Livestock Science 282 (2024) 105438

Contents lists available at ScienceDirect

Livestock Science

journal homepage: www.elsevier.com/locate/livsci

Phenotypic associations between linearly scored traits and sport performance in the Swedish Warmblood horse population

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HIGHLIGHTS

- There are differences in linearly scored traits between jumping and dressage horses.
- Linearly scored traits are associated with success in show jumping and dressage competition.
- Most associations are linear, but associations with optimal scores also exist.
- Breeding for extremes is not optimal for all traits.
- Linearly scored traits can be a valuable tool to select horses for sport.

ARTICLE INFO

Keywords:
Dressage
Optimum score
Show jumping
Young horse test

ABSTRACT

The goal for most warmblood studbooks is to produce horses that are internationally competitive in sports like show jumping or dressage. The linear scoring system, describing the horse between two biological extremes, is commonly used for a more objective assessment of young horses in many studbooks. However, few studies have examined the phenotypic association between traits linearly scored at a young age and sport performance, and whether there might be an intermediate optimum on the linear scale. This study investigated the phenotypic association between linearly scored traits and competition performance in show jumping or dressage, using the results of linear scoring from young horse performance tests between 2013 and 2021 and competition data between 2014 and 2021 for Swedish Warmblood horses. Sport performance was defined as lifetime accumulated points achieved in show jumping or dressage competitions. Horses were classified as jumping (J) or dressage (D) horses according to their sires' and grandsires' classification. In total, 48 linearly scored traits, assessed on a biological scale from A to I, were analyzed. The phenotypic association between the linear score for each trait and sport performance was studied using linear models for sport performance including fixed effects of sex, birth year and linear and quadratic regression on adjusted linearly scored trait values. Significant differences in LS means between J and D horses were found for all linearly scored traits except for length of body and five traits referring to leg conformation. For J horses, 25 linearly scored traits (eight conformation traits, three gait traits, 13 jumping traits and one behavior trait) were found to be significantly associated ($p < 0.05$) with show jumping performance. A majority of these traits (21 out of 25 traits) showed a linear association with performance, indicating that stronger expression (towards A on the assessment scale) was favorable for performance in show jumping in J horses. For D horses, 21 linearly scored traits (eleven conformation traits and ten gait traits) were significantly associated with dressage performance. Most of these traits (15 out of 21 traits) showed a linear association with performance, while six traits showed an association with optimal scores, indicating that breeding for more extreme expression of the specific trait is not associated with better sport performance. These results underline the importance of linearly scored traits as indicator traits of later sport success.

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https://doi.org/10.1016/j.livsci.2024.105438
Received 11 January 2023; Received in revised form 1 March 2024; Accepted 3 March 2024
Available online 6 March 2024

1. Introduction

The goal for most warmblood studbooks, including the Swedish Warmblood (SWB), is to produce competitive horses at international level in sports like show jumping or dressage (Koenen et al., 2004). However, competition results at a high level can only be achieved later in life. Most breeding organizations therefore use specially designed young horse tests to collect information relevant for future performance in show jumping or dressage (Ricard et al., 2000). The results from these tests are moderately to highly correlated with performance later in life and can therefore be used as early indicators of competition performance traits (Thorén Hellsten et al., 2006).

In addition to the traditional scoring relative to the breeding goal, a linear scoring system for young horses has been introduced in many studbooks (Duensing et al., 2014). Scoring of traits on a linear scale from one biological extreme to another provides a more detailed description of the horse. The linearly scored traits describe different aspects of conformation, gaits and jumping characteristics, for example long to short neck, long to short stride length, powerful to weak take-off. Regarding the biological interpretation, the linear scoring system has no general optimum. Depending on the trait, the most favorable expression could be at one of the two extremes or somewhere in-between.

To enhance the performance and durability of sport horses, it is important to identify the optimal scores for relevant traits when selecting horses for competition and breeding. For example, Jönsson et al. (2014) derived optimal intervals for withers height and cannon bone circumference using health records from young SWB horses assessed at riding horse test (RHT) during 1983–2005. Also, Kristjansson et al. (2016) found optimal conformational measurements on total score for riding ability in Icelandic horses.

Although the linear scoring system has been used in several studbooks for many years, only a few studies have investigated the phenotypic association between linearly scored traits and competition results in show jumping and dressage. In studies on Dutch Warmblood horses (KWPN), significant phenotypic and genetic correlations between several linearly scored conformation, gait and jumping traits and performance in show jumping and dressage competition were found (Koenen et al., 1995; Ducro et al., 2007; Rovere et al., 2017). Their results were consistent with a study on Oldenburg horses by Stock et al. (2021). The mentioned studies were focused on genetic, and sometimes phenotypic, correlations and did not study possible phenotypic intermediate optima.

For SWB, a linear scoring system was introduced in 2013 at the young horse test (YHT) for three-year-old horses and in 2014 at the RHT for four-year-old horses and five-year-old mares that have had a foal (Viklund and Eriksson, 2018). Since 2017, estimated breeding values (EBVs) for linearly scored traits are officially published by the Swedish Warmblood Association. In 2021, the first age cohort with linearly assessed horses in SWB reached the age of 11 years, and these horses have thus had time to achieve competition results at advanced level in show jumping or dressage. The availability of such data makes it possible to investigate the association between linearly scored traits and show jumping and dressage performance in SWB horses, and to identify optimal scores for these traits in relation to competition performance.

The objective of this study was to investigate the phenotypic associations between linearly scored traits, assessed at YHT and RHT, and performance in show jumping and dressage competitions. More specifically, the aims were to:

1. describe differences in linearly scored traits (least squares means) between jumping and dressage horses in the SWB population,
2. investigate the phenotypic effects of linearly scored trait scores on lifetime accumulated competition points, and
3. identify possible intermediate linearly scored trait optima for show jumping and dressage competition performance, using linear models including both linear and quadratic regressions.

2. Materials and methods

2.1. Population

Pedigree information, results from YHT and RHT, and competition records for all horses in official competitions were obtained from the Swedish Warmblood Association. The study population was restricted to horses with a linear assessment from YHT or RHT between 2013 and 2021. For horses with an assessment from both YHT and RHT (12 %), only the first assessment (YHT) was kept to avoid repeated observations as this was only the case for a small proportion of the horses. The horses were divided into categories according to the classification of their sire and grandsire, as described by Bonow et al. (2023). Sires and grandsires were assigned to one of four categories (jumping, dressage, allround or Thoroughbred) according to breeding values, own performance and offspring performance. In the present study we only considered two categories of horses: jumping (J) and dressage (D). J horses were defined as horses with jumping sire and jumping grandsire, and D horses were defined as horses with dressage sire and dressage grandsire. In total 4216 horses were classified as J, and 3152 horses as D. Horses can compete from four years of age. In total 2414 of the J horses in the dataset had competed in show jumping and 1178 of the D horses had competed in dressage by October 2021. The competing horses in this study were born between 2009 and 2017. A description of the studied population is presented in Table 1.

