Genetic Evaluation of Swedish Warmblood Horses

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Abstract

The main breeding objective for the Swedish Warmblood horse (SWB) is to produce competitive horses for show jumping or dressage. The aim of this thesis was to provide information to improve the breeding programme for SWB by investigating the usefulness of different sources of data for genetic evaluation and by studying the realised selection practices and genetic trends of the SWB population. Data from three information sources were used in the analyses: competitions (in show jumping and dressage), young-horse test for 3-year-olds (YHT) and riding horse quality test (RHQT) for 4-year-old horses. At YHT and RHQT the horses are subjectively scored for conformation, gaits and jumping ability.

The moderate to high heritabilities and high genetic correlations between different traits showed that all three information sources could be integrated in the genetic evaluation with a multi-trait BLUP animal model. The main objective is to breed horses that can achieve good lifetime competition results, and results from YHT and RHQT provide early information of the horses. Multiple information sources allow many horses to be tested, leading to accurate breeding values (EBVs) and opportunities for high selection intensity.

Competition and RHQT data go back to the early 1970's and the traits have changed over time due to development of the sport, change in the population and breeding objective, and change in judging at RHQT. The analyses showed that all data can be used in the genetic evaluation to estimate reliable and unbiased EBVs.

The genetic progress in both dressage and show jumping increased considerably in the mid 1980's due to stronger selection of stallions at the improved stallion performance test in the late 1970's, importation of superior stallions, introduction of young-horse testing at RHQT, and the beginning of predicting EBVs based on RHQT data with a BLUP animal model in 1986. The genetic trend of broodmares followed the same trend as non-selected horses, and the achieved genetic progress was primarily a result of stallion selection.

In the future, emphasis should be put on more effective use of EBVs for selection of stallions and mares, both at young age and when progenies of stallions have been tested.

Keywords: Horse breeding, genetic evaluation, breeding value, performance tests, heritability, genetic correlation, genetic trend

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Till min fantastiska familj!

När man är en björn med mycket liten hjärna och tänker ut saker, upptäcker man att en idé som verkade vara riktigt idéaktig inne i hjärnan, är annorlunda när den kommer ut i det fria och andra människor ser på.

Nalle Puh – A.A. Milne

Contents

List of Publications

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

I Viklund, Å., Thorén Hellsten, E., Näsholm, A., Strandberg, E. and Philipsson, J. (2008). Genetic parameters for traits evaluated at field tests of 3- and 4-year-old Swedish Warmblood horses. *Animal* 2(12), 1832-1841.

II Viklund, Å., Braam, Å., Näsholm, A., Strandberg, E. and Philipsson, J. (2010). Genetic variation in competition traits at different ages and time periods and correlations with traits at field tests of 4-year-old Swedish Warmblood horses. *Animal* 4(5), 682-691.

III Viklund, Å., Näsholm, A., Strandberg, E. and Philipsson, J. (2010). Effects of long-time series of data on genetic evaluations for performance of Swedish Warmblood horses. *Animal, in press,* doi:10.1017/S1751731110001175.

IV Viklund, Å., Näsholm, A., Strandberg, E. and Philipsson, J. (2010). Genetic trends for performance of Swedish Warmblood horses. (submitted to Livestock Science).

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Abbreviations

BLUP	best linear unbiased prediction
BWP	Belgian Warmblood
EBV	estimated breeding value
KWPN	Koninklijk Warmbloed Paardenstamboek Nederland (Dutch Warmblood)
PEC	pedigree completeness
RHQT	riding horse quality test
SF	Selle Français
SPT	stallion performance test
SvRF	Swedish Equestrian Federation
SWA	Swedish Warmblood Association
SWB	Swedish Warmblood
UELN	universal equine life number
YHT	young-horse test for 3-year-olds

Introduction

The interest for equestrian sport in Sweden has increased substantially in the last 40 years. In 1970, 680 riders participated in competitions (SRC, 1972) and today about 25,000 licensed riders compete every year. Consequently the demand for good sport horses has increased and the main breeding objective for Swedish Warmblood horses (SWB) has been formulated as the production of internationally competitive sport horses in both show jumping and dressage. A well-functioning breeding programme is crucial to achieve the breeding objective and can only be designed if the past and present conditions and trends of the population are known.

Estimation of breeding values plays an important role in a breeding programme. Breeding values with a BLUP animal model based on results from performance test for 4-year-old horses have been estimated for SWB since 1986 (Árnason, 1987). The result from this test was assumed to provide early, indirect measures of competition performance. To better reflect the breeding objective it was desired to include competition data into the genetic evaluation. Such data have been published for a long time in the year-book of the Swedish Equestrian Federation (SvRF) and have been computerised at the Department of Animal Breeding and Genetics at the Swedish University of Agricultural Sciences since the early 1970's. Moreover, in 1999 a young-horse test for 3-year-olds was introduced, and inclusion of data from this test could enable earlier estimation of breeding values and thus also earlier selection. It is important to make use of all data sources both to get as reliable and early proofs as possible and to ensure the credibility of the breeding values among breeders, trainers and riders.

This thesis aims at providing information useful for improvement of the breeding programme for SWB by investigating the usefulness of different sources of data for genetic evaluation and by studying the realised selection practices and genetic trends of the SWB population.

Background

The Swedish Warmblood Horse

Historically, the SWB was mainly used in the cavalry (Graaf, 2004). The interest for competition grew stronger after the Swedish success in the Olympic Games in 1924 and it led to a demand for a change in the breeding objective to also include suitability for competition. At the same time the request of horses for the cavalry decreased. In the end of the 1920's the Swedish Warmblood Association (SWA) was founded to join the breeders and to improve the SWB. The breeding objective has changed over the years. In the beginning the aim was to produce all-round horses, whereas today specialised breeding towards show jumping or dressage is practiced within the same population. The breeding objective for the SWB is "to produce a noble, correct and durable riding horse which through its temperament, rideability, good movements and/or jumping ability is internationally competitive" (ASVH, 2006).

An open studbook has always been practised and the SWB studbook is open to include good horses of most European Warmblood breeds provided they contribute to the breeding objective. The main contributions to SWB during the first half of the 20th century were stallions of Hanoverian, Trakehner and thoroughbred origin. In later years, primarily Holstein and Dutch bloodlines have been integrated into SWB to improve jumping ability.

The SWB has undergone a radical change in the last 3-4 decades. In the early 1970's only 2000 mares were covered. After some fluctuations, with a peak of 8000 mares covered in 1990, the annual number has stabilised at about 5000 mares which are covered by about 200 licensed stallions. This amounts to about 5% of the European Warmblood sport horse breeding population. In the mid 1980's more than 90% of the broodmares were covered by natural service whereas today more than 90% of the mares are artificially bred (Thorén Hellsten et al., 2009). Artificial insemination based on transported fresh semen is the most common method used. The international exchange, mainly with stallions, both live animals and imported semen, has also increased substantially in the last 20 years. In the late 1980's, 80% of the mares were covered by a Swedish-born stallion whereas today more than 80% of the mares are covered by foreign-born stallions (Thorén Hellsten et al., 2009).

Despite the relatively small population, Swedish riders have reached notable success at European, World and Olympic levels in show jumping, dressage and eventing. The majority of the successful horses have been Swedish-bred or stallions active in SWB breeding (Philipsson, 2005).

Performance testing of SWB horses

The Swedish government started to arrange conformation shows in the late 19th century with the aim to select horses for breeding. In 1914 an obligatory control with minimum requirements for potential breeding stallions was regulated in Swedish law in order to increase the quality of stallions used in breeding. This testing procedure has developed throughout the years and since the late 1970's 3-, 4-, and 5-year-old SWB stallions are tested for soundness, conformation, gaits, jumping and temperament during a week-long stallion performance test (SPT) to be approved for breeding. Annually 30 to 50 stallions participate in SPT and about 30% become approved for breeding (Olsson et al., 2008). However, in 1986 the government handed over the responsibility for evaluation of horses for breeding purposes to the breeding organizations, e.g. to the SWA for SWB horses.

In 1973 the Riding Horse Quality Test (RHQT) for 4-year-olds was introduced by a local breeding organisation of the SWA, and was later spread nationally. The aims of this one-day field test were to provide information for genetic evaluation of stallions and mares, and to evaluate the overall quality of young sport horses as regards conformation, health, jumping ability, gaits and rideability. At evaluations for gaits under rider and jumping, the horses also receive a score for temperament and general appearance. All traits are scored between 1 (very poor) and 10 (excellent). The test is annually carried out at about 20 locations all over Sweden. Most of the participating horses (95%) are 4 years old, but also 5-year-old mares that had a foal as 4-year-olds are allowed to participate. An initially unique feature was that the test is open for both genders and 54% of the tested horses are males (stallions or geldings). Approximately one-third of all 4-year-olds participate in RHQT.

A new young-horse test for 3-year-olds (YHT) was introduced in 1999 to provide an even earlier opportunity for genetic evaluation of stallions and mares, to enable early selection of mares, find talented horses for the sport, and to encourage early handling of the young horse. The YHT replaced the traditional conformation show of mares which was considered not to reflect the whole breeding objective. At this one-day field test, horses of both genders (55% mares) are evaluated for their conformation, gaits at hand and free, jumping ability and temperament and general appearance for jumping. Each trait is evaluated on the scale 1 (very poor) to 10 (excellent). About 40% of all three-year-olds participate in this test.

Competition data, mainly from show jumping and dressage, have been recorded since the early 1960's. From the beginning there were few competing horses but today more than 35% of the horses born have a competition record from official competitions. At each competition the 25% best horses are placed and receive so-called upgrading points. The number of points is determined by the placing and the level of the competition. The horse receives more points for a better placing and at a more advanced level. Every year the annual records of each horse are compiled allowing the use of life time records.

