from the previous step were used in regression analysis through linear modelling. Sex (male/female) was set as a fixed effect, the asymmetry value was used as the dependent variable and the YHT score factor as a predictor. Models were also computed for the chosen sets of variables without sex as a fixed effect.

4. Results

4.1 Study population

Table 1. Study population. Horses were recorded with the Sleip app, generating three movement asymmetry values per horse, at five different young horse tests (Event 1-5). They were also assigned to the categories J, D, AR or Th according to their pedigree. Asymmetry values were excluded if the number of strides analysed were <20 for forelimb asymmetry or <15 for hindlimb asymmetry. Asymmetry values were also excluded if SD >100% of mean when trial mean for either of the asymmetry values was ≥0.5 in the Sleip app. When either forelimb or hindlimb values were excluded for a horse, the individual total asymmetry value was automatically also excluded.

	Event 1	Event 2	Event 3	Event 4	Event 5	Total
Horses participating in study *(% of YHT participants)*	30 *(45%)*	13 *(23%)*	24 *(36%)*	23 *(51%)*	26 *(46%)*	116 *(40%)*
Number of J *(% of study participants)*	15 *(50%)*	7 *(54%)*	5 *(21%)*	9 *(39%)*	15 *(58%)*	51 *(44%)*
Number of D *(% of study participants)*	13 *(43%)*	6 *(46%)*	15 *(63%)*	13 *(57%)*	11 *(42%)*	58 *(50%)*
Number of AR *(% of study participants)*	2 *(7%)*	0 *(0%)*	4 *(16%)*	1 *(4%)*	0 *(0%)*	7 *(6%)*
Number of Th *(% of study participants)*	0 *(0%)*	0 *(0%)*	0 *(0%)*	0 *(0%)*	0 *(0%)*	0 *(0%)*
Values excluded due to no of strides *(% of asymmetry values gathered)*	8 *(9%)*	12 *(31%)*	7 *(10%)*	16 *(23%)*	5 *(6%)*	48 *(14%)*
Values excluded due to high variation *(% of asymmetry values gathered)*	4 *(4%)*	2 *(5%)*	2 *(3%)*	4 *(6%)*	6 *(8%)*	18 *(5%)*

4.2 Differences in vertical movement asymmetry between the subgroups dressage, show jumping and all-round bred horses

One-way-ANOVA was performed for forelimb asymmetry, hindlimb asymmetry and total asymmetry respectively using the three categories “dressage”, “show jumping” and “all-round”. There was no significant difference in either forelimb or hindlimb asymmetry between the groups. However, for the total movement asymmetry, i.e. the sum of absolute values of forelimb and hindlimb asymmetry, there was a significant difference. Post-hoc analysis with student t-test corrected with the Bonferroni method determined that the dressage subgroup displayed a smaller (0.76 ± 0.40) total movement asymmetry than the show jumping subgroup (1.05 ± 0.53, p <0.01).