2.2. Traits

A total of 48 linearly scored traits were investigated, comprising 21 conformation traits, 13 gait traits, 13 jumping traits, and one temperament trait. Only traits that were assessed at both YHT and RHT were considered. The linear scoring system for SWB has a nine-point-scale of A-I, where E is the center score and A and I correspond to the two biological extremes. Scores A-I were converted to numerical values 1–9 to enable statistical analyses. At RHT, horse owners can choose to have their horses assessed either in free jumping or jumping under rider. Two traits, distance estimation and behavior, are only assessed during free jumping, so horses that participated in jumping under rider at RHT did not have any scores for these two traits. During the first year with linear scoring (YHT, 2013), the protocol was slightly different to that used from 2014 onwards, e.g., foreleg activity in trot and balance, reaction, and behavior in jumping were added in 2014, and the trait pastern

Table 1
Number of Swedish Warmblood jumping (J) and dressage (D) horses with a linear assessment and number of J horses and D horses with competition results in show jumping and dressage, respectively, by birth years 2009–2018.

Birth year	Number of assessed J horses	Number of assessed D horses	Number of J horses competing in show jumping	Number of D horses competing in dressage
2009[†]	21	13	20	7
2010	603	413	444	221
2011	522	370	402	192
2012	423	339	308	175
2013	395	297	302	165
2014	358	264	240	115
2015	391	297	253	116
2016	463	394	254	106
2017	558	371	191	81
2018	482	394	–	–
Total	4216	3152	2414	1178

[†] Only mares that were five years old in the first year with linear assessment at the Riding Horse Test (2014).

(upright – straight) was divided into separate traits for front and hind limbs 2014. Additionally, the traits action in canter and approach to assignment in jumping had different definitions of the extreme values from 2014 onwards. Hence, fewer records were available for traits that were not included or had another definition in 2013. The studied traits and their definitions are listed in Table 2 and 3.

Achieved lifetime accumulated points in show jumping or dressage competitions are defined as the breeding goal traits in SWB (Swedish Warmblood Association, 2021). Horses that are placed in an official competition, defined as the 25 % best in each competition, receive points. A horse receives more points for a better placing, a placing at a more advanced level, or both. Horses that are not placed receive no points, but their starts are recorded. Qualification to compete on advanced level is achieved by reaching predefined results on lower levels. For the present analysis, J and D horses were classified as "competing horses" if they had at least one record from an official competition in its main discipline, regardless of whether they had received points or not. Out of 2414 competing J horses, 1654 horses (68.5 %) had achieved points in show jumping, and of 1178 competing D horses, 582 horses (49.4 %) had achieved points in dressage. The distribution of points was right-skewed and was therefore $\log_{10}$-transformed before the analyses. Because some horses had zero points, the number 1 was added before logarithmic transformation in order to enable transformation. The distribution of competition points was similar between linearly scored horses and all horses classified in the same discipline and the same birth year period.

2.3. Statistical analyses

2.3.1. Differences between J and D horses for linearly scored traits

Analysis of variance was performed using the General Linear Models (GLM) procedure in SAS (SAS Institute Inc., 2016). Each linearly scored trait, in total 48 traits, was analyzed separately with the linear model:

$$Y_{ijkl} = \mu + sex_i + event_j + category_k + e_{ijkl} \quad (1)$$

where Y_{ijkl} is the observed linear score (1, 2,…, 9), μ is the population mean, sex_i is the fixed effect of the i_{th} sex (male or female), $event_j$ is the fixed effect of the j_{th} combination of year and location (1, …, 341), $category_k$ is the k_{th} fixed effect of category (J or D) and e_{ijkl} is the random residual $\sim IND(0, \sigma_e^2)$. Least squares (LS) means were estimated and compared between category J and D. The residuals were continuous and for most traits approximately normally distributed. Traits for which the residuals were clearly deviating from normal distribution are marked in Tables 2 and 3.

2.3.2. Effect of linearly scored traits on performance and detection of trait optima

Each category of horses (J and D) was analyzed separately, and each linearly scored trait was analyzed with procedure GLM in SAS, in total 96 analyses. The following linear model was used:

$$Y_{ijk} = \mu + sex_i + event_j + e_{ijk} \quad (2)$$

where Y_{ijk}, μ, sex_i, and $event_j$ were as described for (1) and e_{ijk} is the

Table 2
Mean score, standard deviation (SD) and range for linearly scored conformation and gait traits in Swedish Warmblood jumping (J) horses and dressage (D) horses (N = 7368) assessed at young horse test or riding horse test 2013–2021. LS means (LSM) for J horses (N = 4216) and D horses (N = 3152) and significance level (Sign) between LS means for J and D horses.

