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Animal Genetics and Genomics

An overview of international genetic evaluations of show jumping in sport horses[1]

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ABSTRACT

The breeding of sport horses to compete in the Olympic disciplines of show jumping, eventing, and dressage is fast becoming a global industry with the increased use of reproductive technologies, including artificial insemination and embryo transfer. Reproductive technologies have facilitated the dissemination of genetics from elite horses across multiple countries and breeds as breeders are no longer limited by location. Due to this increased level of crossbreeding, there is an increased need for estimated breeding values (EBVs) for sport horse performance that can be compared across breeds and countries. However, the implementation of across-breed or across-country genetic evaluations has been limited by the differences in each studbook's individual breeding programs and genetic evaluations. Consequently, the aim of this review was to compare the genetic evaluations for show jumping of sport horse studbooks worldwide. The top sport horse studbooks in the world according to the World Breeding Federation for Sport Horses Studbook Rankings 2019 were contacted by email to request information on their current breeding programs and genetic evaluations. Twenty-six of the 51 studbooks contacted replied to this request but only 18 of these studbooks conducted their own genetic evaluations or were part of a larger genetic evaluation in their country of origin. The other eight studbooks were not involved in genetic evaluations at present but expressed an interest in the implementation of such in the future. Overall, many differences were identified among the genetic evaluations of each studbook or each country. The definition of show jumping performance differed within each evaluation and the methods and models utilized also differed. Despite some stallions and mares being registered in multiple studbooks or having progeny in multiple studbooks, these differences make comparison of EBVs across studbooks difficult. Further transparency and collaboration of sport horse studbooks with organizations such as Interstallion, will be essential to facilitate any future implementation of international genetic evaluations for show jumping performance.

Key words: best linear unbiased prediction, breeding, genetic evaluations, heritability, show jumping, sport horses

INTRODUCTION

Sport horses are bred worldwide with the aim to compete in the Olympic sports of show jumping, dressage, and eventing. In Ireland alone, the sport horse industry contributes an estimated €816 million to the Irish economy; breeding is the largest sector and accounts for €271 million (33.2%) of this contribution, most of which is generated in the rural economy (Corbally and Fahey, 2017). The success of the sport horse industry is multifactorial; however, implementing successful breeding programs and the genetic improvement of the sport horse are vital to maintaining this success, as unlike environmental effects such as feeding or management, the effect of genetic gain is cumulative and permanent (Falconer and Mackay, 1996). Many sport horse studbooks already have breeding programs in place to enable them to identify and select genetically superior stallions and mares to become parents of the next generation of horses. However, the estimated breeding values (EBVs) published, and the traits included in these evaluations vary among the different studbooks; this could be because of different breeding goals attributable to the different studbooks or, simply due to the availability of data.

Since 1980, there has been a significant increase in the uptake of reproductive technologies in sport horse breeding, including artificial insemination (AI; Aurich, 2012) and embryo transfer (Stout, 2012). For example, in 1985 only 1.4% of German Sport Horses were artificially inseminated, but by 2012 this had increased to nearly 90% (Aurich, 2012). The use of AI has facilitated the dissemination of genetics from breeding stallions across multiple countries and breeds and has led to the globalization of sport horse breeding as breeders are not limited by location. Despite this large exchange of genetic material across breeds, the implementation of across-breed or across-country genetic evaluations has been limited by the differences in each studbook's individual breeding programs and genetic evaluations. Therefore, the objective of this study was to compare the genetic evaluations for show jumping of multiple sport horse studbooks. The knowledge of differences or similarities in the individual breeding programs may be of importance to studbooks and other researchers to inform them of the steps needed to implement successful across-breed or across-country genetic evaluations for sport horses.

MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for the present study as no new data were generated during the present study.

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Collation of Information

The 51 studbooks included in the final 2019 World Breeding Federation for Sport Horses (WBFSH) world ranking list for show jumping were contacted by email in July 2020 to request information on their current breeding programs and genetic evaluations. Each studbook was asked did they carry out genetic evaluations and to provide any documentation on these evaluations reporting the traits evaluated, the methods and models used, and the results to enable us to compare the methods used by the different genetic evaluations worldwide. Studbooks were sent a maximum of four follow-up emails and if the studbook did not reply in this timeframe or did not have sufficient information available in the form of scientific papers or studbook publications they were subsequently removed from the study. Of the 51 studbooks contacted, the present study is based on 26 (51%) sport horse studbooks (Table 1).

RESULTS AND DISCUSSION

World Breeding Federation for Sport Horses

The WBFSH publishes both individual and studbook rankings each month for each discipline from April to October each year (www.WBFSH.org; accessed October 8, 2021). The final rankings for that year are then published at the end of this cycle. The individual rankings for show jumping are based on a points system, whereby horses are awarded points for each international competition they compete in; points are awarded based on the results and the difficulty of the competition. The number of points earned by each horse determines its position in the individual ranking (www.WBFSH.org). The studbook rankings are calculated based on the top 6 horses from the individual rankings in each discipline.