Genetic evaluation of sport horses

BLUP animal model is the most widespread method for estimation of breeding values (EBVs) in sport horse populations (e.g. in Germany, the Netherlands, Denmark, Sweden, France, Belgium and Ireland). The use of BLUP animal model for genetic evaluation of horses is suitable for several reasons. The pedigrees of horses are often recorded with high accuracy and completeness. The performance traits are not sex-limited; thus horses of both genders are tested and compete on equal terms. Horses have a low reproduction rate due to the long pregnancy and rather low foaling rate, in SWB approximately 64% of the covered mares give birth to a foal (Johansson, 2010). This automatically means long generation intervals. In horse breeding young and old breeding stallions are used simultaneously and the BLUP method allows correct comparison between horses from different generations. The owners of the broodmares choose stallions for covering by different criteria, and the stallions are marketed and priced in variable ways, leading to non-random mating, which can be handled by the animal model.

Simultaneously with the estimation of EBVs, adjustments for, and estimation of various environmental factors that affect the trait are made. Examples of such factors are sex, age, birth year, year and location of the show or event. The choice of effects for adjustments to be included in the model is crucial and relies on the structure of the horse breeding and the circumstances at the young-horse tests and the competitions. Among the SWB breeders 62% have only one broodmare (Olsson, SWA, pers. comm., 2010-06-10) and therefore it is not possible to adjust for the specific circumstances formed by the individual breeder.

To estimate EBVs useful at selection for sport performance, the horses must be tested for traits that are closely correlated to the breeding objective. The traits have to show moderate or high heritabilities and be recorded fairly early in the horses' life. Competition results at advanced levels are not achieved until rather late in life and therefore special testing of young horses is preferred (Ström and Philipsson, 1978). It is also important that as many horses as possible are tested from each year cohort. The traits must be continuously recorded and include information from several generations - this is particularly important for the accuracy of EBVs for broodmares. Last but not least, correct registered identity of all horses connected to the correct results and pedigree is crucial to estimate unbiased EBVs. This is important to consider when imported horses are to be evaluated (Thorén Hellsten et al., 2009).

Main issues

Breeding values based on results from RHQT have been estimated with a BLUP animal model since 1986 (Árnason, 1987). At that time the breeding objective was focused on producing all-round horses and the stallions were ranked by a total index calculated as the average of the indexes for gaits, jumping and conformation. The RHQT data were supposed to reflect competition performance, and preliminary studies on smaller data sets confirmed the positive correlations (Lundkvist, 1983; Ohlsson and Philipsson, 1992; Wallin et al., 2001). Competition data were used to produce annual and lifetime summaries of the performance of each stallion's offspring. When the breeding objective became more specialised towards competition in show jumping and dressage, the demand increased for a genetic evaluation including competition data. The change in breeding objective also led to the introduction of the YHT in 1999, where young horses of both genders were evaluated for sport in both gaits and jumping. Altogether, it has been considered important to investigate the possibilities of developing an integrated breeding value including information from competition, RHQT and YHT.

The first question to address is: How useful are data from the different information sources? To be valuable in genetic evaluation the traits have to show moderate to high heritabilities and high correlations to the breeding objective. For competition data there are different possible traits available and horses compete at various ages. Hence it is important to investigate the most suitable measures of competition performance.

The second question concerns the long period of data availability from both competition and RHQT. Have the traits changed over time and how should long-time continuous series of data be handled in genetic evaluation? During the 30-40 years of recording, both competitions and the population have expanded substantially. Moreover, the competitions have evolved because of technical developments in the sport. It can be hypothesised that competition traits have changed over time. RHQT traits have officially been the same throughout the years of recording, but it is unclear whether the subjective evaluations of the traits have changed. Such a change may be the result of modifications of the breeding goal and the new generation of judges with experience of sport horses rather than of the cavalry type of horse.

The third question is: How do we integrate different sources of information in the genetic evaluation? Moreover, which traits are of interest when estimating breeding values for show jumping or dressage?

The fourth question is: How effective have present breeding tools been in delivering genetic progress? A new breeding value reflecting the current breeding objective will enable the estimation of genetic trends in both disciplines. Analyses of the trends may show when changes in genetic progress have occurred and indicate strengths and weaknesses in how selection of breeding stallions and broodmares has been practised. Thereby advice could be given for improved selection of SWB horses.

Aims of the thesis

The overall aim of the thesis was to investigate the usefulness of different sources of data for genetic evaluation of both male and female Swedish Warmblood horses (SWB) at different ages. More specifically, the aims were to:

- estimate heritabilities for and genetic correlations between traits judged at YHT and RHQT and competition traits at different time periods
- investigate the effect of including long-time continuous series of data on genetic evaluations
- investigate the genetic trends of performance of SWB stallions and mares
- provide information to be used for improvement of the breeding programme of SWB by investigating factors affecting the genetic progress

Summary of the investigations

Materials

A summary of data and traits used in Paper I-IV is shown in Table 1. RHQT data provided from SWA were used in all the papers (I-IV). From the introduction of RHQT in 1973 and until 2003 there were 16,540 judged horses (Paper I), until 2007 there were 18,216 judged horses (Paper III) and between 1988 and 2007 there were 14,006 judged horses (Paper II). In Paper IV the genetic evaluation included 19,307 horses judged until 2009.

In Paper I and IV data from YHT, also provided from SWA, were included. Between 1999 and 2003 there were 4110 judged horses (Paper I) and until 2009 there were 10,911 judged horses included in the genetic evaluation (Paper IV).

Competition results were obtained from the SvRF, but have been processed by the Department of Animal Breeding and Genetics at SLU since 1972 and later also by the Swedish Horse Board for use in evaluations and student research projects. The results were from official competitions, and most years only placed horses were reported. Data from show jumping and dressage competitions were included in Paper II-IV. Paper II and III comprised 38,707 horses that had competed in show jumping or dressage between 1961 and 2006. In the genetic evaluation used in Paper IV, 43,337 competing horses were included in the analyses. The distribution of competition data were skewed, and thus transformed with a 10-logarithm to an almost normal distribution.

Table 1. Summary of original data and main traits used in Paper I-IV

Trait	In Paper
YHT	
Type (scale 1-10)	I
Head-neck-body (scale 1-10)	I
Correctness of legs (scale 1-10)	I
Walk at hand (scale 1-10)	I
Trot at hand (scale 1-10)	I
Free canter (scale 1-10)	I
Free jumping, technique and ability (scale 1-10)	I
Free jumping, temperament and general appearance (scale 1-10)	I
RHQT	
Type (scale 1-10)	I, II, III, IV
Head-neck-body (scale 1-10)	I, II
Correctness of legs (scale 1-10)	I, II, IV
Walk at hand (scale 1-10)	I
Trot at hand (scale 1-10)	I, III
Walk under rider (scale 1-10)	I, II, IV
Trot under rider (scale 1-10)	I, II, IV
Canter under rider (scale 1-10)	I, II, III, IV
Gaits, temperament and general appearance (scale 1-10)	I, II, IV
Jumping, technique and ability, free or under rider (scale 1-10)	I, II, III
Jumping, temperament and general appearance (scale 1-10)	I, II, III
Withers height (cm)	I, IV
Competition[1]	
Dressage, accumulated points up to 6 and 9 years of age	II
Dressage, lifetime accumulated points	II, III, IV
Dressage, accumulated placings up to 6 and 9 years of age	II
Dressage, lifetime accumulated placings	II
Dressage, ratio between points and placings up to 6 and 9 years of age	II
Dressage, lifetime ratio between points and placings	II
Show jumping, accumulated points up to 6 and 9 years of age	II
Show jumping, lifetime accumulated points	II, III, IV
Show jumping, accumulated placings up to 6 and 9 years of age	II
Show jumping, lifetime accumulated placings	II
Show jumping, accumulated placings up to 6 and 9 years of	II
Show jumping, lifetime accumulated placings	II

[1]All competition traits were transformed with 10-log

In Paper IV genetic trends were investigated using breeding values from the annual official genetic evaluation in 2009. Trends were studied for breeding stallions and broodmares and tested horses not used in breeding. Breeding stallions were defined as stallions with a SWB studbook number and at least one tested progeny in YHT, RHQT or competition. There were 881 breeding stallions born between 1960 and 2002. The number of tested males not selected for breeding included 31,321 horses born between 1960 and 2005. Broodmares were defined as a) mares tested in YHT, RHQT or competition with at least one registered progeny or b) mares with SWB studbook number with at least one registered progeny. The condition of a test record or studbook number was to assure that the mares had been selected for SWB breeding. Foreign mares with progeny exported to Sweden were thus excluded. There were 25,355 broodmares included. The number of tested mares not used in breeding amounted to 13,339.

In all papers pedigree data from SWA were used. In 2009 the database included 225,921 horses. Each record contained a unique database number (ID), name, studbook number (breeding animals only), foreign number (if imported), identification number, sex, birth year, year of death, gelded, ID of sire and dam, and name of sire and dam. Not all records were complete. A coefficient of Pedigree Completeness (PEC) based on five ancestor generations was calculated for each horse in the database (MacCluer at al., 1983). For the whole pedigree database the average PEC value was 0.69 (Paper IV). For breeding stallions the average PEC value was 0.90 and for broodmares 0.93 (Paper IV). For tested horses in RHQT the average PEC value was 0.96 and for all competition horses 0.82 (Paper II).

Methods

Multiple-trait animal models were used (Paper I-IV). Fixed effects in the models used for the genetic analyses were determined using SAS Proc GLM analyses (SAS Institute Inc., 2010). Estimation of (co)variances and prediction of breeding values were performed using the DMU package for analysis of multivariate mixed models (Madsen and Jensen, 2008).

All models included a random genetic effect of animal and a random residual effect. For YHT traits the model included the fixed effects of sex and event (combination of test location and test year) (Paper I). For RHQT traits the fixed effects were sex, event and age (Paper I-IV). For competition based on lifetime performance, birth year and sex were included as fixed effects (Paper II-IV).