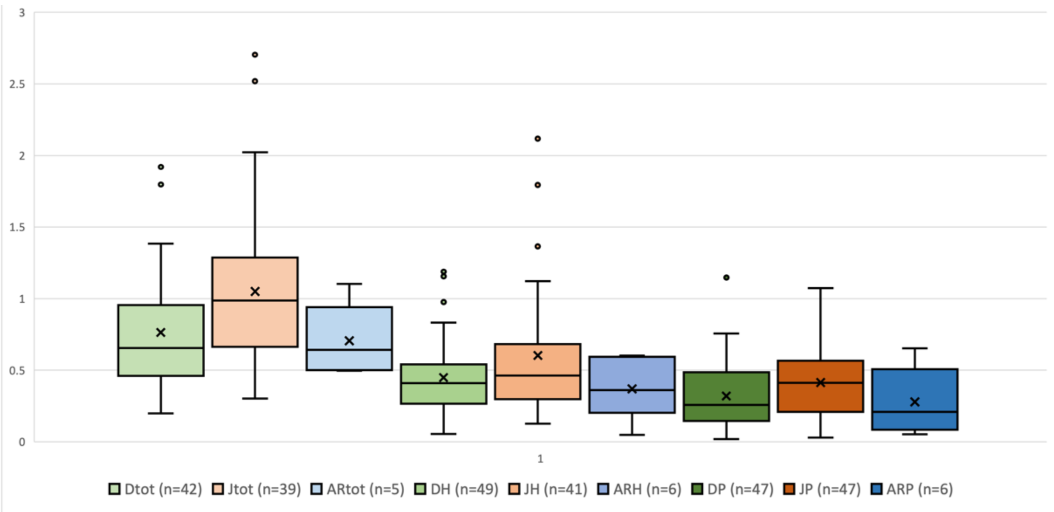
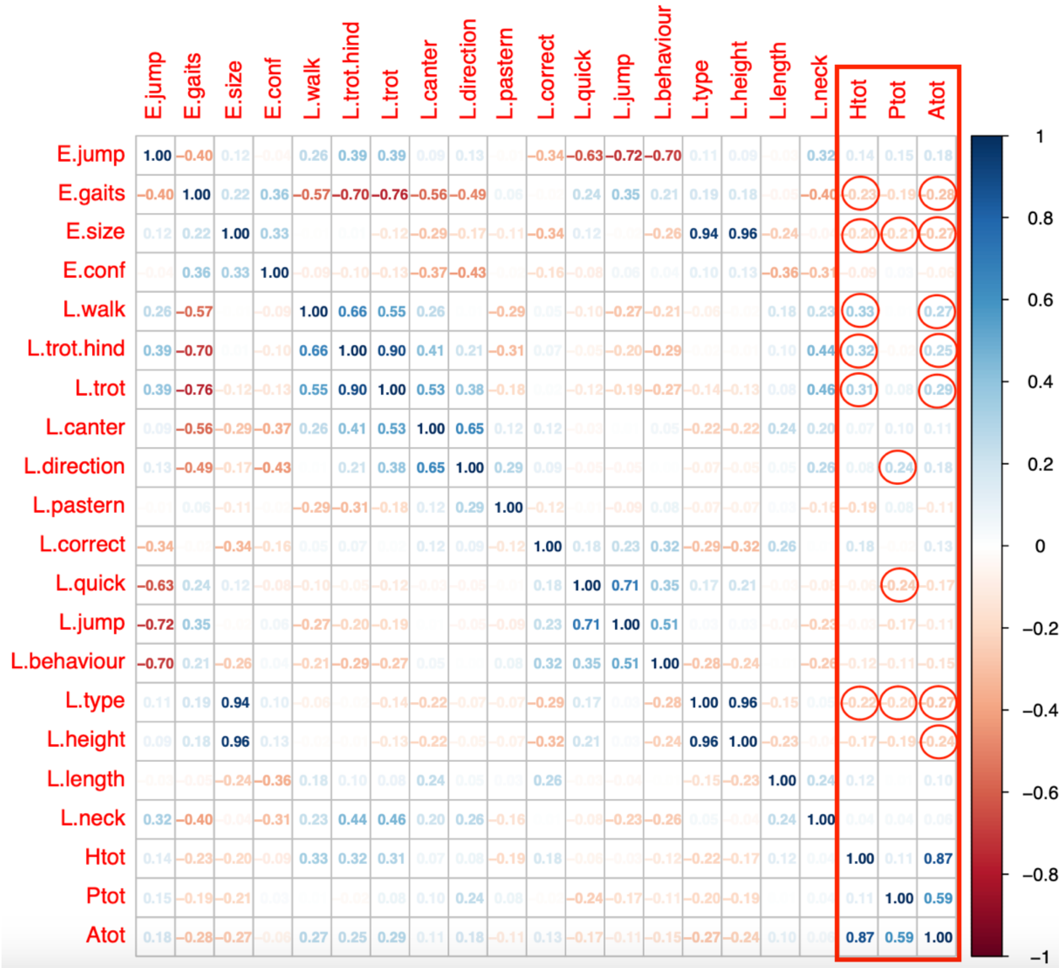


Figure 2. Sums of total (tot), forelimb (H), hindlimb (P) trial mean vertical movement asymmetry in Sleip within the subgroups dressage (D), show jumping (J) and all-round (AR).

4.3 Correlations between vertical movement asymmetries and scores in the YHT

A correlation matrix was computed for Htot, Ptot, Atot and the 18 YHT score factors using Pearson's correlation coefficient in RStudio. Correlations with absolute values ≥0.20 were chosen for regression analysis. There were 17 such correlations (circled in red).

Table 2. Correlation matrix as a heat map. Each cell represents the correlation coefficient between two variables. The colour of the correlation coefficient indicates the direction and strength of the correlation; blueish colour indicates a positive correlation between the two variables, a redish color a negative correlation, and the intensity of the color represents the strength of the correlation. A rectangular red frame marks the area of interest for the current study and the correlations with absolute values ≥ 0.20 chosen for regression analysis are circled in red. The reader is referred to appendix 2 and 1 for a deeper understanding of what constitutes YHT score factors.



4.4 Regression analysis

Asymmetry values were centred, and linear models were fitted in RStudio for each of the chosen pairs of variables, initially including sex (male/female) as a fix effect. Sex had no significant effect on asymmetry values in either of the models (data not shown). Subsequently, additional linear models were constructed for the same pairs of variables, but without considering sex as a fixed effect.

Table 3. Summary of the linear models constructed from the movement asymmetry and YHT data. In three of these the asymmetry value could not be explained by the YHT value (p >0.05). These models are highlighted in red. The reader is referred to appendix 1 and 2 for detailed information on what constitutes the different predictors.

Dependent variable	Predictor 1	Coefficient of predictor 1 (C1)	p-value (C1)	Adjusted r^2
Htot.c	E. gaits	-0.2677	0.0356	0.04021
Atot.c	E. gaits	-0.4094	0.00859	0.06841
Htot.c	E. size	-0.08564	0.0649	0.02856
Ptot.c	E. size	-0.05426	0.0579	0.03075
Atot.c	E. size	-0.1399	0.0136	0.05927
Htot.c	L. walk	0.27579	0.00178	0.09974
Atot.c	L. walk	0.2808	0.0105	0.06435
Htot.c	L. trot hind	0.3832	0.00233	0.09442
Atot.c	L. trot hind	0.3675	0.0191	0.05256
Htot.c	L. trot	0.28162	0.00404	0.08344
Atot.c	L. trot	0.3249	0.00726	0.07176
Ptot.c	L. direction	0.2535	0.0245	0.04761
Ptot.c	L. quick	-0.1115	0.0233	0.04858
Htot.c	L. type	-0.09032	0.0467	0.03493
Ptot.c	L. type	-0.05089	0.0698	0.02715
Atot.c	L. type	-0.14121	0.011	0.06356
Atot.c	L. height	-0.14639	0.0272	0.04553

In fourteen of the seventeen models YHT values could be used to predict asymmetry values ($p \leq 0.05$). They explained up to nearly 10% of the variance in asymmetry values (adjusted $r^2 < 0.10$).