The top studbook in the 2021 WBFSH ranking for show jumping studbooks was the Belgian Warmblood studbook (Table 1). Over the last 10 yr, the Belgian Warmblood studbook has been ranked number one studbook twice and the lowest ranking this studbook has received was fifth in 2014 and 2015. Over this same period, the Dutch Warmblood studbook was ranked as the number one studbook five times; the lowest ranking the Dutch Warmblood studbook received in those years was fourth in 2016. Not all studbooks have been as consistent as the Belgian Warmblood and Dutch Warmblood studbooks, with some studbooks falling slowly down the rankings and others rising through the rankings quite rapidly, for example, the Mecklenburg studbook have risen from 35th place in 2015 to 16th in 2021. Eleven of the

Table 1. The studbooks included in the present study, whether they conduct evaluations or not, and their latest, median, lowest, and highest rankings based on the WBFSH world rankings for show jumping studbooks from 2012 to 2021

Studbook name	Abbreviation	2021 ranking	Median ranking	Highest ranking	Lowest ranking	Genetic evaluations
Belgian Warmblood	BWP	1	3	1	5	Yes
Selle Francais	SF	2	4	2	9	Yes
Holsteiner[*]	HOLST	3	4	1	8	Yes
Dutch Warmblood	KWPN	4	2	1	4	Yes
Irish Sport Horse	ISH	10	13	8	17	Yes
Belgian Sport Horse	SBS	11	6	3	13	Yes
Westphalian[*]	WESTF	12	8	2	12	Yes
Swedish Warmblood	SWB	13	11	6	15	Yes
Studbook La Silla	SLS	17	16	14	20	No
American Holsteiner[*]	AHHA	19	24	19	56	Yes
Polish Horse Breeders Association	PZHK	20	26	18	32	Yes
Danish Warmblood	DWB	22	18	15	26	Yes
Australian Warmblood	AWHA	23	46	23	57	No
Breeding Association for German Horses[*]	ZfDP	24	24	18	33	Yes
Estonian Sport Horse	ESHB	25	31	25	55	No
Spanish Sport Horse	CDE	27	26	20	34	Yes
Dutch Warmblood North America	KWPN NA	30	41	30	54	Yes
Anglo-Arab	AA	38	29	22	38	Yes
Hungarian Sport horse	HSH	39	31	25	39	Yes
Slovenian Warmblood	SSW	40	41	35	50	No
American Warmblood	AWR	44	51	44	53	No
New Zealand Hanoverian	NZHS	48	48	45	51	No
Canadian Sport Horse	CSHA	53	43	30	53	No
Luxembourg Saddle Horse Studbook[†]	SCSL	—	29	21	—	No
Trakhener[*,†]	TRAK	—	42	37	—	Yes
International Sporthorse Registry Oldenburg[†]	ISREG	—	45	43	—	No

[*]Studbook is a member of the German Equestrian Federation (FN).
[†]Studbook not included in the WBFSH rankings 2021.

studbooks in the 2021 WBFSH Top 20 are included in the present analysis; 10 of these studbooks currently conduct genetic evaluations. Some of the earliest research on the genetic evaluations of sport horses were carried out on Swedish (Ström and Philipsson, 1978) and German (Bruns et al., 1980; Bruns, 1981) horses. The Dutch sport horses first introduced genetic evaluations in the late 1980s (Huizinga and Van der Meij, 1989), followed closely by the French studbooks (Tavernier, 1990, 1991) and then the Irish Sport Horse (Reilly et al., 1998).

Genetic Evaluations

Just eight studbooks, the Swedish Warmblood, Spanish Sport Horse, Danish Warmblood, Hungarian Sport Horse, Holsteiner, Polish Horse Breeders Association, Dutch Warmblood, and the Irish Sport Horse, run their own genetic evaluations. All other studbooks were part of multistudbook multibreed evaluations. All the German studbooks are members of the Fédération Equestre Nationale (FN), the German Equestrian Federation. The FN enlists the central computing center for genetic evaluations of horses and dairy cattle in Germany, Vereinigte Informationssysteme Tierhaltung (VIT) to carry out an integrated breeding value estimation of sport horses on behalf of the FN and its members each year (Jaitner and Reinhardt, 2003). Estimated breeding values for both of Belgium's studbooks, the Belgian Warmblood and the Belgian Sport Horse are calculated by the University of Leuven. In the case of the French studbooks, Selle Francais and Anglo-Arab, the joint genetic evaluations are undertaken by the Institut Français du Cheval et de l'Équitation. For studbooks that are the daughter studbook of a much larger studbook, such as the Dutch Warmbloods in North America and the American Holsteiner, they follow the breeding programs of their respective parent studbooks and are therefore a part of the genetic evaluations of their parent studbooks.

Breeding Goals and EBVs

The breeding objectives of any organization should be clear and well-defined, reflect the desired characteristics of the animal and the relative importance of each characteristic, and should form the basis of any selection index (Dekkers and Gibson, 1998). Sport horse studbooks usually include the equestrian disciplines (i.e., show jumping, dressage, and/or eventing) and the level of competition that they wish to select for in their breeding objective (Koenen et al., 2004). However, many of the other traits included in equine breeding goals (i.e., the nobility, rideability, and character of the horse) are subjectively defined and hard to quantify, suggesting that current selection responses in sport horse breeding programs may be suboptimal (Koenen et al., 2004).

Each studbook calculates different EBVs based on the traits deemed as important to that organization, as outlined in the breeding objective for that breed (Koenen and Aldridge, 2002; Koenen et al., 2004). The Irish Sport Horse, the Hungarian Sport Horse, and the two Belgian studbooks only publish one single EBV. In comparison, the other studbooks that are conducting genetic evaluations generally publish two or more EBVs with one being for show jumping (Table 2). Other EBVs published most often include dressage, eventing, conformation, or performance test EBVs. For the purpose of this review, the focus is solely on EBVs produced for show jumping performance.