To investigate whether traits remained constant over time, data were divided into three time periods and analysed in multiple-trait analyses. Traits (e.g., score for trot, lifetime accumulated points in show jumping) recorded in different time periods were considered as different traits (Paper I and II). Genetic parameters of traits and genetic correlations between traits recorded in different time periods were estimated.

The effect of long-time continuous series of data on genetic evaluation (Paper III) was studied by comparing EBVs from three different analyses: 1) including all data, 2) excluding data from early period and 3) considering performance traits in early and late period as different traits. Correlations and differences between EBVs, average accuracy of EBVs, and the predictive ability estimated in a cross validation were studied. For the cross validation one part of the data set was excluded at a time. For the data excluded the expected phenotypic values of the horses were calculated from the estimates and compared to the real phenotypic values by the correlation and the root mean squared error.

The genetic trends were calculated as the average EBV by birth year for all breeding horses and/or tested horses as well as for breeding stallions and broodmares separately (Paper IV). EBVs were produced by a routine genetic evaluation of SWB as part of this study. The annual genetic progress was computed by linear regressions of average EBVs for different time periods and categories of horses.

Main findings

Suitability of data of different sources for genetic evaluation

Both YHT and RHQT showed moderately high heritabilities (0.2-0.5) for most traits reflecting the breeding goals of SWB (Paper I). The heritabilities for YHT traits were slightly higher than for RHQT traits. There were high positive genetic correlations between similar traits at the two tests (0.82-0.90) (Paper I). Inclusion of YHT data into the genetic evaluation will enable earlier estimation of breeding values.

Among the different analysed competition traits, i.e. upgrading points, placings and the ratio between points and placings, upgrading points showed the highest heritabilities and genetic variances (Paper II). This trait was therefore considered most suitable to describe the breeding objective.

Lifetime competition results are recommended to use in the genetic evaluation of SWB because higher heritabilities (0.16 for dressage and 0.28 for show jumping) when all competition results were included compared to results only from young horses up to six years of age (0.11 for dressage and 0.24 for show jumping) (Paper II). The genetic correlations between accumulated competition results up to six years of age, nine years of age and lifetime results were high (0.84-1.00). The accuracy increased when results from more years were added because more information on the horse was obtained. Accumulated lifetime performance allows competition results to be available for genetic evaluation early in life because horses are compared within birth year.

High genetic correlations were estimated between traits tested at RHQT for 4-year-olds and at competition (Paper II). The correlations between show jumping and jumping traits at RHQT were 0.88 for both jumping technique and ability, and for temperament for jumping. Between individual gaits and temperament for gaits evaluated at RHQT and dressage competition the genetic correlations ranged between 0.50 (walk) and 0.76 (temperament for gaits). The results imply that information from the RHQT should be included in the genetic evaluation, because they were highly correlated with the breeding objective traits, results appear early in life, and heritabilities are moderately high. Due to pre-selection of horses for competition, integrated breeding values with results from young-horse tests and competition results are preferable to indexes only including competition results because they help to describe the pre-selection that takes place.

There were low but slightly favourable genetic correlations in the range -0.05 to 0.40 between gait and jumping traits in YHT and RHQT (Paper I). Between gait traits judged at RHQT and show jumping there were positive genetic correlations, with the highest correlation of 0.34 estimated between canter under rider and show jumping (Paper II). Between jumping traits judged at RHQT and dressage competition the genetic correlations were slightly negative to slightly positive. Overall, the results indicate only weak correlations, and thus, there are good opportunities for selection for both show jumping and dressage within the same population.

Changes in traits over time and choice of data and model for genetic evaluation

Some traits judged in RHQT had changed character during the years of testing. In Paper I the data were divided into three time periods and the two later periods (1988-1995 and 1996-2003) showed higher heritabilities than traits judged in the early period (1973-1987), 0.16-0.46 compared to 0.09-0.28. The genetic correlations between some traits judged during 1973-1988 and 1996-2003 clearly deviated from unity (e.g. 0.48 for correctness of legs and 0.60 for trot at hand).

For competition traits the genetic parameters also differed over time. Competition data were divided into three birth-year periods in Paper II: 1953-1983, 1984-1991 and 1992-2002. Heritabilities for show jumping were higher for horses born in 1992 and onwards (0.28-0.34) compared with horses born earlier (0.20-0.31). For dressage the highest heritabilities were estimated for horses born between 1953 and 1983 (0.15-0.18), for horses born in 1984 and onwards the heritabilities ranged from 0.12 to 0.17. Genetic correlations between first and last period ranged from 0.54 to 0.71 for show jumping traits and from 0.40 to 0.85 for dressage traits.

Estimation of EBVs with the bivariate model, where traits from different time periods were regarded as different traits, was assumed to give the most accurate EBVs (Paper III). EBVs estimated with models with all data or only data from the last period were compared to EBVs from the bivariate model. EBVs did not differ between the models, and a cross validation test confirmed that the predictive ability did not differ between the three models. However, accuracies of EBVs for older horses decreased considerably when only data from the late period were included. Hence, use of the univariate model with all data in the genetic evaluation was recommended due to less complex calculations to achieve almost the same results as from the bivariate model. It also gave the overall highest reliability of the EBVs for both young and old horses.

Genetic trends

Between birth years 1960 and 1984 the annual genetic progress was close to zero for all traits (Paper IV). Thereafter the genetic progress increased substantially due to stronger selection of stallions in SPT, introduction of RHQT and BLUP evaluation, and importation of some superior stallions. The improvement rate for show jumping was almost twice as high as for dressage, 0.056 genetic standard deviation units compared to 0.032. The reasons were most likely a continuously improved system for evaluation of jumping capacity at SPT, higher heritability for show jumping than dressage and importation of mainly show jumping stallions.

There was a very high genetic progress for breeding stallions born between 1979 and 1990, especially in show jumping (Paper IV). After, the progress among stallions has stagnated in show jumping. There are two possible reasons for this. First, the previous strong selection of stallions including imports of high quality jumping stallions had resulted in a genetic level of SWB approaching the level of exporting populations making it more difficult in later years to find superior stallions abroad. Secondly, selection of Swedish–born stallions has not been as extensive as it should be despite the fact that the whole SWB population has reached an increasingly high genetic level.

The genetic trend of broodmares followed the same trend as non-selected horses (Paper IV), thus the genetic progress made so far is primarily a function of strong selection of stallions. For breeding stallions the intensity was close to zero until birth year 1984. Thereafter, for birth years 1985 to 2002, the selection intensities corresponded to selection of the 5% best stallions for show jumping and the 28% best stallions for dressage.

Accuracy and generation interval

The accuracy at selection was 0.60 in show jumping for both mares and stallions, and 0.41 and 0.48 in dressage for stallions and mares, respectively. The accuracies for mares were calculated as the average accuracy for all mares between 3 and 18 years of age since all those mares could theoretically be available for breeding. The accuracies for stallions were taken from another study, where a BLUP evaluation on SPT data had been performed (Olsson et al., 2008).

The generation interval was calculated to 11.1 years for stallions and 10.3 years for mares. Most stallions are approved for breeding at the age of 3 or 4 years, and the average age at first progeny was 5.7 years. For mares the average age at first progeny was 6.9 years. Almost a fifth of all mares had only one progeny.

General discussion

In this thesis different components of the breeding programme (Figure 1) of the SWB are analysed as well as the realized genetic trend that is the actual outcome of the breeding programme. This discussion will highlight aspects of the current status of the SWB breeding programme and the opportunities to increase the effectiveness in SWB breeding.

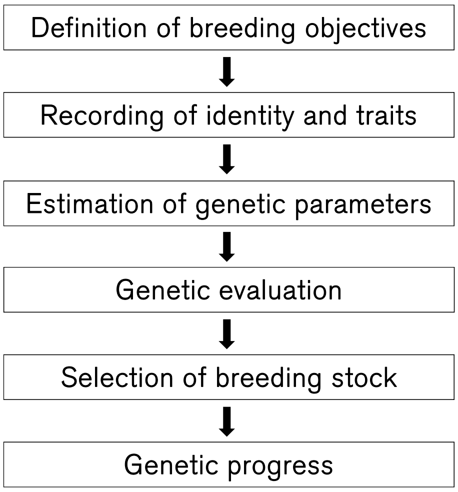

Figure 1. Schematic outline of a breeding programme.

Breeding objective

The main breeding objective for SWB is to produce internationally competitive horses in show jumping and dressage. The overview by Koenen et al. (2004) showed that the majority of the breeding objectives for Warmblood horses in Europe include conformation, gaits and performance in show jumping and dressage. Of 18 breeding organisations, ten gave dressage and show jumping the same weight, six gave show jumping the highest weight and the remaining two organisations gave dressage the highest weight. The Dutch Warmblood studbook (KWPN) was the highest ranked studbook in the world based on individual competition results in both dressage and show jumping in 2009 (WBFSH, 2010). KWPN has a breeding objective that puts equal weights on dressage and show jumping (Koenen et al., 2004). The same is true for several of the top ten Warmblood studbooks in both disciplines on the ranking, for example the studbooks of the SWB, Belgian Warmblood (BWP), Danish Warmblood, Hanoverian Warmblood and Oldenburg Warmblood.

Reported estimates of genetic correlations between dressage and jumping traits are somewhat contradictory, ranging from negative to positive relationships. In Paper I and II the correlations were low to moderately positive between dressage and jumping traits indicating no antagonism between these traits. Canter was the individual gait that was closest related to jumping traits, whereas walk and trot seemed not to be genetically related to jumping traits (Paper I and II). Similar results have been shown in other studies (Huizinga et al., 1990; Schade, 1996; Lührs-Behnke et al., 2006a; Lührs-Behnke, 2006b; Ducro et al., 2007). Despite low positive correlations between the goal traits, the SWB has had a substantial genetic progress in both disciplines (Paper IV) due to selection for both sport traits.