			All horses			J horses	D horses	
	Trait	Extreme values	Mean	SD	Range	LSM	LSM	Sign
Type	Type	*refined – heavy*	4.77	0.72	2–8	4.81	4.72	****
	Body: shape a	*long – short*	4.72	0.71	2–7	4.73	4.70	n.s.
	Body: shape b	*long legged - short legged*	4.77	0.72	1–8	4.81	4.72	****
	Body direction	*uphill – downhill*	5.05	0.58	3–8	5.13	4.87	****
Head-neck-body	Length of neck	*long – short*	4.81	0.66	2–8	4.84	4.69	****
	Position of neck	*vertical – horizontal*	4.74	0.74	2–7	4.97	4.58	****
	Shape of neck	*arched – straight*	4.90	0.85	2–8	5.14	4.71	****
	Withers	*high – low*	4.88	0.65	2–7	4.81	4.88	****
	Position of shoulder	*sloping – straight*	5.21	0.70	3–8	5.32	5.06	****
	Line of back	*straight – swayback*	5.13	0.58	2–9	5.14	5.09	****
	Loins	*long – short*	4.79	0.63	2–8	4.77	4.83	****
	Shape of croup	*sloping – straight*	4.65	0.64	2–8	4.62	4.68	***
	Length of croup	*long – short*	4.93	0.60	3–7	5.00	4.92	****
Correctness of legs	Foreleg a	*over at knee – back at knee*	5.08	0.33	3–7	5.08	5.07	n.s.[b]
	Foreleg b	*toed in – toed out*	5.03	0.74	2–9	5.07	4.90	****
	Pastern, front[a]	*upright – weak*	5.10	0.42	2–8	5.10	5.11	n.s.[b]
	Hind leg a	*sickle – straight*	4.94	0.62	1–7	4.93	4.94	n.s.
	Hind leg b	*cow hocked – bowlegged*	5.00	0.48	3–8	5.06	5.04	n.s.[b]
	Pastern, hind[a]	*upright – weak*	5.13	0.46	3–9	5.13	5.14	n.s.[b]
	Correctness in movement	*winging – paddling*	5.09	0.52	3–8	5.06	5.14	****
	Hoofs	*large – small*	4.98	0.38	3–7	4.92	5.00	****
Walk	Cadence	*even – uneven*	4.92	0.51	2–9	5.03	4.83	****
	Stride length	*long – short*	4.96	0.85	1–8	5.14	4.69	****
	Suppleness	*supple – stiff*	4.86	0.83	2–8	5.09	4.64	****
Trot	Stride length	*long – short*	5.07	0.76	1–8	5.30	4.74	****
	Elasticity	*elastic – inelastic*	5.09	0.87	1–8	5.46	4.76	****
	Foreleg activity[a]	*shoulder free – short*	4.94	0.77	1–8	5.22	4.68	****
	Hind leg position	*under the body – behind the body*	4.99	0.75	1–8	5.27	4.75	****
	Hind leg activity	*active – inactive*	4.90	0.83	1–8	5.16	4.66	****
Canter	Rhythm	*even – uneven*	4.76	0.62	1–7	4.83	4.68	****
	Stride length	*long – short*	4.73	0.77	1–8	4.80	4.62	****
	Action[a]	*round – flat*	4.88	0.76	1–7	5.00	4.71	****
	Elasticity	*elastic – stiff*	4.95	0.79	1–9	5.04	4.88	****
	Movement: direction	*uphill – downhill*	4.96	0.70	1–9	5.13	4.79	****

*$P < 0.05$, **$P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$, n.s. = not significant.
[a] N=3698 for J horses; N = 2788 for D horses.
[b] residuals were not approximately normally distributed and significance test may be affected.

Table 3
Mean score, standard deviation (SD) and range for linearly scored jumping and temperament traits in Swedish Warmblood jumping (J) horses and dressage (D) horses ($N = 7368$) assessed at young horse test or riding horse test 2013–2021. LS means (LSM) for J horses ($N = 4216$) and D horses ($N = 3152$) and significance level (Sign) between LS means for J and D horses.

			All horses			J horses	D horses	
	Trait	Extreme values	Mean	SD	Range	LSM	LSM	Sign
Take-off	Power	*powerful – weak*	4.99	0.87	1–9	4.71	5.41	****
	Quickness	*quick – slow*	4.74	0.84	1–9	4.63	5.03	****
	Direction	*upwards – forwards*	4.90	0.95	1–8	4.61	5.35	****[d]
Technique	Foreleg	*bent – hanging*	4.72	0.89	1–8	4.58	5.00	****
	Back	*rounded – hollow*	5.06	0.88	2–9	4.78	5.39	****
	Haunches	*open – tight*	4.75	0.88	1–9	4.54	5.10	****
Jumping overall	Scope	*much – little*	5.08	0.94	2–9	4.63	5.66	****
	Elasticity	*elastic – stiff*	4.91	0.83	1–8	4.81	5.07	****
	Carefulness	*too careful – not careful*	4.64	0.93	1–9	4.54	4.87	****
	Balance[a]	*balanced – unbalanced*	4.88	0.61	1–7	4.85	4.93	****[d]
	Reaction[a]	*quick – slow*	4.88	0.73	2–9	4.76	5.15	****
	Approach to assignment[a]	*focused – unfocused*	4.76	0.97	2–9	4.65	4.91	****
	Distance estimation[b]	*secure – insecure*	4.98	0.82	2–9	4.86	5.12	****
	Behavior[c]	relaxed – tense	5.11	0.98	2–9	4.96	5.23	****

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, n.s. = not significant.
[a] N=3698 for J horses; $N = 2788$ for D horses.
[b] N=3857 for J horses; $N = 3116$ for D horses.
[c] Temperament trait; $N = 3339$ for J horses; $N = 2751$ for D horses.
[d] residuals were not approximately normally distributed and significance test may be affected.

random residual $\sim$IND(0, σ_e^2) . The resulting residuals, i.e. adjusted trait values, were used as explanatory variables in the model for competition performance. The competition performance traits lifetime accumulated points in show jumping for J horses and in dressage competitions for D horses, both $\log_{10}$-transformed, were analyzed using the linear model:

$$Y_{ijkl} = \mu + sex_i + by_j + b_1 \times \text{ residual linear score}_k + b_2 \times \text{residual linear score}_k^2 + e_{ijkl} \quad (3)$$

where Y_{ijkl} is the is the lifetime accumulated point in show jumping or dressage transformed with 10-logarithm, μ is the population mean, sex_i is the fixed effect of the i_{th} sex (male or female), by_j is the fixed effect of the j_{th} birth year (2009, …, 2017), $b_1 \times$ residual linear $score_k$ and $b_2 \times$ residual linear $score_k^2$ are the linear and quadratic regressions of the residual of one linearly scored trait at the time, and e_{ijkl} is the random residual $\sim$IND(0, σ_e^2). For traits for which there was a significant quadratic regression effect, the regression coefficients from the analyses were used to plot graphs to illustrate the association between the linearly scored trait and lifetime accumulated points. The graphs were plotted using a scale with a mean equal to that of the linearly scored trait within group (J or D) and extended to +/- 2 standard deviations from the mean. This choice of scale was made to avoid biasing toward rare extreme values when using quadratic regressions, and to better represent the actual use of the assessment scale.

3. Results

3.1. Differences between J and D horses for linearly scored traits

Mean scores, standard deviations, and range for linearly scored traits for J and D horses, and LS means for linearly scored traits for J and D horses, respectively, are presented in Table 2 (linearly scored conformation and gait traits) and Table 3 (linearly scored jumping and temperament traits). The significance level for the difference between LS means for J and D horses is also given in Tables 2 and 3. For most traits, mean scores were close to 5, corresponding to the center letter E. Examples of distributions of scores for one conformation trait (shape of neck), one gait trait (trot elasticity) and one jumping trait (scope) for J and D horses are presented in Fig. 1. For J horses, the LS means ranged from 4.54 (carefulness in jumping and jumping technique of haunches) to 5.46 (elasticity in trot) (Tables 2 and 3). For D horses, the LS means ranged from 4.58 (position of neck) to 5.66 (scope in jumping). The differences between LS means for J and D horses were significant ($P < 0.0001$ and $P < 0.001$) for all conformation traits except for body length and five traits referring to correctness of legs. For gait, jumping, and temperament traits, all differences in LS means between J and D horses were highly significant ($P < 0.0001$). The largest differences were seen for traits describing aspects of trot and for the jumping traits scope, power and direction of take-off, and technique of back and haunches.