Linear regression revealed that the horse’s factor for evaluating gait trait (E. gaits), evaluating size trait (E. size), linear type (L. type), height (L. height), walk (L. walk), trot (L. trot) and trot hind factor (L. trot hind) all had a significant influence on their centred total asymmetry value (Atot.c) ($p \leq 0.05$). Similarly, the evaluating gait factor (E. gaits), linear walk (L. walk), trot (L. trot), type (L. type) and trot hind factor (L. trot hind) all had a significant influence on their centred forelimb asymmetry value (Htot.c) ($p \leq 0.05$). Only two factors significantly influenced the centred hindlimb asymmetry value (Ptot.c), and those were the linear jumping quickness (L. quick) and linear direction (L. direction) ($p \leq 0.05$). The reader is referred to appendix 1 and 2 for detailed information on what constitutes the predictors i.e. the YHT score factors.

5. Discussion

In the present study associations between vertical movement asymmetries and YHT scores in 3-year-old SWB horses were investigated, as well as differences in vertical movement asymmetry between 3-year-old SWB horses intended for different use within equestrian sports. Results show that horses bred for dressage displayed a lower total movement movement asymmetry than horses bred for show jumping ($p < 0.01$). Further, results show correlations between 17 pairs of asymmetry-YHT score factor combinations (Table 2), out of which 14 could be successfully modeled with linear regression ($p \leq 0.05$) (Table 3).

5.1 Differences in vertical movement asymmetry between the subgroups dressage, show jumping and all-round bred horses

In this study the dressage bred horses displayed a lower total vertical movement asymmetry than horses bred for show jumping ($p < 0.01$) (Figure 2). There are multiple possible explanations to this. The difference between the groups could be due to a training effect. It is possible that horses bred for dressage have more training with trot in hand since trot gait scores are more important to them, which could have resulted in less erroneous motion during the Sleip recording. On the other hand, trot strides with erroneous motion and low-quality data are meant to be filtered by the application before results are reported. In this context it is important to recognize that the application filtering of erroneous motion was not verified manually.

Another possible explanation is that dressage horses might have a larger vertical movement amplitude of the head and pelvis, i.e. a larger range of motion (ROM) than horses bred for show jumping, which would make the application less sensitive to deviant motion in these horses. Movement asymmetry values are based on % of the horses' ROM, meaning a deviant motion of the same magnitude will have a lesser effect on stride asymmetry in a horse with a greater ROM than a horse with a smaller ROM. It is reasonable to think a dressage horse has a greater range of motion since subjective assessments consistently show they possess bigger movements and more elasticity. In this context the author wants to highlight there is no available scientific documentation on the potential difference in vertical ROM in the poll and pelvis between groups of horses of different lineage.

The difference between the subgroups may also be explained in relation to breeding for performance; possibly symmetrical movement is favored more in the dressage discipline than in show jumping leading to an unconscious selection towards lesser movement asymmetries in dressage horses. This argument is contradicted by the generally low degree of movement asymmetry seen in the present study together with the evidence on low human temporal resolution; the movement asymmetries displayed by these horses are generally barely visible with the human eye and should therefore not influence breeding selection. However, in the present study correlations were seen between several gait or conformation scores and movement asymmetry values, implying that horses with better gait and conformation scores display a lower degree of movement asymmetry. This agrees with the finding that dressage horses displayed a lower degree of movement asymmetry. Maybe the real reason for the differences between discipline subgroups was due to gait and conformational qualities rather than lineage, although there is of course a large overlap and further analyses would be required to correct for lineage to determine this. The correlations in the present study were nonetheless low ($|r| <0.30$) (Table 2) and the coefficient of determination in the linear models relatively low (adjusted $r^2 <0.10$) (Table 3) and the results need validation in future research with larger horse populations before more definitive conclusions on the presence of these associations can be drawn.

5.2 Associations between vertical movement asymmetry values and YHT score factors

Interestingly, the different movement asymmetry values were significantly ($p \leq 0.05$) influenced by several YHT score factors when linear regression was performed, but they only explained a small part of the variance in asymmetry values (adjusted $r^2 <0.10$) (Table 3). Generally desired gait and conformational qualities were associated with a lower degree of vertical movement asymmetry in the present study. The only significant association between asymmetry values and jumping scores (Ptot.c and L.quick) displayed the opposite association; a less desirable, slow take-off was associated with lower asymmetry values. This should probably be seen in the light of that good gait quality was associated with lower degrees of movement asymmetry; these horses were likely to a higher extent of dressage lineage and given the increased specialization within the SWB horse (Ablondi *et al*. 2019a) they probably also possessed less talent for jumping.