Show Jumping

Traits included in the estimation of breeding values for show jumping

The vast majority of sport horse studbooks produce an EBV for show jumping ability however, the traits included vary among the studbooks; most studbooks base all or part of their genetic evaluations for show jumping on competition results with some studbooks also considering scores from performance tests and/or studbook inspections (Table 3). The Polish Horse Breeders Association is the only studbook that carries out genetic evaluations for sport horses based on performance tests alone. The Polish Horse Breeders Association publishes an index value for jumping that considers 16 traits scored by the judges, trainers, and riders of the horse. The judges score each animal for free jumping, jumping under rider, walk, trot, and canter. The trainers score each animal for trainability, temperament, character, free jumping, jumping under rider, walk, trot, and canter. The

Table 2. The EBVs published by each studbook

Studbook	Show jumping	Dressage	Eventing	Conformation	Performance tests	Other
Irish Sport Horse	X					
Hungarian Sport Horse	X					
Belgian Warmblood and Belgian Sport Horse	X					
Holsteiner and American Holsteiner				X	X	
Polish Horse Breeders Association	X	X				General
FN Germany	X	X			X	
Spanish Sport Horse	X	X	X			Endurance
Swedish Warmblood	X	X		X		
Danish Warmblood	X	X		X		
Dutch Warmblood and Dutch Warmblood North America	X	X		X		Loose movement, free jumping, osteochondrosis
Selle Francais and Anglo-Arab	X	X	X	X		Gaits, jumping ability

Table 3. Brief description of the traits included in each studbooks genetic evaluations for show jumping ability

Studbook	Competition records	Performance tests	Studbook inspections
Irish Sport Horse	Highest level two double clear rounds have been achieved		
Hungarian Sport Horse	Blom-transformed rankings that considers the level the horse competes at and its placing within competition		
Belgian Warmblood and Belgian Sport Horse	Jumping performances at both a national and recreational level		
Polish Horse Breeders Association		Free jumping, jumping under rider, walk, trot, canter, trainability, temperament, character, rideability, dressage ability, and jumping ability	
FN Germany	Transformed rank achieved for all starts, competition results for young horses, highest level achieved	Exact traits not specified	
Spanish Sport Horse	Points earned in competition and weighted classification of the competition level		
Swedish Warmblood	Accumulated points earned	Technique and ability, temperament and general impression	
Danish Warmblood	Results of all starts in national and international competition	Young horse test: loose capacity, loose canter, and loose technique, and manners, capacity, canter, and technique under rider Championship test: jumping ability evaluated directly or as a combination of rideability, capacity, and technique	
Dutch Warmblood and Dutch Warmblood North America	Placing at specific shows throughout its entire career.	Ability scores from individual suitability tests and from multiple-day tests	Upper beam scores for free jumping
Selle Francais and Anglo-Arab	Competition results at national and international level		

rider scores each animal for rideability, dressage ability, and jumping ability.

Both the Irish Sport Horse and the Hungarian Sport Horse base their genetic evaluations on one single competition trait. In the Irish Sport Horse, this trait is known as the lifetime performance rating of the horse and is the top level of competition the horse has attained two double clear rounds. Show jumping performance of the Hungarian Sport Horse is measured with weighted Blom-transformed rankings that consider both the level the horse competes at and its placing within competitions (Mezei et al., 2015). The Belgian evaluations are also based on competition results but split into two levels: the first trait refers to jumping performances at national level while the second trait considers jumping performances at a recreational level. The Spanish Sport Horse also base their genetic evaluations for show jumping on performance records from competition. However, they evaluate the points earned in competition and the weighted classification of the competition level as two separate traits. The French evaluations also evaluate their show jumping horses on two traits based on competition results; these traits differ slightly from those evaluated in the other studbooks as the first trait is a logarithm transformation of the annual sum of points allocated to each event the horse competes at according to the place and level of the event, while the second trait considers the ranks in each event. The French evaluation not only considers national jumping competitions but also all results from international competition, greater than or equal to 2* level, for horses with French riders and for Selle Francais or Anglo-Arab horses with foreign riders.

The genetic evaluations of the Swedish Warmblood, Danish Warmblood, and the Dutch Warmblood horses consider both competition results and studbook inspection/test data. The Swedish Warmblood genetic evaluations consider the least number of traits of these three studbooks: The main jumping index is based on accumulated points from competition, while the two subindexes—technique and ability, and temperament and general impression—reflect the results from the Swedish Warmblood young horse tests. The Danish Warmblood produces three EBVs for young horse test, championship test and national sports competitions which are then combined into an overall index value for jumping: 1) the young horse test (mainly 3/4 yr olds) EBV is based on seven traits—capacity, canter, and technique scored while loose, and manners, capacity, canter, and technique under rider, 2) the championship test (4, 5, and 6 yr olds) EBV is based on a horse's jumping ability, either evaluated directly or as a combination of rideability, capacity, and technique, and 3) the national sports competitions EBV is based on the results of all starts in national show jumping competition and international competitions with Danish riders. The Dutch Warmblood currently base their genetic evaluations on four traits: 1) upper beam scores for free jumping from studbook inspections, 2) ability scores from the 1-d "individual suitability test for horses" test, 3) ability scores from the multiple-day tests for both mares and stallions, and 4) competition data consisting of the horse's placing at specific shows throughout its entire career. The German FN publish three EBVs and an index value for show jumping: 1) the TSP EBV is based on the transformed rank achieved for all starts, 2) the ABP EBV is based on competition results for young horses, 3) the HEK EBV is based on the highest level of jumping achieved derived from the overall starts as a single observation per horse, and 4) the JPf, is an index value based on both competition data and scores from performance tests.