Specialized breeding towards one discipline is often practised within populations with a multi-trait breeding objective. However, it is important to test at least the young horses for all traits in the breeding objective. If the horses are tested in only one discipline, important information is lost. The tested horses are then pre-selected based on their talents and will not reflect the population as a whole, which will lead to biased breeding values. Another argument for testing young horses in both disciplines is to stimulate versatile training of young horses which is important for the durability of the horse. Braam et al. (2009) showed that horses with competition results in more than one discipline at an early age had a longer competition career.

There has been a debate about the breeding objective of the SWB where it has been suggested that the breeding objective should be divided into two separate goals: one for show jumping and one for dressage. To investigate the opinion of the majority of the active horse people, a questionnaire was sent to trainers, riders, breeders and riding school head coaches (Jönsson, 2006). The result showed that only 21% of the participants wanted separate breeding objectives for show jumping and dressage in the future. Thus the multi-purpose breeding objective has a high acceptance among customers of SWB horses. However, since 2002 stallions have been selected at SPT as talents for either jumping ability or dressage traits. Thus, no talents for either sport discipline have been lost. Thereby the interests of specialized breeding as well as for more versatile horses can be accommodated within SWB. The pre-condition is that as many young horses as possible are tested for both disciplines to ensure unbiased EBVs.

Identification of horses

Correct identification of the horses is a crucial prerequisite for breeding. Since the 1930's SWB breeding stallions and broodmares are given a studbook number. Beginning in 1980, a unique identification number is given to all SWB foals at registration. Among the horses included in the investigations of this thesis, the horses born before 1980 which were not used in breeding were mainly horses that had results in competition or RHQT and hence were given temporary identification numbers. The PEC values reported in Paper II and IV showed that the pedigrees on average were close to complete for five ancestor generations for tested horses in RHQT (0.96) and horses used in breeding (0.90 for stallions and 0.93 for broodmares). Thorén Hellsten et al. (2009) showed the importance of complete and correct pedigree registers for estimation of reliable and unbiased EBVs. When the authors simulated no pedigree available for foreign stallions, the EBVs changed on average by one genetic standard deviation.

To participate in competitions in Sweden, the horses must have a competition license and the results are linked to this license number. Not until 1996 did it become mandatory to have the horse registered in a breeding association to get a license (Philipsson, 1997). Before that change much manual work was required to correctly identify the competing horses. Today, if possible, SvRF connects new license numbers to the unique number of identification given by SWA. Imported horses are more difficult to identify. They can get a competition license connected to their foreign number and if they later are registered in SWA, for example if an imported mare is put in SWB breeding, the connection to her competition results may be lost. Preferably only one identification number for each horse should be used, both within each country and across countries. Thorén Hellsten et al. (2008) concluded that the lack of unique identification number of horses across countries was a problem when using international sport horse data. The Universal Equine Life Number (UELN) system has been agreed upon worldwide between the major horse breeding and competition organisations (EU, 2008). The use of this number would facilitate both national, and maybe in the future, international genetic evaluations. However, the transition to UELN is made gradually as new horses are born and before all existing horses have the UELN it is very important that the original number from the birth population is kept unchanged under all circumstances.

Recording of traits

To be useful in breeding, recorded traits should reflect the breeding objective, be simple to record for as many horses as possible, and be suitable for the age and training level of the horse.

Competition

Competition data are clearly important if the breeding objective is focused on producing horses for the sport. Which competition traits can be used depends on what is recorded by the national equestrian federation. In the Swedish data, annual number of placings at different levels and upgrading points were recorded. With few exceptions, the data included only placed horses. In other Warmblood populations different competition traits have been analysed. Examples of such traits are earnings (Schade, 1996; Hassenstein, 1998), highest level during life time (Van Veldhuizen, 1997), percentage of marks of the available marks in dressage competition (Stewart et al., 2010). In Belgium, Germany and Ireland rank in competition has been used in genetic evaluation (Janssens et al., 1997; Hassenstein, 1998; Reilly et al., 1998).

Horses are pre-selected before entering competition based on talent and pedigree. Approximately 30% of the registered SWB foals were placed at competitions (Paper II). The proportion competing horses of the registered foals increased from 16% for the birth year period until 1983 to 37% for the birth year period 1992 to 1999. This is a lower percentage than in a French study that showed that 57% of the born Selle Français (SF) horses had performance in show jumping up to 7 years of age (Dubois and Ricard, 2007). Considering that the Swedish data included mainly placed horses (i.e. among the 25% best in each competition) and the French data included all started horses, the difference may not be as large between the populations.

Some of the competing horses are never placed in a competition and if recording is based on placed horses this leads to further selection of the data. From 2007, all horses that started in each competition are reported in a complete ranking to SvRF (Edlén, SvRF, pers. comm., 2010-06-02). Thus it will be possible to analyse rank in competition in the future. The data will be less selected, and when all started horses contribute with information the level of the competition can be determined. However, the ranking is probably more accurate for the top horses than for the bottom placed horses. If the rank is transformed, for example by square root as done by Hassenstein (1998), the difference is increased between the first compared to the last places in a competition so that higher rivalry of the first place is considered. Ranking methodology is probably a good approach, but the reported heritabilities for rank in show jumping are lower (0.06-0.16) than the heritability for lifetime accumulated points in the SWB data which was estimated to 0.27 (Paper II; Janssens et al., 1997; Hassenstein, 1998; Reilly et al., 1998). However, the figures for ranks must be cautiously interpreted because they may be based on a single competition and need adjustment for average number of competitions and the repeatability between these.

Young-horse testing

A sport horse reaches its maximum level of performance after several years. If the genetic evaluation were to include only competition results the EBVs could not be estimated within a reasonable time, prolonging the generation interval and decreasing the selection intensity. Moreover, older horses are more influenced by rider and training than younger horses, leading to less accurate EBVs. For these reasons, performance testing of young horses has been applied in SWB as well as in most other Warmblood populations (Thorén Hellsten et al., 2006).

In YHT and RHQT the horses are subjectively scored by judges. In Paper I it was shown that the fixed effect of event, which includes the effect of judge, was highly significant. To harmonize the judging, courses for judges are given regularly. In KWPN and BWP linear scoring is practised for evaluation of young horses (Ducro et al., 2007; Rustin et al., 2009). With linear scoring the evaluation becomes more objective because the traits are described on a linear scale between the two biological extremes rather than evaluated in relation to an ideal conformation or performance. However, the linear scoring gives more of a description of the horse whereas the traditional scoring is related to the desired trait and shows how much the horse resembles the breeding goal. A combination of both scoring systems would probably be the best way to evaluate young horses.

Today approximately 40% of the registered SWB foals participate in YHT or RHQT or both, corresponding to about 60% of the available 3- to 4-year-old horses. This is in the same range as earlier reported by Thorén Hellsten et al. (2006). It is a higher proportion compared to other Warmblood populations that apply field testing of young horses at specific young-horse tests (Thorén Hellsten et al., 2006). In Germany 13% of the registered foals were tested and in the Netherlands and Denmark 28% were tested. In Germany and the Netherlands this type of test is only available for mares, whereas the Swedish and Danish young-horse tests are available for both genders. Allowing also geldings to participate in the tests potentially increase the proportion of tested horses, leading to more reliable genetic evaluation.

Although not all horses participate in young-horse tests those that do are probably not as selected as competition horses because they have not yet shown their talents and the tests are designed so that also amateurs should be able to participate with their horses. However, the last years, participation in RHQT has decreased because arrangements similar to competitions have been developed for 4-year-old horses. The major drawbacks with these new tests are that the horses are tested for either show jumping or dressage, and at such a high level that the pre-selection of the horses, and riders, is considerable. To increase the number of horses tested for both disciplines to assure reliable EBVs in the future, the RHQT should be a compulsory test before entering the more advanced test for 4-year-olds. Another important feature of the RHQT is that it also includes a health examination which promotes the animal welfare aspects on training and competition with young horses.

Estimation of genetic parameters

For breeding purposes, traits with moderate to high heritabilities and high correlations to the breeding objective are desired. Statistical models that best describe the circumstances for recording must be developed to estimate accurate genetic parameters.

Statistical models

Horses can compete for many years, from 4 years of age up to over 20 years of age. Age at performance is often considered when analysing competition results (e.g. Huizinga and van der Meij, 1989; Tavernier, 1991; Reilly et al., 1998; Lührs-Behnke et al., 2006a and 2006b; Stewart et al., 2010). In this thesis accumulated results were used and it was therefore not possible to include age as a fixed effect. To take into account that horses are at different stages in their career at different ages, and that competitions have evolved and expanded through the years, the fixed effect of birth year was included in the model (Paper II-IV). The effect of sex was also significant and males were more successful in competition than mares, more so for dressage than for show jumping (Paper II). Árnason (1987) and Reilly et al. (1998) also found that males were superior to females in their studies of Swedish RHQT data and Irish show jumping competition data, respectively. The sex distribution of dressage horses, where 66% were males, also showed that dressage riders prefer male horses, possibly because males often are more even tempered than mares. When using accumulated results the male horses could not be divided into stallions and geldings because a male horse could have results both as a stallion and later as a gelding. Stewart et al. (2010) showed that stallions were superior to geldings in dressage competition. This difference was expected because these stallions are selected for breeding partly due to their competition performance. Kearsly et al. (2008) also showed that stallions competing in eventing received highest scores in show jumping and dressage, whereas the effect of sex was not significant for cross country.

In Germany and Denmark the quality of the rider is considered as a fixed effect when analysing competition traits (Jaitner and Reinhardt, 2003; Interstallion, 2010). In Sweden there are not so many professional riders and it is difficult to classify the riders. However, there is a dependency between the quality of the horse and quality of the rider, and the best riders often have the best horses. Including rider as a fixed effect in the model therefore probably results in a biased, decreased genetic variance of the competition trait, whereas neglecting rider quality may cause an upward bias of the genetic variance.