Interpreting the slope of the models requires knowledge of the format and direction of the scoring protocol; sometimes higher scores mean the scored trait is greater or desirable, sometimes it means it's smaller or undesirable. For example, L.walk increases with a stiff walk with smaller stride length and uneven cadence. L.walk has a positive coefficient when modeled with the movement asymmetry values Atot.c and Htot.c, meaning a stiff, uneven, choppy walk resulted in greater Atot.c and Htot.c. But in the case of E.gaits, a greater score is associated with subjectively better gait scores in relation to the breeding goal. The coefficients in the models with Atot.c and Htot.c are negative, indicating a higher gait score resulted in lower Atot.c and Htot.c.

It is tempting to draw conclusions from the significant associations in the linear models, but these should be interpreted with caution. First, they should be interpreted in the light of the low coefficient of determination in the respective models (all <10%) (Table 3). This means the degree of movement asymmetry in the horses can only to a small extent be predicted using the YHT score factors. Second, the significant difference in movement asymmetry between the dressage and show jumping bred population needs to be taken into account; the lineage of these horses should be considered an important possible confounder. Almost all the significant relationships in the linear models agree with the expected results from dressage versus show jumping bred population. For example a dressage horse is expected to have larger, more supple gaits with even cadence; qualities that were associated with lower movement asymmetry values. Therefore, if future research is conducted comparing vertical movement asymmetry with gait and show jumping scores, it would be advisable to correct data for the horse's lineage.

Sex is from previous studies known to significantly influence the YHT scoring (Holmström & Philipsson 1993; Viklund *et al*. 2010) and was therefore initially included in the models. It was subsequently removed since it did not have a significant influence in any of the models in the present study. This could be due to the relatively small study population or because sex did not have a significant influence on the present study population or the investigated variables.

5.3 Choice of methods

The quality and processing, as well as the relevance of variables and exclusion criteria from the Sleip recordings can be discussed. As previously mentioned, the app filtering of erroneous motion was not verified manually. Also, the recordings were done in different settings so external conditions will always constitute a source of error. Conditions that could have affected the quality of the recordings include the presence of a highly trafficked road nearby in event 1,3 and 5; the absence of walls/fence/trees framing the “running isle” in event 2; difference in lighting throughout the day; difference in footing between events, etcetera. To best compare recordings, they would ideally have identical conditions, but the nature of the study made this impossible.

During evaluation of vertical displacement of the poll horses are also supposed to be held very loosely to allow them to move their head freely. This is sometimes difficult to achieve especially in horses that make unexpected movements where the handler is unable to follow or do not run on a straight line, such as young horses in new environments. This was the situation of the present study and therefore there is a probability some of the horses’ head movements were restricted by the handlers. However, the representative recording the horses continuously oversaw this and never encountered a situation where this was an obvious problem.

Another limitation to the recordings is the unregulated speed of movement. Speed of movement has previously shown to affect the regularity in the movement of the horse, the percent of vertical movement asymmetry and its standard deviation (Peham *et al*. 1998). The circumstances of the present study did not allow for any control of the speed with which the horses trotted. Perhaps using one handler for all horses would reduce some of the mentioned uncertainties with head movement and speed, but this is rarely a possibility and could also backfire as some horses are expected to react negatively to being handled by a new person in an unknown environment.

The concept of summarizing HDmin with HDmax and PDmin with PDmax is not previously described to the authors’ knowledge. In the present study, where the objective was to get a general sense of “degree of movement asymmetry” on a population level, this seemed like a sensible way to reduce the number of variables for the analysis. It is important to recognize the precise meaning and implications of Htot, Ptot and Atot as individual variables is not documented, and the reader is advised to consider them as very general indicators of movement asymmetry on a population level.

The purpose of the exclusion criteria for Sleip recordings was to exclude unreliable recordings of low quality. The criteria were based on clinical experience. It should be highlighted that the exclusion criteria for high inter-stride variability was partly based on trial standard deviation, partly on trial HDmin/HDmax/PDmin/PDmax mean. Thus, there was a selection towards horses with movement asymmetries consistent with possible lameness; horses with a higher degree of movement asymmetry but high inter-stride variability were excluded, but some of these recordings might have represented good enough quality recordings of healthy horses. Standard deviation as a measure is more sensitive to few values that differ greatly than to multiple values that differ slightly, meaning that one big erroneous movement of a recorded horse of magnitude x will have a greater impact on the standard deviation than multiple smaller erroneous movements of which the sum is x. In consequence, a horse that is more consequent in its movement asymmetry is less likely to be excluded from the study population, given that none of the horses in this example were filtered by the application before data processing.

To increase statistical power, factors from Nazari-Ghadikolaei *et al*. (2023) were used to reduce the number of analysed YHT score variables. This can be discussed as some scores of interest, in example pastern angle that has previously been associated with orthopaedic status (Magnusson & Thafvelin 1990), locomotion scores (Jönsson *et al*. 2014b) and early retirement (Ducro *et al*. 2009), was not at all included in these factors. In addition, the YHT score factors are more complex to interpret than the YHT scores. However it was desirable to reduce the number of variables in the present study and this was an available scientific method to do so. Of course there was a wish to include detailed variables in the analysis but this had to be weighed against the risk of making a type one error, which is always the risk when analysing a large number of variables.

