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Genetic insights into distance-specific performance and ability to race barefoot in trotting horses in Sweden

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Cover: Elitkampen 2025, Coldblooded trotters. Photo: Mia Törnberg

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Abstract

Most horses used for harness racing in Sweden are Swedish Standardbred trotters (SB), but there is also a local breed, the Swedish-Norwegian Coldblooded trotters (CB) that race in separate races and are classified as endangered. Up to now, the two breeding programmes have mainly been focused on improving racing performance. This thesis aimed to study the genetic background of new traits, and the possibility to include them in the genetic evaluation of SB and CB. More specifically, Paper I aimed to study whether racing time could be treated as genetically distinct traits over short-, medium-, and long-distance races in CB. The aim was also to study re-ranking among top-ranked sires and their relationship to the rest of the population, to evaluate if distance-specific performance could promote the use of stallions that are less related to the population, and to control the high inbreeding rate in CB. The results showed that racing time can be treated as one trait over all distances. Some re-ranking based on breeding values for stallions was seen across the distances. Still, the relationship between stallions was close to half-siblings, and their relationship to the rest of the population was similar for the top-ranked stallions in all distances. In Papers II–IV, two traits reflecting the trotters' ability to race barefoot were analysed in terms of their genetic background, correlation to performance, and impact on the career length. Racing barefoot has previously been linked to improved racing speed in SB, but not all trotters have hooves that tolerate racing barefoot. Two traits, proportion of barefoot races and barefoot status, were defined for SB and CB, where low to moderate heritability was estimated, and a favourable genetic correlation to performance was found. For both breeds, the results showed that the higher the proportion of barefoot races as a young horse, the shorter the career length. In summary, a trait reflecting the ability to race barefoot seems feasible to include in the genetic evaluation. However, the possible link between a higher proportion of barefoot races at a young age and reduced career length needs to be considered.

Keywords: Swedish Standardbred trotter, Swedish-Norwegian Coldblooded trotter, harness racing, performance, novel traits, barefoot racing, inbreeding, breeding programme, heritability, career length

Genetiska insikter om distansspecifik prestation och förmåga att tävla barfota hos svenska travhästar

Abstract

De flesta hästar som används i travsport i Sverige är svenska varmblodstravare (SB), men det finns också en lokal ras, den svensk-norska kallblodstravaren (CB) som tävlar i separata lopp och som är klassad som utrotningshotad. Hittills har avelsprogrammen främst varit inriktade mot att förbättra prestation. Syftet med denna avhandling var att studera den genetiska bakgrunden hos nya egenskaper att potentiellt inkludera i avelsvärderingen för SB och CB. Mer specifikt så var målet i artikel I att utvärdera om kilometertid kan klassas som olika egenskaper ur ett genetiskt perspektiv för korta, medellånga och långa lopp för CB. Syftet var också att studera omrangering av topprankade hingstar samt deras släktskap till resten av populationen, för att se om distansspecifik prestation kan främja hingstar som är mindre besläktade till populationen, och hjälpa till att kontrollera den snabba inavelsutvecklingen hos CB. Resultaten visade att kilometertid kan betraktas som en och samma egenskap över olika distanser. Viss omrangering bland hingstarna förekom, men deras släktskap var i nivå med att vara halvsyskon och släktskapet till resten av populationen skilde sig inte nämnvärt mellan distanserna. I studierna II–IV undersöktes nya egenskaper kopplade till förmåga att tävla barfota genom att skatta deras genetiska bakgrund, korrelation till prestation samt effekt på karriärlängd. Att tävla barfota har tidigare kopplats till förbättrad kilometertid hos SB men inte alla travhästar har hovar som tål barfotatävlande. Två egenskaper, andel barfotalopp samt barfota-status definierades och låga till medelhöga arvbarheter skattades for SB och CB, samt en gynnsam genetisk korrelation till prestation. För båda raserna visade resultaten att en högre andel barfotalopp som ung var kopplad till en kortare karriärlängd. Summerat, så kan en egenskap som beskriver förmåga att tävla barfota vara möjlig att inkludera i avelsvärderingen. Den potentiella kopplingen mellan en högre andel barfotalopp som ung med en förkortad karriärlängd behöver dock tas hänsyn till.

Keywords: Varmblodstravare, Kallblodstravare, travsport, prestation, nya egenskaper, barfotatävlande, inavel, avelsprogram, arvbarhet, karriärlängd

Dedication

To my beloved family

"An understanding of the natural world is a source of not only great curiosity, but great fulfilment."

Sir David Attenborough

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. Berglund, P. Andonov, S. Strandberg, E. Eriksson, S. (2023). Should performance at different race lengths be treated as genetically distinct traits in Coldblooded trotters? Journal of Animal Breeding and Genetics, 141(2), pp. 113-234. https://doi.org/10.1111/jbg.12837

II. Berglund, P. Andonov, S. Jansson, A. Olsson, C. Lundqvist, T. Strandberg, E. Eriksson, S. (2025). The ability to race barefoot is a heritable trait in Standardbred and Coldblooded trotters. Genetics Selection Evolution, 57(1), 8. https://doi.org/10.1186/s12711-025-00958-2

III. Berglund, P. Andonov, S. Strandberg, E. Eriksson, S. Better hoof, better horse - Genetic correlations between ability to race barefoot and performance in Swedish trotting horses (submitted)

IV. Berglund, P. Andonov, S. Strandberg, E. Eriksson, S. The impact of barefoot racing in young Swedish trotters on career length (manuscript)

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The contribution of Paulina Berglund to the papers included in this thesis was as follows:

I. Performed statistical analyses, discussed results together with co-authors, drafted the manuscript with input from co-authors, and were responsible for correspondence with the scientific journal.

II. Planned the study with co-authors, performed statistical analyses, discussed results together with co-authors, drafted the manuscript with input from co-authors, and were responsible for the correspondence with the scientific journal.

III. Planned the study with co-authors, performed statistical analyses, discussed results together with co-authors, drafted the manuscript with input from co-authors, and were responsible for the correspondence with the scientific journal.

IV. Planned the study with co-authors, performed statistical analyses, discussed results together with co-authors, drafted the manuscript with input from co-authors.

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Abbreviations

BLUP	Best Linear Unbiased Prediction
CB	Swedish-Norwegian Coldblooded trotter
DMRT3	Doublesex and mab-3 related transcription factor 3
OCS	Optimum Contribution Selection
RELN	Reelin
SB	Swedish Standardbred trotter
SNP	Single-Nucleotide Polymorphism
STAU2	Staufen double-stranded RNA binding protein 2

1. Introduction

1.1 History and development of harness racing in Sweden

1.1.1 From sledge racing on ice to professional sport

Harness racing has a long history in Sweden and holds a strong tradition in our society. From the 16^{th} century, the farmers arranged sledge racing on the ice, competing for things like planting seeds or even the competitor's horse (Figure 1) (Borgerud 2024). Later, the sulky became more frequently used and in the 19^{th} century, the trotting industry grew, and farmers competed with their horses on short tracks at local markets. In 1882, Sweden's oldest trotting association was established in Arvika (Wermlands Trafvsarsällskap). The oldest racetrack was built in 1907 in Jägersro in southern Sweden. Today, there are 32 local trotting associations and 33 racetracks. The Swedish Trotting Association, created in 1900, is the umbrella organisation responsible for national competitions, regulations, horse registration, and breeding plans.

Sweden is among the top three biggest nations in the world in the trotting industry, and there are about one million visitors at the racetracks annually (Svensk Travsport 2025a). Watching and betting in trotting races is very popular in Sweden, and the sport is broadcast on TV several days a week, in contrast to Thoroughbred racing, which is not as popular as trotting in Sweden. Today, there are about 14,500 trotting horses in active training in Sweden, trained by more than 3600 trainers (Svensk Travsport 2024a). The betting company ATG, which is owned by the Swedish Trotting Association to 90% and to 10% by the national Thoroughbred horse racing association, has an annual turnover of about 1,1 billion euros (ATG 2025).

Figure 1. Ice sledge racing in Stockholm around 1800–1814 by Martin Rudolf Heland, Photo: Nordiska Museet.

1.1.2 Regulations of trotting races

Regulations of trotting races in Sweden are described in detail in the book of regulations, which is updated every year. The regulations are in place to standardize all trotting races held in the country to ensure fair sports for the competitors, but also for the bettors. The regulations are also important to ensure that animal welfare is never violated, and there are special regulations, e.g., on allowed gear and the usage of the whip.

The races

Most racetracks in Sweden measure 1000 m, but the races are most commonly raced over 1640 m, 2140 m, or 2640 m (Svensk Travsport 2025b). Up to 15 horses can participate in each race, and there are two different methods to start races. When the horses start behind a moving car, it is called auto-start. For this start method, eight horses line up behind the car, the remaining horses (positions 9 to 12) create a second line, and positions 13 to 15 create a third line. The second starting method is called volt-start. In volt-start, the horses are divided into groups and circle before turning up on the starting line simultaneously when the signal is given. In races with volt-start, horses can start at different positions (with additions in 20 m intervals) depending on, e.g., previous earnings or age as a handicap to make the race more competitive, making the actual race distance in the same race differ between horses.

According to the regulations set by Svensk Travsport (2025a), trot is the only allowed gait in a trotting race, and if the horse paces or breaks over to gallop, disqualification often follows. The horse may continue the race if the driver brings the horse back to trot without gaining position in the incorrect gait.

Age restrictions

In Sweden, the trotters can start racing from the age of two or three years, depending on the breed. The warmblood trotters, i.e., Standardbred trotters (SB), race from the age of two, and the Swedish-Norwegian Coldblooded trotter (CB) from the age of three. These two breeds race in separate races, and somewhat different regulations regarding the maximum age exist, and the regulations have changed over time. In SB, males (geldings or stallions) born in 2006 or earlier were allowed to race to 12, whereas females (mares) born in the same years were allowed to race to 10 years of age. Males born in 2007 or later were allowed to race until age 14, and females born in the same years to age 12. The current regulations allow SB females and males to race until age 14; this applies to females born in 2012 and later, while CB are allowed to race to age 15 (Svensk Travsport 2025c).

Barefoot racing

There are strict regulations on the horses' tack in trotting races that also vary with age and depending on the season. Two-year-old SB are not allowed to race without shoes, i.e., barefoot; CB that start racing at three years of age, however, are permitted to race barefoot starting from the same age. Since 2015, horses have only been allowed to race barefoot between March and November. Between December and February, all horses must race shod. These regulations are explicit for competitions because trotters generally train with shoes to protect the hoof from wear and tear. On race days, the horses' shoeing condition is reported separately for front and hind hooves. Given that the race is not in winter, the trainer can choose to race the horse with shod or barefoot front hooves in combination with shod or barefoot hind hooves. The horses' shoeing condition has been recorded since 2005 and is part of the information given to bettors before the race starts.

The most common shoeing condition in SB and CB is fully shod (Svensk Travsport 2023a). Between 2005 and 2022, 7.5% to 13.2% of the observations of three-year-old SB were from fully barefoot starts (Svensk Travsport 2023a). In SB four years and older, 15.7% of the observations in 2005 were from fully barefoot horses, which increased to 28.7% in 2022. For CB, for which barefoot racing is less common, the corresponding numbers for older horses have changed from 4.1% in 2005 to 7.9% in 2022 (Svensk Travsport 2023a).

1.2 The horse - from farmer's helper to sports athlete

1.2.1 The Swedish Standardbred trotter

Origin

The Swedish Standardbred trotter originates mainly from American trotters, i.e., Standardbred trotters (Figure 2), but also from French trotters (Svensk Travsport 2025d). The origin of the Standardbred trotter is the Thoroughbred, which has been shown in genomic studies (Bjørnstad *et al.* 2000). Hambletonian, born in 1849, is considered a founder sire of Standardbred trotters because of his contribution in breeding with over 1000 offspring; his pedigree traces to Thoroughbred but also to Norfolk trotter lines (Svensk Travsport 2025e). The first physical book with collected pedigrees of Swedish Standardbred trotters was published in 1938 (Svensk Travsport 2025f). There are about 63,000 SB in Sweden, which makes it the second most common horse breed in Sweden, and the most commonly used breed for trotting races, with 90% of the race starts in Sweden (Svensk Travsport 2025d).

Breeding programme

The studbook of SB is open to other trotter breeds, and an SB stallion is allowed to cover up to 150 mares per year in Sweden (Svensk Travsport 2025g). In 2024, six out of 88 active breeding stallions covered more than 100 mares (Svensk Travsport 2024b). The total number of coverings in the same year in Sweden was 3493. Breeding of SB is performed with natural coverings or insemination (fresh, chilled or frozen semen) and has, over the years, gone from mainly importing breeding material to being an exporter. Swedish mares covered abroad (842 mares in 2024) are mainly transported to France owing to their regulations that do not allow transportation of fresh or frozen semen (Svensk Travsport 2024b).

Figure 2. Standardbred trotter stallion Venerate. Photo: Mia Törnberg.

The breeding goal of the Swedish Standardbred trotter is to produce sound and competitive horses that are easy to handle, are naturally good trotters, and have a good temperament with a strong will to win (Svensk Travsport 2025g). The horses should have a favourable conformation, be internationally competitive, and have a good reproduction if bred after their racing career.

Work by Árnason *et al.* (1982) laid the basis for the genetic evaluation of Swedish Standardbred trotters, which initially included the traits summarised earnings, earnings per start, percentage placings (first to third), and best racing time for horses aged 3 to 5 years. Later, start status (whether the horse has started in a competition or not) and number of starts were also included as traits (Árnason *et al.* 1988).

From 1992, the genetic evaluation was performed with BLUP (Best Linear Unbiased Prediction) using animal models where the model and appropriate trait transformations were developed by Árnason (1999). The models for estimating breeding values are the same for all performance traits and include the genetic base group (Standardbred trotter or French trotter) combined with sex (male or female), the year of birth combined with sex, the effect of the breeding value (animal), and residual. The base group consists of horses with unknown parents or only one known parent.

The breeding values for the horses are scaled and presented as an index, with a mean of 100. The mean is based on horses born thirteen years ago until three years ago from the current year. One genetic standard deviation for the traits corresponds to 10 units in the index.

The index consists of the following trait indices and weights:

$$Total\ index = 0.05 \times number\ of\ starts + 0.75 \times competition\ performance + 0.2 \times start\ status$$

Where competition performance is the average of the indices for placings, earnings and earnings per start.

Heritability estimates used in the genetic evaluation for performance traits used in the genetic evaluation of SB range from 0.18 for the number of starts to 0.44 for earnings per start. The strongest correlations (genetic and phenotypic) in the genetic evaluation are those between best racing time and earnings, estimated at -0.94 and -0.88, respectively. The weakest genetic correlations are found between start status and the remaining performance traits (range |0.44–0.54|). Number of starts is not included as a correlated trait in the genetic evaluation, because the best horses tend to start in few races, and so do the least good ones, leading to strange estimates (Árnason 1999).

1.2.2 The Swedish-Norwegian Coldblooded trotter

Origin

The Coldblooded trotter (Figure 3) is a breed native to Sweden and Norway. According to FAO, the breed has the status “endangered” (which is the third level on a scale with six levels, ranging from not at risk to extinction) (FAO 2025). It originates from horses with a long history in the Swedish and Norwegian society as versatile horses used for transporting not only people, but also goods between for example Stockholm and northern Sweden and Norway for trade. Farmers’ sledge racing on ice in trot was seen as a way of finding the most suitable horses for breeding in the 18th century, and most horses at this time were of the native Coldblooded type (Uhlin 2007). In the 19th century, agriculture and the military's demand for bigger horses (at the time, few horses were as tall as 140 cm at the withers) resulted in the creation of the breed known as the North Swedish horse. The Swedish Coldblooded trotter was officially separated from the North Swedish horse in 1964, due to the different breeding goals where the Coldblooded trotters were bred for sports performance while the North Swedish horse was bred for usage in agriculture and forestry (Bohlin & Rönningen 1975). Similarly, in Norway, the Coldblooded trotter was split from the heavier draught horse (Dole horse) in 1965, and since 2000, there has been a joint breeding programme for the Coldblooded trotters in Sweden and Norway (Svensk Travsport & Det Norske Travselskap 2019). There is a common belief that before the parentage verification of CB was established in 1964, Standardbred trotters were, to some extent, crossed with CB to enhance racing performance. This has also been verified in genomic studies where SB, CB, and The North Swedish horse were compared at genomic regions known to influence racing performance (Velie *et al.* 2019a).

Figure 3. Swedish-Norwegian Coldblooded trotter stallion Gorm. Photo: Mia Törnberg.

Genetic evaluation

The Swedish Trotting Association and the Norwegian Trotting Association are responsible for the breeding programme for the Swedish-Norwegian Coldblooded trotter. The overall breeding goal is to produce healthy and sound horses and to improve their racing performance, durability, and temperament (Svensk Travsport 2025g). Furthermore, emphasis is put on keeping the breed-specific type and controlling inbreeding in the population.

The first common genetic evaluation between the countries was published in 1994 using BLUP with an animal model. Traits included in the genetic evaluation are start status, best racing time per kilometre, summarised earnings, and percentage of placings (1-2). Trait definitions and transformations were based on work by Árnason *et al.* (1988) and Klemetsdal (1988). The model is the same for all traits and includes the combined effect of the country of registration, sex, and year of birth, breeding value (animal), and residual. In contrast to SB, the base for the mean index has remained unchanged over the years. Also, unlike SB, an increase in the index of 10 units corresponds to one standard deviation of the index. In CB, the total index comprises the summarised earnings that are standardised within the country of registration and year of birth and start status (started in a race or not). Best racing time and placings are not part of the total index; however, they are included as correlated traits when estimating the breeding values.

$$Total\ index\ = 0.6\ \times earnings + 0.4\ \times start\ status$$

The heritability currently used in the genetic evaluation for performance in CB ranges from 0.20 for start status to 0.35 for best racing time. The strongest genetic correlations in the genetic evaluation are those between best racing time and earnings, as well as between earnings and placings (|0.90|). As in SB, the weakest genetic correlations were those between start status and the remaining performance traits, all estimated at |0.60|.

1.3 Inbreeding

1.3.1 Background

Since the end of the 19th century, stallions have had to be approved to be used for breeding in Sweden, and by the 1950s, the domination of a few popular sires being used in Coldblooded trotter breeding raised concerns regarding the inbreeding level (Uhlin 2007). An inbred offspring is the result of breeding (close) relatives with each other. The higher the inbreeding level, the greater the risk of recessive deleterious alleles being expressed phenotypically (Simm *et al.* 2020). The level of inbreeding in a population is commonly measured as F (inbreeding coefficient), or ΔF, which gives the rate of inbreeding per generation. The inbreeding coefficient ranges from 0 to 1 and is defined as the probability of two alleles at a locus being identical by descent (inherited from a common ancestor) (Simm *et al.* 2020). For CB born in 2009, the inbreeding coefficient based on pedigree information was estimated to be 6.4% (Velie *et al.* 2019b).

In the 1950s, it became possible to register offspring in the studbook from Swedish mares covered with Norwegian (approved) sires (Uhlin 2007), spreading the Norwegian sire lines to Sweden. To mention some of the most influential Norwegian stallions, Stegg, born in 1937, had 958 offspring. Steggbest, born in 1947 and sired by Stegg, had 866 offspring and was the grandsire of 1714 horses. More recent matadors that are descendants from Stegg include Troll Jahn, born in 1971, that sired 1373 offspring and had 1819 grand-offspring, and also Elding, born in 1983, with 1343 offspring. In the 21st century, Moe Odin, sired by Elding, and Swedish-born Järvsöfaks dominated the breeding with 1164 and 1471 offspring, respectively. The numbers given above are all collected from the database breedly.com (Svensk Travsport 2025h).

The number of foals born per year is decreasing in both Sweden and Norway. In 2024, 510 mares were covered in Sweden and 490 in Norway. These are historically low numbers and of major concern for the future of the breed, especially in Norway, where numbers used to be twice as large as those in Sweden (Svensk Travsport 2024c).

1.3.2 Risks associated with inbreeding

Inbreeding can give rise to numerous issues related to health and fertility, which lead to decreased fitness or performance, i.e., inbreeding depression

(Simm *et al.* 2020). In other horse populations, inbreeding has negatively affected racing performance in Thoroughbreds (Todd *et al.* 2018) and Standardbred trotters (Samsonstuen *et al.* 2020). In SB, it has also been shown to shorten the career length (Árnason 2006). In Friesian horses, genetic disorders resulting in stillbirth (Ducro *et al.* 2015) and retained placenta are outcomes linked to the high level of inbreeding in the population (Sevinga *et al.* 2004).

More specifically, in CB the increased inbreeding level in the population has been shown to negatively affect the performance, e.g., lower earnings for individuals with higher inbreeding (Klemetsdal 1998). Also, an increased inbreeding level has been associated with an increased risk for arthritis in the carpal joint in CB (Dolvik & Klemetsdal 1994).

1.3.3 Efforts to reduce inbreeding

Today's breeding system for CB allows Swedish stallions to mate with 70 Swedish mares and 25 Norwegian mares per year, and vice versa for Norwegian stallions (Svensk Travsport 2025g). Olsen *et al.* (2013) suggested to implement optimum contribution selection (OCS), which is a method to achieve genetic gain in performance, but at the same time, restricts the increase in inbreeding (Meuwissen 1997). However, until today, this has not been implemented in the breeding programme.

In 2023, a new initiative was established to help reduce inbreeding in CB. Breeding a foal with an expected inbreeding coefficient lower than 3.4% (based on seven generations of pedigree) gave extra money to breeders and owners when the foal was born and also started their first races (Svensk Travsport 2023b).

1.4 Potential new traits in the breeding programmes for Swedish trotters

This thesis explores the genetic background of some potential new traits in Swedish trotters. The following sections introduce these traits and their relevance for Swedish trotters.

1.4.1 Distance-specific races

Racing time is a trait of high importance in breeding programmes of trotting horses due to its moderate heritability and strong correlation to other performance traits such as earnings and placings (Árnason *et al.* 1988; Árnason 1999; Suontama *et al.* 2012). In the genetic evaluation of CB, racing time is included as best racing time per kilometre for 3- to 6-year-olds, regardless of the distance of the race at which the record was held. Therefore, we hypothesised that dividing the trait into distance categories might favour different horses, depending on what distance they are good at. Ideally, this could promote the use of more stallions in breeding that are less related to the population.

As previously mentioned, Swedish trotting races are divided into short-distance (1640 m), medium-distance (2140 m) and long-distance races (2460 m) and it would be practically feasible to distribute prize money to races that are held over a distance that promotes the use of less popular stallions that are less related to the population, if shown to be the case. As Olsen and Klemetsdal (2020) pointed out, it has been difficult to find acceptance to implement methods in the breeding programme that restrict owners in their usage of the stallions in their breeding by implementing methods such as OCS, as suggested by Olsen *et al.* (2013).

Therefore, finding new traits that can be easily implemented in the genetic evaluation and that would favour the use of less popular stallions and lower the inbreeding level in the population would be of value for the future of the breed.