3.2. Effect of linearly scored traits on performance and detection of trait optima

The estimated linear and quadratic regression coefficients of show jumping and dressage performance in J and D horses, respectively, on the residuals of linearly scored traits adjusted for sex and event and significance levels, are presented in Table 4 (linearly scored conformation and gait traits) and Table 5 (linearly scored jumping and temperament traits). Twenty-five linearly scored traits (eight conformation traits, three gait traits, 13 jumping traits and one behavior trait) were significant ($p < 0.05$) for show jumping performance for J horses, while 21 linearly scored traits (eleven conformation traits, ten gait traits) were significant for dressage performance for D horses. Nine traits were significant for both show jumping and dressage performance: type (refined – heavy), body shape (long legged – short legged), body direction (uphill – downhill), position of neck (vertical – horizontal), shape of neck (arched – straight), position of shoulder (sloping – straight), hind leg activity in trot (active – inactive), elasticity in canter (elastic – stiff) and direction of movement (uphill – downhill). All traits describing aspects of trot were highly significant for dressage performance, whereas only one of these traits was significant for show jumping performance (hind leg activity). For J horses, all 13 traits describing aspects of jumping were significant for show jumping performance, whereas none of these traits was significant for dressage performance. Traits describing aspects of walk were not significant for either show jumping or dressage performance. Except for foreleg (over at knee – back at knee) and hind leg (sickle – straight) for dressage performance, traits describing aspects of correctness of legs were not significant for either show jumping or dressage performance.

In total, the linear regression coefficients were found to be significant in 41 cases and the quadratic regression coefficients in ten cases (Tables 2 and 3). Among the ten traits, four were associated to show

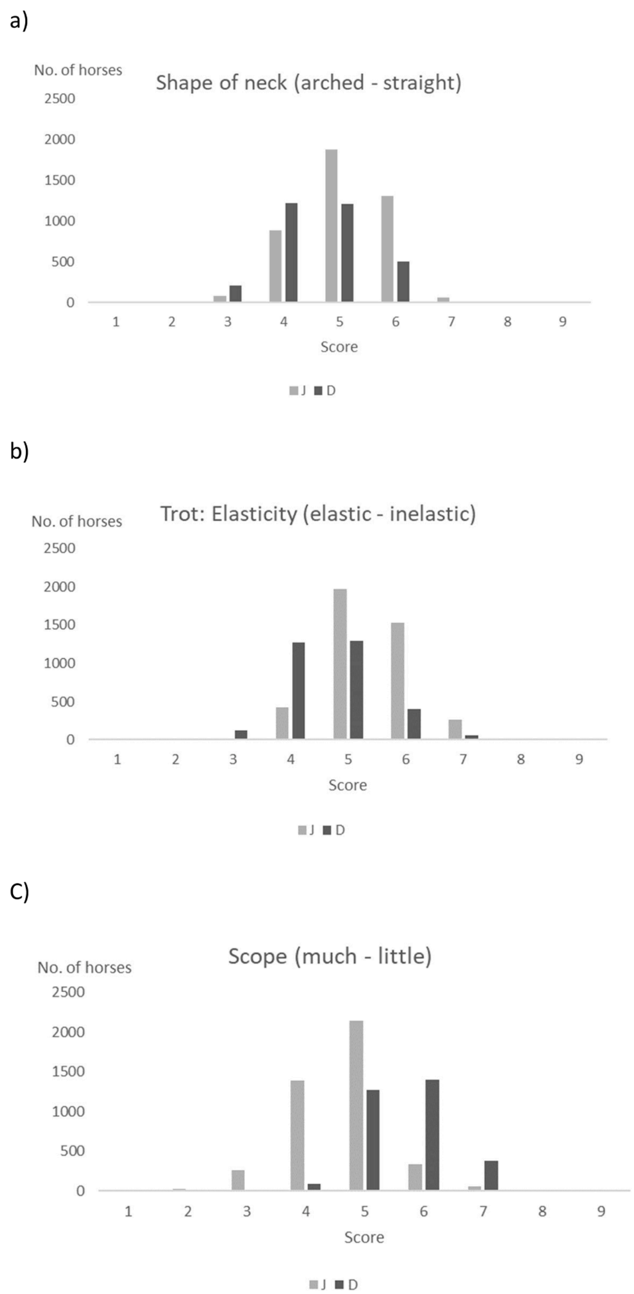

Fig. 1. Examples of distribution of linearly scored traits assessed at in jumping (J) and dressage (D) horses at Young Horse Test and Riding Horse Test for shape of neck (a), elasticity in trot (b) and scope (c). The assessment scale A to I is transformed to numerical values 1 to 9.

jumping performance and six to dressage performance. For show jumping the quadratic coefficients were positive. Body direction and jumping technique regarding both back and haunches showed a trend with the highest logarithmic lifetime accumulated competition points towards score 1 (A) (Fig. 2). Even though the quadratic coefficients were significant there were no upward trends towards the other end of the scale. For length of loins, on the other hand, there was an increasing trend towards both 1 (A) and 9 (I) (Fig. 2). For dressage, the quadratic coefficients were all negative resulting in optima. These optima were intermediate except for foreleg activity in trot where the trend flattened out towards 1 (A) (Fig. 3).

4. Discussion

4.1. Studied traits

This is one of the first studies based on a large number of horses to investigate the phenotypic association between linearly scored traits and competition performance in show jumping and dressage, and the potential optima for these traits. Because of the descriptive nature of the linear scoring, the system is independent of breeding goals and has the advantage of being applicable when assessing traits with the same definition in different studbooks. Thus, it is possible to compare trait differences between horse populations (Sperrle et al., 2016). The linear scoring system can therefore be a useful tool for future international genetic evaluation across studbooks. Also, the linear scoring gives a more detailed description of the horse compared to traditional subjective scoring of the horse relative to the breeding goal (Duensing et al., 2014). This may be of importance when assessing traits with intermediate optimum, such as traits associated to correctness of legs (Duensing et al., 2014; Viklund and Eriksson, 2018).