Ideally event should have been included in the models as a fixed effect, but the study population was estimated too small to allow this. Event is usually a fixed effect in models constructed from YHT scores since it has shown to influence for example gait scores (Holmström & Philipsson 1993).

5.4 Limitations and strengths

There are some limitations to the present study. First, the study population is not for certain an accurate representation of the 3-year-old SWB horse population. Previously about 40% of the 3-year-old SWB horses were shown at YHT. Most probably horses expected to score “badly”, that lack talent or are behind their age group in growth, development, temperament or training were shown to a proportionally little extent. Second, not all YHT participants were asked to take part in the present study. In order not to disturb the event, handlers generally did not get the question before completion of the riding test and even then not all handlers were asked; to maintain a social license to operate people in obvious distress were not asked to participate. In addition, to secure a decent number of participants, some handlers showing a great number of horses were asked beforehand to take part in the study. All these factors could have led to a selection bias in the study population. The author also wants to highlight that the number of all-round bred horses was very small in comparison to the other subgroups. It was big enough to constitute its own population in statistical analysis, but the reader is advised to draw any conclusions about this subgroup with great caution.

Another limitation to the study is the low variation in YHT scores. For the majority of the linear YHT scores, almost all results were between 4-6 on the 1-9 scale, increasing the difficulty in determining significant differences. The human factor is always a possible source of error when subjective evaluations are made, and the present study is no exception. The judges were however experienced and have had continuous education and regular calibration meetings. A low variance in scores and poor inter-rater reliability has previously been demonstrated in French experts when scoring gait quality in Franches-Montagnes horses (Gmel *et al*. 2020). To overcome some of the challenge of low variance and high number of assessed qualities per horse, the factor analysis was used to increase statistical power in the present study.

When interpreting the results it is also important to remember even though the data is not novel, this approach to handling the data is novel. To the author's knowledge no previous attempts have been made to compare vertical movement asymmetry of the poll and pelvis to subjective scores in breeding evaluations. In the present study Pearson's correlation coefficients and linear modelling with sex as a fixed effect were used to investigate the associations between movement asymmetry values and YHT score factors. Future research could reveal more accurate and precise methods to better evaluate these associations. However, this seemed like a sensible approach at this early stage of investigation.

Strengths of the study includes the geographical distribution of events. Holmström & Philipsson (1993) saw significant differences in conformational measurements between events, possibly representing regional differences in conformation. This could be explained by an overrepresentation of local sires, regional differences in breeding tradition or skill amongst breeders. For this reason, it was valuable to include events from multiple regions to achieve a more accurate representation of the SWB horse. The recordings were also performed during two consecutive years, thereby including horses born in different years and therefore increased diversity in the study population.

5.5 Comparison to previous research

The YHT score factor L.type significantly explained Atot.c and Htot.c, respectively, in the linear models (Table 3). A greater L.type-factor can be referred to greater height at withers and a generally heavy conformation type. Its coefficients when modeled with Atot.c and Htot.c are negative, indicating larger and more robust horses get smaller movement asymmetry values. This can be compared with the findings by Jönsson *et al*. (2014a), where horses of intermediate size with higher evaluating scores for type performed better later in life and displayed a greater longevity. These results seem contradicting, but they are also based on very different measures and should be compared with caution.

The significant associations between lower movement asymmetry values and higher evaluating gait scores and uphill gaits with greater stride length and even cadence is interesting in the light of previous research where similar qualities and better evaluating gait scores for the walk and trot were associated with a greater longevity (Wallin *et al*. 2001; Jönsson *et al*. 2014a) and locomotion score in RHQT veterinary inspections (Jönsson *et al*. 2014b). Good rhythm, ground covering, limb energy and free shoulder movements were favorable traits (Jönsson *et al*. 2014b). Similarly, stiff movement and small overreach in walk were negatively associated with the locomotion score in walk (Jönsson *et al*. 2014b) just like in trot (Jönsson *et al*. 2014a).

The fact that few conformation scores were correlated with movement asymmetry values in the present study could be interpreted as if they had no significant influence on the vertical movement asymmetry in the horses. This could also be because of the small study population and reduction of YHT scores to factors, or because the impact of conformation on equine locomotion has previously been overestimated. Of course, it could also be because conformation characteristics affects locomotion in a way not measured in the present study, or because those characteristics result in movement asymmetries later in life. Previously, conformation explained 15% of the locomotion score in RHQT veterinary examination (Jönsson *et al*. 2014a) and 11% and 7% of orthopaedic status in the studies by Magnusson & Thafvelin (1990) and Holmström & Philipsson (1993), respectively.

5.6 Practical implications

This study is to the author's knowledge the first to compare vertical movement asymmetry in trot to YHT scores. It can be viewed as a pilot study in the area. First, the results of the study further validates that young horses, not yet subjected to a large amount of exercise, display vertical movement asymmetries to a relatively high extent. This should be interpreted against the background that many owner-sound horses have displayed subtle gait asymmetries in previous research, and that the clinical implications of subtle movement asymmetries in the young horse are not known.

However, there are interesting implications to the correlations in the present study that should be investigated further. The significant correlations between vertical movement asymmetry measures and gait score factors suggests horses with better quality gaits move less asymmetrically. In the case this is a result of their gait quality, it would be interesting to follow up on degree of movement asymmetry, health and longevity in the young SWB horses to determine whether good walk and trot quality seems to impact or predict the vertical movement asymmetry in the individual in the long term, and if this has any health or performance implications.