1.4.2 The ability to race barefoot

The importance for racing performance

About 25 years ago, Swedish trotting horses started to race without shoes (barefoot) at competitions. In 2005, the shoeing condition of the horses became routinely registered at all Swedish trotting races where shod/barefoot was registered for front and hind hooves separately. Racing barefoot was seen as a way of making the horses run faster in races, and when the horse's shoeing condition had to be reported before the race, this information became available for bettors. Solé *et al.* (2020) later proved what had been known in the industry for many years, that racing barefoot significantly reduces racing time in SB. However, the authors showed that the largest effect was achieved by removing all shoes and racing fully barefoot, then the racing time was reduced by 0.7 s per kilometre compared to when racing fully shod. Racing fully barefoot compared to fully shod was also related to a 26% higher risk of disqualification, e.g., for gallop. It was possible to reduce racing time by racing barefoot front or hind only (with 0.3 s per kilometre compared to fully shod) however, the shoeing condition on the hind hooves was believed to be the limiting factor because this had a larger effect on the risk of disqualification than the shoeing condition on the front hooves (Solé *et al.* 2020).

Factors affecting the ability to race barefoot

Given the results from Solé *et al.* (2020) showing increased risk of disqualification when racing barefoot, the actual reason for this is yet unknown. However, the authors speculated that the horses' ability to tolerate racing barefoot hind could be connected to hoof quality. To follow up on why some trotters tolerate racing barefoot hind repeatedly (barefoot racers) and some do not (non-barefoot racers), Spörndly-Nees *et al.* (2023) studied the chemical composition of the hoof wall in the two groups. The results showed higher concentrations of elements in the hoof wall (sulphur, nitrogen, arginine, proline, and cysteine) in barefoot racers, which can be connected to having durable hooves.

Besides individual differences in hoof quality that may affect the ability to tolerate repeated barefoot racing, breed differences related to hoof quality have been found by Ott and Johnson (2001). Therefore, it is reasonable to believe that the ability to race barefoot is also affected by genetics. If so, the genetic correlation to racing performance in Swedish trotters, e.g., earnings, placing, racing time, and number of starts, would also be of interest to further study to assess its suitability for inclusion in the genetic evaluation. Until now, the genetic background of the ability to race barefoot and its link to performance have not yet been studied.

The impact of barefoot racing – from a welfare and racing longevity perspective

The age of the horse when barefoot racing is allowed in competitions is, as previously mentioned, controlled by national regulations set by the Swedish Trotting Association. However, in Europe, regulations differ between countries. In Finland, which also has races with their domestic breed of Coldblooded trotters (Finnhorse) and Standardbred trotters, the age when the horses are allowed to start racing barefoot is set to three and four years of age, respectively (The European Trotting Union 2025). In Sweden, both SB and CB are allowed to race barefoot from three years of age (Svensk Travsport 2025c).

There is an ongoing discussion in Sweden and the rest of Europe regarding barefoot racing in the context of regulations and possible animal welfare concerns, because not all horses tolerate racing without shoes. In France, where barefoot racing is allowed for horses four years and older, regulations restricting the frequency of barefoot racing were recently implemented (The European Trotting Union 2024). An argument for not racing barefoot with horses younger than four years old was that it could damage the hoof wall, which would have a negative impact on the horses later in their career (Le Trot 2024). Studies on the effect of barefoot racing are few and often include few horses. In Italian trotters, injuries caused by interference (when one hoof causes injuries on another leg) have been shown to be more common in horses racing barefoot, which could affect their future racing career (Dabbene *et al.* 2018). In a small study including six French trotters, racing barefoot repeatedly induced increased sensitivity in the hoof and inflammation in the distal phalanx (Cirale-EnvA 2015). On the other hand, Bertuglia *et al.* (2014) did not see any increased risk of musculoskeletal injuries in Italian Standardbreds racing barefoot compared to those racing shod.

To the best of our knowledge, no studies have analysed the effect of barefoot racing at a young age on the career length in trotters. Therefore, the Swedish Trotting Association has expressed the need for large-scale studies that could assess the effect of barefoot racing in young Swedish trotters on their career length, to base new regulations on. Having durable horses that can have a long racing career is not only of economic interest for owners and trainers of trotting horses, but also important for the industry, for which the social acceptance of the sport is of great value.

2. Aims of the thesis

The overall aim of this thesis was to study the potential of including new traits in the breeding programmes of Swedish trotters to improve the selection of trotters with regard to genetic diversity, soundness, and longevity. The more specific aims were:

- To study if distance-specific performance in Swedish-Norwegian Coldblooded trotters could be treated as genetically distinct traits and aid in selecting stallions less related to the rest of the population (Paper I)
- To assess the genetic background of the ability to race barefoot, defined as proportion of barefoot races and barefoot status in Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters (Paper II)
- To analyse the genetic correlation between the ability to race barefoot and performance in Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters (Paper III)
- To investigate the impact of barefoot racing in young Swedish trotters on their career length (Paper IV)

3. Summary of the studies

In this thesis, four studies were conducted. Paper I focused on exploring the genetics behind the trait racing time per kilometre over different distances in Swedish-Norwegian Coldblooded trotters. In Papers II–IV, the genetic background as well as the influence on career length of novel traits reflecting the ability to race barefoot in Swedish Standardbred trotters and Coldblooded trotters were investigated.

3.1 Materials

The data material used for the studies in this PhD thesis was received under license from The Swedish Trotting Association and treated as confidential information. However, competition results and pedigree information for individual horses can be retrieved online at Travsport.se and are available to everyone.

3.1.1 Trait definitions

Distance-specific performance

In Paper I, data from Coldblooded trotter races in Sweden from 1995 to 2021 with horses aged 3–12 years were included. The trait racing time per kilometre in the format of, e.g., 1320 (1 minute and 32.0 seconds) was divided into three different traits based on the race distances: short-distance (1640 m), medium-distance (2140 m), and long-distance (2640 m). These are the three most common race distances for trotters in Sweden. The actual race distance for each horse (i.e., with handicap) was used to separate the racing times. With this taken into consideration, the short-distance races ranged from 1609 to 1700 m, medium-distance races between 2040 and 2300 m, and the long-distance races between 2460 and 2760 m. Trait descriptions and transformations applied for the distance-specific traits are shown in Table 1, and the number of horses and observations per race-distance are shown in Table 2.

Ability to race barefoot

In Paper II, three traits were defined to reflect the ability to race barefoot in Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB). For all traits, barefoot was defined as racing with barefoot hind hooves and shod or barefoot front hooves. Data from the years 2005–2022 in SB and from the years 2005–2021 in CB were included. Standardbred trotters born 2002–2018 and CB born 2002–2017 that were 3–10 years old were included. The trait definitions and transformations are shown in Table 1, while the number of horses included per trait is shown in Table 2.

The proportion of barefoot races was created to measure the relative frequency of barefoot races, where, for the first definition (proportion of barefoot races I), which was also included in Paper III, the raw values for the proportion of barefoot races were used. For the trait proportion of barefoot races definition II, horses that never raced barefoot were excluded. Transformations were applied to create normally distributed traits. A square root transformation was applied for SB, and for CB, the proportion of barefoot races was raised to the power of 0.02. However, this presentation of results will be focused on the first trait definition, including both horses with and without barefoot races. Although the distribution of these traits differs, as shown in Figure 4, general findings were similar for the two trait definitions.

For the proportion traits included in Papers II and III, SB were required to have started at least 10 races and CB 5 races. The trait distributions for proportion of barefoot races I (Papers II and III) and proportion of barefoot races II (Paper II) for SB and CB are shown in Figure 4.

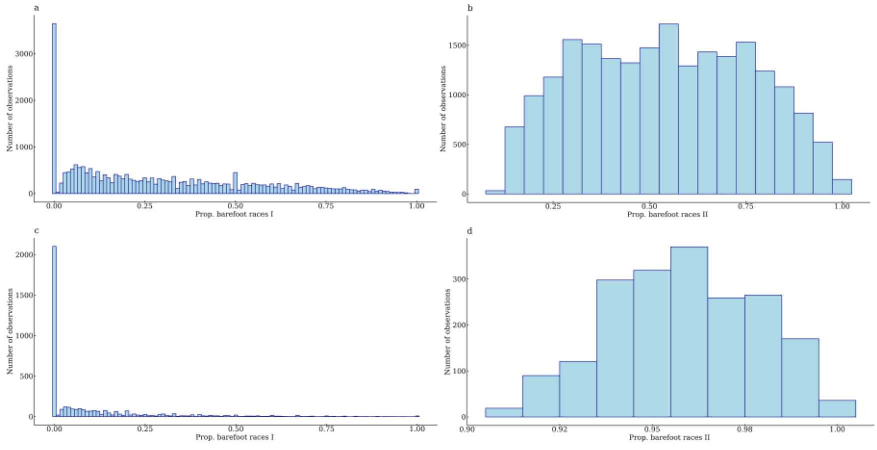

Figure 4. Trait distribution for proportion of barefoot races I and II in Standardbred trotters (a) and (b) and in Coldblooded trotters (c) and (d).

In Paper IV, racing data from 2005 to 2022 in SB and from 2005 to 2021 in CB were used to create three datasets to study the effect of the proportion of barefoot races in young trotters on the career length. The first dataset consisted of barefoot data and racing results from 3-year-old SB (SB3yo). The second dataset included 3- and 4-year-old SB (SB3+4yo), and the third dataset 3- and 4-year-old CB (CB). No minimum requirement for the number of barefoot races was set for the proportion of barefoot races in Paper IV. However, SB3yo and CB were required to have raced at least 5 races, and SB3+4yo at least 10 races to be included. The number of horses included ranged from 1392 to 12,161 (Table 2).

An additional trait named barefoot status was included in Papers II and III. Barefoot status was a binary trait, created to reflect whether or not the horse raced barefoot (hind) in a given race. For this trait, there was no minimum requirement for the number of races. However, horses that were trained by trainers who had never started a horse barefoot were removed. Repeated observations made it possible to correct for effects such as race level (earnings), trainer, track condition, season, etc., for this trait. The number of horses and observations for barefoot status in SB and CB are shown in Table 2.

Table 1. Description of traits in Papers I–IV and their transformations in Swedish Standardbred trotters (SB)[a] and Swedish-Norwegian Coldblooded trotters (CB)[b]

Trait	Breed	Paper	Transformation	Description
Short-distance	CB	I	None	Best racing time per kilometre in 1640 m distance
Medium-distance	CB	I	None	Best racing time per kilometre in 2140 m distance
Long-distance	CB	I	None	Best racing time per kilometre in 2640 m distance
Proportion of barefoot races I	SB / CB	II, III, IV	None	Proportion of barefoot races (in hind) in non-winter season
Proportion of barefoot races II	SB	II	Proportion of barefoot races$^{0.5}$	Proportion of barefoot races (in hind) in non-winter season, only barefoot racers

	CB	II	Proportion of barefoot races$^{0.02}$	Proportion of barefoot races (in hind) in non-winter season, only barefoot racers
Barefoot status	SB / CB	II, III	None	Barefoot (in hind) in a race or not
Best racing time	SB	III	Ln (best racing time per kilometre - 68.2)	Best racing time per kilometre (in the format of e.g. 1122 is 1 min, 12 s and 2 tenths of a second) minus 1082 (68.2 s = 1 min and 8.2 s)
	CB	III	(Best racing time per kilometre)$^{0.5}$	Best racing time per kilometre (in the format of e.g. 1202 is 1 min, 20 s and 2 tenths of a second) minus 1000.
Earnings	SB	III	Ln (earnings + 1000)	Summarised earnings in SEK
	CB	III	Earnings$^{0.25}$	Summarised earnings standardised within the country of registration and birth year
Earnings per start	SB	III	Ln ((earnings + 1000) / number of starts)	Summarised earnings in SEK per start
Placings	SB	III	((Placings x 100) / number of starts)$^{0.8}$	Percentage of 1st to 3rd placings
	CB	III	((Number of placings x 100) / number of starts)$^{0.5}$	Percentage of 1st to 2nd placings
Number of starts	SB	III	(Number of starts in races)$^{0.2}$	

[a] Performance and barefoot data from Standardbred trotters aged 2-5 and 3-10, respectively. For performance, data from 2-year-olds was only included from the year they turned three.

[b] Performance data from Swedish-Norwegian Coldblooded trotters aged 3-12 (Paper I), 3–6 (Paper III) and barefoot data from horses aged 3-10 (Papers II and III).

3.1.2 Performance and pedigree data

Standardbred trotters

The performance data used for Papers II–IV consisted of all racing records from Swedish trotting races in 2005–2022. In total, 1,442,500 records from 64,350 horses were included in the raw data. Detailed information from every race event was included: date, track, track condition, starting method, placing, racing time, earnings, driver, trainer, and shoeing condition.

The number of unique horses and observations included in Papers I–IV are summarized in Table 2. To create the performance traits in Paper III to be similar to those used in the genetic evaluation, a separate data file with summarized performance from horses born between 1976 and 2019 was used. This file contained yearly summaries of earnings, best racing time per kilometre for auto- and volt-start, number of placings 1–3, and number of races. The data editing for the performance traits resulted in 115,185 horses left for analysis. Pedigree data included horses born from 1800 until 2022, with a total number of 305,044 individuals.

Swedish-Norwegian Coldblooded trotters

The data file used for Paper I consisted of Swedish racing results from the years 1995–2021, including 173,141 records after data editing. For the barefoot traits (Papers II–IV), data were extracted from the years 2005–2021. The number of horses and observations in each Paper after data editing are shown in Table 2. The data file contained the same detailed information about each race event as described above for SB. The traits proportion of barefoot races I and barefoot status as defined in Paper II, were further studied in Paper III including the same number of horses and observations.

In Paper III, a data file containing yearly summarized race data was used to create the performance traits. This data file contained information about Swedish and Norwegian races, such as earnings, best racing time per kilometre for auto- and volt-start, number of placings 1–2, and number of races each year. After data editing, 16,360 horses born between 1978 and 2017 were used for the analysis of performance in Paper III. The pedigree for CB included horses born from 1800 until 2021 and consisted of 118,239 individuals.

Table 2. Number of horses and observations per breed and trait in Papers I-IV in Coldblooded trotters (CB) and Standardbred trotters (SB)

Paper	Breed	Trait	N horses	N obs
I				
	CB	Short-distance	8375	46,356
		Medium-distance	11,193	130,512
		Long-distance	3341	11,006
II				
	SB	Proportion of barefoot races I	24,928	724,232
		Proportion of barefoot races II	21,281	649,091
		Barefoot status	25,973	875,056
	CB	Proportion of barefoot races I	4050	97,682
		Proportion of barefoot races II	1947	60,292
		Barefoot status	3384	93,376
III				
	SB	Proportion of barefoot races I	24,928	724,232
		Barefoot status	25,973	875,056
	CB	Proportion of barefoot races I	4050	97,682
		Barefoot status	3384	93,376
IV				
	SB	Proportion of barefoot races as 3-years-old	12,161	12,161
		Proportion of barefoot races as 3- and 4-years-old	13,922	13,922
	CB	Proportion of barefoot races as 3- and 4-years-old	1392	1392

3.2 Methods

3.2.1 Estimation of genetic parameters and statistical models (Papers I, II, and III)

Bayesian models with Gibbs sampling

In Papers I and II, variance components and heritability were estimated with Gibbs sampling in the BLUPF90 suite of programs (Misztal *et al.* 2014). In Paper I, a trivariate model including racing time per kilometre in short-, medium-, and long-distance races was used to estimate the genetic correlations. The estimates were based on 6875 samples saved for post-Gibbs analysis.

In Paper II, a threshold model where barefoot status (indicated as barefoot = 2 or otherwise = 1) was run as a single-trait model separately for SB and CB. The estimates were based on 4250 and 7750 samples passed to the post-Gibbs analysis for SB and CB, respectively.

Different methods of deciding whether convergence had been reached were studied in the post-Gibbs analysis. All saved samples were passed to RStudio (R Core Team 2023) and plotted for visual inspection. From this, the appropriate burn-in period was determined and whether the chains had reached convergence was inspected. From the program Postgibbsf90, the autocorrelation between drawn samples was inspected to avoid correlated samples, and the effective sample size was checked to be large enough to assure that the chains had been run for an appropriate number of iterations.

Variance components from post-Gibbs analysis were presented both as mean and median, the heritability was obtained from each iteration and presented as the posterior mean value of all iterations.

Mixed linear animal models

In Paper III, genetic correlations were estimated between the barefoot traits and performance in SB and CB using bivariate mixed linear animal models. The analyses were performed with the DMU program (Madsen & Jensen 2013).

Statistical models

In Paper I, the statistical model was the same for the three race distances and included the fixed effects of age, country of registration, sex, year of the race, season, track, track condition, starting position on the track, gallop in the race or not, trainer level and driver level. Random effects included in the model were year-season, trainer, additive genetic, and permanent environment.

For the proportion of barefoot races I (Papers II and III), the statistical model was the same for SB and CB and included the fixed effects of sex and year of birth. For barefoot status (Papers II and III), the model was the same for SB and CB and included the fixed effects of age, sex, year of the race, season, track, track condition, trainer level, race distance, and level of the race (earnings). Random effects included were trainer, year-season, additive genetic, and permanent environment.

Correlations

In Paper I, correlations between estimated breeding values (EBVs) for the top-ranked breeding stallions (CB born 2005–2012) in the distance-specific traits were estimated with Spearman rank correlation. Also, genetic correlations between short-, medium-, and long-distance races were estimated. In Paper II, both Spearman rank correlation and Pearson's correlation were estimated between EBVs for the proportion traits and barefoot status for SB stallions born 1992–2013 and CB stallions born 1992–2011.

In Paper III, genetic correlations between the barefoot traits (proportion of barefoot races and barefoot status) and performance traits included in the genetic evaluation for SB and CB were estimated.

3.2.2 Pedigree analysis

Inbreeding and relatedness

In Paper I, the inbreeding level in CB was studied for horses born between the years 1940 and 2021 with all available pedigree information. Horses were grouped according to birth year, and the average inbreeding level and number of discrete generation equivalents per group were estimated with the CFC software (Sargolzaei *et al.* 2006). Top-ranked stallions born 2005–2012 based on EBVs were grouped according to race distances to estimate the average relationship within and between groups using a pedigree with seven generations. Also, the average relationship to the rest of the population was estimated.

In Paper IV, inbreeding was estimated for SB and CB separately with INBUFGF90 from the BLUPF90 suites of program (Misztal *et al.* 2014), including all pedigree information.

3.2.3 Survival analysis

In Paper IV, the impact of the proportion of barefoot races at a young age on career length in SB and CB was studied using survival analysis.

Censoring

Different rules for censoring the data were applied for SB and CB. However, horses that raced in the highest age allowed at the time of the last race were treated as censored in both breeds. In SB, age restrictions differed between sexes and birth years according to the regulations set by the Swedish Trotting Association. In Figure 5 the rules for censoring of data in SB are displayed with examples for females (mares) and males (geldings/stallions) born in different years. Horses that raced within two years before the data ended (2022-12-18 for SB and 2021-12-29 for CB) were censored. In CB, horses were censored by the same rules for all birth years. In SB3yo, 30% was censored, and for SB3+4yo and CB, 33% and 39% were censored, respectively.

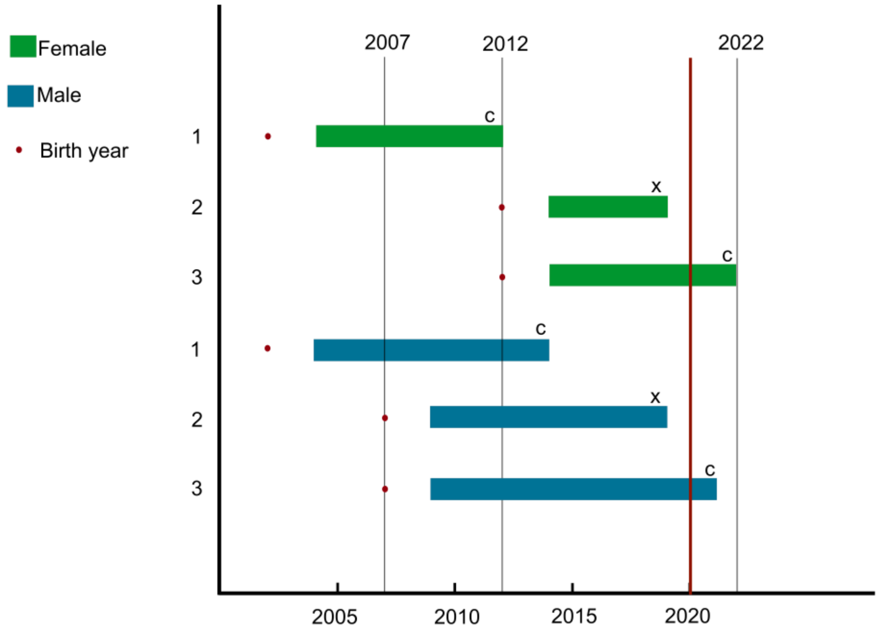

Figure 5. Example of censoring of Standardbred trotters depending on sex, birth year, and age at last race. Horses that raced within two years from 2020-12-18 (indicated by the red line as the cutoff) were treated as right censored. Also, horses racing in the last year of their allowed career were censored. The letter X indicates the end of the career, and C indicates censored.

Cox proportional hazard model

The Cox proportional hazard model (Cox 1972; Therneau & Grambsch 2000) was used to fit the data with the RStudio package Survival from Therneau (2024). The survival time, i.e., career length, was measured in days starting from the first race in the year when the horse was three years old. The effects included in the models were year of birth, sex, started as a 2-year-old or not (SB only), number of starts, early earnings, early earnings^2, inbreeding coefficient, proportion of barefoot races, best racing time, and an interaction of early earnings and early earnings^2 with sex. Inbreeding, best racing time, the two effects of earnings, and the interaction between earnings and sex were included as regressions in the model. The fixed effects were split into different levels depending on the group of horses analysed. In SB3yo, the levels for proportion of barefoot races were: ≤ 0.05, > 0.05 & ≤ 0.15, > 0.15 & ≤ 0.3, > 0.3 & ≤ 0.5, and > 0.5. For SB3+4yo, the first four levels remained the same as for the 3-year-olds, but two levels were added, > 0.5 & ≤ 0.7, and > 0.7. For CB, the proportion of barefoot races for 3- and 4-year-olds was grouped as ≤ 0.05, > 0.05 & ≤ 0.15, > 0.15 & ≤ 0.3, and > 0.3. Year of birth was split into the following groups: 2002–2006, 2007–2010, 2011–2014, or 2015–2018 (2015–2017 for CB). The number of starts were grouped as 5–10, 11–15, or 11–30 for SB3yo, 10–14, 15–20, 21–25, 26–30, or 31–53 for SB3+4yo and 5–10, 11–15, 16–20, or 21–55 for CB.

Survival curves

Survival curves were plotted from the models used in the Cox analysis. The median survival times, i.e., career length, including confidence intervals, were estimated for the different levels of proportion of barefoot races and the first quartile, mean, and third quartile of the inbreeding coefficient (SB only). Median survival time for best racing time per kilometre (seconds over one minute) was estimated for 12 s, 17 s, and 24 s in SB and 25 s, 31 s, and 40 s in CB.

Survival curves were fitted separately for males and females in both breeds. For the different levels of proportion of barefoot races, inbreeding, and best racing time, effects in the model that were included as regressions were set to the mean value for horses in the datasets (SB3yo, SB3+4yo, and CB). The year of birth was set to 2002–2005 for all three datasets to create the survival curves. In both groups of SB, whether they started as a 2-year-old or not was set to not started. The number of races was set to 5–10 in CB and SB3yo and to 10–14 for SB3+4yo. For creating the survival curves for best racing time and inbreeding, the proportion of barefoot races was set to ≤ 0.05 in all datasets.