The Swedish Warmblood (SWB) has strong genetic connectedness to most well-known warmblood studbooks (Thorén Hellsten et al., 2008; Ruhlmann et al., 2009; Pettersson et al., 2016). The results from this study can thus be relevant also in a wider perspective of international sport horse breeding, especially as linear traits are scored and defined in similar ways in several countries (Duensing et al., 2014). In this study the breeding goal traits were measured as lifetime accumulated points in show jumping and dressage, respectively, which also are the defined breeding goal traits in SWB and the measurement used for the routine genetic evaluation (Viklund et al., 2011). Other measurements of competition performance are practiced in genetic evaluation of sport horses in other studbooks, for example "highest level achieved in competition" in German studbooks (Welker et al., 2018) and in KWPN (Rovere et al., 2016).

The effect of rider may have a strong influence on both the assessment under rider at RHT and in future competitions. Some studies have corrected for the effect of rider in the model used, e.g., Rovere et al. (2017) classified the rider effect into six groups based on the highest level achieved by the rider before riding the horse that produced the record. However, it was not possible to include the rider effect in the model in our study because information about rider at RHT was not available in the data, and because competition performance was measured as lifetime accumulated points and a horse may have several different riders during its competition career.

4.2. Differences between J and D horses for linearly scored traits

In the linear scoring system in SWB, all horses are assessed according to the same standardized procedure using the same scale regardless of the discipline they were bred for (SWB, 2021). In this study, all mean scores for horses assessed at YHT or RHT were close to 5 (4.64–5.21), which corresponds to the letter E on the linear assessment scale. This was also seen in a study by Ducro et al. (2007), where mean scores for linearly scored gait and jumping traits in Dutch Warmblood were close to the center of the assessment scale (between 19.6 to 22.1 on a scale ranging from 1 to 40). However, in our study there were significant differences in LS means between J and D horses for all traits except some describing aspects of correctness of legs (for which extreme values are undesirable; Koenen et al., 1995). Borowska & Lewczuk (2023) found significant differences in LS means for six linear conformation traits between warmblood dressage and jumping horses in Poland, of which two referred to correctness of legs. One of the traits was stance of forelegs (over at knee – back at knee) that was one of few traits where there was no significant difference found in the present study.

The LS means showed clear differences between discipline-specific traits for J and D horses, providing further indication of the specialization process in the SWB population reported by Bonow et al. (2023). For

Table 4
Linear and quadratic regression coefficients with significance level, of linearly scored conformation and gait traits on competition results in show jumping and dressage in Swedish Warmblood of jumping (J; $N = 2414$) and dressage (D; $N = 1178$) horses, respectively.

		J horses, show jumping				D horses, dressage			
	Trait	Linear		Quadratic		Linear		Quadratic	
Type	Type	−0.052	*	−0.025	n.s.	−0.081	*	0.042	n.s.
	Body: shape a	0.027	n.s.	0.004	n.s.	−0.039	n.s.	−0.001	n.s.
	Body: shape b	−0.059	*	0.016	n.s.	−0.149	***	−0.061	n.s
	Body direction	−0.102	**	0.083	*	−0.154	**	−0.052	n.s.
Head-neck-body	Length of neck	0.015	n.s.	0.031	n.s.	−0.100	*	−0.005	n.s.
	Position of neck	−0.076	**	−0.026	n.s.	−0.098	*	−0.029	n.s.
	Shape of neck	−0.058	**	−0.008	n.s.	−0.089	**	−0.039	n.s.
	Withers	−0.005	n.s.	−0.004	n.s.	−0.028	n.s.	−0.066	n.s.
	Position of shoulder	−0.054	*	0.012	n.s.	−0.111	**	−0.001	n.s.
	Line of back	0.011	n.s.	0.049	n.s.	0.050	n.s.	−0.147	**
	Loins	0.043	n.s.	0.064	*	−0.017	n.s.	0.000	n.s.
	Shape of croup	−0.031	n.s.	−0.004	n.s.	−0.057	n.s.	−0.023	n.s.
	Length of croup	0.004	n.s.	0.049	n.s.	−0.041	n.s.	0.001	n.s.
Correctness of legs	Foreleg a	−0.035	n.s.	0.020	n.s.	−0.111	n.s.	−0.040	n.s.
	Foreleg b	0.017	n.s	0.014	n.s.	0.047	n.s.	−0.087	*
	Pastern, front[a]	−0.091	*	−0.021	n.s.	0.010	n.s.	−0.060	n.s.
	Hind leg a	0.024	n.s.	0.043	n.s.	−0.125	**	−0.118	*
	Hind leg b	−0.049	n.s.	0.012	n.s.	−0.021	n.s.	−0.010	n.s.
	Pastern, hind[a]	−0.079	n.s.	0.038	n.s.	0.007	n.s.	−0.132	*
	Correctness in movement	0.011	n.s.	0.031	n.s.	0.010	n.s.	−0.045	n.s.
	Hoofs	0.011	n.s.	0.016	n.s.	−0.009	n.s.	−0.025	n.s.
Walk	Cadence	−0.035	n.s.	0.004	n.s.	−0.078	n.s.	0.008	n.s.
	Stride length	0.011	n.s.	−0.010	n.s.	−0.030	n.s.	−0.048	n.s.
	Suppleness	0.011	n.s.	0.031	n.s.	−0.056	n.s.	−0.045	n.s.
Trot	Stride length	−0.015	n.s.	0.009	n.s.	−0.169	****	−0.038	n.s.
	Elasticity	−0.023	n.s.	0.014	n.s.	−0.199	****	−0.029	n.s.
	Foreleg activity[a]	−0.052	n.s.	0.010	n.s.	−0.166	****	−0.074	*
	Hind leg position	−0.043	n.s.	−0.016	n.s.	−0.147	***	−0.041	n.s.
	Hind leg activity	−0.082	***	0.015	n.s.	−0.149	****	−0.030	n.s.
Canter	Rhythm	−0.048	n.s.	0.041	n.s.	−0.128	**	−0.066	n.s.
	Stride length	−0.037	n.s.	0.020	n.s.	−0.061	n.s.	−0.082	*
	Action[a]	−0.046	n.s.	0.043	n.s.	−0.148	***	−0.017	n.s.
	Elasticity	−0.080	***	0.013	n.s.	−0.134	***	−0.008	n.s.
	Movement: direction	−0.068	*	0.003	n.s.	−0.189	****	−0.053	n.s.

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, n.s. = not significant.
[a] N=2040 for J horses; $N = 981$ for D horses.