The linear models use the YHT score factors as predictors and the movement asymmetry values as dependent variables, but to which degree vertical movement asymmetry affects the judgement in the YHT was not investigated in the present study. If this turned out to be the reality it would be a very interesting finding, since it would imply humans might indirectly perceive subtle gait asymmetries to a greater extent than expected. This could perhaps lead to new aids for subjective lameness assessment. Statistical associations in the present study suggests that horses that moved less symmetrically when recorded with Sleip were considered by the judges to have more stiff or downhill movement with uneven cadence in the walk and trot. Maybe human temporal resolution does not allow for an observer to decide with certainty whether a horse is subtly lame or free from lameness, but subtle vertical movement asymmetries are perceived as a small part of an integral picture of the horse's movement pattern.

The significant difference in total degree of vertical movement asymmetry measures in horses with dressage or show jumping lineage is not very helpful to the practitioner assessing individual horses. There was quite an extensive overlap in degree of movement asymmetry between the two groups so lineage could not really be used as a predictor for movement asymmetry on an individual level. It would however as previously mentioned be interesting to follow up on this; if symmetrical movement in vertical movement asymmetry assessment turns out to be associated with better performance in the dressage discipline, maybe an objective gait assessment tool could be useful in breeding selection.

With extensive research, maybe objective gait assessment could be used to predict health and longevity to some extent in the SWB horse. Even if that is the case, individual health or durability assessment will probably never be predicted with certainty using the available tools at one occasion; there seems to be too much variation and overlap in degree of movement asymmetry between individuals. Using population studies as a basis for individual assessment will always lead to some misjudgment due to individual variation, and there will always be a tangible risk that the individual results would be given too much attention as predictors of future health or performance. Since vertical movement asymmetry is associated with lameness assessment, and lameness is widely associated with poor welfare and unfitness to compete, there is a fair risk such individual assessment can have negative social and monetary consequences to breeders and handlers. This would need to be weighed against the benefits of introducing a measure to help breed more durable horses suited for their intended work. Previous research in longevity in the SWB horse have called for health recordings to assist breeders in working towards the goal of a durable horse (Wallin *et al*. 2001; Jönsson *et al*. 2014a), and currently there are no such health recordings.

6. Conclusions

The strive to produce durable horses that perform on a high level leads to the search for optimal qualities in the SWB horse. Insufficient knowledge of the influence and importance of different conformational, gait and jumping qualities on orthopaedic health can result in improper selection of horses for breeding in order to achieve the durability goal. In the present study, a number of traits, mostly gait-related, based directly on YHT scores had a statistically significant influence on the vertical movement asymmetry in horses measured with an objective gait assessment application. Further research should be performed in this area to validate the results of the present study. Entire chapters in veterinary textbooks are dedicated to the influence of conformation on orthopaedic health but no convincing associations between vertical movement asymmetries and specific conformational measures were seen in the present study.

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Popular science summary

Locomotor problems is the most common group of diagnoses in Swedish equine veterinary practice and the most common cause of death or euthanasia. The desire to understand horse locomotion and hopes to prevent injuries that restrict horse welfare and performance has led to a technical advancement that allows analysis of vertical movement asymmetry in horses not only in a hospital setting, but now also in any given environment through a phone application. Vertical movement asymmetry is currently the most sensitive method to measure lameness, the most common representation of equine locomotion problems.

This technical advancement has allowed to detect lameness with more precision than previous subjective methods but has raised new questions. Research in the past decade has revealed many horses considered sound by their owners or veterinary practitioners display subtle vertical movement asymmetries of the same magnitude as some horses considered unsound. This overlap in sound and unsound horses poses a new challenge to the equine practitioner and motivates further research as to the character, source and implications of these asymmetries.

Different conformation, gait and jumping characteristics are by tradition believed to predict horse's potential for performance and soundness. Many attempts have been made to investigate the associations between these qualities, but causal relationships supported by strong scientific evidence are lacking. Unsettled definitions, difficulties in quantification, confounding factors and complex interactions make the search for causal relationships challenging.

The Swedish Warmblood is bred for performance. To improve performance and conformation qualities, so called "young horse tests" (YHT) are arranged each year, and since rate of participation is decent (40% of eligible three-year-olds) they provide some insight to the young horse population. Linear profiling, a method of describing characteristics on a scale between two biological extremes, has added a new dimension to the tests and hopes are it will facilitate research through increased objectivity.

The aim of this study was to investigate possible associations between scores in the YHT and degree of vertical movement asymmetry in 3-year-old Swedish Warmblood horses using an objective gait analysis tool. We also wanted to investigate possible differences in vertical movement asymmetry between horses intended for different equestrian disciplines. A total of 116 three-year-old Swedish Warmblood horses were recorded with the Sleip app in conjunction with YHT events for a total of 5 events. The recording was done separately to the test in a controlled environment. The horses were later assigned to a category jumping (J), dressage (D), all-round (AR) or thoroughbred (Th), based on their pedigree. 50 scores from YHT were retrieved from the Swedish Warmblood Association (SWB) and transformed into 18 factors. Movement asymmetry values were retrieved from the Sleip app and converted to forelimb asymmetry, hindlimb asymmetry and total asymmetry for each individual. The sum of all movement asymmetry values was significantly ($p <0.01$) lower in horses bred for dressage as compared to horses bred for show jumping.