3.3 Main findings

3.3.1 Genetic background of distance specific traits in Coldblooded trotters (Paper I)

In Paper I, racing time over three distances were studied in CB to analyse whether they can be treated as genetically distinct traits and thereby used in the breeding programmes to potentially promote the use of stallions less related to the population. The heritability for racing time per kilometre in CB over short-, medium-, and long-distance races was estimated in the range of 0.27–0.28. The results showed that the genetic correlations between the three race distances were all approaching one. The genetic correlation between racing time in short- and medium-distance races and medium- and long-distance races was estimated to be 0.99, and that for short- and long-distance races was estimated to be 0.97.

Further, based on estimated breeding values (EBVs) for the three race-distances, co-selection and re-ranking of top 10 and top 30 stallions with best EBV was studied. In Figure 6, the co-selected stallions in top 10 and 30 are shown. Among the top 10 stallions in short, medium, and long distances, four were co-selected. The corresponding number among the top 30 stallions was 19.

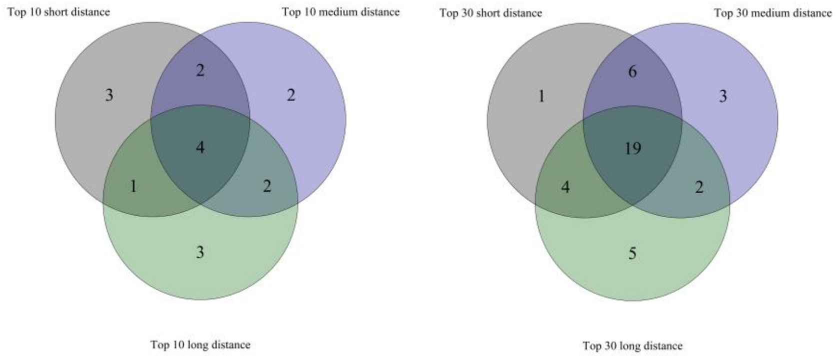

Figure 6. Co-selected stallions in the top ten (left) and top 30 (right) based on estimated breeding values for racing time per kilometre in short-, medium-, and long-distance races.

The Spearman rank correlation between EBVs for all breeding stallions in the data was 0.86 between short- and medium-distance races, and 0.61 between short- and long-distance and medium- and long-distance races.

The relatedness among the two sets of top-ranked stallions was high, and in the magnitude of being half-siblings. For the top 10 stallions in short-, medium-, and long-distance races, the relatedness was estimated in the range 0.31–0.33. The relatedness among stallions in the top 30 was slightly lower, estimated at 0.23–0.24. However, the relatedness to the rest of the population born in the same years (2005–2012) was about 0.17 for all groups compared.

The average inbreeding level for the population based on pedigree information from horses born between 1940 and 2021 is shown in Figure 7. The inbreeding coefficient has steadily increased in the population over the years studied, at a rate of ΔF = 0.012 per generation (0.001 per year). This corresponded to an effective population size (N_e) of 42. For horses born in 2021, the average inbreeding coefficient was estimated at 0.083.

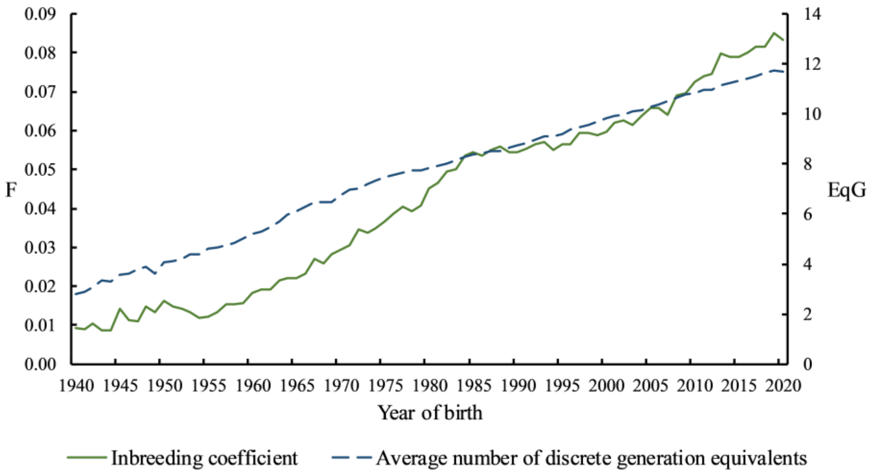

Figure 7. The inbreeding coefficient (F) for Swedish-Norwegian Coldblooded trotters born from 1940 to 2021 and the number of discrete generations (EqG).

3.3.2 The genetic background of the ability to race barefoot (Paper II)

Proportion of barefoot races

In Paper II, novel traits reflecting the ability to race barefoot in SB and CB were defined, and the genetic contribution to these traits was studied. The average proportion of barefoot races for horses aged 3 to 10 years, using definition I, was 0.29 for SB and 0.10 for CB. For trait definition II, which only included horses that had raced barefoot, the average proportion of barefoot races was 0.34 for SB and 0.20 for CB. The proportion of barefoot races increased somewhat over the birth years for both breeds. However, for SB, the increase was larger than for CB (from 0.27 to 0.31 and from 0.28 to 0.35, in trait I and trait II, respectively, compared with from 0.08 to 0.09 and from 0.12 to 0.19 in CB for the same traits). In SB, the main effect of sex was not significant, but for CB, males had a significantly higher proportion of barefoot races than females.

In Table 3, estimated variance components and heritability are shown. The heritability for proportion of barefoot races I was estimated at 0.28 for SB and at 0.17 for CB. For the proportion of barefoot races II with only barefoot racers, the heritability was estimated at 0.23 for SB and 0.25 for CB. Accuracies for EBVs for breeding stallions born from 1992 to 2013 in SB were 0.84 for trait I and 0.87 for trait II. In CB, the accuracies of the EBVs for breeding stallions born from 1992 to 2011 for traits I and II were estimated to be 0.74 and 0.75, respectively.

Barefoot status

A third trait definition, barefoot status, which was a binary trait where racing barefoot hind and barefoot or shod in front was registered for each race. Repeated measurements made it possible to correct for factors pointed out as important for racing barefoot or not in a race. The influence of the trainer was partly dealt with by excluding horses trained by trainers who only raced with shod horses. This was done not to let horses that, on principle, always were raced shod influence the analyses. By doing this, approximately one-third of the trainers of SB and two-thirds of the trainers of CB were excluded. This led to the removal of 3% of the data in SB and 18% in CB.

In Figure 8 and Figure 9, the effects of age, race level (prize money), year, and season on the probability of racing barefoot are shown for SB and CB, respectively. In both SB and CB, the probability of racing barefoot increased with age and prize money in the race, especially for SB, where the probability of racing barefoot was more than 50% for races in the two groups with the highest prize money. In CB, the probability of racing barefoot was generally low, and for horses racing in the two groups with the highest prize money, the probability was still only about 10% to 13%. Summer seasons had the highest probability of barefoot racing in both breeds. Over the years studied, the probability of racing barefoot has been fluctuating in SB, while for CB it has remained at a relatively stable level.

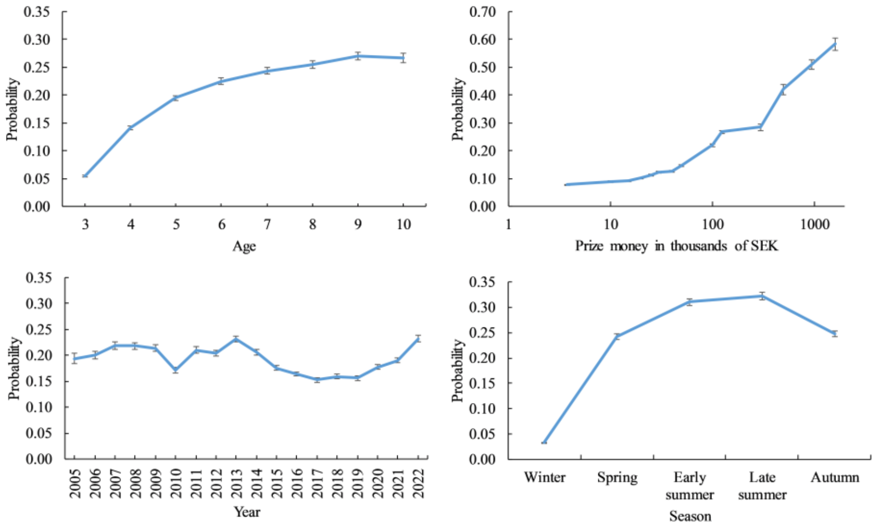

Figure 8. The probability of racing barefoot in Standardbred trotters for different levels for the effect of age, prize money (race level), year, and season.

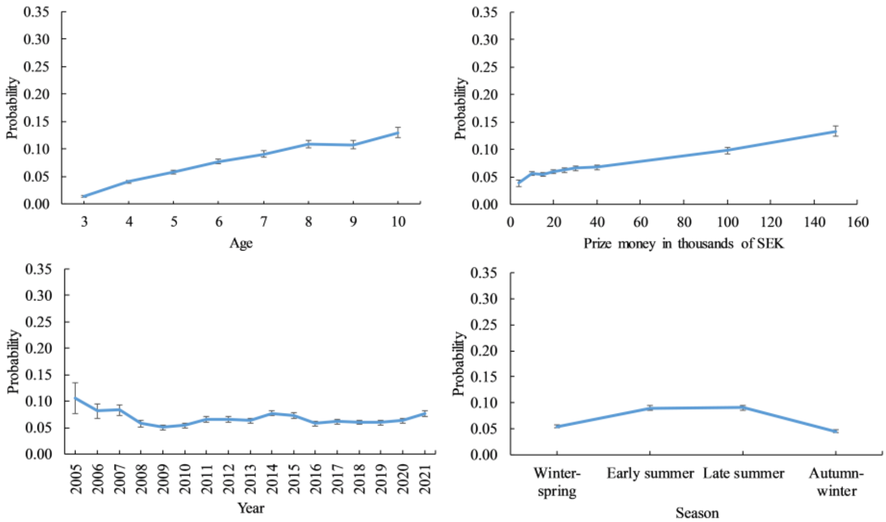

Figure 9. The probability of racing barefoot in Coldblooded trotters for different levels for the effect of age, prize money (race level), year, and season.

For the other factors in the model (results not shown), there were similar trends in both breeds: a higher probability of racing barefoot in races with start method auto-start, in shorter race distances, and if the trainer was professional. In SB, mares had a higher probability of racing barefoot than males, but for CB, males had a higher probability.

Variance components, heritability, and repeatability for barefoot status are shown in Table 3. The mean heritability for barefoot status was 0.08 in SB and 0.07 in CB, on the underlying (liability) scale. The EBVs for SB breeding stallions born 1992–2013 and CB breeding stallions born 1992–2011 had a mean accuracy of 0.79 and 0.67, respectively. The variance explained by the trainer was lower than the additive genetic effect and the permanent environment effect.

In SB, the Pearson correlation coefficient between the proportion of barefoot races (I and II) and barefoot status was 0.63 and 0.64, while the Spearman rank correlation was 0.60 for both traits. In CB, the correlations were stronger than for SB, and the Pearson correlation coefficient was 0.82 and 0.76, while the Spearman rank correlation was 0.77 and 0.67, for trait I and trait II, respectively.

Table 3. Estimates of variance components, heritability, and repeatability for the proportion of barefoot races I, II, and barefoot status for Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB) [a]

Breed	Trait	σ_s^2	σ_a^2	σ_t^2	σ_p^2	σ_e^2	h^2	r
SB	Prop. barefoot races I		$0.020_{0.002}$			$0.050_{0.001}$	$0.284_{0.020}$	
	Prop. barefoot races II		$0.011_{0.001}$			$0.039_{0.001}$	$0.225_{0.020}$	
	Barefoot status	$0.830_{0.155}$	$0.135_{0.011}$	$0.316_{0.010}$	$0.523_{0.011}$	$1.000_{0.002}$	$0.081_{0.008}$	0.397
CB	Prop. barefoot races I		$0.005_{0.001}$			$0.024_{0.001}$	$0.171_{0.038}$	
	Prop. barefoot races II		$0.0001_{0.00003}$			$0.0003_{0.00002}$	$0.254_{0.064}$	
	Barefoot status	$0.007_{0.003}$	$0.112_{0.043}$	$0.266_{0.024}$	$0.576_{0.040}$	$1.000_{0.006}$	$0.066_{0.026}$	0.407

[a] Posterior means for year season (σ_s^2), additive genetic (σ_a^2), trainer (σ_t^2), permanent environment (σ_p^2) and residual (σ_e^2) variance with heritability (h^2) and repeatability (r). Standard deviations and posterior standard deviations are shown as subscripts.

3.3.3 Genetic correlations between the ability to race barefoot and performance (Paper III)

The ability to race barefoot was shown to be partly explained by genetic causes in the population of SB and CB with low to moderate heritability estimates (Paper III). The traits barefoot status and proportion of barefoot races I that included all horses (barefoot racers as well as horses always racing shod) were further studied with regard to their genetic correlation to performance to understand how selecting for the ability to race barefoot would influence the horses' performance.

Most horses that had an observation for proportion of barefoot races and barefoot status also had performance data (99% in SB and 97% in CB). However, more horses had performance data than information about barefoot starts, resulting in 21% and 22% of SB that had performance data also having data for the proportion of barefoot races and barefoot status, respectively. In CB, 24% and 20% of the horses with performance data had data for the proportion of barefoot races and barefoot status, respectively.

Table 4 shows the genetic and residual correlations between the barefoot traits (proportion of barefoot races and barefoot status) and performance traits. Favourable correlations, i.e., negative correlation between best racing time per kilometre and positive correlation to the rest of the performance traits, were estimated for all trait combinations except for placings in SB (r_g: -0.01 ± 0.034). The residual correlations had the same direction as the genetic except for placings in SB (r_e: 0.20 ± 0.012). In both SB and CB, the genetic correlations were generally stronger between the proportion trait and performance than those for barefoot status and performance. In SB and CB, the proportion of barefoot races had the strongest correlation to best racing time (0.50 and 0.62, respectively). For barefoot status, the strongest correlation was found with the number of starts in SB (0.63) and again with the best racing time in CB (0.59).

Table 4. Genetic (r_g) and residual (r_e) correlations between proportion of barefoot races (Proportion), barefoot status (Status), and performance in Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB). Standard errors are shown as subscripts

		$\mathbf{r_g}$		$\mathbf{r_e}$
Breed	Performance trait	Proportion	Status	Proportion
SB	Best racing time	-0.50 $_{0.032}$	-0.38 $_{0.028}$	-0.28 $_{0.011}$
	Earnings	0.49 $_{0.032}$	0.37 $_{0.031}$	0.34 $_{0.011}$
	Earnings per start	0.42 $_{0.035}$	0.11 $_{0.030}$	0.28 $_{0.012}$
	Placings	0.47 $_{0.035}$	-0.01 $_{0.034}$	0.19 $_{0..012}$
	Number of starts	0.43 $_{0.042}$	0.63 $_{0.031}$	0.20 $_{0.012}$
CB	Best racing time	-0.62 $_{0.089}$	-0.59 $_{0.093}$	-0.18 $_{0.028}$
	Earnings	0.52 $_{0.098}$	0.50 $_{0.097}$	0.15 $_{0.026}$
	Placings	0.41 $_{0.105}$	0.26 $_{0.120}$	0.03 $_{0.029}$

Mean EBVs per year of birth for the proportion of barefoot races and barefoot status were extracted from the bivariate models (estimated with best racing time per kilometre) for SB and CB (Figure 10). For the proportion of barefoot races, an increase in mean EBV in the populations was seen for both breeds. In both SB and CB, this corresponded to an improvement of 0.04 genetic standard deviations per year (0.42 genetic standard deviations per generation in SB and 0.47 in CB).

For barefoot status, a negligible genetic gain was seen in SB (0.005 genetic standard deviations per year and 0.06 per generation); for CB, a somewhat larger genetic gain was seen (0.03 genetic standard deviations per year and 0.34 per generation).

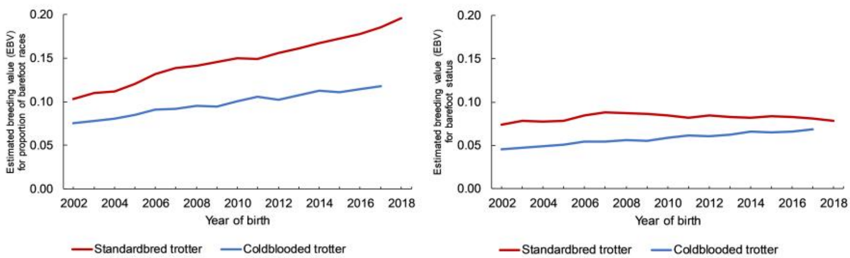

Figure 10. Genetic trends for proportion of barefoot races and barefoot status in Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters.

3.3.4 The effect on racing longevity when racing barefoot as young (Paper IV)

Standardbred trotters

The possible effect on the career length was studied for the following factors for SB: year of birth, sex, started as a 2-year-old or not, number of starts as young, early earnings, inbreeding, proportion of barefoot races as young, and best racing time as young. The factors that were shown to increase the probability of ending the career were those with a coefficient above zero and, correspondingly, a hazard ratio (HR) above one. For SB3yo, the HR increased with a higher proportion of barefoot races. Compared to the reference group that raced 5% barefoot or less, the HR increased to 1.14 for the two groups of horses racing more than 30% barefoot. Also, for SB3+4yo, the results showed a significant increase in HR for higher proportion of barefoot races. In Figure 11, survival curves for three levels of proportion of barefoot races are shown for SB3yo (< 0.5, > 0.15 & ≤ 0.3, and > 0.5). In males, with a median career length of 1501 days in the reference group, racing more than 50% barefoot led to a reduced career length by 123 days (Table 5). In females, where the median career length was 1030 days in the reference group, horses that raced more than 50% barefoot had a reduced career length by 83 days. Also for SB3+4yo the pattern was similar with a reduction in career length by 130 days in males and 75 days in females in the groups racing more than 70% barefoot compared to those racing 5% barefoot or less (results not shown).

For SB3yo, having a higher inbreeding coefficient was shown to increase the hazard with an HR of 1.02, i.e., for each percentage unit increase in inbreeding, the hazard ratio increased by 2%. This was also significant for SB 3+4yo, however, the HR was 1.01. Being born in more recent years and starting in many races were favourable for the career length with an HR<1 in SB3yo. This also applied for the SB3+4yo. Being a male, having higher early earnings, and the interaction between sex and earnings were significant for SB3yo with an HR<1, but not in the dataset for SB3+4yo.

Starting the career as a 2-year-old was not significant for the career length in SB3yo but significant for the dataset SB3+4yo. Best racing time did not have any effect on the career length in any of the datasets studied for SB.

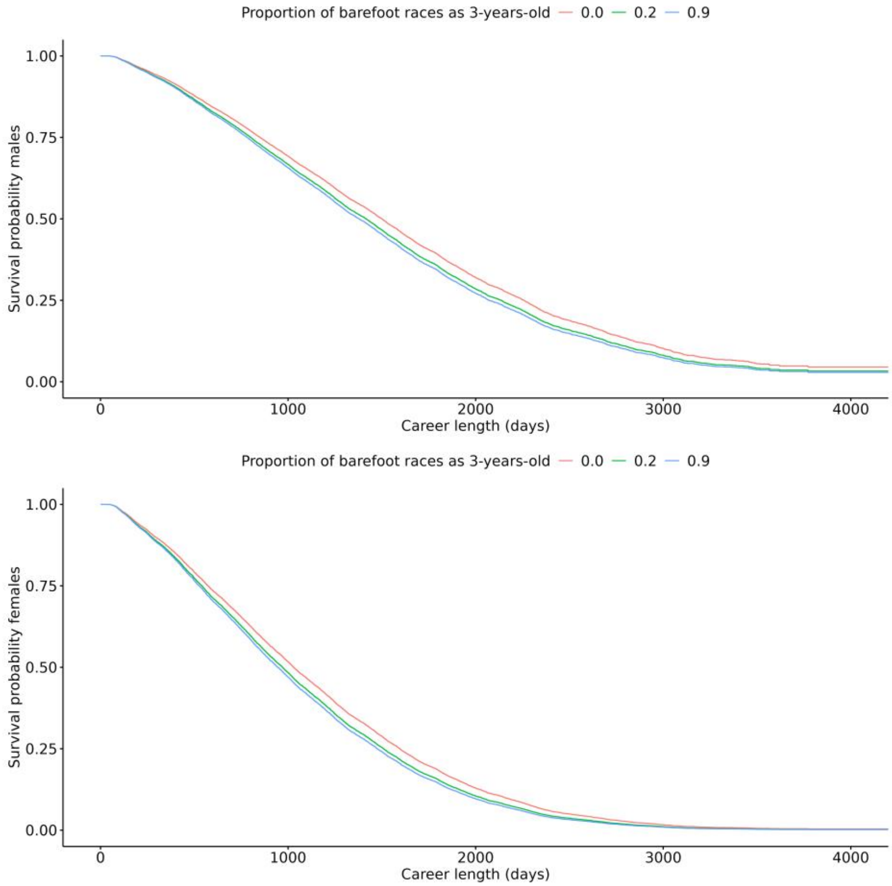

Figure 11. Survival curves for three levels of proportion of barefoot races (≤ 0.05, > 0.15 & ≤ 0.3, and > 0.5, displayed as the mean value per group in 3-year-old Standardbred trotter. Upper figure: males, lower figure: females.

Table 5. Median survival time, difference in days, upper and lower CI for Swedish Standardbred trotters racing five races or more as 3-year-olds for different levels of proportion of barefoot races, where the first level is the reference

Sex	**Level**	**Median survival time (days)**	**Diff days +/-**	**Lower CI 95%**	**Upper CI 95%**
Male	≤ 0.05	1501		1411	1601
	> 0.05 & ≤ 0.15	1429	-72	1317	1539
	> 0.15 & ≤ 0.3	1415	-86	1308	1524
	> 0.3 & ≤ 0.5	1381	-120	1283	1497
	> 0.5	1378	-123	1282	1490
Female	≤ 0.05	1030		968	1111
	> 0.05 & ≤ 0.15	979	-51	904	1060
	> 0.15 & ≤ 0.3	971	-59	898	1049
	> 0.3 & ≤ 0.5	947	-83	879	1026

Coldblooded trotters

A higher proportion of barefoot races, as well as a slower best racing time, when young were both associated with a significantly shorter racing career in CB. Most CB (74%) raced 5% or less barefoot as 3- and 4-year-olds, and only 67 horses were racing more than 30% barefoot. For horses racing more than 30% barefoot, the HR was estimated to be 1.67. In Table 6, the median career length for each level of proportion of barefoot races is shown for CB. The median career length for males in the reference group, racing 5% barefoot or less, was 1688 days. Racing more than 30% barefoot reduced the career length by 523 days in males. The median career length for females in the reference group racing 5% or less barefoot was 1094 days. Racing more than 30% barefoot shortened the career length by 316 days. Survival curves for CB for three levels of proportion of barefoot races (≤ 0.05, > 0.15 & ≤ 0.3, and > 0.3) are shown in Figure 12.

As previously seen in SB, the HR was shown to decrease in more recent birth years, where the group of horses born from 2015 to 2017 had an HR of 0.22 compared to the group of horses born from 2002 to 2006. Also, a higher number of starts as 3- and 4-year-olds was shown to decrease the HR. Horses racing in the group with 20–55 races had an HR of 0.59 compared to the reference group, which included horses racing 5–10 races. For the best racing time per kilometre in the format of seconds over one minute, the HR was 1.12, which means that for every second slower the horse races, the hazard of ending the career increases by 12%.