Table 5
Linear and quadratic regression coefficients with significance level, of linearly scored jumping and temperament traits on competition results in show jumping and dressage in Swedish Warmblood of jumping (J; $N = 2414$) and dressage (D; $N = 1178$) horses, respectively.

		J horses, show jumping				D horses, dressage			
	Trait	Linear		Quadratic		Linear		Quadratic	
Take-off	Power	−0.192	****	0.028	n.s.	−0.031	n.s.	0.052	n.s.
	Quickness	−0.099	****	−0.000	n.s.	0.001	n.s.	−0.041	n.s.
	Direction	−0.133	****	0.020	n.s.	0.050	n.s.	0.021	n.s.
Technique	Foreleg	−0.102	****	0.021	n.s.	−0.031	n.s.	0.0126	n.s.
	Back	−0.118	****	0.041	*	−0.021	n.s.	0.014	n.s.
	Haunches	−0.046	*	0.030	*	−0.069	n.s.	0.028	n.s.
Jumping overall	Scope	−0.173	****	0.006	n.s.	−0.016	n.s.	0.037	n.s.
	Elasticity	−0.078	****	0.028	n.s.	−0.055	n.s.	0.033	n.s.
	Carefulness	−0.060	**	−0.017	n.s.	0.014	n.s.	0.015	n.s.
	Balance[a]	−0.131	****	0.005	n.s.	−0.001	n.s.	0.029	n.s.
	Reaction[a]	−0.137	****	−0.022	n.s.	0.003	n.s.	−0.010	n.s.
	Approach to assignment[a]	−0.109	****	0.010	n.s.	−0.012	n.s.	0.008	n.s.
	Distance estimation[b]	−0.084	****	−0.014	n.s.	−0.006	n.s.	0.001	n.s.
	Behaviour[c]	−0.038	*	−0.003	n.s.	0.007	n.s.	0.014	n.s.

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, n.s.=not significant.
[a] N=2040 for J horses; $N = 981$ for D horses.
[b] N=2118 for J horses; $N = 1157$ for D horses.
[c] Temperament trait; $N = 1744$ for J horses; $N = 959$ for D horses.

gait and jumping traits, the differences were highly significant ($p < 0.0001$) and the largest differences were seen for traits describing aspects of trot, and for the jumping traits scope, power and direction of take-off, and technique of back and haunches. This highlights the importance of trot for dressage horses and of scope (height and width of the jump) and jumping technique for show jumping horses. For all gait traits, D horses had mean scores closer to 1 (A) than did J horses, which means they had longer strides, showed more elasticity, etc. For all

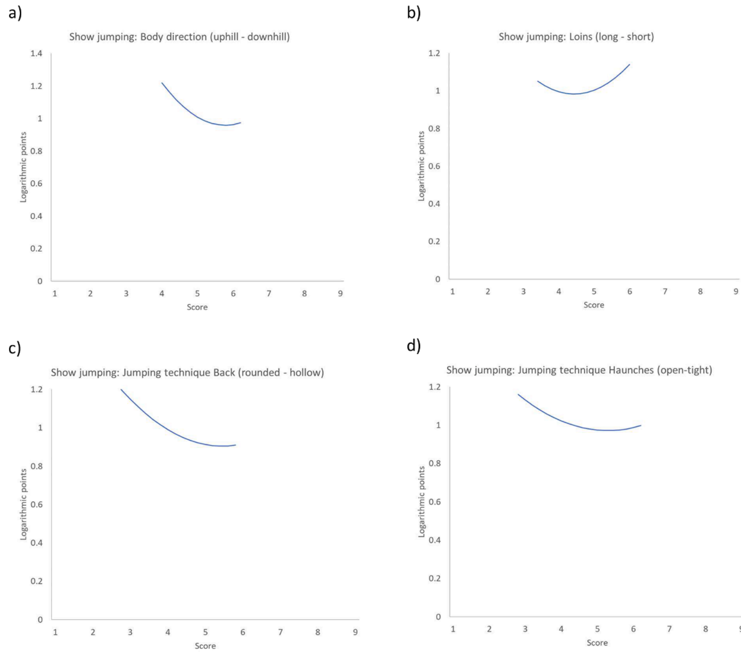

Fig. 2. Illustration of the associations between competition performance in **show jumping** (lifetime accumulated logarithmic points) and linearly scored traits based on the significant quadratic regression coefficient. The assessment scale A to I is transformed to numerical values 1 to 9. The graphs were plotted using a scale with a mean equal to that of the linearly scored trait within jumping horses and extended to +/- two standard deviations from the mean.

jumping traits, J horses had mean scores closer to 1 (A) than did D horses, meaning stronger and quicker take-off when jumping, more scope, etc. in J horses. Rovere et al. (2015) also concluded that the specialization process in Dutch Warmblood had resulted in differences in phenotypic mean trait values regarding linear movement traits between dressage and jumping horses. In the Polish study by Borowska & Lewczuk (2023) only one linear movement trait (balance in canter) and no linear jumping traits showed significant differences in LS means between dressage and jumping horses. The lack of significance regarding jumping traits may be due to their smaller data set, in which only 139 horses were assessed in jumping.

4.3. Association between linearly scored traits and show jumping performance

For J horses, all of the linearly scored jumping traits had a significant phenotypic association with show jumping, as did elasticity in canter. The importance of these traits was also shown by Ducro et al. (2007) who estimated significant positive phenotypic correlations (0.10–0.16) between linearly scored jumping traits and show jumping in KWPN horses. Both Ducro et al. (2007) and Rovere et al. (2017) also found high genetic correlations between linearly scored free jumping traits and show jumping and moderate genetic correlations between linearly scored canter traits and show jumping. In Oldenburg horses, Stock et al. (2021) found significant correlations between EBVs for linearly scored jumping traits and EBVs for show jumping performance.

In our study, eight conformation traits (type, body shape (long legged – short legged), body direction, position of neck, shape of neck, position of shoulder, length of loins and front pastern) were significant on a phenotypic level for show jumping, which suggests that some conformation traits of a warmblood show jumping horse are associated with competition performance. In contrast, Koenen et al. (1995) found low phenotypic correlations, close to zero, between linearly scored conformation traits and show jumping.

In our study, the linear scores for walk and trot traits were not significant at a phenotypic level for show jumping (except for hind leg activity in trot) indicating that these gaits are generally not associated with show jumping performance. This was also seen in a study by Ricard et al. (2020), who concluded that assessing gait traits using accelerometers and judge scores in order to improve jumping performance is unhelpful, because the genetic correlations are low. Ducro et al. (2007) and Rovere et al. (2017) also found low genetic correlations between linearly scored walk and trot traits and show jumping performance. However, because our study was based on phenotypic associations, comparisons with results from genetic analyses should be made with caution.