Correlation coefficients between movement asymmetry values and YHT score factors were calculated using Pearson's method. Seventeen significant ($|r| \geq 0.20$) correlations were found and subsequently used for linear models. In these models, fourteen YHT score factors significantly ($p \leq 0.05$) explained their respective movement asymmetry value. These factors consisted of one jumping factor, three conformational factors and ten gait related factors. The coefficient of determination was generally low (adjusted $r^2 <0.10$).

Overall, what is considered to be good gaits in walk and trot seem to be associated with a lower degree of vertical movement asymmetry. There are however some limitations to the study. The study population is relatively small ($n = 116$), and most likely skewed in the sense that it probably primarily includes the best developed horses that are believed to do well in their test. Also because of novel data handling, the practical implications can't be fully determined. The study should be viewed as a pilot study and the results do all the same raise interesting questions about human conception of subtle gait asymmetries and the importance of vertical movement symmetry to performance in the Swedish Warmblood, and should be further investigated.

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In addition, I want to thank Elsa Paulssons Minnesfond that generously provided me with the funds to travel to different regions for data collection, something that greatly improved the quality of this project.

Lastly, I want to make an honourable mention of the horse that sparked my interest in combining these areas of research, the extraordinary Bruce the Boss (SWB). His early retirement due to strain injuries represents the fate of many sport horses and has inspired me to enter veterinary medicine and dig into how orthopaedic health can be predicted and maintained to improve horse welfare.

Appendix 1

Judging protocol currently used in Young Horse Tests within the SWB.

Unghästtest

Arrangör/Datum…………………………………………………………………….

Nr. Hästnamn: | Kön: | Reg nr:
Uppfödare: | Ägare: | Visas av
e. | u. | Färg:

Linjärbeskrivning — Mankhöjd__________cm

	EXTERIÖR	Extremvariant	A B C	D E F	G H I	Extremvariant	Kommentar
1	Typ	ädel	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	grov	≤ väl proportionerlig
2	Kroppsform a	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	
3	Kroppsform b	högställd	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	lågställd	
4	Kroppens riktning	uppförsbacke	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	framvikt	
5	Halsens längd	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	≤ brett ansatt
6	Halsens position	vertikal	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	horisontell	≤ lågt ansatt
7	Halsens form	välvd	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	rak	≤ grov övergång huvud-hals
8	Manke	hög	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	låg	
9	Bogens position	liggande	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	brant	≤ djup bål
10	Rygg	rak	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	svank	
11	Ländrygg	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	≤ karp
12	Korsets lutning	stupande	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	rakt	
13	Korsets längd	långt	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	
14	Framben	bockbent	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	sabelbent	≤ knipt ≤ parallellförskj. ≤ felaktigt inskenad
15	Framben	intåad	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	uttåad	≤ gracil ≤ fransysk
16	Framkotor	upprätade	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	veka	≤ långa ≤ korta
17	Bakben	krokhasig	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	rakhasig	≤ knipt under has
18	Bakben	hastrång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	hjulig	
19	Bakkotor	upprätade	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	veka	≤ långa ≤ korta
20	Rörelsernas korrekthet	nystar	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	biljarderar	
21	Hovar	stora	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	små	≤ ojämn storlek ≤ understuckna trakter

	GÅNGARTER		Extremvariant	A B C	D E F	G H I	Extremvariant	Kommentar
22	Skritt	takt	taktmässig	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	oregelbunden	
23	Skritt	steglängd	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	
24	Skritt	energi	överilad	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	oengagerad	
25	Skritt	rörlighet	rörlig	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	låst	
26	Trav	steglängd	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	≤ otaktmässig
27	Trav	elasticitet	elastisk	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	oelastisk	≤ markbunden
28	Trav	framb. aktivitet	bogfri	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort/låst	
29	Trav	bakb. position	väl undersatt	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	bakom sig	
30	Trav	bakb. aktivitet	aktiv	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	inaktiv	
31	Galopp	takt/rytm	taktmässig	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	oregelbunden	
32	Galopp	språnglängd	lång	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	kort	
33	Galopp	aktion	rund	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	flack	
34	Galopp	elasticitet	elastisk	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	oelastisk	
35	Galopp	balans	balanserad	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	obalanserad	
36	Gångart: rörelseriktn.		uppförsbacke	≤ ≤ ≤	☐ ☐ ☐	≤ ≤ ≤	framvikt	

Domarsignatur

____

ASVH: 2019-01-23

Unghästtest

Arrangör/Datum……………………………………………………………………….