Factors that were not shown to be significant for the career length in CB were sex, early earnings, and the interaction between sex and early earnings.

Table 6. Median survival time, difference in days, upper and lower CI for Swedish Coldblooded trotters racing 5 races or more as 3- and 4-years-old for different levels of proportion of barefoot races where the first level is the reference

Sex	**Level**	**Median survival time (days)**	**Diff days +/-**	**Lower CI 95%**	**Upper CI 95%**
Male	≤ 0.05	1688		1350	2500
	> 0.05 & ≤ 0.15	1466	-222	1119	2225
	> 0.15 & ≤ 0.3	1464	-224	1102	2285
	> 0.3	1165	-523	855	1932
Female	≤ 0.05	1094		843	1650
	> 0.05 & ≤ 0.15	941	-153	711	1502
	> 0.15 & ≤ 0.3	927	-167	700	1542
	> 0.3	778	-316	547	1309

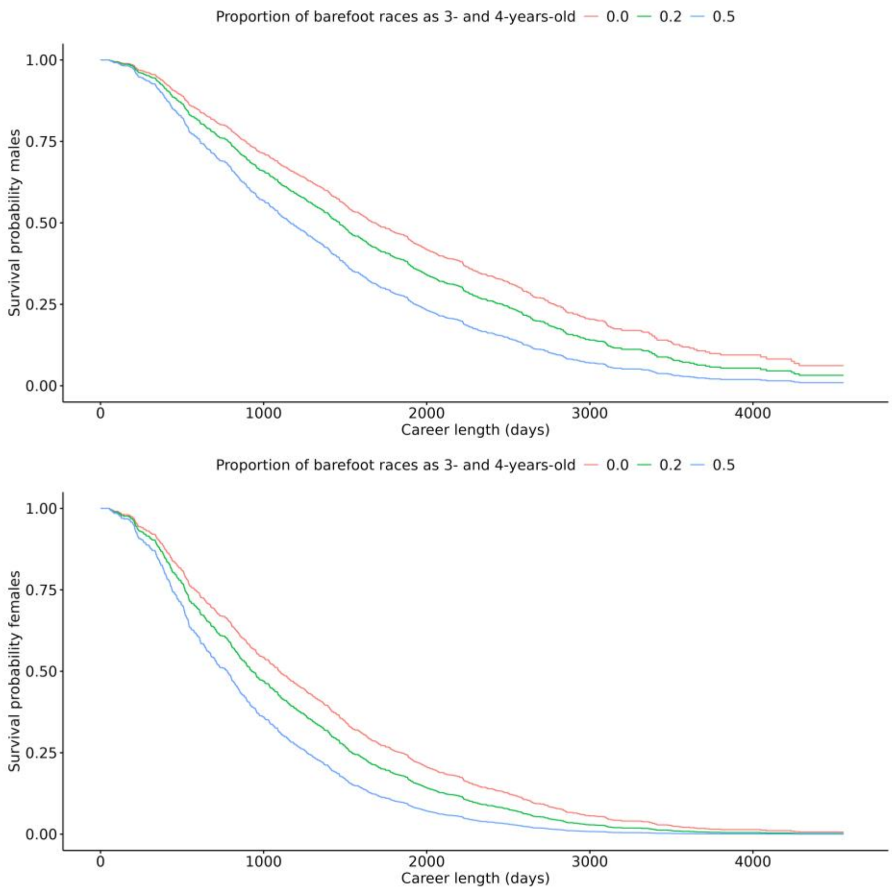

Figure 12. Survival curves for three levels of proportion of barefoot races (≤ 0.05, > 0.15 & ≤ 0.3, and > 0.3), displayed as the mean value per group in 3- and 4-year-old Coldblooded trotters. Upper figure: males, lower figure: females.

4. General discussion

The breeding programmes for Swedish trotters have, since the early 1990s, been performed with linear animal models using pedigree data and have resulted in great genetic progress in performance traits (Árnason & Vleck 2000). In SB, a population that originally consisted of horses imported mainly from the US, but also from France, the annual genetic progress for racing performance from 2001 to 2011 is estimated to be 6.2% of the phenotypic standard deviation (Árnason 2011). When the paper by Árnason (2001) was published, the best racing time achieved in SB 3- to 5-year-old was 1 min and 10.1 s per kilometre (performed by a stallion born in 1993). Currently, the Swedish record in horses aged 3 to 5 is 1 min and 8.8 s per kilometre held by a gelding born in 2018 (Svensk Travsport 2025i).

In CB, the annual genetic progress in racing performance from 2001 to 2011 corresponds to 3.5% of the phenotypic standard deviation (Árnason 2011). The current record for racing time in 3- to 6-year-old CB is from 2005 when Järvsöfaks finished with the time 1 min and 17.9 s per kilometre (Svensk Travsport 2025i). The intense selection for racing performance in SB and CB has clearly resulted in improved performance, but alongside this, it has made the effect of inbreeding depression on performance less apparent, although it exists (Klemetsdal 1998; Árnason 2006; Samsonstuen *et al.* 2020).

4.1 Inbreeding

4.1.1 Current status and the role of individual breeders

In Paper I, the effective population size in CB was estimated to be 42 and the inbreeding rate to be 1.2% per generation. The recommendation from FAO is an effective population size of 50 as a minimum and correspondingly, an inbreeding rate of max 1% per generation. Both SB and CB have significantly higher inbreeding levels in the populations compared to, e.g., the Swedish Warmblood riding horse, which is also intensively selected for sports performance, where the inbreeding level has been estimated to about 1% in the population based on genomic information (Ablondi *et al.* 2019). In Paper IV where the inbreeding levels were estimated for inclusion as an effect in the model for career length, data including all horses born in 2021 showed an inbreeding level of 8.8% and 8.3% for SB and CB, respectively. However, in Paper I, the focus was on CB, which is a small population that requires extra caution to avoid mating closely related individuals. The studbook of CB is closed, which does not allow for influx of new genetic material as is possible for SB. The merging of the Norwegian and Swedish breeding programmes in 2000 did not lead to the use of more stallions less related to the population. Olsen and Klemetsdal (2020) showed that when clustering horses born in 2013 based on the contribution of sires, the group with the lowest average relationship coefficient to the rest of the population (range 0.10 to 0.13) had Pelle Babs (a Swedish horse) as the most influential stallion. The group with the second lowest average relationship to the rest of the population (range 0.11 to 0.14) had the Swedish stallion Idenors Tindex as the most influential stallion. For all horses born in 2013, 0.5% and 1.6% were clustered in their groups, respectively.

Although multiple studies have come up with feasible strategies to limit the increase of inbreeding in the population in CB, e.g., OCS, as suggested by Olsen *et al.* (2013), and the use of clusters in the population as suggested by Olsen and Klemetsdal (2020), the actual use of this in practice is up to the trotting associations, among others. Individual breeders are those that should be convinced to use less popular sires, which may decrease the chance of selling the offspring at a reasonable price to get by financially. The domination of a few popular sires in breeding, and likewise, a rapid reduction in the number of covered mares, makes it urgent to stimulate a different direction of breeding decisions, and also to encourage mare owners and stallion keepers to continue breeding CB.

4.1.2 Other strategies to reduce and monitor inbreeding

Examples from other populations with high inbreeding levels

In Friesian horses, that similarly to CB, have an effective population size below the recommended value, and also an inbreeding rate > 1% per generation, strategies that have been shown to be the most efficient in reducing the inbreeding rate were mean kinship selection and stratified mating quotas (Steensma *et al.* 2024). In CB, mating quotas have been reduced over the years, and economic rewards to breeders for producing an offspring with an expected inbreeding coefficient below 3.4% are two current strategies to reduce the inbreeding level. Also, CB stallions that do not fulfil the required performance in sports, but have a rare pedigree, can by exception get approved as breeding stallions. Putting further restrictions on the number of offspring per sire based on their mean kinship to the rest of the population, or only allow stallions with lower kinship than the average as Steensma *et al.* (2024) found to be effective in Friesian horses, might, however, not be well accepted by CB stallion owners.

To the best of our knowledge, the increased relationship between individuals of CB has not led to any severe genetic disorders such as those reported in Friesian horses, e.g., dwarfism (Leegwater *et al.* 2016) and hydrocephalus, "water head" (Ducro *et al.* 2015). However, it should be noted that there are signs of inbreeding depression also in CB (Dolvik & Klemetsdal 1994; Klemetsdal 1998). In Paper IV, the inbreeding level for CB did not show any significant effect on the career length. However, it would be interesting to include more data in such an analysis in the future, since the strict data editing performed in Paper IV, only allowed for horses with shoeing data and at least five races as 3- and 4-year-olds to be included. For SB, with up to 13,922 horses (compared to 1392 in CB), inbreeding had a negative effect on the career length with an HR > 1, which is also in line with results from Árnason (2006).

The possibility of using genomic data to estimate inbreeding

Inclusion of genomic data to estimate the effect of inbreeding on career length would also be of interest because the inbreeding level based on pedigree information and genomic information in CB has previously been shown to differ (Velie *et al.* 2019b). The benefit of using genomic data is that it would give more accurate information, not being influenced by possible faults made in the pedigree before 1964 when parentage verification became mandatory in Swedish trotters. The actual probability of full-sibs inheriting the same allele from a heterozygous parent is not exactly 50% (Visscher *et al.* 2006). Therefore, when using pedigree data to estimate inbreeding levels, it can influence the degree of homozygosity for an individual, and may give an underestimation of inbreeding coefficients and the effect of inbreeding depression (Nishio *et al.* 2023). In neither CB nor SB, are genotype data routinely collected at present, and large-scale studies of genomic datasets would require extensive sample collection. With a planned transition to Single-Nucleotide Polymorphism (SNP) -array based parentage verification of horses in Sweden in the near future, this may change, however.

4.2 Inclusion of new traits to broaden the breeding goal in Swedish-Norwegian Coldblooded trotters

4.2.1 Distance-specific traits

Paper I did not show that distance-specific performance could promote stallions that were less related to the population. This, together with the fact that the genetic correlation between short-, medium- and long-distance races was very strong, and the high relatedness among top-ranked stallions (although some re-ranking did occur) implies that it would not help to decrease the inbreeding rate in the population. In Thoroughbred racing, having horses that are specialized in short- (sprinter), medium- (miler) and long-distance (stayer) races is a well-known approach, and genomic studies have shown that genomic differences between the horses in the MSTN gene (that affects muscle growth) are linked to their best racing distance (Hill *et al.* 2010). The genetic correlation between the best racing time for distance-specific performance was in Thoroughbreds strong between short- (1000 m – 1400 m) and medium-distance (1600 m – 2400 m), and between medium- and long-distance (2800 m – 4000 m), estimated at 0.87 and 0.84, respectively, while that between short- and long-distance was 0.47 (Sharman & Wilson 2023). Compared to trotting races in Sweden, the distances (1640 m, 2140 m, and 2640 m) are in a much narrower span. Genomic studies of CB showed that the MSTN allele with the highest frequency was the "stayer" allele, indicating that the current race distances are linked to endurance rather than sprint performance, but no significant association to performance was found (Velie *et al.* 2018a). As the trotting races are constructed today, with the traditional distances at 1640 m, 2140 m, and 2640 m, adding a shorter race distance, i.e., sprint race, or a longer race distance does not seem reasonable to implement.

In CB that has a closed studbook and only compete against each other, with the exception of when they occasionally compete in the same races as the Finnish trotter (Finnhorse), a strict selection for improved speed from a breed perspective, might be questionable, because it only makes the whole population race faster. From the individual owner's perspective, breeding a horse that runs fast and is competitive in races is still of high interest.

4.2.2 Temperament traits in the breeding programmes of Swedish-Norwegian Coldblooded trotters

Another trait complex that might be of interest in the search for traits that could broaden the breeding goal for the CB might be temperament-related traits. It has been suggested by people in the industry that some horses have a difficult in temperament when driving and it was suggested that it could be linked to the sire of these horses. In the breeding plan, the temperament of the breed is described as energetic, willing to cooperate, and lively (Svensk Travsport & Det Norske Travselskap 2019). Subjective measurements of temperament in horses using questionnaires aimed at owners have previously shown that a factor accounting for traits such as excitability and being speedy was unique for CB and did not show up for any other native Norwegian horse breeds studied (Olsen & Klemetsdal 2017). Also in SB, a factor including the trait excitability, but also factors linked to anxiousness (including fearfulness and loose self-control) and agreeableness (including learning, cooperation, and will to win) have been formed using questionnaires aimed at trainers (Berglund *et al.* 2025). These factors were shown to be heritable at 0.13 to 0.50, with a favourable genetic correlation to performance traits, i.e., low excitability and, especially, anxiousness, and higher agreeableness were linked to a higher number of starts, earnings, placings, and faster racing time. How large-scale objective temperament assessments of horses would be performed in CB would have to be solved, if the inclusion of temperament traits were to be considered.

4.3 The ability to race barefoot

4.3.1 Potential for inclusion in the genetic evaluations

A trait already routinely recorded in both SB and CB is the shoeing condition of the horses at competitions. Having horses that have hooves that can tolerate racing barefoot is of high value due to its link to improved speed (Solé *et al.* 2020). Defining a trait that would quantify the horses' ability to repeatedly race barefoot would therefore not only indirectly help to possibly improve hoof quality, but also to balance the gait as previously suggested by Solé *et al.* (2020), and could therefore be of importance for animal welfare, performance, and economy.

The two traits defined in Paper II, which were further analysed in relation to performance in Paper III, were the proportion of barefoot races and barefoot status. Because the proportion trait was a summarised trait over years, the only effects that could be corrected for were those constant across these years, i.e., sex and year of birth. Barefoot status, a binary trait with repeated observations, had the advantage of the possibility to correct for environmental factors (race level, trainer, year, etc.). Both traits were shown to be heritable, although the proportion trait had a heritability that in Paper II was estimated at 0.28 in SB and 0.17 in CB, while barefoot status (using a threshold model) was estimated at 0.08 and 0.07 in SB and CB, respectively. Also, the accuracies for the estimated breeding values were moderate to high for breeding stallions for both traits in SB and CB (with mean values in the range of 0.67–0.87).

In Paper III, variance components and the heritability for both traits were estimated using linear bivariate models. Here, the heritability for the proportion of barefoot races was similar to study II, while for barefoot status, the heritability differed more between Paper II and Paper III. The heritability is known to differ depending on what scale it is estimated on; this has also been shown by Carlén *et al.* (2006) and Kadarmideen *et al.* (2000) for production traits in dairy cattle, where the heritability was greater on the liability scale than the observable scale. This is also in accordance with the results from Papers II and III.

One might expect faster progress in the trait if threshold models were applied (greater heritability), still, it is more time demanding to run such a model and for practical reasons less attractive because the genetic evaluation in SB and CB is performed using linear models today (also for the binary trait start status). When it comes to the EBVs for barefoot status, one would expect a strong correlation between those obtained from the threshold model and those from the linear model, as Carlén *et al.* (2006) found correlations estimated at 0.99 for mastitis in the full lactation period between EBVs in the linear model and the threshold model. Further, the proportion trait is a summarised trait that could easily be included in the multi-trait model used in the genetic evaluation of SB and CB that is already based on summarised performance, such as earnings, best racing time, placings, number of starts (SB only) etc., whereas barefoot status with its repeated observations would require a separate model to correct for all the effects.

In Paper III, the genetic correlations estimated between the barefoot traits and performance in SB and CB were favourable (except for placings and barefoot status, where the correlation was close to zero). Somewhat stronger correlations were seen between the proportion of barefoot races and performance than for barefoot status and performance. Further, the genetic improvement was greater for the proportion of barefoot races than barefoot status in both breeds, which suggests that the trait is more closely linked to performance. The small genetic improvement in barefoot status seen in CB but not SB indicates that the trait, to some extent, is linked to performance in CB.

4.3.2 The biological relevance of the ability to race barefoot

Genetics behind the ability to have a balanced trot at high speed

Although the barefoot traits studied are indirect measurements of biological attributes of SB and CB, from the results obtained from the studies II, III, and IV, together with the relatively few published papers on the subject, one might speculate on the biological background of the traits. The Swedish-Norwegian Coldblooded trotter is known as the less good natural trotter among the two breeds, although it is claimed by the trainers that CB has improved its trotting technique thanks to the intense selection of good trotters in the breeding programme over the years (Svensk Travsport 2023a). One indication of this could be the genetic improvement for barefoot status found for CB but not SB. Also, the probability of racing barefoot was found to increase with age in both SB and CB in Paper II. Leleu *et al.* (2004) found that with age, the Standardbred trotter has shown improved technique with longer strides and more symmetrical movement. Also, Kallerud *et al.* (2021) found that in young SB defined as sound, locomotor asymmetries are common.

In SB, genomic studies have revealed that a mutation in the *Doublesex and mab-3 related transcription factor 3* (*DMRT3*) gene (from the wild-type C to A) helps to coordinate and keep trot without breaking over to gallop (Andersson *et al*. 2012). While the frequency of the beneficial A allele in SB has remained close to 100% in the period 1950-2010, the corresponding value in CB was 30% over the same period, where the A allele was found to be important for earnings, best racing time, placings and start status but had no effect on disqualification frequency (i.e. gallop) (Jäderkvist *et al.* 2014).

However, Jäderkvist Fegraeus *et al.* (2017) found that when instead using the number of disqualifications (i.e., due to gallop), CA horses had significantly fewer disqualifications than CC horses. In contrast, no significant difference was found between AA and CC horses. The authors speculated that AA horses might have an increased risk of pacing (not allowed), but also found that CC horses had better performance later in life than AA horses, which could be why the A allele is not fixed in the breed. However, the fact that genetic variation exists within both SB and CB for the proportion of barefoot races and also barefoot status, indicates that the traits are not linked to *DMRT3*, which is fixed in the population of SB. Recently, Sigurðardóttir *et al.* (2025) found evidence that other genes, such as *Reelin* (*RELN)* and *Staufen double-stranded RNA binding protein 2* (*STAU2*) (genes that are linked to coordination and learning), might interact with *DMRT3* and, hence, are also important for gait quality in Icelandic horses. The results implied that not only *DMRT3* plays an important role in the coordination and quality of the gaits in horses.

Further, the balance of the hoof itself requires a skilled trainer and farrier, who together work to optimise performance regarding the shape, mass, and moisture in the hoof wall (Bras & Morrison 2021). Racing shod or barefoot is known to have an impact on the hoof as well as the limb in the stance face (when the hoof is in contact with the ground) (Roepstorff *et al.* 1999).

Hoof quality

No hoof, no horse is a common saying that emphasizes the hooves' major role in equine welfare and the ability to perform in sports. For trotting horses, having hooves that are durable is a prerequisite for racing barefoot at competitions. In studies II-IV, barefoot was defined as barefoot hind hooves based on the results obtained by Solé *et al.* (2020), where it was shown that the risk of gallop and disqualification remained low while performance was still improved when the horse raced shod hind. The same authors further explained that this is in line with the general perception of trainers, who claim that the hind hooves are the limiting factor for being a barefoot racer.

The higher frequency of barefoot racing in shorter race distances in SB and CB found in Paper II might be related to less wear of the hooves, while the longer races might require more durable hooves that tolerate the increased wear and tear, and therefore fewer trainers choose to race barefoot in long-distance races. In Finnish Standardbreds, the reaction to applying pressure with a tool on the sole and heel of the hooves after trotting races was found to be greater among horses that also had galloped in the race, compared to those who did not gallop when racing barefoot (Hytönen 2024). In the same study, data from races during the summer season (where barefoot racing is allowed) showed that 0.2% of the horses examined had worn down their hooves to the degree where blood was found. These results may indicate that sore hooves could contribute to breaking over to gallop and thereby get disqualified in trotting races.

Individual differences in the ability to race barefoot in SB have also previously been linked to chemical properties of the hoof, such as concentration of arginine and copper, suggesting that there could be genetic differences between horses in terms of hoof quality (Spörndly-Nees *et al.* 2023).

4.3.3 Durability of trotting horses

Having horses that are durable and can perform over many years is of interest to owners, trainers, and the industry in general. As the number of SB and CB born per year is decreasing, it lies in the interest of the Swedish Trotting Association that the horses start in more races and have longer racing careers to fill out the available spots in the arranged races. Also, for the so-called social license to operate, it is important that trotting horses are healthy and that the sport itself does not interfere with the expected life length or harm the horses. In Paper IV, the effect of barefoot racing in young SB and CB on the career length was studied. This is a first step towards understanding the impact of repeatedly racing without shoes at an early age on racing durability, a topic that is currently debated in the industry but has lacked scientific studies to base regulations on.

The results from Paper IV showed that a higher proportion of barefoot races at a young age was associated with a shorter career length. Although the results were consistent across breeds and the two groups of SB, the exact reason why the horses ended their career is unknown. While the results show that a higher number of races at a young age was associated with a longer career, it suggests that the trainers can adapt the amount of training and competing of young horses so as not to have a negative effect on the durability of the horses. The most common health problem in SB reported by veterinarians and trainers is orthopaedic diseases; however, in Sweden, trotters are rarely insured to cover sport-related injuries, and large-scale statistics on trotters' health status from insurance companies cannot be obtained (Holmquist 2023). In Swedish Warmblood riding horses, where over 50% of the population is insured by the same company, the type of orthopaedic injuries has been shown to differ between horses that actively compete and those who do not, although the overall risk of orthopaedic diseases did not differ between the groups (Bonow *et al.* 2025).

The results for CB, showing a drastic decrease in durability when racing a large proportion of the races unshod as a young horse, must be interpreted with caution, especially owing to the few horses analysed (1392 horses compared with up to 13,922 horses in SB). If it is true that barefoot racing in younger ages has a more negative impact on the career length in CB than in SB, one could possibly look for culling reasons in horses of coldblooded type versus warmblooded type. The main culling reasons for coldblooded horses in the Swedish Cavalry born in the 1970s were shown to be temperamental problems (23% in coldbloods vs 3% in warmbloods), musculoskeletal (14% in coldbloods and 56% in warmbloods) and hoof problems (8% in coldbloods and 3% in warmbloods). However, it should be noted that these horses were not trotters, although the coldbloods in the study could possibly be North Swedish horses that belonged to the same studbook as CB, less than a generation earlier.

In Finland, the trotters are allowed to start racing barefoot at age 3 (Standardbreds) and 4 (Finnhorse).The reason for this breed difference is unknown to us and there are no published studies supporting the difference in regulations between the two breeds (The European Trotting Union 2025). However, from the results in Paper IV, one could argue that it is reasonable that the regulations should differ between SB and CB in Sweden as well.

5. Conclusions

- Racing time at short-, medium-, and long-distance races was found not to be genetically distinct traits in CB
- Some re-ranking was found among the top-ranked stallions between the three race distances, but their average relationship was close to being half-siblings
- The high inbreeding rate in CB is still a concern for the future of this breed and actions to promote stallions that are less related to the population are recommended
- The ability to race barefoot, defined as proportion of barefoot races and barefoot status was low to moderately heritable in SB and CB with moderate accuracies for breeding stallions
- The genetic correlation between the two barefoot traits and performance was favourable and including one of the traits in the genetic evaluation of SB and CB would be possible
- A higher proportion of barefoot races as a young horse was associated with a shorter career length, mainly for CB but also to a smaller extent for SB

6. Future research

The investigation in this PhD-project of the genetic background of distance-specific performance and ability to race barefoot in trotters are, to the best of my knowledge, the first of their kind. Although racing time is a common trait to include in the breeding programmes for racehorses in general (Thiruvenkadan *et al.* 2009a; Thiruvenkadan *et al.* 2009b), treating it as separate traits depending on the distance, has previously only been studied in Thoroughbred racehorses (Williamson & Beilharz 1998; Sharman & Wilson 2023). In Paper I, it was concluded that racing time can be treated as one trait over the most common distances raced in CB. However, the inbreeding level in the population is still increasing, and finding methods to promote sires that are less related to the population that will be accepted and used by the breeders is important for the future of this local breed. Others have previously suggested methods that have proven to work well to reduce inbreeding levels in a small population (Meuwissen 1997; Olsen *et al.* 2013; Steensma *et al.* 2024), that would also be feasible to implement in CB.