Direction and power of take-off, balance, scope, and technique of the back were jumping traits that had a highly significant ($p < 0.0001$) association with show jumping performance. These results are in agreement with findings in a study by Stock et al. (2022), where the strongest genetic trends in Oldenburg jumping horses were seen for power of take-off and jumping ability.

The majority of the linearly scored traits that were significant for show jumping showed a linear association, which indicates that expressions towards one of the two extremes are more favorable. Thus, the more towards 1 (letter A) a horse is scored on the linear assessment scale, the higher the probability of that horse competing on a high level in show jumping. The selection of horses for breeding and sport will thereby take place at this part of the assessment scale, and horses classified in the other direction, towards 9 (letter I), are of less interest. Significant quadratic regression coefficients were found for four traits. When plotted in relation to the phenotypic mean and standard deviation it was demonstrated that for three of the traits, there continued to be a general trend indicating improved competition results associated with lower values of the linearly scored traits. For the fourth trait, length of loins, the plotted graph indicated that a length deviating from the average population would be beneficial for competition performance. However, the graph shows that the differences are small and therefore length of loins will probably have no major importance when selecting show jumping horses.

It is worth noting that the show jumping sport is changing over time, likely adding new traits to the most favorable characteristics of a high-performing horse. For example, since 2022, time faults have become more costly at international competitions and more restricted rules regarding hind boots and spurs has been introduced, and in 2023 the maximum depth of pole cups was reduced (FEI, 2022). Such changes

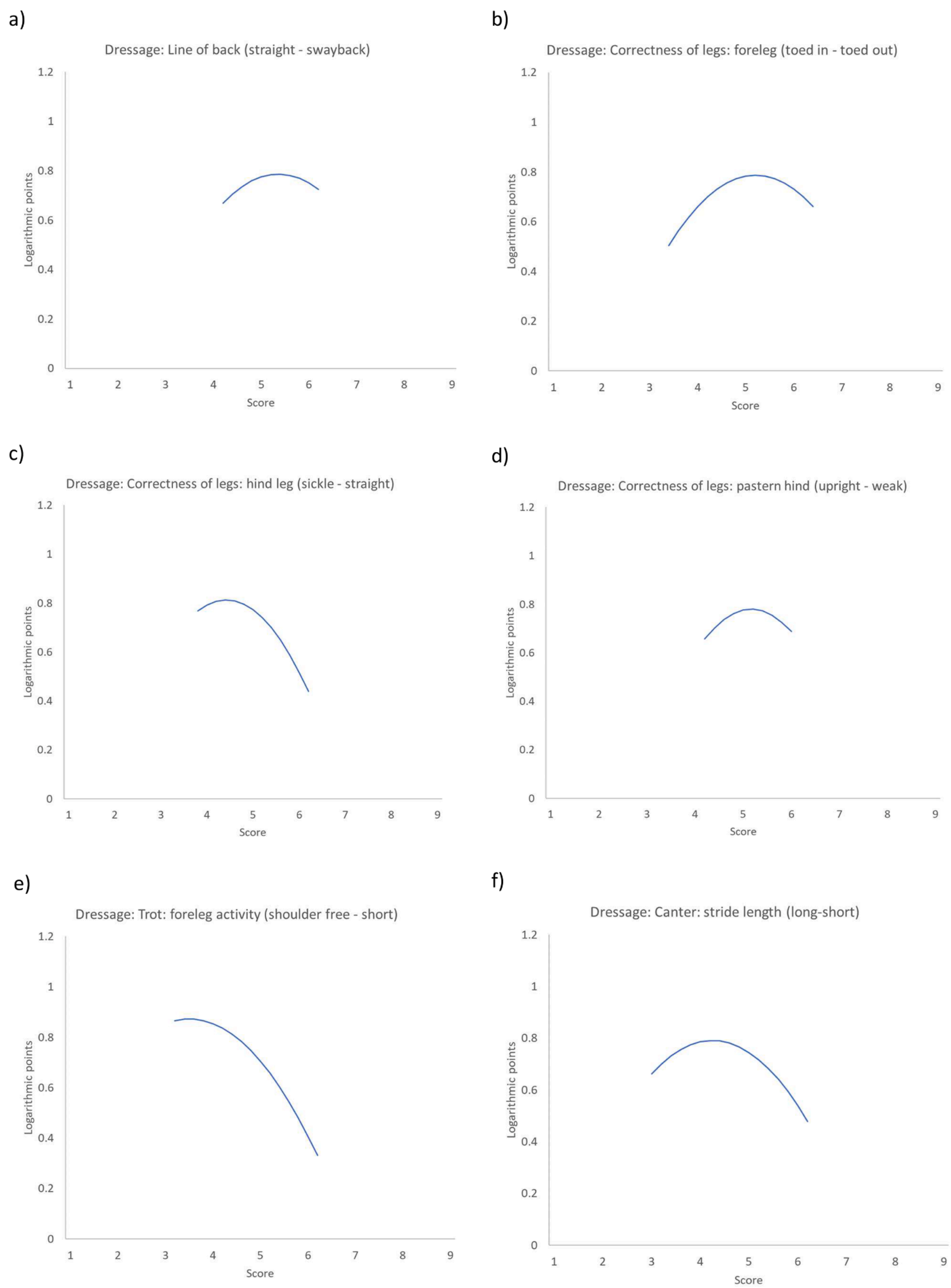

Fig. 3. Illustration of the associations between competition performance in **dressage** (lifetime accumulated logarithmic points) and linearly scored traits based on the significant quadratic regression coefficient. The assessment scale A to I is transformed to numerical values 1 to 9. The graphs were plotted using a scale with a mean equal to that of the linearly scored trait within dressage horses and extended to +/- two standard deviations from the mean.

indicate that horses will probably need to be quicker, more sensitive, and more careful to be successful at international level in the near future.