For young-horse test data, the effect of event was shown to be most important (Paper I). The tests are carried out at about 20 different locations all over Sweden. Even if the implementation of the tests is carefully regulated, the conditions may differ between the locations and the judgment may differ between judges as discussed above. Effect of sex was also significant: stallions received better scores than mares and geldings. Colts that are kept as stallions up to three or four years of age are probably the most promising stallions, and therefore more talented and better trained than the geldings. For RHQT, where 5-year-old mares that have had a foal as 4-year-olds are allowed to participate, the effect of age was also significant; the older mares received higher scores.

Heritabilities

The levels of the heritabilities estimated in the studies of this thesis indicate that both competition and young-horse test data are suitable for genetic evaluation of SWB (Paper I-II).

In general, heritabilities for competition traits are lower than performance test values because the traits are influenced by several non-genetic factors such as rider and training. Heritabilities for lifetime accumulated upgrading points in dressage or show jumping were at the same level as estimates of heritabilities of competition traits in other Warmblood populations (e.g. Huizinga and van der Meij, 1989; Aldridge et al., 2000; Brockmann and Bruns, 2000; Lührs-Behnke et al., 2006a and 2006b; Stewart et al., 2010). However, comparisons of results from different studies are difficult because of different trait definitions, transformations, age groups and statistical models.

For RHQT and YHT data the heritabilities for dressage-related traits were in same range as in other studies based on field performance test of young horses (Huizinga et al., 1990; Brockmann, 1998; Bösch et al., 2000; Lührs-Behnke et al., 2006b; Ducro et al., 2007; Stock and Distl, 2007). For jumping traits the heritabilities were similar (YHT) or lower (RHQT) than reported in the other studies.

In young-horse tests the heritabilities for dressage-related traits such as individual gaits were higher than for jumping traits (Paper I) and for competition it was the opposite; the heritability for show jumping was higher than for dressage (Paper II). Jumping traits at young-horse tests showed higher genetic variances and almost three times higher residual variances than gait traits. An important reason was probably the traditional difference in use of the scale by the judges. For jumping the whole scale (1-10) was used by judges, whereas the judges of gaits never gave a score under five as long as the horse was not lame. Regarding the competition traits the possible explanations to the differences are that show jumping horses compete more often, resulting in higher heritabilities, and that dressage riders probably influence the horse more by training for competition than show jumper riders, as Kearsley et al. (2008) showed for eventing horses. Additionally, the results of a dressage horse are dependent on subjective judgments by one or several judges whereas the results in show jumping depend on objective measures such as penalties for fallen obstacles and exceeded time limits.

There were higher heritabilities for RHQT traits judged in later periods (1988-1995 and 1996-2003) compared with heritabilities in the early period (1973-1987) (Paper I). In later periods the judging was more harmonised than in the early period leading to lower residual variances. Moreover, gait and jumping traits showed higher genetic variances in the later periods, probably due to influence of importation of foreign stallions. Show jumping also showed somewhat higher heritabilities for horses born in the late period (1992-2002) compared with the early period (horses born 1953-1983), whereas dressage traits showed the opposite with lower heritabilities for horses born in the late period (Paper II). The latter could be explained by the fact that the horses were still rather young in the late period and for dressage horses the results at advanced levels, when the genetic capacity is fully expressed, come rather late in life.

Genetic correlations

There were high genetic correlations between performances at different ages, both between performance at RHQT and competition and between competition at early age and later in the horse's life (Paper II). Other studies confirm the high genetic correlations between competition performance for different age groups (Huizinga and van der Meij, 1989, Tavernier, 1992; van Veldhuizen, 1997; Ricard and Chanu, 2001) and between performance at young-horse test and later competition performance (Lührs-Behnke et al., 2006a and 2006b; Ducro et al., 2007). The results imply that information from RHQT and competition of young horses, thereby at rather low levels, are useful information in genetic evaluation but that lifetime records are even more useful due to their higher heritabilities.

The genetic correlations between traits recorded in different time periods were less than unity, especially between first and last time periods (Paper I and II). This was not surprising considering the development of competitions, and changes of the judgments and the horse population towards a modern sport horse. No other Warmblood population has reported such differences over time. However, there is no other study including 30-40 years of performance records as in our study. The Icelandic horse population have a long tradition of testing horses and the genetic correlations between traits evaluated before and after 1990 were in the same range as in this thesis (Árnason and Sigurdsson, 2004). In the Icelandic horse population the change in traits was due to a re-definition of traits in 1990.

Genetic evaluation

Different ways to treat long-time continuous series of data in genetic evaluation were investigated in this thesis (Paper III). The three analyses were: use of all data from the whole time period, exclusion of data from the early period, or handling traits from the early and late time periods as different traits. In the Icelandic horse population traits evaluated before and after 1990 are treated as different traits in the official genetic evaluation (Árnason et al., 2006) and in Paper III this bivariate approach was assumed to give the most correct EBVs. Today, the genetic evaluation for SWB for dressage includes ten traits (Paper IV) and if every trait were divided into two traits this could lead to computational difficulties associated with the large covariance structure (Árnason et al., 2006). However, there were no difference in predictive ability among the three models, and only minor differences in accuracy of EBVs when using all data compared with the bivariate approach. In fact the overall accuracy of the EBVs was highest when all data were used with the univariate model. Thus, all data from the beginning of recording should be used in the genetic evaluation.

To use all information sources in the genetic evaluation, a multi-trait animal model is proposed. Traits evaluated at young-horse tests are used as indicator traits for the breeding objective, i.e. competition performance. The advantages of using all these information sources are that young-horse tests include less selected data than competition data and enable early estimation of EBVs. Several test opportunities allow a larger number of horses to be tested and included in the genetic evaluation, resulting in more reliable EBVs and opportunities for higher selection intensity. However, information from SPT is not included because it would make the EBV highly dependent the stallion's own performance until a large number of offspring have been evaluated, due to the relatively high heritabilities at SPT. The stallions participating in SPT are also subjected to a strong pre-selection before entering the test. Multi-trait BLUP animal models with information from different tests and competitions are used for genetic evaluation in both Germany and the Netherlands (Jaitner and Reinhardt, 2003; Interstallion, 2010).

EBVs are of no use unless they are communicated to, and accepted by, the breeders. Official EBVs for SWB stallions and mares are published by SWA on the internet (http://www.blup.se). A stallion has to have at least 15 progenies tested at young-horse tests to get an official EBV. For mares, own performance or at least one tested progeny at young-horse test or competition is required. The site is open for the general public and has become popular among breeders, horse buyers and horse owners. In the future the site can be developed and offer a test mating function generating expected EBV and inbreeding level of the unborn foal. Another possible function is matching partners according to EBVs where the breeder gives the most important criteria for the mating.

Selection

Clearly the selection of stallions was intensified with the introduction of SPT (Paper IV). The selected stallions born between 1960 and 1984 were not better than the average horse for the sport, whereas the selection intensity for show jumping stallions born between 1985 and 2002 corresponded to horses being among the 5% best. At SPT in 2010 there were nine 4-year-old stallions approved for breeding of which three were SWB. In 2006 there were 5449 registered foals in SWB and if 50% of them were colts and 10% were exported or dead yearly, 1787 possible 4-year-old stallions would be remaining in 2010. Then the selected proportion within SWB was only 0.2%, which is much lower than the calculated selected proportion of stallions born between 1985 and 2002. Thus, the system has not been able to identify the very best stallions among all males born.

Stallions get approval for breeding for a period of six years after the SPT. Thereafter the stallion is evaluated primarily on his progenies. Also other relatives may contribute to the evaluation. Unfortunately, it may take a long time before a correct evaluation including enough progenies can be performed. Along with the internationalisation the number of stallions has increased and because the number of broodmares is rather constant some stallions never get enough progeny to be re-evaluated.

Stallions can also be approved for breeding in SWB based on their performance in the sport or at a stallion performance test in another Warmblood association recognised by the SWA. Most of these stallions are foreign and some are too old to be tested in the regular SPT. Because the genetic levels of these stallions are more difficult to predict than of the stallions doing their SPT in Sweden they contribute to a greater uncertainty in the selection intensity practised.

Selection of breeding horses by EBVs from a BLUP animal model instead of phenotypic merits results in faster genetic improvement, as exemplified by Árnason and Van Vleck (2000). This is due to increased accuracy of selection. The selection intensity for Swedish Standardbred trotters increased considerably for both stallions and mares with the implementation of an index based on BLUP animal model (Árnason, 1997). Today, selection of young SWB breeding stock is mainly based on phenotypic merits. Olsson et al. (2008) estimated the accuracy at selection of stallions to 0.60 for show jumping and 0.41 for dressage based on phenotypic evaluations at SPT. The authors suggested that a BLUP evaluation using information from SPT, RHQT and competition could improve the accuracy at selection of stallions after performance testing.

Paper IV showed that broodmares had no better EBVs than non-selected mares tested at young-horse tests or competitions. In a French study of SF the best 71% mares were selected for breeding (Dubois and Ricard, 2007). According to a recent enquiry only 23% of the SWB breeders considered the EBV of the mare at selection (Olsson, SWA, pers. comm., 2010-06-10). An important issue for SWA in the future is therefore to improve the quality of mare selection by an intensified advisory service. The proportion of tested mares in breeding increased substantially with the introduction of YHT (Paper IV). More than 88% of the broodmares born from 2003 to 2005 had been tested, mainly at YHT because they were young horses. This test is a good opportunity to get a judgement of the horse before competition or breeding, and the judges should be able to give breeding advice to the mare owners.