One could also study the potential of including temperament traits, i.e., mental qualities, in the breeding programme because they are known to be important for performance and have been shown to be heritable in SB (Berglund *et al.* 2025). Also, in genomic studies, candidate genes important for performance and learning abilities have been found in CB (Velie *et al.* 2018b).

Including traits in the breeding goal in the future that are related to health and durability is in line with the increased focus on career longevity and improving animal welfare, to justify the use of horses for sports. The ability to race barefoot is in this thesis an indirect measurement of a biological trait of interest that one could speculate is linked to hoof durability, because not all horses have hooves that can tolerate racing barefoot. Utilizing information that is already routinely collected at racetracks over many years including hundreds of thousands of horses such as the shoeing condition is of great value when previous studies of hoof traits in most cases includes very few horses.

The proportion of barefoot races and barefoot status showed potential for inclusion in the genetic evaluations of Swedish trotters; however, the results from the survival analysis indicated that barefoot racing in young horses could have a negative effect on the durability of the horses. Therefore, including traits in the genetic evaluation of Swedish trotters that indicate the capability to withstand wear and tear of the hooves, could be of interest to increase the race durability of the horses. The increased number of controls of racehorses after finishing the races that started in 2024 could, in the future, help to analyse the direct effect of barefoot racing on the hoof status (Svensk Travsport 2023c). However, if barefoot racing becomes banned, it will no longer be possible to include the barefoot traits studied in this thesis in the genetic evaluation of trotters in Sweden. A more in-depth mapping of why horses end their career, i.e., voluntary for breeding or involuntary due to, e.g., injuries, may also increase the knowledge on why having a higher proportion of barefoot races when young increases the hazard ratio.

In the future, the genetic evaluation of trotters in Sweden will most likely undergo a switch to genomic breeding values. The transition from parentage verification that is currently performed using microsatellites in horses, over to SNPs is already in progress in, e.g., German Warmblood riding horses (Nolte *et al.* 2022). Especially for traits where the heritability is generally low, one could see the benefit of using genomic breeding values (Muir 2007), for example, in traits linked to fertility and diseases (Stock & Reents 2013). Accuracies have also been shown to be higher for genomic breeding values compared to those from traditional EBVs (Haberland *et al.* 2012).

Also, the use of genomic relationship data could aid in breeding decisions that will maintain the genetic diversity in regions where two copies of recessive alleles are known to cause genetic disorders (Engelsma *et al.* 2011). Especially for CB where mare owners today are concerned about that they cannot find unrelated stallions to breed with.

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Popular science summary

Harness racing in Sweden has a long tradition and the first racetracks were built in the early 20th century. The sport has become a part of Swedish culture, and today, Sweden ranks among the top three nations for harness racing in the world.

Traditionally, the domestic Swedish-Norwegian Coldblooded trotter was used by farmers for multiple purposes, but since the 1950s, the breed has mainly been used for harness racing. The use of a few extremely popular sires has resulted in an increased relationship between individuals, which today is one of the major concerns in this breed. Most trotters in Sweden are, however, of the Standardbred type. The Swedish Standardbred trotter, which competes in races separated from the Coldblooded trotters, originates from the importation of mainly American Standardbreds but also French trotters. Although improved racing performance is the main objective in the breeding programme for both Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters, there is an interest in including new traits related to health and durability. The overall aim of this thesis was to study new traits to analyse the potential of including them in the breeding programme for Swedish trotters.

Can genetics tell us which horse is best at what distance?

In Sweden, trotting horses most commonly race over short- (1640 m), medium- (2140 m), and long-distance (2640 m) races. In Thoroughbred racehorses, it has previously been shown that some horses perform better at short- and some at long-distance, which is linked to genetic differences between the horses. If this would be true also for the Swedish-Norwegian Coldblooded trotter, it could potentially help to promote the use of sires that are less related to the rest of the population and help to decrease the high inbreeding levels in the breed.

However, results showed that for Swedish-Norwegian Coldblooded trotters, the distance the horses performed best in (as in fastest racing time per kilometre) was not linked to genetic differences between the horses. Although the top-ranked stallions for the three distances differed somewhat, their relationship to the rest of the population was similar between distances.

Other possibilities to improve the breeding programmes in terms of health and durability in Swedish trotters

Today, performance in trotting races such as racing time, earnings, number of placings etc., is of greatest value when deciding on what horses should be bred and contribute to the next generation of trotters. However, in the breeding goal for Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters, the importance of breeding healthy and durable trotting horses is also mentioned.

No hoof, no horse is a common saying that points to the importance of having functional and durable hooves to be able to last and perform in equine sports. In Swedish trotting races, as in many other countries, racing barefoot (i.e., without shoes) is a common strategy to make the horse race faster. However, it has been shown that taking off the protective shoe might cause wear and tear of the hoof, imbalance in gaits, and an increased risk of breaking over to gallop (not allowed and might lead to disqualification). Hence, racing barefoot poses a risk of violating animal welfare at competitions. If the ability to race barefoot varies among trotters, due to genetic differences between the horses, it would be possible through breeding practices to improve the ability to race barefoot and indirectly traits that are possibly connected to this, such as hoof durability and balance.

Better hoof, better horse

Two traits were defined to reflect the ability to race barefoot in Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters. The first trait, proportion of barefoot races, was a summarised trait that measured the relative frequency of barefoot races among horses that were between 3 and 10 years old. The second trait, barefoot status, indicated if the horse raced barefoot or not for each race event, making it possible to correct for factors such as the age, trainer of the horse, prize money in the race, racetrack, and condition of the track, to mention some.

Results showed that variation among the horses in proportion of barefoot races and barefoot status could, to a low to moderate degree, be explained by genetic differences between the horses. It was also shown that if one of these traits were included in the breeding programme for Swedish trotters, it would also have a positive effect on performance. This means that it would be possible to breed for the ability to race barefoot while also improving performance.

Barefoot racing in young trotters had an effect on the career length

We found that a higher proportion of barefoot races as a young horse was associated with a shorter career length for both Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters.

The results of this thesis showed that it would be feasible to include a trait reflecting the ability to race barefoot in the breeding programme of Swedish trotters. However, more studies to investigate the possible link between the amount of barefoot racing as a young horse, and the reason for ending the career are recommended.

Populärvetenskaplig sammanfattning

Travsport har en lång tradition i Sverige och de första travbanorna byggdes under tidigt 1900-tal. Sedan dess har travsporten blivit en del av svensk kultur och idag är Sverige rankat som den tredje största travnationen i världen.

Traditionellt sett så användes den inhemska svensk-norska kallblodstravaren av lantbrukare för olika syften men sedan 1950-talet så används rasen framförallt i travsport. Användandet av ett litet antal populära hingstar har resulterat i ett högt släktskap mellan individer, vilket idag är ett av de största bekymren inom rasen. De flesta travhästar i Sverige är dock av varmblodstyp. Den svenska varmblodstravaren som tävlar i separata lopp från kallblodstravaren härstammar från import av amerikanska varmblodstravare men också franska travhästar. Även om förbättrad prestation är huvudmålet med avelsprogrammen för varmblodstravare och kallblodstravare så finns det ett intresse av att inkludera nya egenskaper kopplade till hälsa och hållbarhet. Det övergripande målet för denna avhandling var att studera nya egenskaper för att analysera potentialen att inkludera dem i avelsprogrammen för svenska travhästar.

Kan genetiken säga oss vilken häst som är bäst på vilken distans?

I Sverige tävlar travhästar framför allt över kort distans (1640 m), medeldistans (2140 m) och lång distans (2640 m). Hos engelska fullblod är det sedan tidigare känt att vissa hästar presterar bättre på korta och andra på långa distanser är kopplat till genetiska skillnader mellan hästarna. Om detta skulle stämma även för kallblodstravare kunde det potentiellt främja användningen av hingstar som är mindre besläktade till populationen och hjälpa till att minska de höga inavelsnivåerna.

Resultaten visade dock att för kallblodstravare så var vilken distans hästarna presterade bäst i (sett i kilometertid) inte kopplat till genetiska skillnader mellan hästarna. Även om de topprankade hingstarna för de tre distanserna skilde sig något, så var deras släktskap till den övriga populationen liknande mellan distanserna.

Andra möjligheter att förbättra avelsprogrammen sett till hälsa och hållbarhet hos svenska travhästar

Idag är prestation sett till kilometertid, prissumma, andel placeringar etc. av stort värde vid urvalet av vilka hästar som ska användas i avel och därmed får bidra till nästa generation travhästar. I avelsmålet för svenska travhästar nämns också vikten av att producera hälsosamma och hållbara travhästar. Ingen hov, ingen häst är ett vanligt ordspråk som pekar på vikten av att ha funktionella och hållbara hovar för att prestera inom hästsporten. I svenska travlopp, såväl som i andra länder, är det vanligt att tävla barfota (dvs. utan skor) för att få hästen att springa snabbare. Dock har det tidigare visats att om skon tas av kan hoven utsättas för ett stort slitage, skapa obalans i trav samt öka risken för galopp (vilket inte är tillåtet och kan leda till diskvalificering). Därför kan barfotatävlande potentiellt äventyra djurvälfärden vid travtävlingar. Om förmågan att tävla barfota hos travhästar varierar på grund av genetiska skillnader mellan hästarna, skulle det vara möjligt att genom avel förbättra förmågan att tävla barfota och indirekt egenskaper potentiellt kopplade till detta såsom hovkvalitet och balans.

Bättre hov, bättre häst

Två egenskaper definierades för att reflektera förmågan att tävla barfota hos svenska varmblodstravare och svensk-norska kallblodstravare. Den första egenskapen, andel barfotalopp, var en summerad egenskap som mätte den relativa frekvensen av barfotalopp för hästar mellan 3 och 10 års ålder. Den andra egenskapen, barfota-status, indikerade om hästen tävlade barfota eller inte för varje lopp, vilket gjorde det möjligt att korrigera för faktorer som hästens ålder, tränare, prissumman i loppet, vilken bana samt banförhållande, för att nämna några. Resultaten visade att variationen mellan hästarna i andel barfotalopp samt barfota-status kunde till en låg till medelhög grad förklaras av genetiska skillnader mellan hästarna. Vidare visade sig båda dessa egenskaper vara fördelaktiga för prestation ifall de skulle inkluderas i avelsprogrammet. Detta innebär att det skulle vara möjligt att avla för förmåga att tävla barfota och samtidigt förbättra prestation.

Barfotatävlande hos unga travhästar påverkade karriärlängden

Vi fann att en högre andel barfotalopp som ung var kopplat till en kortare karriärlängd för varmblodstravare såväl som kallblodstravare.

Resultaten i denna avhandling visar att det skulle vara fullt möjligt att inkludera en egenskap som beskriver förmågan att tävla barfota, i avelsprogrammet för svenska travhästar. Fler studier för att undersöka den potentiella kopplingen mellan att tävla barfota som ung och anledningen till att hästar avslutar sina tävlingskarriärer rekommenderas.

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ORIGINAL ARTICLE

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Should performance at different race lengths be treated as genetically distinct traits in Coldblooded trotters?

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Abstract

Speed, in the form of racing time per kilometre (km), is a performance trait of the Swedish–Norwegian Coldblooded trotter included in the joint Swedish–Norwegian genetic evaluation. A few popular stallions have dominated Coldblooded trotter breeding, which has led to an increasing average relationship between individuals in the population. This study investigated the scope for broadening the breeding goal by selecting for racing time per km over different race lengths (short: 1640 m, medium: 2140 m and long: 2640 m), as this could encourage the use of breeding sires that are less related to the population. Performance data on three- to 12-year-old Coldblooded trotters in all Swedish races run 1995–2021 were obtained from the Swedish Trotting Association. These data consisted of 46,356 observations for 8375 horses in short-distance races, 430,512 observations for 11,193 horses in medium-distance races and 11,006 observations for 3341 horses in long-distance races. Variance components and genetic correlations were calculated using a trivariate animal model with Gibbs sampling from the BLUPF90 suite of programs. Breeding values for the three traits were then estimated using univariate animal models with the same fixed and random effects as in the trivariate model. Heritability estimates of 0.27–0.28 and genetic correlations between racing time per km at the different distances of 0.97–0.99 were obtained. Despite the strong genetic correlation between the traits, there was some re-ranking among the top 10 and top 30 stallions based on distance-specific breeding values. Estimated rank correlation between breeding values for racing time per km in short- and medium-distance races was 0.86, while between short- and long-distance races and between medium- and long-distance races it was 0.61. Mean relationship within the top 10 and top 30 stallions based on breeding values for racing time per km at each distance was 0.31–0.33 and 0.23–0.24 while mean relationship to the rest of the population ranged from 0.17 to 0.18 for all groups, although the 10 and 30 top-ranking stallions differed somewhat in the traits. Estimated average increase in inbreeding was 0.1% per year of birth and 1.2% per generation. The strong genetic correlation between racing time per km at different distances did not support their use as genetically distinct traits. Re-ranking of stallions for racing time per km at different race lengths could favour the use of a larger number of stallions in breeding, but according to our results it would not promote the use of stallions that are less related to the total population. Other traits like longevity or health traits, for example, career length and orthopaedic status, may be more relevant in broadening the breeding goal and preventing a few sires dominating future breeding, and this would be interesting to study further.

KEYWORDS

genetic correlation, performance, race length, re-ranking, speed

1 | INTRODUCTION

The Coldblooded trotter, an indigenous horse breed in Sweden and Norway, has been bred for harness racing over many decades. The Swedish Coldblooded trotter was granted its own studbook in 1964, when the breed officially split from the North Swedish horse. The Norwegian Coldblooded trotter originates from the native Norwegian Dole horse (Bjørnstad & Røed, 2001), which is believed to be closely related to the North Swedish horse, and has had its own studbook since 1939 (FAO, 2023). Since 2000, there has been a joint breeding programme for Coldblooded trotters in the two countries and a large overlap and exchange of breeding animals. Today, there are about 10,000 Coldblooded trotters in Sweden (personal communication Olsson, 2023) and 15,300 in Norway (Norsk Hestesenter, 2022).

Effective population size for the breed, including both Swedish and Norwegian horses, is estimated to be 50 when including horses born until 2013 (Olsen & Klemetsdal, 2020). A downward trend in number of mares covered each year has occurred in both countries. In Norway, 1359 mares were covered in 2007 (Norsk Hestesenter, 2010), but only 792 in 2020 (Norsk Hestesenter, 2021). In Sweden, 684 mares were covered in 2007 (HNS, 2012) and 654 in 2020 (HNS, 2021).

Genetic evaluation of Coldblooded trotters is mainly based on performance in harness racing from 3 to 6 years of age (Svensk Travsport, 2023a). The traits contributing information in the current statistical model for estimation of breeding values (EBVs) are best annual racing time per km (average time per km taken for an individual to complete the race), summarized earnings, percentage of races with first or second place and racing status (whether the horse has completed at least one race as a 3- to 6-year-old).

The small number of popular stallions used for breeding has resulted in an increasing relationship and inbreeding in the population, for example, Klemetsdal (1998) reported significant negative correlations between earnings and inbreeding level in the population. Increased inbreeding level has also been associated with lower fertility in Coldblooded trotter mares (Klemetsdal & Johnson, 1989) and increased risk of bilateral carpal joint arthritis (Dolvik & Klemetsdal, 1994).

Olsen and Klemetsdal (2020) showed that the use of a few popular stallions in Sweden and Norway has contributed to a genetic bottleneck in the population of Coldblooded trotters. According to Olsen et al. (2013), optimal contribution selection (Meuwissen, 1997) could be a useful tool to prevent further increases in inbreeding in the Coldblooded trotter and overuse of a few stallions, but this has so far not been implemented. It is crucial for breeders to produce horses that are attractive to buyers. Choosing a stallion that is less popular may lead to unsold or underpriced horses. To avoid overuse of individual stallions, annual breeding quotas are in place and were reduced in 2021, from a maximum of 80 to 70 mares covered in Sweden and from a maximum of 30 to 25 mares covered in Norway for Swedish stallions, and vice versa for Norwegian stallions (Svensk Travsport, 2021). However, further limitations in the number of mares covered may have economic consequences for owners and keepers of breeding stallions. A system guiding mare owners to select stallions from a different family cluster within the breed has been suggested as a solution to maintain genetic variation (Olsen & Klemetsdal, 2020). Other than the costs of setting up such as system, as pointed out by Olsen and Klemetsdal (2020), this would require mare owners to recognize the value of choosing a stallion that is less related to the population rather than choosing the stallion based on performance only.

It has not yet been determined whether the genetic evaluation model from 1994 could be revised in such a way that it favours the use of a greater number of less closely related stallions, to keep the genetic variation from declining and to reduce the inbreeding rate. In Sweden, trotters compete in short-, medium- and long-distance races, most commonly 1640, 2140 and 2640 m, respectively. If performance measured as racing time per km for different race lengths are genetically distinct traits, and selection for performance at different race lengths favours different stallions, then one option would be to select for performance depending on race length. Dividing the trait racing time per km for different race distances into different traits could potentially distinguish between sprinters and stayers, which could broaden the breeding goal and enable selection of more stallions that are less closely related to each other and to the rest of the population. There are no previous studies on Coldblooded trotters, or trotting horses in general, investigating this issue.

The aim of this study was therefore to estimate genetic parameters and EBVs for racing time per km for Coldblooded trotters in short-, medium- and long-distance races, and to analyse the potential re-ranking of breeding sires based on their EBVs for racing time per km over the different distances. The study also aimed at comparing the average relationship among top-ranked stallions for the three race distances and their relationship with the rest of the population. The outcome of this study would aid in providing useful information for the trotting associations about whether broadening the breeding goal in this way would help to reduce inbreeding and loss of genetic variation in the breed.

2 | MATERIALS AND METHODS

2.1 | Data material

The data used for this study were provided by the Swedish Trotting Association and consisted of racing performance results from Swedish trotting races during the period 1995–2021. All data were on Coldblooded trotters, which compete in separate races from Standardbred trotters. Coldblooded trotters are allowed to race from 3 to 15 years of age, but horses older than 12 years were removed from the dataset owing to few observations for these age groups, so the final dataset covered horses born between 1983 and 2018. Individual records were removed if they were: (a) from ridden Monté races (1.9%), (b) from horses that had been disqualified in that race (11.6%) and (c) three standard deviations or more above the mean value for racing time per km for a given race distance, resulting in 270, 528 and 48 observations removed from short-, medium- and long-distance races, respectively.

Descriptive analysis and data editing were performed with RStudio (R Core Team, 2022). The final dataset consisted of racing results for 4653 mares and 7258 geldings or stallions. These 11,911 unique horses had in total 187,874 observations from races after filtering the data based on the conditions mentioned above (Table 1).

The original pedigree information included 118,239 horses. From this, a pedigree file including seven ancestral generations for each animal in the final dataset was extracted and used for estimation of variance components and breeding values, comprising a total of 23,965 animals. For analyses of relationship within the group of top-ranked stallions per race distance and their relationship to the rest of the contemporary population, a pedigree including seven ancestral generations for all animals born during 2005–2012 was used (including 32,716 animals). For estimation of inbreeding coefficient, the original pedigree file with all available ancestry information was used.

2.2 | Trait definition

The trait studied was racing time per km, defined as the average time per km taken for an individual to complete the race. The value is recorded in four-digit format, for example, 1308 means 1 min, 30 s and 8 tenths of a second. The raw time format was kept in the analyses for easier interpretation of the results for the industry, and because the number of minutes was one for all observations, so it did not make any difference for the analysis if it was changed into seconds or not. The actual start distances stated in race descriptions were used to divide races into the three distance groups, based on definitions used by the Swedish Trotting Association (Svensk Travsport, 2023b). For short-distance races ($N = 46{,}356$), the distance ranged from 1609

TABLE 1 Number of observations (N) per race distance, number of individual horses, mean age of horses, mean and maximum number of starts per horse, mean racing time per km, standard deviation, and minimum and maximum racing time per km.

				No. of starts per horse		Racing time per km[b]			
Race distance[a]	N	Individual horses	Mean age	Mean	Max	Mean	SD	Min	Max
Short	46,356	8375	7	6	69	1308	39	1179	1432
Medium	130,512	11,193	7	12	137	1321	37	1191	1434
Long	11,006	3341	7	3	31	1307	30	1221	1398

[a]Where short-, medium- and long-distance races most commonly are 1640, 2140 and 2640 m, respectively.

[b]Where 1308 refers to 1 min, 30 s and eight tenths of a second.

to 1700 m, for medium-distance races (N = 130,512), it ranged from 2040 to 2300 m and for long-distance races (N = 11,006), it ranged from 2460 to 2760 m.

Descriptive statistics for the three race distances are presented in Table 1. The highest mean racing time per km was found for medium-distance races. According to the data, 7712 of the horses had started in both short- and medium-distance races, 2952 horses had started in both short- and long-distance races, 3262 horses had started in both medium- and long-distance races, and 2928 horses had started in all three race distances. The phenotypic distribution of racing time per km for each distance was similar to a normal distribution (not shown), and therefore their residuals were assumed to be normally distributed and no transformation of the data was required.

2.3 | Estimation of variance components and breeding values

Several models including various fixed and random effects, and interactions between fixed effects, were tested with the HPMIXED procedure in SAS (SAS Institute Inc, 2016). The choice of factors in the final model, presented below, was based on the level of significance of the fixed effects or the proportion of variance explained by the random effects, and whether the model fulfilled the assumption of normally distributed residual errors. The models all included the random effect of horse, trainer and a year–season interaction. Pairwise differences between the levels of each main effect were computed with the LSMEANS statement in SAS and adjusted for multiple comparisons using Tukey's method.

2.3.1 | Description of fixed effects

Most Swedish Coldblooded trotters are located in the northern half of Sweden and the majority of races are held in that area. Therefore, the grouping of race dates into seasons was based on the meteorological length of the seasons in the city of Sundsvall according to the Swedish Meteorological and Hydrological Institute. Winter was defined as lasting from 1 December to 24 March, spring from 25 March to 24 May, summer from 25 May to 24 September and autumn from 25 September to 30 November. The number of observations per season ranged from 1962 to 57,168 (Table 2). In total, races were held on 35 race tracks and for every race, track conditions were noted as a measure of how heavy or light the track surface was for each race, expressed as: easy, somewhat heavy, heavy or winter track. For long-distance races, heavy tracks were grouped with somewhat heavy tracks owing to few observations (72 observations for heavy tracks). Most races were held on easy track conditions (Table 2). The number of observations per track ranged from 2 to 5578 for short-distance races, 3 to 14,614 for medium-distance races and 18 to 1854 for long-distance races. A maximum of 15 horses (15 different positions) can participate in each race, and the range of number of observations per racing position was 11–7415, 124–26,237 and 10–2429 for short-, medium- and long-distance races, respectively. If the horse galloped or not in the race was also registered, although gallop is not allowed, the horse is only disqualified if it: gains position or speed when it gallops, gallops a too long distance (depends on how far from start it happens), gallops repeatedly in the race or cross the finishing line in gallop (Svensk Travsport, 2023c).