Genetic evaluation methods The methods and models used in each studbook's genetic evaluations are outlined in Table 4. All studbooks, excluding the Belgian Studbooks and the Spanish Sport Horse studbook, that replied to the email request for information on the methods used specified they use an animal model in their evaluations. The type of animal model, i.e., repeatability, single-trait, or multitrait, depends on the studbook and the traits being evaluated (Table 4).

The effects accounted for by each model are also outlined in Table 4. The most common effects accounted for in the genetic evaluation models include sex and age, and it is widely accepted that the sex and age of the horse have a strong impact on performance in sport horses (Koenen and Aldridge, 2002; Welker et al., 2018). On average, stallions and geldings achieve a higher level of performance than mares (Koenen and Aldridge, 2002; Rovere et al., 2016) and the performance of a horse in competition increases with age but will eventually plateau for older horses (Rovere et al., 2016). Different studbooks consider age differently in their genetic evaluation models with some models including the age at highest performance (Ducro et al., 2007), the year of the highest performance (Rovere et al., 2016), or the year of birth of the horse (Viklund et al., 2010). The effect of age in sport horses is dependent on several external factors including the decisions and circumstances as to why and when a horse begins its career and how it develops thereafter (Welker et al., 2018). Therefore, Welker et al. (2018) proposed considering the maximum age of the horse in competition in the model to somewhat compensate for these external factors, to consider the duration of a horse's performance career and the chances afforded to them to reach the highest levels in competition.

The cooperation of a horse with its rider is of utmost importance in show jumping and previous research has determined that a rider's personality can affect this cooperation when riding emotionally reactive horses (Visser et al., 2008). Thus, it is unsurprising that rider has been noted in multiple studies as an important effect to include in statistical models evaluating a horse's performance (Kearsley et al., 2008; Stewart et al., 2012; Rovere et al., 2016; Bartolomé et al., 2018). Including rider as either a class effect or a random effect decreased both the genetic and residual variances

Table 4. Methods implemented in the genetic evaluation of show jumping by each studbook

Studbook	Model type	Effects accounted for in model	Base population	Standardization
Irish Sport Horse	Single-trait animal model	Sex, year of level achieved, thoroughbred percentage	Rolling base: all Irish Sport Horse mares between 4 and 18 yr old	Mean = 100, SD =20
Belgian Warmblood and Belgian Sport Horse	Not specified	Sex, age, competition, permanent environment	Rolling base: all horses between 7 and 18 yr old	Mean = 100, SD =20
Spanish Sport Horse	Not specified	Not specified	Not specified	Mean = 100, SD =20
Danish Warmblood	Young horse test: multitrait animal model All others: single-trait repeatability animal model	Young horse test: place × date, age × sex Championship test: place × date, type of event, rider, horse Competitions: competition ID, age × sex, rider, horse	Rolling base: all horses between 3 and 17 yr old	Mean = 100, SD =20
Dutch Warmblood	Animal model	Not specified	All Dutch Warmblood horses	Mean = 100, SD =20
FN Germany	HEK: single-trait animal model All others: multitrait repeatability animal model	HEK: sex, year, age of horse at latest start All others: competition, age × sex, rider	Rolling base: stallions between 11 and 15 yr old, having passed a stallions' performance test or having at least five offspring	Mean = 100, SD =20
Hungarian Sport Horse	Repeatability animal model	Not specified	Not specified	
Polish Horse Breeders Association	Multitrait animal model	Training facility × assessment year	All horses and sires	Mean = 100, SD =20
Selle Francais and Anglo-Arab	Multitrait animal model	Trait 1: age, class × year, sex, animal genetic value, permanent environmental effect Trait 2: age, sex, animal genetic value, permanent environmental effect	Rolling base: animals born 5 yr before the evaluation with reliability ≥0.22	Mean = 0, SD = 20
Swedish Warmblood	Multitrait animal model	Sex, year of birth, level of scores at different assessment times	Rolling base: tested horses between the ages of 4 and 18	Mean = 100, SD = 20

associated with show jumping performance in Dutch warmblood horses (Rovere et al., 2016); however, Rovere et al. (2016) concluded that including rider as a fixed effect that accounts for the level and experience of the rider would be a more effective approach than including a random effect for each rider. Similarly, Bartolome et al. (2018) determined that including the horse–rider interaction (RHI) as a random effect within a model was a better fit than just including the rider; the traits evaluated using these effects had higher heritability estimates when the RHI effect was included in place of the rider alone (Bartolome et al., 2018). In reality, including the effect of rider is often simply not possible due to the structure and/or distribution of the data (Bartolomé et al., 2018; Welker et al., 2018).

In the pursuit of accurate across-breed genetic evaluations in sport horses, where crossbred animals are the norm, one might consider breed classes as an important factor to consider in a genetic evaluation model (Stewart et al., 2010). However, of the studbooks that responded to our request for information, the ISH is the only studbook that currently considers the effect of breed in their model, in the form of the continuous effect of thoroughbred percentage (TB%) where each animal has a TB% value between 0 and 1. The significance of TB%, when fitted as a class effect with four (Schröder et al., 2010) or eight (Koenen et al., 1995) levels has previously been evaluated for conformation traits in Hannoverian warmblood horses (Schröder et al., 2010) and for both conformation and competition traits in the Dutch Warmblood (Koenen et al., 1995). Furthermore, the Hannoverian warmblood horse model also included the proportion of Trakehner and Holsteiner breeds as fixed effects in that model (Schröder et al., 2010). The proportion of Trakehner and Holsteiner breeds, and TB% were significant effects for all conformation traits in the Hannoverian warmblood horses (Schröder et al., 2010). The TB% was also significant in the analysis of most of the conformation traits in the Dutch Warmblood but was not considered a significant effect in the analysis of the show jumping or dressage data (Koenen et al., 1995). Other studbooks have previously included breed in their genetic evaluation models by grouping together the country of origin of the main breeds that are part of that studbook; for example, previous research conducted in the Spanish Sport Horse has included the breed effects as country of origin such as Germany, France, the Netherlands, Spain, and Other, instead of including the individual breed groups (Bartolome et al., 2018).