Genetic progress

Until the mid 1980's the genetic progress for performance traits in SWB was close to zero (Paper IV). Thereafter the improvement rate increased substantially, especially for show jumping. The cause of this development was fourfold: 1) intensified selection of stallions, both Swedish and imported stallions, in the improved SPT introduced in the late 1970's, 2) importation of very good stallions, primarily show jumpers, 3) opportunity to evaluate young horses on their conformation and talent for both show jumping and dressage at RHQT introduced in 1973 and 4) starting in 1986, estimation of breeding values with a BLUP animal model based on RHQT data, primarily used for progeny testing.

The genetic trend in a population should certainly be monitored by the breeding organisations and used as a tool for analysis of different parts of the breeding programme, but with few exceptions it is not often analysed and published in the scientific literature. Árnason (1987) studied the genetic progress for SWB based on RHQT data from birth year 1973 to 1979. This was before the intensified selection of stallions, but still the author found a positive genetic trend for gaits and jumping. The German Warmblood population showed early genetic progress in both show jumping and dressage for horses born from 1970 to 1982 (Bruns, 1990). Like SWB, the SF population had a breakpoint for genetic progress in show jumping in the mid 1980's (Dubois and Ricard, 2007). Since, nearly the same genetic progress was made in both SWB and SF in show jumping. This may be surprising because the SF has been bred mainly for show jumping, whereas SWB has a dual purpose breeding objective and SWB comprises only a third as many broodmares as SF. However, as Thorén Hellsten et al. (2009) showed, importation and use of some superior show jumping stallions have contributed to the improved ability of SWB horses for jumping. In a recent study of British sport horses the estimated genetic progress was 0.047 genetic standard deviations in dressage between birth year 1985 and 2001 (Stewart et al., 2010). This was higher than for the SWB population during the same period (0.032). Like SWB the British population has imported high quality stallions from other populations empirically known to have a high genetic standard.

The genetic progress in show jumping was almost twice as high as in dressage (Paper IV). Historically SWB was regarded as a dressage horse and the genetic level for show jumping was initially low. Importation of mainly show jumping stallions, the improved evaluation of jumping traits in the new SPT and the higher heritability for show jumping resulted in faster progress in show jumping.

When the genetic trend was given separately for broodmares, stallions and males and females not used in breeding it became clear that the genetic progress was solely due to stallion selection (Paper IV). However, in later years the trend for EBV for all stallions has stagnated in show jumping but not in dressage. The same trends are seen among the 50% best of the stallions in each discipline as for all stallions, excluding the hypothesis that the stagnation could be caused by unfavourable correlations between the two disciplines among selected stallions. As mentioned earlier, the system has not been able to select the best stallions and this has recently become more severe in show jumping than in dressage. The increased average genetic level of the whole population indicates that it would be possible to find high quality stallions within the SWB population. Today there are few SWB stallions tested at the SPT the majority of the stallions at SPT are from other populations. It would be desirable to test a larger proportion of SWB stallions for breeding.

A recent enquiry to SWB breeders in 2010 found that 62% of the breeders had only one broodmare, and 31% had two to three broodmares (Olsson, SWA, pers. comm., 2010-06-10). Many of these breeders do not have the opportunities to raise a stallion at home, which probably contributes to early gelding. Hence, a large proportion of young SWB colts never become screened as possible stallion prospects. To increase the number of screened colts within the population, the SWA could provide contacts to farms specialised in young colts, where the owners at a reasonable cost could leave their colts to be raised together with other colts and handled by professionals. The colts should be regularly evaluated by the breeding evaluation committee and those that do not fulfil the standards could be gelded. The purpose of this proposal is not to select more stallions, but to increase the group of potential breeding stallions and provide a better opportunity to select the best ones.

Conclusions

Data from competitions and the two young-horse performance tests (YHT and RHQT) provides useful information to the genetic evaluation of SWB.

Integrated breeding values with results from both competitions and young-horse tests are proposed due to pre-selection of horses for competition, higher heritabilities, earlier recording at young-horse performance tests, and high correlations between RHQT and competition. Data from both RHQT and YHT should be used because more test opportunities for young horses will allow a larger number of horses to be tested, leading to more reliable breeding values and opportunities for higher selection intensity.

Lifetime accumulated competition results are recommended to use in genetic evaluation because of increased accuracy when more years are added and more information about the horse is obtained. Horses would be compared within birth years, which allow accumulated lifetime performance to be used throughout life.

Although some traits have changed over time, EBVs were not affected. Data from the whole period of recording can therefore be used in the genetic evaluation.

The genetic progress in both dressage and show jumping increased substantially in the mid 1980's due to stronger selection of stallions at the improved SPT in the late 1970's, importation of superior stallions, introduction of young-horse testing at RHQT, and the beginning of prediction of EBVs with a BLUP animal model in 1986.

The genetic trend of broodmares followed the same trend as non-selected horses and the achieved genetic progress so far is primarily a result of stallion selection.

In the future emphasis should be put on more effective use of EBVs for selection of both stallions and mares at both young age and when progenies of stallions have been tested. Because of the strongly increased genetic level in the population, high quality stallions can be selected within the SWB population to a higher extent than at present.

Future research

If EBVs are to be useful for the breeders and an effective tool in breeding, the indexes have to be easily understood by the breeders. The importance of the different information sources need to be studied further to be able to explain the variation in EBVs for stallions and mares of different ages, time periods and variable sources of information.

To get a complete picture of the relationships between traits of SWB the genetic correlations between results at YHT and competition performance should be estimated. It is now eleven years since the introduction of YHT and there are enough horses with results from both YHT and competition to perform reliable genetic analyses.

Every year about 1000 SWB foals are shown at foal inspections. Preliminary studies have indicated high genetic correlations between traits at foal inspection and gait and conformation traits at YHT (Edlén, 2008). It would be interesting to further investigate the value of this inspection for breeding purposes.

It takes several years before a sport horse reaches its maximum performance level. During these years considerable resources, both in the form of work and money, have been invested in the horse. A breeding value for durability would facilitate selection of healthy horses. A possible way to measure durability could be by using number of active years in competition as has been proposed by Braam et al. (2009). However, the challenge is to get enough reliable EBVs for this trait in time for selection purposes. Another approach would be to study the usefulness of the health examinations at the RHQT to predict the longevity of the horses.

The increased international exchange of breeding stallions or their semen raises the desire of a joint genetic evaluation among genetically well-connected horse populations. This is only possible if the breeding organisations are willing to share their information. The Nordic Warmblood associations have agreed to work together in a project named Nordic Interstallion. If this project works well, more Warmblood associations might want to join in the future.

The competition traits used in SWB genetic evaluation are based on accumulated upgrading points earned by horses that are placed in competitions. Traditionally only placed horses have been reported to SvRF. Since 2007 all started horses in a competition have been reported. This gives opportunities to investigate the trait rank in competition that is used in some other Warmblood populations and to compare the results with the present use of lifetime points.

To have a horse with a good temperament is as important as to have a horse with a talent for sport. Willingness to work and cooperativeness can to some extent be evaluated from the temperament scores given at the regular young-horse tests. To be able to breed for temperament the criteria for a good temperament must be more precisely determined and characterized, and standardized measurements should be developed. Preferably the evaluation can be done during the regular young-horse testing. When enough horses have been tested the genetic parameters should be calculated and then breeding values of temperament traits might be estimated.

All traits evaluated in Swedish young-horse tests are scored on a scale 1 (very poor) to 10 (excellent), but the whole scale is seldom used, especially for conformation and gait traits. A more objective description of the horse's strengths and weaknesses could probably be done if linear scoring of the traits were applied. It would be interesting if the SWA tested linear scoring at young-horse tests in parallel with the traditional scoring that evaluates the horses in relation to the breeding goal.

Genomic selection has lately become an important tool in breeding of dairy cattle. So far it has not been used in breeding for sport horse performance. However, horse geneticists should follow the development and investigate whether genomic selection can be an effective tool in future horse breeding. The key is probably to get large enough reference population to classify the relationships between present EBVs and the genomic information.

Avelsvärdering av svenska ridhästar

Bakgrund

Ursprungligen användes den svenska varmblodiga hästen mest inom kavalleriet. I takt med att militären avhästades och att tävlingsintresset ökade ändrades användningsområdet och idag används den som sporthäst i framför allt hoppning och dressyr. Avelsmålet lyder ”En ädel, korrekt och hållbar varmblodshäst som genom sitt prestationsinriktade temperament, sin ridbarhet, goda rörelser och/eller hoppförmåga är internationellt konkurrenskraftig” (ASVH, 2006). I praktiken innebär det ofta att en specialiserad avel bedrivs för antingen hoppning eller dressyr inom samma population. Ett väl fungerande avelsprogram är avgörande för att uppnå avelsmålet, och kan bara utformas om tidigare och nuvarande förhållanden och trender i populationen är kända.

En viktig del i avelsprogrammet är avelsvärderingen där hästarnas förväntade nedärvningsförmåga skattas. Inget avelsframsteg kommer att göras i rasen om inte de genetiskt bättre hästarna väljs till avel. Förutsättningarna för en korrekt avelsvärdering är att de egenskaper den baseras på har ett starkt samband med avelsmålet, att egenskaperna är ärftliga och att sambandet mellan olika egenskaper är kända. Dessutom är det viktigt att de bästa tillgängliga metoderna används för beräkningarna. Redan 1986 började Sverige som första land att använda BLUP-metoden för avelsvärdering av ridhästar. Idag används metoden av alla större europeiska varmblodsförbund.