Information about the driver and trainer of each horse at the races was also provided in the dataset. There were 1528 individual drivers and 5033 individual trainers in total. The level of the driver and trainer (professional or amateur) was stated for each race. Because of changes in the regulations for amateur and professional drivers and trainers over the years, these data were converted to the current definition of either amateur driver/trainer or professional driver/trainer (Svensk Travsport, 2023d) before analysis of the data (number of observations shown in Table 2).

2.3.2 | Statistical model

A trivariate model including the three traits (i.e. racing time per km values for short-, medium- and long-distance races) was created and used for estimation of variance components. The BLUPF90 suites of programs by Misztal et al. (2014) was used to estimate variance components and heritability values. Gibbs sampling was used to estimate variance components in the Gibbsf90+ program, due to problems with convergence when using REML for this purpose.

The final model used for estimation of variance components was:

$$y = Xb + Z_{ys}ys + Z_t t + Z_a a + Z_{pe}pe + e$$

where y is the vector of the observations (racing time per km) for the three traits; X, Z_{ys}, Z_t, Z_a and Z_{pe} are incidence matrices; vector b includes the fixed effects of sex (mare or gelding/stallion), age (3–12 years), year of the race (1995–2021), season (winter, spring, summer or autumn), country of the horse (registered in Sweden or Norway), gallop during the race (yes or no), track (35 different tracks), track conditions (easy, somewhat heavy, heavy and winter track), starting method (auto-start or circular volt-start), starting position on the track (1–15), driver level (professional or amateur) and trainer level (professional or

TABLE 2 Total number of individual horses and number of observations (in brackets) for each factor (excluding starting position and track) and its level for the three race distances[a].

Factor	Levels	Individual horses (observations)					
		Short-distance		Medium-distance		Long-distance	
Sex	Gelding or stallion	5184	(30,861)	6823	(44,829)	2402	(8665)
	Mare	3191	(15,495)	4370	(85,683)	939	(2341)
Age, years	3	1677	(2852)	3366	(11,217)	47	(52)
	4	2450	(4707)	4690	(18,346)	613	(867)
	5	3042	(6767)	4991	(21,078)	986	(1632)
	6	3115	(7396)	4774	(20,675)	1137	(2055)
	7	2855	(7025)	4.160	(17,933)	1039	(1795)
	8	2419	(6079)	3391	(14,849)	934	(1625)
	9	1848	(4478)	2590	(10,643)	705	(1244)
	10	1410	(3345)	1898	(7682)	492	(849)
	11	921	(2340)	1249	(5015)	334	(536)
	12	586	(1367)	775	(3074)	204	(351)
Season	Winter	3757	(8442)	6061	(25,826)	1376	(2341)
	Spring	4340	(9067)	6820	(24,609)	1286	(1962)
	Summer	6507	(21,108)	9419	(57,168)	2213	(4703)
	Autumn	3892	(7739)	6544	(22,909)	1208	(2000)
Country	Sweden	6558	(41,713)	7883	(117,825)	2818	(10,088)
	Norway	1817	(4643)	3310	(12,687)	523	(918)
Gallop	Yes	5875	(14,869)	8487	(40,201)	1591	(2757)
	No	6924	(31,487)	9946	(90,311)	2834	(8249)
Track conditions	Light track	8039	(40,265)	10,887	(113,082)	3141	(9795)
	Somewhat heavy track	2756	(4148)	5112	(11,359)	742	(915)
	Heavy track	309	(328)	950	(1112)		
	Winter track	967	(1615)	1871	(4959)	237	(296)
Starting method	Auto-start	4414	(13,249)	5352	(20,341)	801	(1278)
	Volt-start	7642	(33,107)	10,865	(11,0171)	3229	(9728)
Driver level	Professional	7158	(37,703)	9487	(105,025)	2853	(9292)
	Amateur	3558	(8653)	6335	(25,487)	1072	(1714)
Trainer level	Professional	3412	(14,911)	4910	(44,009)	1348	(4219)
	Amateur	6144	(31,445)	8360	(86,503)	2299	(6787)

[a]Where short-, medium- and long-distance races most commonly are 1640, 2140 and 2640 m, respectively.

amateur). The numbers of observations and of individual horses for each level of fixed effects included in the trivariate analysis are shown in Table 2. The same effects were included for all three traits; vector ys is the random effect of the year–season interaction; vector t is the random effect of the trainer; vector a is the random effect of the animal; vector pe is the random permanent environmental effect; and vector e is the random residual effect.

The (co)variance for year–season, trainer, animal, permanent environmental and residual error for short- (s), medium- (m) and long-distance (l) races was assumed to be:

$$\mathrm{Var}\begin{bmatrix} ys_s \\ ys_m \\ ys_l \end{bmatrix} = \begin{bmatrix} \sigma^2_{ys_s} & \sigma_{ys_{s,m}} & \sigma_{ys_{s,l}} \\ & \sigma^2_{ys_m} & \sigma_{ys_{m,l}} \\ \text{sym.} & & \sigma^2_{ys_l} \end{bmatrix} \otimes \mathbf{I}_{ys};\ \mathrm{Var}\begin{bmatrix} t_s \\ t_m \\ t_l \end{bmatrix} = \begin{bmatrix} \sigma^2_{t_s} & \sigma_{t_{s,m}} & \sigma_{t_{s,l}} \\ & \sigma^2_{t_m} & \sigma_{t_{m,l}} \\ \text{sym.} & & \sigma^2_{t_l} \end{bmatrix} \otimes \mathbf{I}_{t};$$

$$\mathrm{Var}\begin{bmatrix} a_s \\ a_m \\ a_l \end{bmatrix} = \begin{bmatrix} \sigma^2_{a_s} & \sigma_{a_{s,m}} & \sigma_{a_{s,l}} \\ & \sigma^2_{a_m} & \sigma_{a_{m,l}} \\ \text{sym.} & & \sigma^2_{a_l} \end{bmatrix} \otimes \mathbf{A}_{a};\ \mathrm{Var}\begin{bmatrix} pe_s \\ pe_m \\ pe_l \end{bmatrix} = \begin{bmatrix} \sigma^2_{pe_s} & \sigma_{pe_{s,m}} & \sigma_{pe_{s,l}} \\ & \sigma^2_{pe_m} & \sigma_{pe_{m,l}} \\ \text{sym.} & & \sigma^2_{pe_l} \end{bmatrix} \otimes \mathbf{I}_{pe};$$

$$\mathrm{Var}\begin{bmatrix} e_s \\ e_m \\ e_l \end{bmatrix} = \begin{bmatrix} \sigma^2_{e_s} & 0 & 0 \\ & \sigma^2_{e_m} & 0 \\ \text{sym.} & & \sigma^2_{e_l} \end{bmatrix} \otimes \mathbf{I}_{e}$$

Several runs using different numbers of iterations, burn-in and thinning were analysed before the final parameters were set. In total, 400,000 iterations were run with a burn-in period of 125,000. Every 40th sample drawn was stored, which resulted in 6875 samples being passed to posterior analyses. Post-Gibbs analysis was performed with postgibbsf90 to obtain posterior standard deviation and posterior statistics. Visual inspection of trace plots in RStudio was performed to determine whether the chains had reached convergence.

Heritability estimates (h^2) for racing time per km in short-, medium- and long-distance races were calculated as:

$$h^2 = \frac{\sigma_a^2}{\sigma_t^2 + \sigma_a^2 + \sigma_{pe}^2 + \sigma_e^2}$$

where σ_a^2 is the estimated additive genetic variance, σ_t^2 is the estimated trainer variance, σ_{pe}^2 is the estimated permanent environmental variance and σ_e^2 is the estimated residual variance.

Repeatability (r) for racing time per km in short-, medium- and long-distance races was calculated as:

$$r = \frac{\sigma_a^2 + \sigma_{pe}^2}{\sigma_t^2 + \sigma_a^2 + \sigma_{pe}^2 + \sigma_e^2}$$

Using the variances estimated with the trivariate model, univariate models including the same fixed and random effects were run with Blupf90+ to obtain EBVs with standard error for racing time per km for each race distance.

The accuracy (r_{TI}) of each EBV was calculated as:

$$r_{TI} = \sqrt{1 - \frac{PEV}{\sigma_a^2}}$$

where PEV is prediction error variance for short-, medium- or long-distance races.

2.4 | Rank correlations and proportion co-selected

Spearman's rank correlation ρ was estimated for rank position of breeding stallions based on EBVs for the three distances, using cor.test in RStudio (R Core Team, 2022). Re-ranking of the top 10 and top 30 stallions (born during 2005–2012, with at least one offspring) for the three race distances was then studied. The proportion of co-selected stallions among the top stallions for the three traits was calculated.

2.5 | Relatedness and inbreeding coefficient

Pedigree data were analysed using the CFC software (Sargolzaei et al., 2006). The average pairwise relationship within three groups of stallions born during 2005–2012 and ranked among the top 10 and top 30 on EBVs for the different race distances, together with their relationship to the rest of the population from the same birth year period, was estimated. Calculations of average relationship within and between groups in the CFC software were based on the methods described by Colleau (2002).

Using the full pedigree, individual inbreeding coefficient was estimated for each animal. Horses were grouped based on the year of birth to estimate the average inbreeding per year from 1940 to 2021 and the average number of discrete generation equivalents.

3 | RESULTS

3.1 | Fixed effects and least squares means for fixed effects

The fixed effects included in the final model analysed in SAS were all highly significant ($p < 0.0001$) for racing time per km in the three distances, except for trainer level for medium-distance races ($p = 0.0004$), starting method for long-distance races ($p = 0.0153$) and starting position in long-distance races ($p = 0.1559$). Least squares means (LSM) for each level of the fixed effects sex, season, country, gallop, track conditions, starting method, starting position, driver level and trainer level are shown in Table 3 (LSM for tracks is not shown). Based on the data, males were on average faster than females, the summer season and easy track conditions gave the lowest LSM for racing time per km, and Norwegian horses racing in Sweden were on average faster than Swedish horses. The main improvement in racing time per km with age occurred from age three to six, and thereafter the curve flattened out (Figure 1). The LSM for racing time per km improved by 3.5 s in short-distance races from 1995 to 2021, while in medium- and long-distance races it improved by 4.1 s and 3.6 s, respectively (Figure 2).

3.2 | Estimated variance components, heritability and repeatability

In preliminary analysis of variance, driver and trainer were both included as random effects in the model.

TABLE 3 Least squares mean and standard error (SE) of racing time per km for each level of different fixed effects (age, year and track not included).

Factor	Level	Short-distance[a] Estimate	SE	Medium-distance[a] Estimate	SE	Long-distance[a] Estimate	SE
Sex	Mare	1331	1	1351	1	1336	1
	Gelding or stallion	1321	1	1340	1	1325	1
Season	Winter	1335	1	1354	1	1341	1
	Spring	1328	1	1347	1	1330	1
	Summer	1319	1	1339	1	1324	1
	Autumn	1322	1	1342	1	1328	1
Country	Sweden	1337	1	1356	1	1339	1
	Norway	1315	1	1335	1	1322	1
Gallop	Yes	1332	1	1350	1	1334	1
	No	1319	1	1341	1	1327	1
Track conditions	Easy	1314	1	1333	1	1323	1
	Somewhat heavy	1326	1	1346	1	1338	1
	Heavy	1342	1	1361	1		
	Winter track	1322	1	1342	1	1331	1
Starting method	Auto-start	1321	1	1343	1	1330	1
	Volt-start	1330	1	1348	1	1331	1
Starting position	1	1323	1	1343	1	1328	1
	2	1324	1	1344	1	1329	1
	3	1324	1	1344	1	1329	1
	4	1325	1	1344	1	1330	1
	5	1325	1	1345	1	1330	1
	6	1325	1	1344	1	1330	1
	7	1325	1	1345	1	1330	1
	8	1326	1	1345	1	1329	1
	9	1326	1	1345	1	1330	1
	10	1326	1	1346	1	1330	1
	11	1327	1	1346	1	1330	2
	12	1327	1	1346	1	1330	2
	13	1326	1	1346	1	1333	3
	14	1335	5	1350	2	1336	4
	15	1326	1	1349	1	1332	4
Driver level	Professional	1323	1	1343	1	1328	1
	Amateur	1329	1	1348	1	1333	1
Trainer level	Professional	1324	1	1345	1	1328	1
	Amateur	1328	1	1346	1	1333	1

[a]Where short-, medium- and long-distance races most commonly are 1640, 2140 and 2640 m, respectively.

However, the driver effect did only account for 2% of the total variation explained for racing time per km in all three distances. This was the case both in the preliminary analysis in SAS as well as in the model used for estimation of variance components in Gibbsf90+. In 37% of the observations, the driver and trainer was the same person and the driver effect could therefore be confounded with the trainer effect. Because of this, only trainer was retained in the final model used for estimation of variance components. The estimated variance explained by the random effect of trainer in the final model was lower than the estimated variance of the additive genetic or permanent environment effects (Table 4).

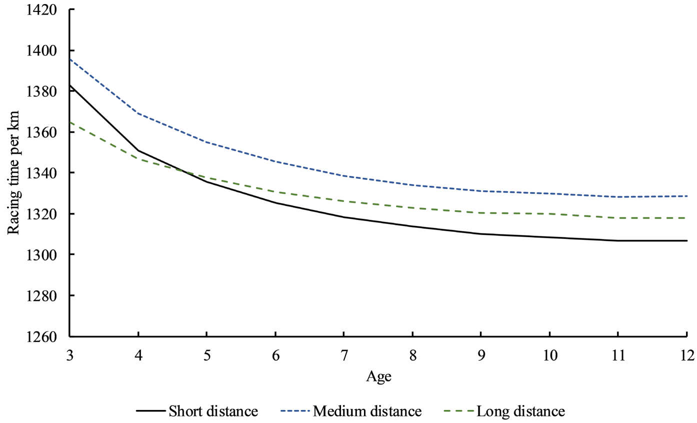

FIGURE 1 Least squares mean of racing time per km in short-, medium- and long-distance races as a function of horse age (years). Racing time per km expressed in four-digit form, where 1380 means 1 min, 38 s and 0 tenths of a second. [Colour figure can be viewed at wileyonlinelibrary.com]

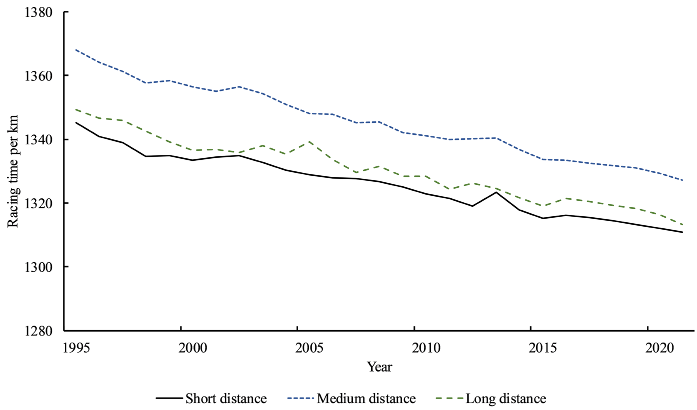

FIGURE 2 Least square mean of racing time per km in short-, medium- and long-distance races as a function of year. Racing time per km expressed in four-digit form, where 1380 means 1 min, 38 s and 0 tenths of a second. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Posterior means for additive genetic (σ^2_a), trainer (σ^2_t), permanent environmental (σ^2_{pe}) and residual (σ^2_e) variance, mean heritability (h^2) from post-Gibbs analysis and repeatability[a] (r) for racing time per km in short-, medium- and long-distance races[b].

Trait (racing time per km)	σ^2_a	σ^2_t	σ^2_{pe}	σ^2_e	h^2	r
Short distance	$285.2_{22.0}$	$117.4_{5.5}$	$384.9_{15.6}$	$250.0_{1.8}$	$0.275_{0.019}$	0.65
Medium distance	$282.7_{20.7}$	$123.5_{5.1}$	$362.1_{13.6}$	$226.5_{0.9}$	$0.284_{0.018}$	0.65
Long distance	$206.9_{16.0}$	$91.1_{6.3}$	$301.4_{12.6}$	$159.4_{2.4}$	$0.273_{0.019}$	0.67

Note: Posterior standard deviations shown as subscripts.

[a]Defined with σ^2_a and σ^2_{pe} in the numerator.

[b]Where short-, medium- and long-distance races most commonly are 1640, 2140 and 2640 m, respectively.

The Post-Gibbs analysis revealed moderate posterior mean heritability (range 0.273–0.284) for racing time per km in short-, medium- and long-distance races (Table 4). Median heritability was the same as the mean for all traits, while the mode ranged in value from 0.269 to 0.283. Posterior distributions of the heritability estimates for the three traits were visually close to normally distributed. The repeatability for the three traits was high and ranged from 0.65 to 0.67 (Table 4).

Estimates of genetic correlations between the traits are shown in Table 5. Mean genetic correlations r_g were very strong (range 0.97–0.99) for racing time per km over the three race distances. Mean correlation for trainer as well as for permanent environment effects were also very

TABLE 5 Posterior mean, standard deviation (SD), 95% posterior standard deviation (PSD) interval, median and mode of genetic correlation (r_g) in racing time per km between short-, medium- and long-distance races[a].

Traits (racing time per km)	Mean	SD	95% PSD interval	Median	Mode
Short–medium distance	0.99	0.002	0.99–1.00	0.99	0.99
Medium–long distance	0.99	0.003	0.99–1.00	0.99	0.99
Short–long distance	0.97	0.009	0.95–0.99	0.97	0.97

[a] Where short-, medium- and long-distance races most commonly are 1640, 2140 and 2640 m, respectively.

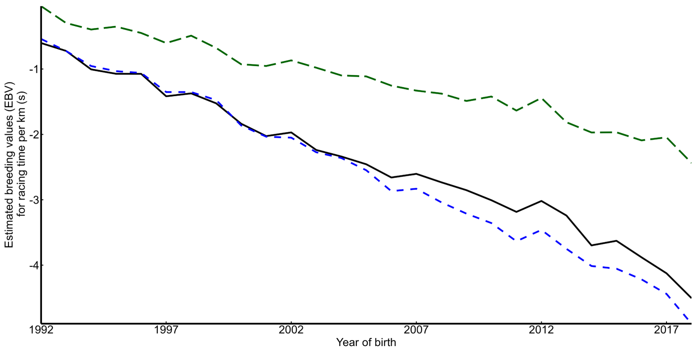

FIGURE 3 Estimated breeding values (EBVs) for racing time per km (transformed to seconds) for short- (black solid line), medium- (blue dashed line) and long-distance races (green longdashed line) for horses born during 1992–2018. [Colour figure can be viewed at wileyonlinelibrary.com]

strong (range 0.98–1.00 and 0.96–0.99, respectively) for racing time per km over the three distances (results not shown).

3.3 | Genetic trends

In short-distance races, the genetic improvement from 1992 to 2018 was −3.9 s per km (Figure 3). For medium-distance races, the genetic improvement during this period was −4.4 s, while for long-distance races it was −2.4 s. This corresponds to an annual change of −0.008, −0.009 and −0.006 genetic standard deviations for racing time per km in short-, medium- and long-distance races, respectively. The improvement per generation would then be −0.09, −0.11 and − 0.06 genetic standard deviations for short-, medium- and long-distance races, respectively.

3.4 | Rank correlation and re-ranking

The rank correlation between EBVs for racing time per km in short- and medium-distance races for all stallions with at least one offspring, without restriction on birth year, was 0.86. The corresponding rank correlation between the EBVs for racing time per km in short- versus long-distance races, and in medium- versus long-distance races, was 0.61 for the same group of stallions.

In total, 64, 70 and 47 stallions (born during 2005–2012 and with at least one offspring) included in the records for short-, medium- and long-distance races, respectively, received EBVs. The number of stallions co-selected among the top 30 for short-, medium- and long-distance races are shown in Figure 4. Of the top 30 stallions for short-distance races, 25 were also in the top 30 for medium-distance races. Of the top 30 stallions for long-distance races, 23 also had an EBV in the top 30 stallions for short-distance races and 21 had an EBV in the top 30 stallions for medium-distance races. Of the seven horses with an EBV in top 30 for short-distance, but not long-distance races, five were excluded from the top 30 for long-distance races because they, or their offspring, had not started in a race of this length. The corresponding number for medium- and long-distance races was 6. The top three stallions were the same in the short- and medium-distance groups, but the best stallion dropped to fifth place in the ranking for long-distance races. The stallion ranked second was the same for the three distance groups. The stallion ranked third for short-and medium-distance races was the top-ranked stallion for long-distance races.

There were four stallions co-selected among the top 10 for racing time per km in the three race distances (Figure 4). Of the top 10 stallions for short-distance races, six were also in the top 10 for medium-distance races. Of the top 10 stallions for long-distance races, five stallions were in the top 10 for short-distance races and six had an EBV among the top 10 for medium-distance races.

Accuracy of EBVs for the top 30 stallions ranged from 0.69 to 0.94 for short-distance races, 0.73 to 0.95 for medium-distance races and 0.54 to 0.90 for long-distance races. For the top 10 stallions, accuracies ranged from 0.73 to 0.94 for short-distance races, 0.72 to 0.95 for medium-distance races and 0.66 to 0.90 for long-distance races.

3.5 | Relatedness

Results from the pedigree structure analysis with all pedigree data included showed that the average family size for full sibling groups was 2.22 (range 2–11). Of the 118,240 horses in the complete pedigree, 106,379 horses had both dam and sire known. The average numerator relationship between stallions born during 2005–2012 with an EBV among the top 10 for racing time per km was 0.31–0.33 and between those among top 30 it was 0.23–0.24, for all three race distances. The relationship between the rest of the population born in the same period and the top-ranked stallions was 0.17–0.18. The average relationship between the top-ranked stallions was higher than within the rest of the population (0.16).

Average inbreeding coefficient (F) in the population of Coldblooded trotters born during 1940–2021, based on the dataset with all pedigree information included, is shown in Figure 5. Average estimated inbreeding coefficient for horses born in 2021 was 0.083. The change in inbreeding per year during the period covered by the data was estimated by regressing ln(1-F) on birth year to 0.001, which gave 0.012 per generation (ΔF) when the generation interval was assumed to be 11.5 years (following Olsen and Klemetsdal (2020)). This corresponded to an effective population size (Ne) of 42.