Hästnamn: Reg nr:

	HOPPNING	Extremvariant				Extremvariant	Kommentar
			A B C	D E F	G H I		
37	Avstamp	kraftfullt	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	svagt	
38	Avsprång: snabbhet	snabbt	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	långsamt	
39	Avsprång: riktning	uppåt	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	framåt	
40	Teknik: framben	böjda	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	hängande	☐ under kroppen ☐ utsträckta
41	Teknik: rygg	rundad	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	sänkt	
42	Teknik: bakben	öppnar upp	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	kniper	
43	Scope	stort	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	litet	
44	Elasticitet	mjuk, elastisk	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	stel	
45	Försiktighet	överförsiktig	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	oförsiktig	
46	Taxeringsförmåga	säker	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	osäker	
47	Balans	balanserad	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	obalanserad	
48	Reaktionsförmåga	snabb	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	långsam	
49	Inställning till uppg.	fokuserad	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	ofokuserad	
50	Beteende	avspänd	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐	spänd	

Poängbedömning

BEDÖMNING		Kommentar	Gångarter	Hoppning
Exteriör	Typ			
	Huvud hals bål			
	Extremiteter			
Gångarter	Skritt			
	Trav			
	Galopp			
Hopp	Teknik o förmåga:			
	Temperament:			
TOTALPOÄNG:				

KLASS GÅNGARTER **Diplom** ☐ **Klass 1** ☐ **KLASS HOPPNING** **Diplom** ☐ **Klass 1** ☐

ÖVRIGT:

RIDPROV (se särskilt protokoll) **Godkänt** ☐ **Ej godkänt** ☐ **Ej utfört** ☐

Domarunderskrift Domarunderskrift

För kvalitetsgradering av stoet skall ansökan skickas till ASVH. Protokoll och verifierade meriter skall bifogas.

Poängförklaring: 10=utmärkt, 9=mycket bra, 8=bra, 7=ganska bra, 6=godkänd, 5=med tvekan godkänd, 4= ej fullt godkänd, 3=ganska dålig, 2=dålig, 1=mycket dålig/ej visningsbar, halvpoäng får användas.

ASVH: 2019-01-23

Appendix 2

Figures 1 and 2 from the article titled "Factor analysis of evaluated and linearly scored traits in Swedish Warmblood horses," authored by A. Nazari-Ghadikolaei, F. Fikse, Å. Gelinder Viklund, and S. Eriksson, published in the Journal of Animal Breeding and Genetics (Volume 140, Issue 4, Pages 366–375). The figures are included in accordance with the permissions obtained from the publisher.

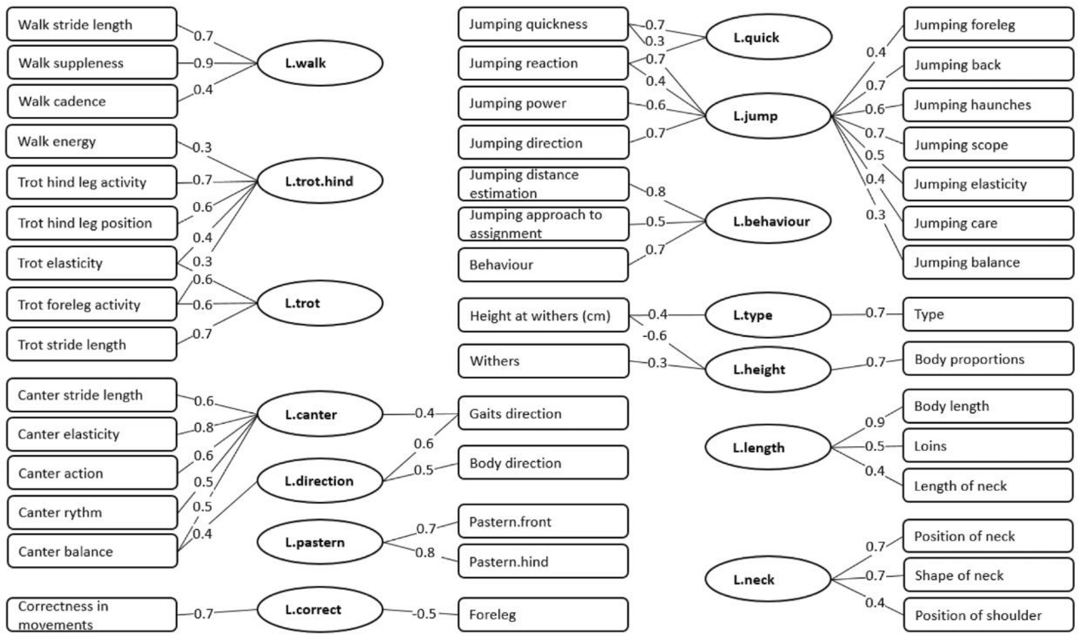

FIGURE 2 Factor loadings with absolute values ≥0.3 for linearly scored traits assessed at young horse tests for Swedish Warmbloods on 14 orthogonally rotated factors.

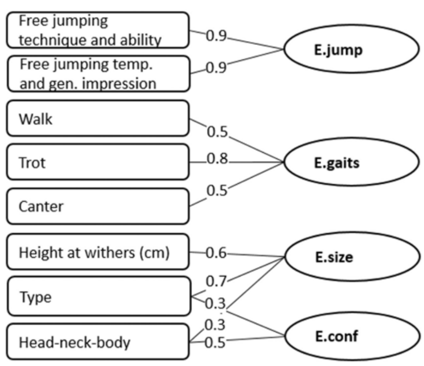

FIGURE 1 Factor loadings ≥0.3 for evaluated traits assessed at young horse tests for Swedish Warmbloods on four orthogonally rotated factors.

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