Heritability estimates of jumping in sport horses Understanding the heritability of a trait is one of the most important factors to consider when devising an effective breeding plan (Lush, 1949). Heritability is defined as the fraction of the observed phenotypic variance of a trait which is attributable to additive genetic variation (Lush, 1949) and while heritability estimates vary by trait, they can also vary within-trait and over-time by population. Therefore, the heritability of show jumping traits can vary due to the phenotypes used in the estimation and the population for which heritability was calculated. In general, heritability estimates for jumping traits measured during station or performance tests generally have a higher heritability than those estimated from competition data (Ricard et al., 2000; Stewart et al., 2011); this may be in part due to the control of environmental factors during station tests (Ricard et al., 2000).

The Belgian Warmblood, Hungarian Sport Horse, and Irish Sport Horse have the lowest heritability estimates, from 0.02 to 0.10, for show jumping performance based on competition results (Janssens et al., 1997; Aldridge et al., 2000; Posta et al., 2009; Mezei et al., 2015). Heritability estimates for show jumping performance based on competition results range from 0.06 to 0.17 in the Spanish Sport Horse (Bartolomé et al., 2013), from 0.08 to 0.28 in the Dutch Warmblood (Rovere et al., 2016), from 0.12 to 0.28 in the Swedish Warmblood (Viklund et al., 2010), and from 0.15 to 0.19 in the French breeds (Langlois, 1980). The highest heritability estimate calculated from competition results was in the German breeds, where the highest level achieved in competition had a heritability between 0.28 and 0.36 (Welker et al., 2018). In comparison, heritability estimates for jumping ability measured during performance tests were estimated between 0.09 and 0.24 in the Swedish Warmblood (Viklund et al., 2008) and as 0.39 in the Dutch Warmblood (Van Veldhuizen, 1997).

Sports status is a simple binary trait (0 or 1) that is used to determine whether a horse has competed at a show jumping event previously or not; this trait has a moderate to high heritability ranging from 0.19 to 0.40 in the Dutch Warmblood (Rovere et al., 2016) to 0.71 in the Belgian Warmblood (Janssens et al., 2007). Other estimates of the heritability of jumping ability in the literature come from free jumping phenotypes where the animal jumps several obstacles without a rider. Heritability for this trait is estimated to be between 0.29 and 0.71 depending on the breed of the animal (Huizinga et al., 1991; Gerber Olsson et al., 2000; Gelinder et al., 2001; Jaitner and Reinhardt, 2003; Posta et al., 2009).

Interstallion

The vast majority of sport horses are crossbred animals; for example, the ISH is not a breed that has evolved from a single origin but is, traditionally, the product of crossing Thoroughbred horses with Irish Draught horses (Reilly et al., 1998). In recent years, there has been an increase in the use of foreign bred stallions and mares being crossed with traditional Irish Sport Horses in the hopes of creating a successful show jumper. This increase in the use of foreign genetics has been observed across all sport horse breeds and can be attributed firstly, to the trade of horses across countries (Thorén Hellsten et al., 2008), and secondly, to an increase in the success, and therefore, uptake of reproductive technologies including AI and the transport of chilled semen over long distances (Thorén Hellsten et al., 2008; Aurich, 2012). Due to this increased level of crossbreeding, there is an increased need for EBVs for sport horse performance that can be compared across breeds and countries.

Interstallion was established in 1998 with the aim of comparing breeding objectives, testing procedures, and genetic evaluations of sport horses across countries and to determine if there was any international comparability of genetic evaluations (Thorén Hellsten, 2008). These issues are handled in dairy cattle by Interbull, a similar organization to Interstallion, that was founded in 1983 and has successfully implemented international genetic evaluation systems using MACE (Multiple-Trait Across Country Evaluation) in cattle (Schaeffer, 1985, 1994; Philipsson, 2005). The MACE system estimates genetic correlations between traits in different countries which are then used to estimate international breeding values for bulls (Philipsson, 2005). The MACE system relies on strong genetic connectedness among different breeding populations to accurately estimate the differences in the average genetic merit of populations and to determine the genetic correlations between traits among the populations (Thorén Hellsten et al., 2008). The MACE system been highly successful in dairy cattle populations as these populations are strongly connected genetically as there are similarities in national breeding objectives worldwide (Berry et al., 2016) and families are often represented across multiple populations with bulls having daughters in many countries.

In comparison, sport horse breeding objectives differ substantially between studbooks, there are known discrepancies in breeding objectives as defined by individual studbooks and practiced by breeders, and there are differences in the definitions of the traits used in each studbook's genetic evaluations (Bruns et al., 2004). Also, AI has not been as widely used in sport horse breeding for as many years as in dairy cattle breeding, but this has been changing in recent years with stallions producing more progeny widely spread among studbooks and countries. Despite this, strong genetic connectedness has been calculated among numerous European sport horse studbooks for show jumping performance traits (Thorén Hellsten et al., 2008, 2009; Ruhlmann et al. 2009a, 2009b). Thus, the implementation of MACE by Interstallion may be possible for at least some of the European studbooks in the near future.