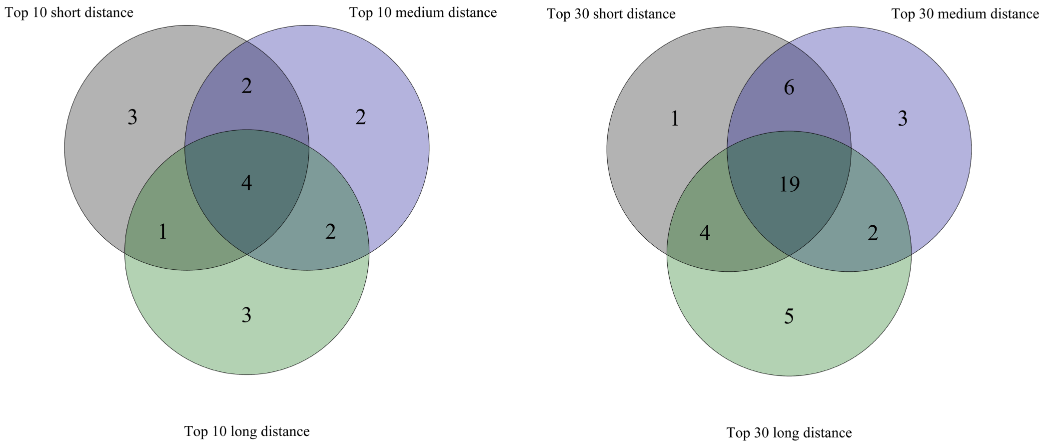

FIGURE 4 Venn diagram representing the number of stallions co-selected in the top 10 (left-hand side) and top 30 (right-hand side) for the trait racing time per km in short-, medium- and long-distance races, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

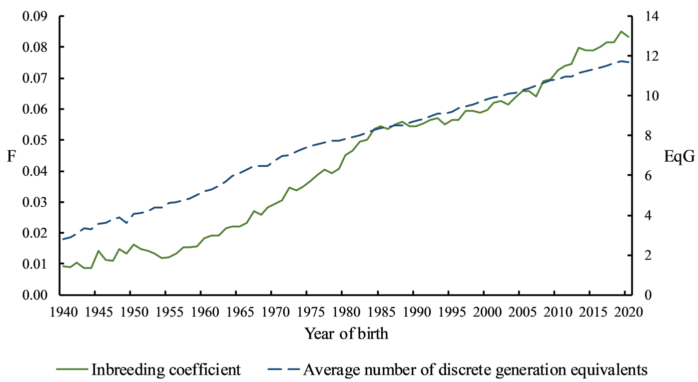

FIGURE 5 Average inbreeding coefficient (F) and average number of discrete generation equivalents (EqG) for Coldblooded trotters born during 1940–2021 including all pedigree information. [Colour figure can be viewed at wileyonlinelibrary.com]

Average number of discrete generations per year of birth for the same period (1940–2021) is also shown in Figure 5. The average number of discrete generation equivalents (EqG) in 2021 was 11.7. For animals born during 2005–2012, the average number of discrete generation equivalents was >10.2 for all year groups when no restriction was placed on number of generations included.

4 | DISCUSSION

4.1 | Genetic parameters for racing time per km in short-, medium- and long-distance races

The estimated heritability (0.27–0.28) of racing time per km in the three race distances was slightly lower than the heritability value of 0.35 used in the current routine genetic evaluation for best annual racing time per km (Árnason, 2021). The discrepancy between lower heritability when dividing the trait into three as in the current study and the heritability used in the genetic evaluation is probably a result of using a repeated records model including all racing data, compared with only the fastest racing time per km per horse. The lower heritability could also be a result of that horses aged 3–12 years were included in the present study, whereas the racing time per km trait used in the official index only includes records for horses aged 3–6 years. Older horses are more influenced by training and management, and can be assumed to be more pre-selected. Moreover, the rather complex model used in this study may have transferred variation explained by the horse to the random trainer effect, resulting in lower additive genetic variance. Finally, the variance components used in the current routine genetic evaluation are not based on the most recent data. The repeatability for the three traits (range 0.65–0.67) was similar to what has been found for racing time per km in Coldblooded trotters previously (0.64–0.65) (Klemetsdal, 1988). In Thoroughbreds, heritability for speed has been estimated to be 0.12 for short-distance (1006–1408 m) and medium-distance (1609–2414 m) races, and 0.07 for long-distance races (2816–4023 m) (Sharman & Wilson, 2023).

4.2 | Genetic correlations and genetic gain

The very strong genetic correlations (0.97–0.99) found between racing time per km in short-, medium- and long-distance races indicate that the traits are not genetically different from each other, and can continue to be treated as one trait. However, it should be noted that the number of stallions receiving EBVs for long-distance races was relatively small, because of the low number of horses competing in this race distance (Table 1). In Thoroughbreds, Sharman and Wilson (2023) also found a very strong genetic correlation between short- and medium-distance races and medium- and long-distance races (0.87 and 0.84, respectively), and a lower genetic correlation (0.47) between short- and long-distance races. It should be noted that the difference in length between short- and long-distance in Swedish trotting races is much less than between short- and long-distance in Thoroughbred races.

The genetic improvement for best annual racing time per km was low until the 1980s, when the first BLUP animal model genetic evaluation of Coldblooded trotters was established (Árnason, 2021). The favourable trend in racing time per km in the early 1990s, as seen in Figure 3, corresponds well with the updated genetic evaluation launched in 1994, when both Norwegian and Swedish Coldblooded trotters were included in a joint evaluation for the first time (Árnason, 2021). The largest genetic improvement in seconds per km over time was seen in short- and medium-distance races (Figure 3). The smaller improvement seen for long-distance races may partly be due to additional pre-selection of the somewhat older horses that start in long-distance races and partly to the focus on results for 3- to 6-year-olds in the official genetic evaluation. The Swedish Trotting Association devotes most of its effort and prize money to short- and medium-distance races, to meet the demand of easier races for younger horses. For 3- and 4-year-olds, the Coldblooded trotter criteria are held and the national derby for these two age groups awards a prize of 500,000 and 700,000 SEK (currently 42,300 and 59,200 EUR), respectively, for the winner over 2140 m of distance (Kallblodsklassikern, 2023). These are the two most prestigious races for a Coldblooded trotter. Interest in competing in long-distance races could probably be increased by distributing more of the prize money to this race length. Another contributing factor could be that the additive genetic standard deviation is roughly 15% lower for racing time per km in long-distance races than for racing time per km over the other two distances.

Even though the best racing time per km is included in the routine genetic evaluation, the total index presented for Coldblooded trotters combines EBVs start status and summarized earnings. The annual absolute change of 0.006–0.009 genetic standard deviations for the three traits analysed in this study is very low, and it should be noted that the generation interval in horses tends to be long. In comparison to the expected genetic gain in dairy cattle (although achieved by genomic selection), the corresponding change per year is 0.467 genetic standard deviations (Schaeffer, 2006). For the trait racing time per km, one should take into consideration the potential limit in how fast the horses can become and that the genetic improvement may slow down with time as shown in Swedish Standardbred trotters by Árnason (2001).

4.3 | Genetics behind best race distance

While the genetic correlations estimated in the present study were close to unity, other studies have shown that different genetic variants can favour performance at different racing distances. In Thoroughbreds, different variants of a single nucleotide polymorphism (g.66493737C>T) in the *myostatin* gene, which is linked to muscle mass, have been shown to be important for racing performance in short- or long-distance races (Hill et al., 2010). Like Coldblooded trotters, Thoroughbreds compete over different race distances, where so-called 'stayers' run >2400 m and 'sprinters' run up to 1400 m (Svensk Galopp, 2023). A study by Hill et al. (2010) found that the T/T genotype was beneficial for stayers and the C/C genotype for sprinters. The C allele has been associated with a smaller proportion of the slow type 1 muscle fibre and larger proportion of the fast and explosive type 2B muscle fibre in the Quarter horse, which is a breed selected for speed over short distances (400 m) (Petersen et al., 2013). However, the frequency of the C allele has been found to be very low in Coldblooded trotters (Velie et al., 2018). In trotting, even short-distance races are relatively long, usually 1640 m in Sweden (Svensk Travsport, 2023b), and it is possible that the same type of muscle fibre is beneficial in all the different race distances.

4.4 | Re-ranking

The results obtained in this study could be used to present EBVs for racing time per km in short-, medium- and long-distance races, which would make it possible for mare owners to choose stallions expected to give good offspring for racing at short and/or long distance. The rank correlation between short- and long-distance races, and between medium- and long-distance races of 0.61, indicates that, despite high genetic correlations, in practice there would be some re-ranking of stallions for racing time per km in long-distance compared with short- and medium-distance races. Selection based on EBVs for racing time per km in long-distance races could possibly promote the use of other stallions than those selected for performance in short- and medium-distance races. However, we found that the same two stallions were ranked in the top three for all three distances. If these were to be even more favoured than at present, due to their superiority for all distances, this could have a negative effect on efforts to promote the use of more stallions.

4.5 | Relatedness

The relationship between stallions with an EBV in the top 10 and top 30 for racing time per km for all three race distances was higher (0.31–0.33 and 0.23–0.24) than the average relationship between animals in the rest of the population (0.16). The fact that the top approved breeding stallions on average had a relationship almost at the level of half siblings is worrying. The trend seen in average inbreeding over the years (Figure 5) was not unexpected. Within the overall period, three time periods (1955–1985, 1985–2005 and 2005–2021) showed slightly different trends, similar to those presented previously by Olsen et al. (2013) and Olsen and Klemetsdal (2020). The average inbreeding coefficient for animals born in 2021 was estimated to be 8.3%, compared with 6.4% for Coldblooded trotters born in 2009 according to Velie, Jäderkvist Fegraeus, et al. (2019). The results in the present study show that the rate of inbreeding is still an ongoing problem. It is important to manage the increase in relatedness and inbreeding to avoid loss of genetic variation within the breed.

4.6 | Potential new traits to broaden the breeding goal

Our results did not provide genetic reasons to justify the inclusion of distance-specific racing time per km in the breeding goal for Coldblooded trotters. However, it would be interesting to study if other traits, for example, affecting health or longevity, may be relevant to consider when broadening the breeding goal to maintain a sustainable Coldblooded trotter population. Starting the career early has been shown to be important for racing longevity in Coldblooded trotters (Velie, Solé, et al., 2019) and in Standardbred trotters (Solé et al., 2017; Tanner et al., 2011). In Standardbred trotters, Ringmark et al. (2016) showed that having a symmetrical locomotion pattern and a good orthopaedic status are important factors for starting the career early. Although, increased training intensity and introduction of new training methods might increase the risk of lameness and asymmetric locomotion (Ringmark et al., 2016). Also, both conformational traits and orthopaedic traits are shown to be of importance for performance such as number of races in Swedish Standardbred trotters (Magnusson & Thafvelin, 1990). The number of horses that compete decreases with age. In the present study, only 775 Coldblooded trotter horses competed in races of medium length at the age of 10, in comparison with 4991 horses competing as 4-year-olds over the same distance (Table 2). It would therefore be interesting to study longevity and its genetic correlations to racing performance traits in the Coldblooded trotter. In Swedish Standardbreds, the number of completed races is included in the genetic evaluation, with a heritability of 0.18 (Árnason, 2021), but this is at present not the case for the Coldblooded trotter. According to Árnason (1999), there is no clear correlation between the number of races and success in other performance traits, such as number of placings, racing time per km or earnings, partly because the very best horses may only compete in a few prestigious races with large prize money.

When discussing health traits, it should be noted that Coldblooded trotter stallions considered for breeding are subjected to a thorough health inspection by two veterinarians and there is a zero-tolerance policy for osteochondrosis and ossification of ungular cartilages (Svensk Travsport, 2023e). Health inspections of young horses have previously been shown to be valuable in general, for example results from palpation and flexion tests on 4-year-olds have been shown to be significant for life length in Swedish Warmblood horses (Wallin et al., 2001).

5 | CONCLUSIONS

In this study, there was some re-ranking of top stallions based on EBVs for racing time per km over different race distances, but the distance-specific traits did not prove to be genetically different from each other. Based on these results, selection based on racing time per km in different race lengths would not promote the use of stallions that are less related to the rest of the population.

AUTHOR CONTRIBUTIONS

All authors contributed to designing the study. S. Andonov, E. Strandberg and S. Eriksson supervised the work. P. Berglund performed the data analyses and drafted the manuscript. All authors read, edited and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Swedish Trotting Association. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the author(s) with the permission of the Swedish Trotting Association.

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RESEARCH ARTICLE

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The ability to race barefoot is a heritable trait in Standardbred and Coldblooded trotters

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Abstract

Background In equine sports, shoes are used to protect the hooves from wear and tear. In Swedish trotting races, pulling off the shoes to race barefoot is popular because it improves racing time. Good hoof quality is essential for high-performance horses, but not all trotting horses have hooves that tolerate barefoot racing. The ability to race barefoot is a complex trait that is known to be influenced by environmental factors, but the genetic basis of this trait has not been studied. The aim of this study was to estimate genetic parameters and correlations between estimated breeding values for three novel traits: two related to the proportion of barefoot races and "barefoot status", a binary trait that reflects the probability of racing unshod in a race, in Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB).

Results For the two traits describing the proportion of barefoot races, single-trait mixed linear animal models were used to estimate variance components for up to 24,958 SB and up to 4050 CB. Estimates of heritability ranged from 0.17 to 0.28. For barefoot status, a binary trait with repeated measurements, 875,056 observations from 25,973 SB, and 93,376 observations from 3384 CB were included. Using a single-trait mixed animal threshold model estimates of heritability for barefoot status were 0.07 and 0.08. The Pearson correlation coefficient between the estimated breeding values for barefoot status and each of the traits describing the proportion of barefoot races for breeding stallions was 0.63 and 0.64 for SB and 0.82 and 0.76 for CB.

Conclusions The traits analyzed reflecting the ability to race barefoot are heritable, with the traits for the proportion of barefoot races showing higher heritability estimates for both breeds than barefoot status. Estimated breeding values for breeding stallions were moderately to strongly correlated for the three traits. The average accuracy of estimated breeding values for breeding stallions was moderate to high for all traits. To breed for the ability to race barefoot, further studies on the genetic correlation of the ability to race barefoot with performance traits and the impact of racing barefoot on career length, are necessary.

Background

"No hoof, no horse" is a well-known saying that pinpoints the importance of good hoof quality for health and performance of horses. In Swedish trotting races, pulling off the shoes to compete barefoot is a common practice to increase the speed of the horse [1]. Racing fully barefoot has been shown to reduce racing time on average by 0.7 s per km in Swedish Standardbred trotters, but also to increase the risk of disqualification and breaking over to gallop [1]. Racing with barefoot hind hooves and

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breaking over to gallop can increase the risk of injuries to the front limbs as a result of interference (i.e. overreaching, brushing, and forging) [2]. However, these results are inconclusive, as a study on Italian Standardbred trotters did not show a significantly elevated risk of retrieving musculoskeletal injuries from racing unshod [3].

Since the end of 2004, information about Swedish trotting horses' shoeing conditions at competitions has been recorded, which is part of the information that bettors receive before the race due to its impact on performance. The Swedish Trotting Association has special regulations regarding barefoot racing, with barefoot racing not being allowed during the winter season nor with 2-year-old horses [4].

There seems to be variation in the ability to race barefoot among Swedish trotters and not all horses have hooves that can tolerate barefoot racing. Previous studies have suggested that the hind hooves are the limiting factor for whether a horse can endure barefoot racing or not [1, 5]. Hence, trainers often choose for the horse to race with barefoot front hooves in combination with shod hind hooves, to increase the speed without elevating the risk of disqualification [1]. Horses that gallop repeatedly, gain position in gallop, gallop a certain distance, or cross the finishing line in gallop are disqualified [4]. Approximately one-third of all starts in Swedish races for 4- to 15-year-old Standardbred trotters were made with fully barefoot horses [6]. The corresponding fraction for fully barefoot Coldblooded trotter starts was one-fourth [6]. Nevertheless, the most common shoeing condition in Swedish trotting races is fully shod. Racing with shoes can also help to balance the gait, especially for Coldblooded trotters, which need the weight of the shoes to trot correctly to a greater extent than Standardbred trotters [6]. It is also possible to race with barefoot hind hooves and shod front hooves, but this is less common [1].

Despite its impact on performance, the genetic background of the ability to race barefoot has not been studied. Traits related to hoof conformation have been shown to be important for performance for several equine sports [7–10] and for longevity for sport horses [7]. Genetic studies on hoof conformation traits have shown estimates of heritability ranging from 0.02 to 0.52 for trotting horses of different breeds: Coldblooded trotter, Finnhorse, and Standardbred trotter [8, 11–13].

The objective of this study was to investigate whether it is possible to breed for the ability to race barefoot as an indirect measurement of hoof quality in Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters. The study aimed at estimating genetic parameters and correlations between estimated breeding values for three novel traits. The first two traits, were related to the ability to race repeatedly with barefoot hind hooves measured as the proportion of barefoot races, and the second trait, "barefoot status", was a binary trait with repeated observations of whether horses started in a race with bare hind hooves or not. Knowledge about the heritability of the ability to race barefoot could serve as a tool to improve the breeding programs for the Swedish Standardbred trotter and the Swedish-Norwegian Coldblooded trotter with regard to performance, health, and welfare.

Methods

Data and pedigree

Data on Swedish trotting races and pedigree information for Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB) were provided by the Swedish Trotting Association. Shoeing condition during the race, i.e., whether the horse was competing with shod front hooves, shod hind hooves, fully shod, or fully barefoot, have been recorded since the end of 2004 for trotting races in Sweden. The original dataset for SB consisted of 1,442,500 racing records from 64,350 horses that competed from 2005 to 2022. The CB race data included performance data from 2005 to 2021 for 173,141 racing records from 8685 horses before data editing. The original pedigree file for SB contained 305,820 animals and that for CB included 118,239 animals.

Trait definition and data editing

From the available information, three trait definitions were formed and used for analysis: two traits related to the proportion of barefoot races and barefoot status. For these traits, barefoot was defined as racing with barefoot hind hooves, but in most cases, the horses were fully barefoot.

Proportion of barefoot races

The proportion of barefoot races was defined as the relative frequency of races in which the horse was barefoot on the hind hooves and shod or barefoot on the front hooves. Two separate traits (I and II) were defined for the proportion of barefoot races. For both traits, the horses were required to have started in at least 10 races for SB and 5 for CB. For the trait proportion of barefoot races II, there was an added requirement of the horse having at least one race with barefoot hind hooves, which removed 3647 non-barefoot racers for SB and 2130 for CB.

Observations were removed for both traits if they were from monté races (i.e., ridden races), had missing shoeing information, had missing pedigree, or if the horse was born outside of Sweden (only for SB). Only observations from March 1st to November 30th were included because racing barefoot in the winter (December to February) has not been allowed since December 1, 2015.

Observations recorded for the track condition “winter track” that occurred outside of the winter season were also removed because no barefoot observations were registered for this track condition. Only racing results from SB born from 2002 to 2018 that were 3 to 10 years of age at the time of the race were included in the analysis. The CB horses included in the study were born between 2002 and 2017 and the results were kept from races in which they were 3 to 10 years old.

The number of observations that remained in the edited dataset used for analyses for the proportion of barefoot races I and II is shown in Table 1. In both breeds, more than half (55 and 64%) of the horses with observations for these traits were geldings or stallions (Table 2). The number of SB and CB horses per birth year was at least 818 and 61, respectively.

Table 1 Numbers of observations and number of horses (in parentheses) in the original dataset and for each trait after editing for Standardbred (SB) and Swedish-Norwegian Coldblooded (CB) trotters

Trait/dataset	Number of observations (horses)	
	SB	CB
Original dataset	1,442,500 (64,350)	173,141 (8685)
Prop. barefoot races I	724,232 (24,928)	97,682 (4050)
Prop. barefoot races II	649,091 (21,281)	60,292 (1947)
Barefoot status	875,056 (25,973)	93,376 (3384)

The main reduction in observations in both traits for both breeds was due to the removal of observations from monté races (46,119 for SB and 4597 for CB), foreign horses (139,170 for SB only), and winter races (races in December, January and February, 181,669 for SB and 24,082 for CB), but the order of the editing rules applied as described above may have influenced this.

Barefoot status

The trait barefoot status was created as a binary trait with repeated observations, where each race for a horse was coded as 2 if it had raced with barefoot hind hooves and 1 otherwise. Observations were removed based on the same criteria as for the proportion of barefoot races I and II, except that data for races in the winter were kept if the track condition was not winter track (only races until 2015). In addition, observations for barefoot status were removed if they were from the starting method “Line start” (not standard, only used when the starting car was not working and therefore few observations had this starting method), or if they were from tracks with few observations. Seven tracks were removed for SB and six for CB, resulting in 33 tracks remaining for SB and 24 for CB. The number of observations per track ranged from 1422 to 105,060 for SB and from 141 to 12,334 for CB.

The SB horses were required to be born between 2002 and 2018 to be included and CB horses between 2002 and 2017. For both breeds, data from races when they were 3 to 10 years old were kept.

Table 2 Least squares (LS) means and standard errors (SE) for the proportion of barefoot races I and II for Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB)

Breed	Trait	Factor	Levels	Number of horses	LS means	SE
SB	Prop. Barefoot races I	Birth year	2002	1573	0.27	0.007
			2018	1023	0.31	0.008
		Sex	Mare	11,151	0.29	0.003
			Gelding/stallion	13,777	0.30	0.002
	Prop. Barefoot races II	Birth year	2002	1294	0.28	0.006
			2018	813	0.35	0.009
		Sex	Mare	9463	0.30	0.003
			Gelding/stallion	11,818	0.30	0.002
CB	Prop. Barefoot races I	Birth year	2002	244	0.08	0.011
			2017	170	0.09	0.013
		Sex	Mare	1629	0.08	0.004
			Gelding/stallion	2421	0.11	0.003
	Prop. Barefoot races II	Birth year	2002	112	0.12	0.010
			2017	61	0.19	0.024
		Sex	Mare	692	0.12	0.005
			Gelding/stallion	1255	0.13	0.004

The LS means from birth years 2003–2017 for SB and from 2003–2016 for CB are not included in the table

Data from trainers without a barefoot race in the dataset were removed to avoid the influence of trainers who were opposed to barefoot racing, which excluded 27% of the trainers of SB horses and removed 3% of the data. In total, 61% of the CB trainers were excluded, which eliminated 18% of the data. Finally, SB horses were required to have started at least 10 races, and CB at least five races to be kept. For this trait, no requirement for the number of barefoot races per horse was made.

The total numbers of observations and number of horses included in the final dataset for barefoot status are shown in Table 1. For SB, 28% of the races were made with barefoot hind hooves and of these, 74% were made fully barefoot. For CB, 11% of the races were with barefoot hind hooves and of these, 59% were made fully barefoot. The use of repeated observations of barefoot status in multiple races allowed for adjustment for race-specific fixed effects in the statistical model, as further described below.

Definition of fixed effects

Each race included information about the date, track, track condition, starting method, race distance, prize money, trainer, and trainer level. Because distribution of races across the country differs for the two breeds, with CB mainly competing in the northern part of Sweden, season of racing was defined differently for the two breeds. For SB, the seasons were defined as winter between December 1 and February 28, spring between March 1 and May 11, early summer between May 12 and July 11, late summer between July 12 and September 31, and autumn between October 1 and November 31. Because the number of observations with barefoot hind hooves for CB during the winter season was small in the years when it was allowed (years 2005–2015 in the data), the winter season was split into two and combined with autumn and spring observations, respectively. As a result, for CB, winter-spring was from January 16 to May 24, early summer from May 25 to July 11, late summer from July 12 to September 24, and autumn-winter from September 25 to January 15 for the CB.

For each race, the track condition was noted as an indicator of the hardness of the track, classified as easy, somewhat heavy, or heavy. For CB, observations with heavy and somewhat heavy track conditions were combined due to relatively few (1155) observations for the former. Observations from winter track conditions were not included for either breed, although observations from other track conditions during the winter season prior to 2015 were included (from 2015 and onwards, racing barefoot was not allowed in winter).

There were two types of starting methods: auto-start (start behind a car) and volt-start (circle start with a maximum of 5 horses per circle). Races were divided into three race distances [14] according to the Swedish Trotting Association's definitions: short-distance (1640 m), medium-distance (2140 m), and long-distance (2640 m). A fourth race distance named marathon (up to 4140 m) was added to account for the 15,432 observations for SB from races that exceeded the distance of the long-distance races.