Det pågår en ständig utveckling av avelsvärderingsmetodiken. Vid införandet 1986 baserades avelsvärderingen enbart på resultat från kvalitetsbedömning som är ett allsidigt unghästtest av fyraåriga hästar av båda könen. Bedömningen infördes 1973 och ungefär en tredjedel av alla fyraåriga hästar bedöms med avseende på exteriör, gångarter och hoppförmåga. Vid den tiden var avelsmålet inriktat på att producera allroundhästar. När avelsmålet blev mer specialiserat för hoppning eller dressyr kom önskemål om att även tävlingsresultat skulle inkluderas i avelsvärderingen. Tävlingsresultat finns registrerat sedan tidigt 1960-tal. Från början hade bara 10 % av hästarna tävlingsresultat och idag har cirka 35 % av alla hästar ett registrerat tävlingsresultat. En annan förändring var att de gamla premieringarna, där ston bedömdes för sin exteriör, ersattes 1999 av ett treårstest där 40 % av alla treåriga hästar av båda könen även bedöms för sin dressyr- och hopptalang.

Syftet med den här avhandlingen var att undersöka hur användbara resultat från treårstest, kvalitetsbedömning och tävling är för att skatta avelsvärden för ston och hingstar i olika åldrar. Det gjordes genom att analysera egenskaper från de olika informationskällorna med avseende på hur ärftliga de är och hur olika egenskaper hänger ihop. Vidare undersöktes om egenskaperna förändrats över tiden och hur det påverkar avelsvärdets tillförlitlighet. Utifrån ett integrerat avelsvärde baserat på de tre olika informationskällorna analyserades slutligen det genetiska framsteget som är resultatet av tidigare avelsarbete.

Sammanfattning av studierna

Analyserna visade att resultat vid treårstest, kvalitetsbedömning och tävling till 20-50 % beror på arvet och kan därmed förbättras genom avel. Ju mindre påverkad en häst är av sin miljö, t ex av träning och ryttare, och ju säkrare en bedömning kan göras, desto högre blir arvbarheten. De egenskaper som bedöms vid treårstest uppvisade något högre arvbarheter än motsvarande egenskaper på kvalitetsbedömning på grund av att den yngre hästen är mindre påverkad av sin miljö. Å andra sidan fås högre arvbarheter för livstidsresultat i tävling än tävlingsresultat enbart vid yngre åldrar beroende på att mer information från flera tävlingsår gör bedömningen av hästens förmåga säkrare. På unghästtesterna (treårstest och kvalitetsbedömning) bedöms hästarna subjektivt av domare och de höga arvbarheterna tyder på god kompetens hos de svenska domarna.

De starka sambanden mellan kvalitetsbedömning och senare tävlingsprestation indikerar att man redan vid fyra års ålder kan förutspå rätt väl om hästen kommer att vara framgångsrik i tävling. Det var också starka samband mellan tävlingsprestationer upp till sex års ålder och livstidsprestation i tävling. Mellan egenskaper som bedöms på treårstest och motsvarande egenskaper som bedöms på ett år äldre hästar vid kvalitetsbedömning var sambanden starka. Även om gångarter bedöms enbart löst och vid hand vid treårstest så visade det sig att det var genetiskt nästan samma egenskaper som de gångarter som bedöms under ryttare. Samma sak gäller löshoppning vid treårstest och hoppbedömningen på kvalitetsbedömning som bedöms antingen under ryttare eller vid löshoppning.

Både tävlingsresultat och resultat från kvalitetsbedömning fanns registrerat under en lång tidsperiod och studierna visade att egenskaperna hade förändrats över tiden. Förklaringen är att antal hästar i tävling har ökat, tävlingstillfällena har blivit fler och tävlingsformerna har utvecklats under tiden. För kvalitetsbedömning har bedömningspunkterna hela tiden benämnts likadant, men på grund av att avelsmålet successivt förändrats och att domarkåren bytts ut så betyder bedömningspunkterna inte samma sak idag som för 35 år sedan. Det faktum att egenskaper förändrats över tid påverkade dock inte säkerheten vid skattning av avelsvärden. Det betyder att data från hela perioden kan användas i avelsvärderingen utan att hänsyn behöver tas till att resultaten kommer från olika tidsperioder.

Mot bakgrund av resultaten i avhandlingens tre första studier skattas idag officiella avelsvärden som inkluderar resultat från tävling, kvalitetsbedömning och treårstest. Dessa avelsvärden användes för att analysera den genetiska trenden för den varmblodiga populationen. Från mitten av 80-talet ökade den genetiska framstegstakten markant. Det hade fyra orsaker: 1) starkare selektion av hingstar i det förnyade bruksprovet i slutet av 70-talet, 2) import av en del utmärkta hingstar, framförallt i hoppning, 3) införandet av kvalitetsbedömning 1973 som gav möjlighet att bedöma unga hästar för prestationsegenskaper och 4) införandet av BLUP-avelsvärdering baserad på resultat från kvalitetsbedömning som främst användes för avkommebedömning av hingstar.

Framstegstakten från mitten av 80-talet och framåt var snabbare för hoppning än för dressyr. Den svenska hästen betraktades ursprungligen som en dressyrhäst och den genetiska nivån för hoppning var inledningsvis låg. I och med det nya bruksprovet i slutet av 70-talet kunde hoppningen testas på ett bättre sätt och tillsammans med import av en del framstående hopphingstar ökade den genetiska nivån för hoppning i populationen i rask takt.

När den genetiska trenden delades upp på hingstar och avelsston blev det tydligt att avelsstona inte var bättre än ston som inte var i avel. Det betyder att det framsteg som gjorts hittills enbart beror på hingsturvalet. Om uppfödarna skulle höja urvalskriterierna för avelston genom att välja enbart de stona med bäst resultat från unghästtester och de med de högsta avelsvärdena, skulle ett större framsteg fås. Det behövs mer information till uppfödarna för att belysa stonas roll i avelsarbetet.

Hingstarna har sedan i mitten av 80-talet varit överlägsna resten av populationen. Däremot har trenden för alla avelshingstar avtagit i hoppning under senare år. Samma avmattning kunde inte ses för dressyr. Teorin om att den specialiserade aveln mot antingen dressyr eller hoppning skulle ha bidragit till stagnationen, genom att både dressyr- och hopphingstarna är medräknade, kunde förkastas då samma trend sågs även för de 50 % bästa hopphingstarna, fast på en avsevärt högre nivå. Anledningen är antagligen att det blivit svårare att finna överlägsna hingstar i utlandet nu när hela den svenska populationen kommit upp på en högre nivå. Majoriteten av hingstarna som används i avel idag är utlandsfödda men med tanke på att den svenska populationen förbättrats kraftigt bör det finnas många fler hingstar av hög kvalitet inom landet som bör tas tillvara.

Kortfattade slutsatser

Resultat från treårstest, kvalitetsbedömning och tävling kan användas vid skattning av avelsvärden för den svenska varmblodiga hästen. Tävling är avelsmålet och resultat från unghästtesterna bidrar med tidig information om hästarna. I och med att alla tre informationskällorna ingår ökar antalet testade hästar vilket leder till säkra avelsvärden och möjlighet till starkare selektion.

Den genetiska utvecklingen av den svenska varmblodiga hästen har varit avsevärd från mitten av 1980-talet. För att få en fortsatt positiv utveckling bör tonvikt läggas på en mer effektiv användning av avelsvärden vid urval av ston och hingstar till avel, både vid ung ålder och efter att avkommorna har testats. På grund av att dagens population har nått en ökad genetisk nivå bör ansträngningar göras för att bättre ta tillvara svenskfödda potentiella hingstämnen.

Framtidsfrågor

Vidare studier behövs för att förstå vilken betydelse olika informationskällor i praktiken har för avelsvärdet för ston och hingstar i olika åldrar, tidsperioder och med olika mängd information.

Hållbarhet och temperament är viktiga egenskaper hos sporthästen som det vore önskvärt att registrera bättre och skatta avelsvärden för.

Årligen bedöms omkring 1000 föl vid fölbesiktning. Det skulle vara intressant att undersöka om och hur bedömningen kan användas för avelsvärdering.

Det omfattande utbytet med andra länder, framförallt av avelshingstar, ökar efterfrågan på en internationell avelsvärdering. En förutsättning är dock att de aktuella länderna är villiga att dela med sig av sin information.

References

Aldridge, L.I., Kelleher, D.L., Reilly, M. and Brophy, P.O. (2000). Estimation of the genetic correlation between performances at different levels of show jumping competitions in Ireland. *Journal of Animal Breeding and Genetics 117,* 65-72.

Árnason, T. (1987). Contribution of various factors to genetic evaluation of stallions. *Livestock Production Science* 16, 407-419.

Árnason, T. (1997). The selection intensity in Standardbred trotters in Sweden as measured by BLUP animal model index. *48th Annual Meeting of the European Association of Animal Production, Vienna, Austria,* 25-28 August. 7 pp.

Árnason, T. and Van Vleck, L.D. (2000). Genetic improvement of the horse. In: Bowling, A.T. and Ruvinsky, A (Eds.) *The Genetics of the Horse*. 411-438. CAB International, Wallingford, United Kingdom.

Árnason, T. and Sigurdsson, Á. (2004). International genetic evaluations of the Icelandic horse. *55th Annual Meeting of the European Association of Animal Production, Bled, Slovenia,* 5-9 September. 17 pp.

Árnason, T., Sigurdsson, Á. and Lorange, J.B. (2006). Global genetic evaluation of the Icelandic horse and genetic connectedness between countries. *In proceeding of the 8th World Congress on Genetics Applied to Livestock Production, Belo Horizonte, Brazil, 13-18 August*, paper 24-16. 4 pp.

ASVH (Avelsföreningen för svenska varmblodiga hästen) (2006). Avelsplan för svensk varmblodsavel (In Swedish) [online]. Available from: http://www.asvh.se/document/avelsplan.pdf [Accessed 10 June 2010].

Braam, Å., Näsholm, A., Roepstorff, L. and Philipsson, J. (2009). Use of competition results for genetic evaluation of longevity in Swedish Warmblood. *60th Annual Meeting of the European Association of Animal Production, Barcelona, Spain,* 24-27 August. 8 pp.