Genomics

Since the advent of genomic selection (Meuwissen et al., 2001), genomic evaluations have been implemented successfully in both national and international livestock breeding programs worldwide (VanRaden et al., 2010; Meuwissen et al., 2016). Nevertheless, no sport horse studbook currently utilizes genomics in their show jumping evaluations. The WBFSH recognizes that one of the challenges in breeding sport horses is the generation interval. About 10 yr elapse between breeding decisions being made and the resulting horse reaching their peak performances (WBFSH, 2021). Genomic selection has the potential to increase genetic gain by reducing these long generation intervals; previous research has shown that integrating genomic information into sport horse breeding programs increases the accuracy of EBVs for young horses without their own performance records and horses without progeny (Haberland et al., 2012). Furthermore, previous research using a simulated genomic dataset proved that the inclusion of genomic data into the genetic evaluations of sport horses can increase the accuracy of EBVs for show jumping performance (Schubertová et al., 2014). Despite this increase in accuracy (Schubertová et al., 2014) and the many other perceived benefits of genomics to sport horse breeding (Stock et al., 2016), the integration of genomic selection in sport horses has proved challenging as it requires sufficiently large reference populations (Mark et al., 2014) that have not yet been feasible to attain but may be achieved through international collaboration.

CONCLUSION

Many studbooks have successfully implemented genetic evaluations for sport horses however these evaluations vary widely with respect to the traits included and the methods for collection of the data related to these traits. This makes comparison of breeding values across populations challenging to implement. As the interest in across-breed evaluations increases, studbooks should endeavor to be more transparent about their breeding programs. Further collaboration of studbooks, via Interstallion, is essential to facilitate the future implementation of international genetic evaluations and would also enable further research to be conducted on the implementation of genomics to sport horse breeding programs.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

LITERATURE CITED

Aldridge, L., D. Kelleher, M. Reilly, and P. Brophy. 2000. Estimation of the genetic correlation between performances at different levels of show jumping competitions in Ireland. *J. Anim. Breed. Genet.* 117:65–72. doi:10.1046/j.1439-0388.2000.00232.x

Aurich, J. E. 2012. Artificial insemination in horses—more than a century of practice and research. *J. Equine Vet. Sci.* 32:458–463. doi:10.1016/j.jevs.2012.06.011

Bartolomé, E., A. Menéndez-Buxadera, A. Molina, and M. Valera. 2018. Plasticity effect of rider–horse interaction on genetic evaluations for Show Jumping discipline in sport horses. *J. Anim. Breed. Genet.* 135:138–148. doi:10.1111/jbg.12315

Bartolomé, E., A. Menéndez-Buxadera, M. Valera, I. Cervantes, and A. Molina. 2013. Genetic (co) variance components across age for Show Jumping performance as an estimation of phenotypic plasticity ability in Spanish horses. *J. Anim. Breed. Genet.* 130:190–198. doi:10.1111/jbg.12001

Berry, D. P., J. F. Garcia, and D. J. Garrick. 2016. Development and implementation of genomic predictions in beef cattle. *Anim. Front.* 1:32–38. doi:10.2527/af.2016-0005

Bruns, E. 1981. Estimation of the breeding value of stallions from the tournament performance of their offspring. *Livest. Prod. Sci.* 8:465–473. doi:10.1016/0301-6226(81)90067-1

Bruns, E., B. Bade, and H. Haring. 1980. Results on a more objective measurement of performance traits of stallions in performance testing at station. *Livest. Prod. Sci.* 7:607–614. doi:10.1016/0301-6226(80)90074-3

Bruns, E., A. Ricard, and E. Koenen. 2004. Interstallion—on the way to an international genetic evaluation of sport horses. In: editor-in-chief: Ynze van der Honing, 55th Annual Meeting of the European Association for the Animal Production; 5–8 September 2004; Bled, Slovenia.

Corbally, A., and A. Fahey. 2017. The contribution of the Sport Horse Industry to the Irish economy. University College Dublin [accessed September 8, 2021]. http://www.horsesportireland.ie/wp-content/uploads/2017/10/The-Contribution-of-the-Sport-Horse-Industry-to-the-Irish-Economy-2017-Corbally-Fahey-2017.pdf

Dekkers, J., and J. Gibson. 1998. Applying breeding objectives to dairy cattle improvement. *J. Dairy Sci.* 81:19–35. doi:10.3168/jds.S0022-0302(98)70151-1

Ducro, B., E. Koenen, J. Van Tartwijk, and H. Bovenhuis. 2007. Genetic relations of movement and free-jumping traits with dressage and show-jumping performance in competition of Dutch Warmblood horses. *Livest. Sci.* 107:227–234. doi:10.1016/j.livsci.2006.09.018

Falconer, D., and T. Mackay. 1996. *Introduction to quantitative genetics*. Longman Group, Essex, UK.

Gelinder, A., A. Skoglund, A. Näsholm, and J. Philipsson. 2001. Relationships between stallion performance test results and sport results in dressage and show jumping. In: editor-in-chief: Ynze van der Honing, 52nd Ann. Meet. EAAP; 26-29 August 2001; Budapest, Hungary.