4.4. Association between linearly scored traits and dressage performance

For D horses, several conformation traits had a significant phenotypic association with performance in dressage. Based on the results, a refined, long legged and uphill body conformation seem to be of high value for a dressage horse, as well as a long, arched neck and a sloping shoulder. Similarly, in the study by Stock et al. (2022), genetic trends for conformation traits in dressage horses indicated significant development towards a larger frame, longer legs, and a shorter back. Positive genetic associations between dressage performance and a sloping shoulder as well as a long neck has previously been shown in the study on Dutch Warmblood by Koenen et al. (1995). An uphill body direction seemed to be favorable for both J and D horses. Also in Icelandic horses, an uphill conformation, measured as the difference in cm between height at front and height at hind and with an optimum of 6 cm, was shown to be one of the most important characteristics for riding ability (Kristjansson et al., 2016). In the Pura Raza Español horse, EBVs for the upper neck-line and angle of shoulder, among 13 morphological linear traits, were found to be useful to predict EBVs for both gait score and total score in dressage test for 4 to 6-year-old horses (Sánchez-Guerrero et al., 2017).

At the phenotypic level, all traits in our study describing aspects of trot and most traits describing aspects of canter were significant for performance in dressage, whereas no trait describing aspects of walk was significant. The importance of trot and canter traits for a dressage horse was also identified in the study by Ducro et al. (2007) where linearly scored traits associated with trot and canter had significant positive phenotypic correlations with dressage performance. Ducro et al. (2007) and Rovere et al. (2017) also estimated moderate to strong genetic correlation between trot and canter and dressage performance. Both studies found that correctness of walk had a low genetic correlation to dressage performance, but that stride length and elasticity in walk had a high genetic correlation. Our results indicate that an elastic trot with shoulder free foreleg activity, active hind legs and an uphill direction of movements seems to be of high importance at the phenotypic level. High importance of such traits was previously reported by Stock et al. (2021), who found strong correlations between EBVs for linearly scored traits and EBVs for dressage performance for carrying power and freedom of shoulders in trot and direction of movement in canter in Oldenburg dressage horses.

Six linearly scored traits that were significant for dressage performance had a significant and negative quadratic regression coefficient, indicating an optimum. Three of the traits were describing different aspects of correctness of legs; toed in to toed out foreleg, sickle to straight hind leg, and upright to weak hind pastern. As pointed out by Koenen et al. (1995), extremes for this category of traits are not desirable and both extremes have an adverse effect on performance in competition. Another conformation trait, line of back, also exhibited an optimum in our study. The graph indicated that the population mean is closely aligned with the optimum with respect to dressage performance. Among the linearly scored gait traits, two showed an association to dressage performance with an optimum; foreleg activity in trot and stride length in canter. The graph of foreleg activity showed a flattening curve towards 1 (A), indicating that breeding for a more extreme expression will not be favorable, although the negative impact on the sport performance would be limited. In terms of canter stride length, neither too short nor too long strides appeared to be advantageous for dressage competition. According to the graph, the studied population could still move slightly towards a longer stride length 1 (A) before the optimum is reached. However, because dressage is a subjectively judged sport known to develop over time (Hess, 2010), the most favorable expressions can change and the most advantageous traits today may not be the same in 10 years.

4.5. Potential use of linear scoring in the future

In order to produce competitive horses at an international level, it is necessary to breed for extraordinary abilities in jumping or dressage. In our study, many linearly scored traits showed a linear association with performance, meaning that scores towards 1 (letter A) on the assessment scale would be more advantageous for sport performance. This may suggest that, in the future, a higher prevalence of horses with more pronounced or distinct expressions of these traits will become more common, as breeders aim to produce horses for elite-level sports. However, breeding for extreme expressions of some specific traits may have negative consequences on health and durability of the horse. For example, it has been shown that heterozygosity of the mutation causing fragile foal syndrome is connected to elasticity in trot, indicating that breeding for that trait could increase the prevalence of the deleterious mutation in the population (Ablondi et al., 2022). Monitoring of health and durability, as well as inbreeding, in the population is highly recommended to avoid extreme breeding that could have negative effects on the welfare of the horse. Such monitoring would require cooperation between the breeding organization, veterinarians, insurance companies, and horse owners. Attention should also be paid to continuous training of judges, to maintain uniformity between judges when scoring linear traits (Gmel et al., 2020). It is important to monitor the population average in relation to the optimum in the breeding program and pay special attention to combining mare and stallion for traits with intermediate optimum scores. A proper knowledge of the genetic correlations among performance and functional traits is of importance for future selection within the breed and this should be investigated in further studies.

4.6. Limitations of the study

One potential limitation of the statistical analysis was that for some of the studied traits the residuals were not normally distributed. However, in our experience contrasts and significance tests from linear models with large number of observations are robust to any deviation from normality. Some authors even go as far as recommending the use of linear models for the analysis of 0/1 traits, where the residuals almost never are normally distributed, mostly owing to the direct interpretability of the estimates (Hellevik, 2009; Gomila, 2021). In our situation, we had a truly continuous dependent variable (lifetime accumulated points).

We used a linear and quadratic regression on the linearly scored traits to objectively decide whether an optimum existed or not. We also tried to use the unadjusted classes as categorical explanatory variables in the model but abandoned that approach because the definition of a non-linear relation became more subjective. Further, we wanted to adjust the linear scores for sex and event, which made the adjusted values (the residuals) continuous variables.

5. Conclusions

This study clearly highlighted linearly scored traits of importance to identify potentially successful show jumping or dressage horses. Differences in linearly scored traits between jumping and dressage horses confirm the specialization within the SWB population. For show jumping horses, all linearly scored jumping traits were found to be of high importance for sport performance, as were some traits associated with conformation and gaits. For dressage horses, all traits associated with trot were highly important, as were several traits associated with conformation and canter. A majority of the traits that were significant for show jumping showed a linear association (21 of 25), meaning that stronger expression of these traits was associated with on average higher competition performance. Among traits that were significant for dressage performance several (6 of 21) showed intermediate optimal scores, indicating that more extreme expression of these specific traits was not associated with better competition performance. The results in this study confirm that linearly scored traits serve as valuable tool for identifying and monitoring the development of traits essential for sport performance in show jumping and dressage horses.

CRediT authorship contribution statement

S. Bonow: Formal analysis, Writing – original draft, Writing – review & editing. **S. Eriksson:** Methodology, Writing – review & editing, Supervision. **E. Strandberg:** Methodology, Writing – review & editing, Supervision. **E. Thorén Hellsten:** Conceptualization, Writing – review & editing, Supervision. **Å. Gelinder Viklund:** Conceptualization, Data curation, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

Swedish Warmblood Association has provided the data for this study and has also supported the supervision by Emma Thorén Hellsten, who is a former employee at the organization.

Åsa Gelinder Viklund has regular commitments for Swedish Warmblood Association, regarding the routine genetic evaluation.

Acknowledgement

We are grateful to the Swedish Warmblood Association for providing data for this study.

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