Brockmann, A. (1998). Entwicklung einer Eigenleistungsprüfung im Feld für Hengste unter Berücksichtigung der Turniersportprüfung. *Doctoral thesis. Göttingen University*, Germany.

Brockmann, A. and Bruns, E. (2000). Schätzung genetischer Parameter für Merkmale aus Leistungsprüfungen für Pfrede. *Züchtungskunde 72*, 4-16.

Bruns, E. (1990). Breeding values and estimation of genetic trends in riding horses. *In proceedings from the 4th World Congress on Genetics Applied to Livestock Production*, 16, 206-208.

Bösch, M., Reinecke, S., Röhe, R. and Kalm, E. (2000). Genetische Analyse von Merkmalen in der Reitpferdezucht – Varianzkomponenten für Merkmale der Fohlenbeurteilung, Stutbuchaufnahme (Exterieurbeurteilung) und Zuchtstutenprufüng. *Züchtungskunde 72*, 161-171.

Dubois, C. and Ricard, A. (2007). Efficiency of past selection of the French Sport Horse: Selle Français breed and suggestion for the future. *Livestock Science 112*, 161-171.

Ducro, B.J., Koenen, E.P.C. and van Tartwijk, J.M.F.M. and Bovenhuis, H. (2007). Genetic relations of movement and free-jumping traits with dressage and show-jumping performance in competition of Dutch Warmblood horses. *Livestock Science 107*, 227-234.

Edlén, M. (2008). Genetisk analyse as data från fölbesiktning och jämförelse med resultat vid treårstest (In Swedish). *Master thesis, No 298. Swedish University of Agricultural Sciences, Department of Animal Breeding and Genetics*. Uppsala. 26 pp.

EU (European Union) (2008). Commission Regulation (EC) no 504/2008 [online]. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008: 149:0003:0032: EN:PDF [Accessed 16 June 2010].

Graaf, K. (2004). *Den svenska varmblodshästens historia under 200 år.* Avelsföreningen för Svenska varmblodiga hästen och Nationella stiftelsen för hästhållningens främjande. ISBN 91-631-5364-5.

Hassenstein, C. (1998). Genetisch statistische Analyse von neuentwickelten Merkmalen aus Turniersportprüfungen für Reitpferde. *Doctoral thesis, Christian-Albrechts-Universität zu Kiel, Germany*.

Huizinga, H.A. and van der Meij,G.J.W. (1989). Estimated parameters of performance in jumping and dressage competition of the Dutch Warmblood horse. *Livestock Production Science 21,* 333-345.

Huizinga, H.A., Boukamp, M. and Smolders, G. (1990). Estimated parameters of field performance testing of mares from the Dutch Warmblood riding horse population. *Livestock Production Science* 26, 291-299.

Interstallion (2010). Breeding programs [online]. Available from: http://www.interstallion.org [Accessed 18 June, 2010).

Jaitner, J. and Reinhardt, F. (2003). National genetic evaluation for horses in Germany. *54th Annual Meeting of the European Association of Animal Production, Rome, Italy,* August 31st-September 3rd. 5 pp.

Janssens, S., Geysen, D. and Vandepitte, W. (1997). Genetic parameters for show jumping in Belgian sporthorses. *48th Annual Meeting of the European Association of Animal Production, Vienna, Austria,* 25-28 August. 5 pp.

Johansson, K. (2010). Analys av dräktighets- och fölningsresultat inom svenska varmblodig ridhäst and svensk varmblodig travhäst åren 2000-2006 (In Swedish). *Master thesis, No 314. Swedish University of Agricultural Sciences, Department of Animal Breeding and Genetics*. Uppsala. 43 pp.

Jönsson, L. (2006). Den svenska varmblodiga hastens avelsmål (In Swedish). *Master thesis, No 285. Swedish University of Agricultural Sciences, Department of Animal Breeding and Genetics.* Uppsala. 53 pp.

Kearsley, C.G.S, Woolliams, J.A., Coffey, M.P. and Brotherstone, S. (2008). Use of competition data for genetic evaluations of eventing horses in Britain: Analysis of dressage, show jumping and cross country phases of eventing competition. *Livestock Science 118*, 72-81.

Koenen, E.P.C., Aldridge, L.I. and Philipsson, J. (2004). An overview of breeding objectives for warmblood sport horses. *Livestock Production Science* 88, 77-84.

Lührs-Behnke, H., Röhe, R. and Kalm, E. (2006a). Schätzung genetischer Parameter für Turniersportleistungen innerhalb Prüfungklassen und der Beziehungen zu den Merkmalen der Zuchtstuten- und Hengstleistungprüfung. *Züchtungskunde 78*, 173-183.

Lührs-Behnke, H., Röhe, R. and Kalm, E. (2006b). Genetische Parameter für Zuchtstutenprüfungsmerkmale der verschiedenen deutschen Warmblutzucht-verbände. *Züchtungskunde 78*, 271-280.

Lundkvist, K. (1983). Kvalitetsbedömning av unga ridhästar – samband mellan bedömningsresultat och framtida brukbarhet (In Swedish). *Master thesis, No 113. Swedish University of Agricultural Sciences, Department of Animal Breeding and Genetics*. Uppsala. 35 pp.

MacCluer, J., Boyce, A.J., Dyke, B., Weitkamp, L.R., Pfennig, D.W. and Parson, C.J. (1983). Inbreeding and pedigree structure in Standardbred horses. The Journal of Heredity 74, 394-399.

Madsen, P. and Jensen, J. (2008). *A user's guide to DMU.* A package for analyzing multivariate mixed models. Version 6, release 4.7. University of Aarhus, Tjele, Denmark.

Ohlsson, L. and Philipsson, J. (1992). Relationship between field test for Warmblood horses as four-year-olds and later competition performance. *43rd Annual Meeting of the European Association of Animal Production, Madrid, Spain,* 14-17 September. 7 pp.

Olsson, E., Näsholm, A., Strandberg, E. and Philipsson, J. (2008). Use of field records and competition results in genetic evaluation of station performance tested Swedish Warmblood stallions. *Livestock Science* 117, 287-297.

Philipsson, G. (1997). Utnyttjande av tävlingsstatistik för avelsvärdering av hingstar och ston – en lägesrapport oktober 1997 (In Swedish). Svenska Hästavelsförbundet. Uppsala. 3 pp.

Philipsson, J. (2005). Importance of young horse testing for genetic evaluation in Sweden. 4. Pferdetage, Uelzen, Feb 22-23. 4pp.

Reilly, M., Foran, M.K., Kelleher, D.L., Flanagan, M.J. and Brophy, P.O. (1998). Estimation of genetic value of showjumping horses from the ranking of all performances in all competitions. *Journal of Animal Breeding* 115, 17-25.

Ricard, A. and Chanu, I. (2001). Genetic parameters of eventing horse competition in France. *Genetics Selection Evolution 33*, 175-190.

Rustin, M., Janssens, S., Buys, N. and Gengler, B. (2009). Multi-trait animal model estimation of genetic parameters for linear type and gait traits in Belgian Warmblood horse. *Journal of Animal Breeding and Genetics 126*, 378-386.

SAS Institute Inc. (2008). SAS OnlineDoc® 9.1.3**.** Cary, NC: SAS Institute Inc. [online]. Available from http://support.sas.com/onlinedoc/913 [Accessed 16 June, 2010].

Schade, W. (1996). Entwicklung eines Besamungszuchtprogramms für die Hannoversche Warmblutzucht. *Doctoral thesis. Göttingen University*, Germany.

SRC (Svenska Ridsportens Centralförbund) (1972). Svenska ridsportens centralförbunds kalender 1971.

Stewart, I.D., Woolliams, J.A. and Brotherstone, S. (2010). Genetic evaluation of horses for performance in dressage competitions in Great Britain. *Livestock Science 128*, 36-45.

Stock, K.F. and Distl, O. (2006). Genetic correlations between conformation traits and radiographic findings in the limbs of German Warmblood riding horses. *Genetics Selection Evolution 38,* 657-671.

Ström, H. and Philipsson, J. (1978). Relative importance of performance tests and progeny tests in horse breeding. *Livestock Production Science 5,* 303-312.

Tavernier, A. (1991). Genetic evaluation of horses based on ranks in competition. *Genetics Selection Evolution 23*, 159-173.

Tavernier, A. (1992). Is the performance at 4 years in jumping informative for later results? *43rd Annual Meeting of the European Association of Animal Production, Madrid, Spain,* 14-17 September. 4 pp.

Thorén Hellsten, E., Viklund, Å., Koenen, E.P.C., Ricard, A., Bruns, E. and Philipsson, J. (2006). Review of genetic parameters estimated at stallion and young horse test and their correlations with later results in dressage and show-jumping competition. *Livestock Science 103*, 1-12.

Thorén Hellsten, E., Jorjani, H. and Philipsson, J. (2008). Connectedness among five European sport horse populations. *Livestock Science* 118, 147-156.

Thorén Hellsten, E., Näsholm, A., Jorjani, H., Strandberg, E. and Philipsson, J. (2009). Influence of foreign stallions on the Swedish Warmblood breed and its genetic evaluation. *Livestock Science* 121, 207-214.

Van Veldhuizen, A.E. (1997). Breeding value estimation for riding horses in the Netherlands. *48th Annual Meeting of the European Association of Animal Production, Vienna, Austria,* 25-28 August. 8 pp.

Wallin, L., Strandberg, E. and Philipsson, J. (2001). Phenotypic relationship between test results of Swedish Warmblood horses as 4-year-olds and longevity. *Livestock Production Science 68*, 97-105.

WBFSH (World Breeding Federation for Sport Horses) (2010). WBFSH Rankings 2009 [online]. Available from: http://www.wbfsh.org/?GB/Rankings/WBFSH%20rankings/2009.aspx [Accessed 9 June, 2010].

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