Gerber Olsson, E., T. Árnason, A. Näsholm, and J. Philipsson. 2000. Genetic parameters for traits at performance test of stallions and correlations with traits at progeny tests in Swedish warmblood horses. *Livest. Prod. Sci*. 65:81–89. doi:10.1016/S0301-6226(99)00176-1

Haberland, A., U. K. von Borstel, H. Simianer, and S. König. 2012. Integration of genomic information into sport horse breeding programs for optimization of accuracy of selection. *Animal* 6:1369–1376. doi:10.1017/S1751731112000626

Huizinga, H., and G. Van der Meij. 1989. Estimated parameters of performance in jumping and dressage competition of the Dutch Warmblood horse. *Livest. Prod. Sci*. 21:333–345. doi:10.1016/0301-6226(89)90093-6

Huizinga, H., S. Korver, and G. Van der Meij. 1991. Stationary performance testing of stallions from the Dutch Warmblood riding horse population. 2. Estimated heritabilities of and correlations between successive judgements of performance traits. *Livest. Prod. Sci*. 27:245–254. doi:10.1016/0301-6226(91)90099-C

Jaitner, J., and F. Reinhardt. 2003. National genetic evaluation for horses in Germany. In: editor-in-chief: Ynze van der Honing, Book of Abstracts or the 54th Annual Meeting of the EAAP; August 31–September 3, 2003; Roma. p. 402.

Janssens, S., N. Buys, and W. Vandepitte. 2007. Sport status and the genetic evaluation for show jumping in Belgian sport horses. In: editor-in-chief: Ynze van der Honing, Book of Abstracts for the 58th Annual Meeting of the EAAP; August 26–29, 2007; Dublin. p. 151.

Janssens, S., D. Geysen, and W. Vandepitte. 1997. Genetic parameters for show jumping in Belgian sporthorses. In: editor-in-chief: Ynze van der Honing, 48th Annual Meeting of European Association for Animal Production; August 25–28; Vienna, Austria. p. 382.

Kearsley, C., J. Woolliams, M. Coffey, and S. Brotherstone. 2008. Use of competition data for genetic evaluations of eventing horses in Britain: analysis of the dressage, showjumping and cross country phases of eventing competition. *Livest. Sci*. 118:72–81. doi:10.1016/j.livsci.2008.01.009

Koenen, E., and L. Aldridge. 2002. Testing and genetic evaluation of sport horses in an international perspective. In: 7th World Congress Applied to Livestock Production; August 19–23; Montpellier, France. p. 367–374.

Koenen, E., L. Aldridge, and J. Philipsson. 2004. An overview of breeding objectives for warmblood sport horses. *Livest. Prod. Sci*. 88:77–84. doi:10.1016/j.livprodsci.2003.10.011

Koenen, E., A. Van Veldhuizen, and E. Brascamp. 1995. Genetic parameters of linear scored conformation traits and their relation to dressage and show-jumping performance in the Dutch Warmblood Riding Horse population. *Livest. Prod. Sci*. 43(1):85–94. doi:10.1016/0301-6226(95)00010-I

Langlois, B. 1980. Estimation de la valeur génétique des chevaux de sport d'après les sommes gagnées dans les compétitions équestres françaises. *Ann. Génét. Sél. Anim*. 12:15–31. doi:10.1186/1297-9686-12-1-15

Lush, J. L. 1949. Heritability of quantitative characters in farm animals. *Heriditas*. 35(1):356–375. doi:10.1111/j.1601-5223.1949.tb03347.x

Mark, T., L. Jönsson, M. Holm, and K. Christiansen. 2014. Towards genomic selection in Danish Warmblood horses: expected impacts and selective genotyping strategy. In: Proc. 10th World Congress on Genetics Applied to Livestock Production; 18–23 August; Vancouver, Canada.

Meuwissen, T. H., B. J. Hayes, and M. E. Goddard. 2001. Prediction of total genetic value using genome-wide dense marker maps. *Genetics* 157(4):1819–1829. doi:10.1093/genetics/157.4.1819

Meuwissen, T., B. Hayes, and M. Goddard. 2016. Genomic selection: a paradigm shift in animal breeding. *Anim. Front*. 6(1):6–14. doi:10.2527/af.2016-0002

Mezei, A. R., J. Posta, and S. Mihók. 2015. Comparison of different measurement variables based on Hungarian show jumping results. *Ann. Anim. Sci*. 15:177–183. doi:10.2478/aoas-2014-0063

Philipsson, J. 2005. INTERBULL—how it began and some achievements. In: Proc. 2005 Interbull Meet., Uppsala, Sweden. Interbull Bull. 33. Uppsala, Sweden: Interbull Centre; p. 131–135.

Posta, J., I. Komlósi, and S. Mihók. 2009. Breeding value estimation in the Hungarian Sport Horse population. *Vet. J*. 181:19–23. doi:10.1016/j.tvjl.2009.03.006

Reilly, M., M. Foran, D. Kelleher, M. Flanagan, and P. Brophy. 1998. Estimation of genetic value of showjumping horses from the ranking of all performances in all competitions. *J. Anim. Breed. Genet*. 115:17–25. doi:10.1111/j.1439-0388.1998.tb00324.x

Ricard, A., E. Bruns, and E. Cunningham. 2000. Genetics of performance traits. In: *The genetics of the horse*. CABI, Oxford. p. 411–438.

Rovere, G., B. Ducro, J. Van Arendonk, E. Norberg, and P. Madsen. 2016. Analysis of competition performance in dressage and show jumping of Dutch Warmblood horses. *J. Anim. Breed. Genet*. 133:503–512. doi:10.1111/jbg.12221

Ruhlmann, C., E. Bruns, E. Fraehr, J. Philipsson, S. Janssens, K. Quinn, E. T. Hellsten, and A. Ricard. 2009a. Genetic connectedness between seven European countries for performance in jumping competitions of warmblood riding horses. *Livest. Sci*. 120:75–86. doi:10.1016/j.livsci.2008.04.016

Ruhlmann, C., S. Janssens, J. Philipsson, E. Thorén-Hellsten, H. Crolly, K. Quinn, E. Manfredi, and A. Ricard. 2009b. Genetic correlations between horse show jumping competition traits in five European countries. *Livest. Sci*. 122:234–240. doi:10.1016/j.livsci.2008.09.006

Schaeffer, L. 1985. Model for international evaluation of dairy sires. *Livest. Prod. Sci*. 12:105–115. doi:10.1016/0301-6226(85)90084-3

Schaeffer, L. 1994. Multiple-country comparison of dairy sires. *J. Dairy Sci*. 77:2671–2678. doi:10.3168/jds.S0022-0302(94)77209-X

Schröder, W., K. F. Stock, and O. Distl. 2010. Genetic evaluation of Hanoverian warmblood horses for conformation traits considering the proportion of genes of foreign breeds. *Arch. Anim. Breed*. 53:377–387. doi:10.5194/aab-53-377-2010

Schubertová, Z., I. Pavlík, and J. Candrák. 2014. The influence of the genomic data on the showjumping horses performance evaluation. *J. Cent. Eur. Agric*. 15:33–40. doi:10.5513/JCEA01/15.2.1447

Stewart, I., I. White, A. R. Gilmour, R. Thompson, J. Woolliams, and S. Brotherstone. 2012. Estimating variance components and predicting breeding values for eventing disciplines and grades in sport horses. *Animal* 6:1377–1388. doi:10.1017/S1751731112000596

Stewart, I., J. Woolliams, and S. Brotherstone. 2010. Genetic evaluation of horses for performance in dressage competitions in Great Britain. *Livest. Sci*. 128:36–45. doi:10.1016/j.livsci.2009.10.011

Stewart, I. D., J. A. Woolliams, and S. Brotherstone. 2011. Genetic evaluations of traits recorded in British young horse tests. *Arch. Anim. Breed*. 54:439–455. doi:10.5194/aab-54-439-2011

Stock, K. F., L. Jönsson, A. Ricard, and T. Mark. 2016. Genomic applications in horse breeding. *Anim. Front*. 6:45–52. doi:10.2527/af.2016-0007

Stout, T. A. 2012. Cryopreservation of equine embryos: current state-of-the-art. *Reprod. Domest. Anim*. 47:84–89. doi:10.1111/j.1439-0531.2012.02030.x

Ström, H., and J. Philipsson. 1978. Relative importance of performance tests and progeny tests in horse breeding. *Livest. Prod. Sci*. 5:303–312. doi:10.1016/0301-6226(78)90058-1

Tavernier, A. 1990. Estimation of breeding value of jumping horses from their ranks. *Livest. Prod. Sci*. 26:277–290. doi:10.1016/0301-6226(90)90065-E

Tavernier, A. 1991. Genetic evaluation of horses based on ranks in competitions. *Genet. Sel. Evol*. 23:159–173. doi:10.1186/1297-9686-23-2-159

Thorén Hellsten, E. 2008. *International sport horse data for genetic evaluation* [doctoral thesis]. Uppsala: Swedish University of Agricultural Sciences.

Thorén Hellsten, E., H. Jorjani, and J. Philipsson. 2008. Connectedness among five European sport horse populations. *Livest. Sci*. 118:147–156. doi:10.1016/j.livsci.2007.12.028

Thorén Hellsten, E., H. Jorjani, and J. Philipsson. 2009. Genetic correlations between similar traits in the Danish and Swedish Warmblood sport horse populations. *Livest. Sci.* 124:15–20. doi:10.1016/j.livsci.2008.11.021

VanRaden, P. M., and P. G. Sullivan. 2010. International genomic evaluation methods for dairy cattle. *Genet. Sel. Evol.* 42(1):1–9. doi:10.1186/1297-9686-42-7

Van Veldhuizen, A. 1997. Breeding value estimation for riding horses in the Netherlands. In: editor-in-chief: Ynze van der Honing, 48th Annual Meeting of European Association for Animal Production; August 25–28; Vienna, Austria. p. 376.

Viklund, A., A. Braam, A. Näsholm, E. Strandberg, and J. Philipsson. 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* 4:682–691. doi:10.1017/S1751731110000017

Viklund, Å., E. Thorén Hellsten, A. Näsholm, E. Strandberg, and J. Philipsson. 2008. Genetic parameters for traits evaluated at field tests of 3-and 4-year-old Swedish Warmblood horses. *Animal* 2:1832–1841. doi:10.1017/S1751731108003030

Visser, E. K., C. G. Van Reenen, M. Z. Blokhuis, E. K. M. Morgan, P. Hassmén, T. M. M. Rundgren, and H. J. Blokhuis. 2008. Does horse temperament influence horse–rider cooperation? *J. Appl. Anim. Welf. Sci.* 11:267–284. doi:10.1080/10888700802101254

WBFSH. 2021. An introduction to genomic selection [accessed September 8, 2021]. https://www.wbfsh.com/genomic-selection

Welker, V., K. Stock, K. Schöpke, and H. H. Swalve. 2018. Genetic parameters of new comprehensive performance traits for dressage and show jumping competitions performance of German riding horses. *Livest. Sci.* 212:93–98. doi:10.1016/j.livsci.2018.04.002