The level of prize money for the winner in a race, reflecting the level of the race, was grouped into 14 classes for SB and nine classes for CB. The number of observations per class ranged from 1164 to 137,081 for SB and from 1044 to 18,061 for CB.

Trainers were classified as professionals or amateurs based on current definitions by the Swedish Trotting Association. Trainers with type A license were classified as professionals, and trainers with type B license were classified as amateurs. In total, there were 4997 unique trainers of SB and 1017 unique trainers of CB.

Statistical models

Proportion of barefoot races

A linear model with the proportion of barefoot races as the response variable and sex and year of birth as fixed effects was analyzed with the function lm in RStudio [15] to estimate least squares means. Because of the combined trait information from all included races for each horse, only fixed effects that were constant across races could be adjusted for in the statistical model (described below). The proportion of barefoot races I was not transformed because it did not help making the distribution of residuals normal. The proportion of barefoot races II was transformed to make the residuals normally distributed. The appropriate power transformation was determined using the Box-Cox function from the MASS package [16] in R [15], separately for each breed, resulting in a square root transformation for SB and raising to the power 0.02 for CB. The trait distributions for proportion of barefoot races I and II (after transformation) are shown in Fig. 1a and b for SB and in Fig. 1c and d for CB.

Variance components were estimated separately for each breed with a single-trait mixed linear animal model with AIREML of the BLUPF90+ (version 2.47) family of programs [17], followed by a separate run of BLUP with the same package to estimate breeding values, using the following model:

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{e}, \tag{1}$$

where $\mathbf{y}$ is the proportion of barefoot races (I or II), $\mathbf{X}$ and $\mathbf{Z}$ are incidence matrices, $\mathbf{b}$ is the vector of two fixed effects: sex (mare or gelding/stallion) and year of birth (2002–2018 for SB and 2002–2017 for CB), $\mathbf{a}$ is the vector of additive genetic effects $\sim \mathrm{N}(\mathbf{0},\mathbf{A}\,\sigma^2_a)$, where

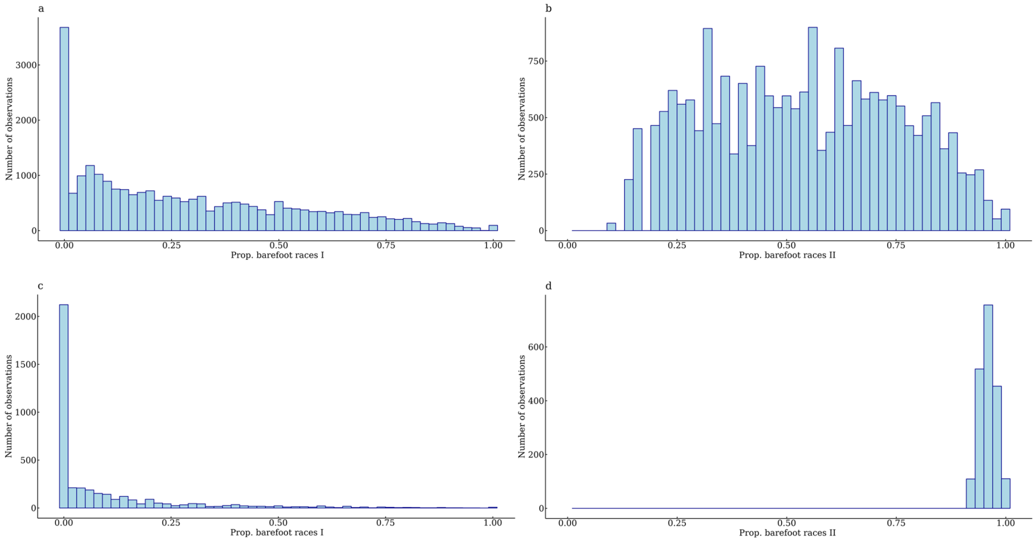

Fig. 1 Trait distribution for the proportion of barefoot races I and II. For Swedish Standardbred trotters, **a** shows the trait distribution for proportion of barefoot races I and **b** shows the trait distribution for proportion of barefoot races II after square root transformation. In **c**, the distribution of proportion of barefoot races I in Swedish-Norwegian Coldblooded trotters is shown and in **d** the distribution of proportion of barefoot races II is shown after Box-Cox transformation with λ = 0.02

A is the numerator relationship matrix, and σ_a^2 is the additive genetic variance, and **e** is the vector of residuals $\sim N(\mathbf{0},\mathbf{I}\sigma_e^2)$, where **I** is the identity matrix and σ_e^2 the residual variance. A pedigree of seven generations with 51,675 SB and 8056 CB horses was used to derive **A** for proportion of barefoot races I. For proportion of barefoot races II, the corresponding numbers were 56,968 for SB and 11,870 for CB. Diagonal elements of **A** accounted for inbreeding.

Barefoot status

Preliminary mixed generalized linear models for the binary trait barefoot status were analyzed with PROC GLIMMIX in SAS [18] to decide on fixed effects and definitions of the classes. The final model in SAS included the random effect of horse and the fixed effects of age, sex, year, season, track, track condition, starting method, race distance, prize money, and trainer level. Level of significance, least squares means, and inverse link transformations (predicted probability) of least squares means were estimated for each fixed effect. Only the random effect of the horse was included in the preliminary model because additional random effects (trainer and year-season interaction) caused problems in SAS due to insufficient memory.

Variance components and breeding values were estimated using the GIBBSF90+ (version 3.16) program of the BLUPF90 software [17]. The following single-trait animal threshold model with repeated observations was used:

$$y = \mathbf{Xb} + \mathbf{Z}_s\mathbf{s} + \mathbf{Z}_t\mathbf{t} + \mathbf{Z}_a\mathbf{a} + \mathbf{Z}_p\mathbf{p} + \mathbf{e}, \quad (2)$$

where **y** is the vector of the binary trait shod or barefoot, $\mathbf{X}$, $\mathbf{Z_s}$, $\mathbf{Z}_t$, $\mathbf{Z}_a$, and $\mathbf{Z}_p$ are incidence matrices, **b** is a vector of fixed effects, vector **s** is the random effect of the year-season interaction $\sim N(\mathbf{0},\mathbf{I}\ \sigma_s^2)$, where **I** is the identity matrix, vector **t** is the random effect of the trainer of the horse $\sim N(\mathbf{0},\mathbf{I}\ \sigma_t^2)$, **a** is the vector of additive genetic effects $\sim N(\mathbf{0},\mathbf{A}\ \sigma_a^2)$, where **A** is the numerator relationship matrix, where σ_a^2 is the additive genetic variance, vector **p** is the random permanent environmental effect $\sim N(\mathbf{0},\mathbf{I}\ \sigma_p^2)$, and **e** is the vector of residuals $\sim N(\mathbf{0},\mathbf{I}\ \sigma_e^2)$, where σ_e^2 is the residual variance, which was set to 1. The **A** matrix was constructed based on seven generations of pedigree with 58,070 animals for SB and 10,464 for CB and with the diagonal element accounting for inbreeding. Vector **b** included 10 fixed effects: starting method (volt-start or auto-start), track (33 levels for SB and 24 levels for CB), track condition (easy, somewhat heavy or heavy for SB and easy or somewhat heavy/heavy for CB), sex (mare or gelding/stallion), age (3–10 years), race year (2005–2022 for SB and 2005–2021 for CB), season (winter, spring, early summer, late summer, autumn or winter for SB; and winter-spring, early summer, late summer or autumn-winter for CB), race level (14 levels for SB and nine for CB), trainer level (professional or amateur) and distance (short-, medium-, long- or (for SB) marathon-distance).

Multiple Gibbs sampling runs with different chain lengths, burn-ins, and thinnings were tested and passed to post-Gibbs analysis. The appropriate chain lengths were decided by analyzing the size of the effective samples and the thinning was based on the sample's autocorrelation. After post-Gibbs analyses and visual inspection of the chains in RStudio to check if they had reached convergence, the final options for SB were set to 400,000 iterations, 60,000 as the burn-in, and a thinning of 80. For CB, the options were set to 700,000 iterations, 80,000 burn-in, and a thinning of 80. In total, 4250 samples for SB and 7750 samples for CB were passed to post-Gibbs analysis in POSTGIBBSF90.

Estimation of heritability, repeatability, and accuracy of estimated breeding values

The heritabilities (h^2) of the two proportions of barefoot races traits were estimated based on estimates of variance components (^) as:

$$\hat{h}^2 = \frac{\hat{\sigma}_a^2}{\hat{\sigma}_a^2 + \hat{\sigma}_e^2}.$$

The heritability of barefoot status was estimated as the posterior mean of heritability obtained from the sampled variances at each iteration (^) as:

$$\hat{h}^2 = \frac{\hat{\sigma}_a^2}{\hat{\sigma}_a^2 + \hat{\sigma}_p^2 + \hat{\sigma}_e^2}.$$

Repeatability for barefoot status was estimated from the posterior means of variance components (^) as:

$$r = \frac{\hat{\sigma}_a^2 + \hat{\sigma}_p^2}{\hat{\sigma}_a^2 + \hat{\sigma}_p^2 + \hat{\sigma}_e^2}.$$

For proportion of barefoot races I and II, the accuracy of the estimated breeding value of a horse (r_{TI}) was based on the prediction error variance (PEV) derived from the mixed model equations by the BLUPF90 program and was calculated according to [19] as:

$$r_{TI} = \sqrt{1 - \frac{PEV}{(1 + F_i)\hat{\sigma}_a^2}},$$

where F_i is the individual's inbreeding coefficient. For barefoot status, the accuracy was calculated manually using the same formula as above, using the squared posterior standard deviation provided by the GIBBSF90+ program as PEV for breeding values.

Correlations between estimated breeding values

Pearson and Spearman rank correlations between estimated breeding values (EBV) for the proportion of barefoot races and barefoot status were calculated for stallions born in 1992 and later that had at least 10 offspring with own racing performance in the data. Stallions that fulfilled these requirements for SB were born from 1992 to 2013, and those for CB were born from 1992 to 2011, resulting in the inclusion of 285 SB and 69 CB stallions for the proportion of barefoot races I, 270 for SB and 49 for CB for the proportion of barefoot races II, and 289 SB stallions and 60 CB stallions for barefoot status.

Results

Fixed effects and least squares means

Proportion of barefoot races

The raw overall mean values for the proportion of barefoot races I in the dataset after editing were 0.29 for SB and 0.10 for CB. For the proportion of barefoot races II, the corresponding numbers were 0.34 for SB and 0.20 for CB. In the mixed linear model fitted in RStudio [15], birth year was significant at $p < 0.0001$ for both traits in SB and at $p = 0.88$ and $p = 0.07$ for CB for proportion of barefoot races I and II, respectively. Least squares means for birth year, which were back-transformed to the original scale for the proportion of barefoot races II, showed an increased proportion of barefoot races for both trait definitions from 2002 to 2018 (SB) and from 2002 to 2017 (CB) (Table 2). However, the increase in barefoot races for CB over birth years was minor when horses that never raced barefoot were included (proportion of barefoot races I) (from 8% for horses born in 2002 to 9% for horses born in 2017). Sex was not significant at $p = 0.12$ for SB but significant at $p < 0.0001$ for CB for the proportion of barefoot races I. Corresponding p-values for the proportion of barefoot races II were 0.91 and 0.02, respectively. Least squares means for sex, back-transformed to the original scale for the proportion of barefoot races II, were similar for SB geldings/stallions and mares for both traits (Table 2). For CB, geldings/stallions had a somewhat higher proportion of barefoot races than mares when including horses that never had raced barefoot (proportion of barefoot races I).

Barefoot status

Least squares means, expressed as the probability of racing barefoot for the fixed effects starting method, track condition, sex, trainer level, and distance group for SB are in Table 3. All fixed effects included in the model were

Table 3 Least squares (LS) means and standard errors (SE) for barefoot status for levels of fixed factors in Swedish Standardbred trotters

Factor	Level	Number of horses	Number of observations	LS means	SE
Starting method	Auto-start	25,750	493,143	0.212	0.005
	Volt-start	25,792	381,913	0.173	0.004
Track condition	Easy	25,973	822,070	0.239	0.003
	Somewhat heavy	19,314	50,713	0.187	0.004
	Heavy	2000	2273	0.156	0.010
Sex	Mare	11,713	360,085	0.200	0.005
	Gelding/stallion	14,260	514,971	0.184	0.005
Trainer level	Professional	20,264	513,562	0.248	0.006
	Amateur	14,993	361,494	0.146	0.004
Distance group	Short	22,866	155,870	0.222	0.005
	Medium	25,971	619,172	0.188	0.005
	Long	18,141	84,582	0.187	0.005
	Marathon	5004	15,432	0.173	0.005

LS means are expressed as a probability of racing barefoot. The fixed effects track, age, season, prize money and year are not included in the table

significant at $p < 0.0001$. The probability of racing barefoot was higher in races in which the starting method was auto-start, on easy track conditions, and in short races. If the horse was trained by a professional trainer or was a mare, the probability of racing barefoot was higher in comparison to horses trained by an amateur trainer or if the horse was a gelding/stallion.

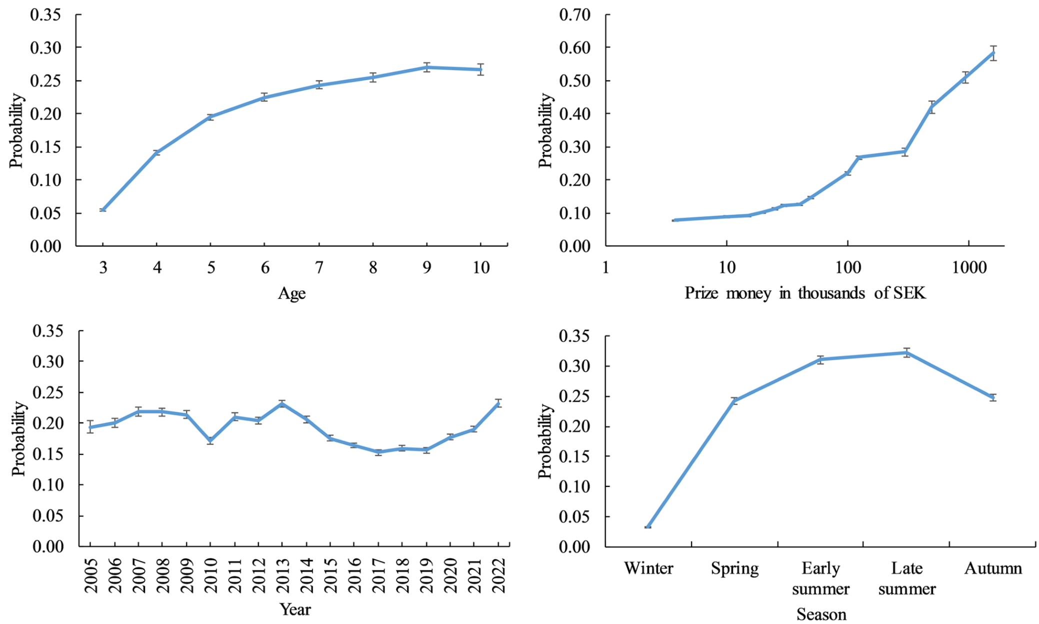

Fig. 2 Least squares mean (probability) of racing barefoot for the trait barefoot status. The probability for each level of the fixed effects is shown: age (years), prize money (where the median price money for each class represents the points on the x-axis in thousands of SEK), year and season in Swedish Standardbred trotters. Bars represent standard errors

In Fig. 2, least squares means (probability) of racing barefoot are shown for age, prize money, year, and season. The probability of racing barefoot was 0.055 and 0.267 for 3- and 10-year-old SB horses, respectively. Prize money had a large effect on whether the horse raced barefoot or not. For races with prize money < 5 K SEK (median 3.75 K SEK), the probability of racing barefoot was 0.077 ± 0.002, compared with 0.583 ± 0.022 for races with prize money > 1 M SEK (median 1.6 M SEK). The probability of racing barefoot has been relatively stable over birth years, fluctuating between 0.15 and 0.23. After 2015, when new regulations for winter races were put in place, the probability of racing barefoot decreased. However, since 2019, the probability of racing barefoot has increased again. Seasonal changes also played an important role in the probability of racing barefoot in SB trotters, with late summer having the highest probability, followed by early summer.

Least squares means (probability) of racing barefoot for CB are shown in Table 4. All fixed effects included in the model were significant at $p < 0.0001$ except for sex ($p = 0.04$) and distance ($p = 0.001$). As for SB horses, the probability of racing barefoot for CB horses was higher for races with starting method auto-start, on easy track conditions, and in short-distance races. Also, CB horses trained by professional trainers had a higher probability of racing barefoot than horses trained by amateurs.

The least squares means (probability) of racing barefoot for the fixed effects of age, prize money, year and season for CB horses are shown in Fig. 3. Similar to SB horses, CB horses were more likely to race barefoot at older ages and in races with more prize money. In 2005, the probability of racing barefoot peaked at 0.106 ± 0.028, while in 2009, the probability was as low as 0.052 ± 0.005. As for SB, the probability of racing barefoot was highest in the summer seasons.

Variance components

Estimates of variance components, heritability, and repeatability for the evaluated traits are shown in Table 5. Estimates of heritability for proportion of barefoot races I and II were moderate: 0.28 ± 0.02, and 0.23 ± 0.02, respectively, in SB, and 0.17 ± 0.04 and 0.25 ± 0.06 in CB. For barefoot status, the estimate of heritability was 0.08 ± 0.01 for SB and 0.07 ± 0.03 for CB. Estimates of repeatability for barefoot status were moderate at 0.40 and 0.41 for SB and CB respectively.

Accuracies and correlations between EBVs

For SB, the average accuracy of the EBVs was moderate to high (0.79–0.87) for breeding stallions born in 1992 and later for all studied traits (Table 6). The Pearson correlation coefficient between the EBVs of stallions for barefoot status and proportion of barefoot races I and II was 0.63 and 0.64, respectively. The corresponding Spearman rank correlation coefficient was 0.60.

The average accuracy for the EBVs for the proportion of barefoot races and barefoot status ranged from 0.67–0.75 for CB breeding stallions born in 1992 and later (Table 6). The Pearson correlation coefficient between the EBVs for barefoot status and proportion of barefoot races I and II was 0.82 and 0.76, respectively. The corresponding Spearman rank correlation for CB of EBVs for barefoot status with those for the proportion of barefoot races I and II was 0.77 and 0.67, respectively.

Table 4 Least squares (LS) means and standard errors (SE) for barefoot status for levels of fixed factors in Swedish-Norwegian Coldblooded trotters

Factor	Level	Number of horses	Number of observations	LS means	SE
Starting method	Auto-start	2592	17,537	0.071	0.004
	Volt-start	3377	75,839	0.062	0.003
Track condition	Easy	3384	85,475	0.079	0.004
	Somewhat heavy	2511	7901	0.056	0.004
Sex	Mare	1303	32,978	0.063	0.004
	Gelding/stallion	2081	60,398	0.071	0.004
Trainer level	Professional	2123	42,766	0.073	0.004
	Amateur	2052	50,610	0.061	0.004
Distance	Short	3119	21,635	0.072	0.004
	Medium	3378	64,257	0.065	0.003
	Long	1730	7484	0.064	0.004

LS means are expressed as a probability of racing barefoot. Track, age, season, prize money and year are not included in the table

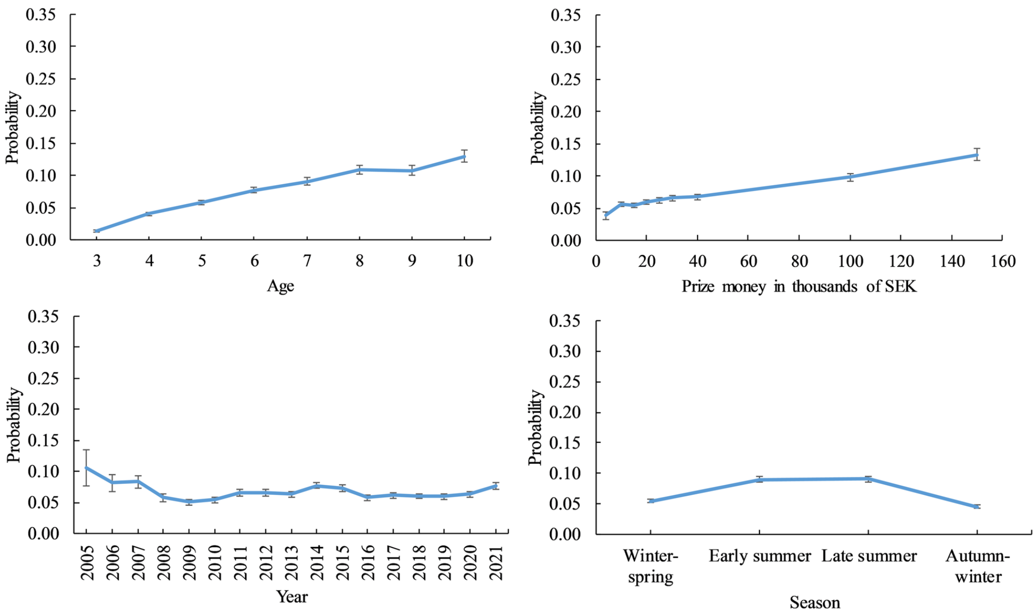

Fig. 3 Least squares mean (probability) of racing barefoot for the trait barefoot status. The probability for each level of the fixed effects is shown: age (years), prize money (where the median price money for each class represents the points on the x-axis in thousands of SEK), year and season in Swedish-Norwegian Coldblooded trotters. Bars represent standard errors

Table 5 Estimates of variance components, heritability, and repeatability for the proportion of barefoot races I, II, and barefoot status for Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB)

Breed	Trait	σ_s^2	σ_a^2	σ_t^2	σ_p^2	σ_e^2	h^2	r
SB	Prop. barefoot races I		$0.020_{0.002}$			$0.050_{0.001}$	$0.284_{0.020}$	
	Prop. barefoot races II		$0.011_{0.001}$			$0.039_{0.001}$	$0.225_{0.020}$	
	Barefoot status	$0.830_{0.155}$	$0.135_{0.011}$	$0.316_{0.010}$	$0.523_{0.011}$	$1.000_{0.002}$	$0.081_{0.008}$	0.397
CB	Prop. barefoot races I		$0.005_{0.001}$			$0.024_{0.001}$	$0.171_{0.038}$	
	Prop. barefoot races II		$0.0001_{0.00003}$			$0.0003_{0.00002}$	$0.254_{0.064}$	
	Barefoot status	$0.007_{0.003}$	$0.112_{0.043}$	$0.266_{0.024}$	$0.576_{0.040}$	$1.000_{0.006}$	$0.066_{0.026}$	0.407

Posterior means for year season (σ_s^2), additive genetic (σ_a^2), trainer (σ_t^2), permanent environment (σ_p^2) and residual (σ_e^2) variance with heritability (h^2) and repeatability (r)
Standard deviations and posterior standard deviations are shown as subscript

Discussion

We report the first genetic parameters for traits that reflect the ability of trotting horses to race barefoot. Having a well-functioning hoof is important for sports performance in horses [8–10]. Although information about shoeing conditions is routinely registered in Swedish trotting races, the potential of using this information in the breeding programs has not been studied. In this study, the trait proportion of barefoot races was created to reflect the ability to repeatedly race barefoot, and the binary trait barefoot status was created to reflect the probability of racing unshod in a race.

Barefoot racing and hoof quality in horses

There is a general perception that hoof quality differs between breeds and between individual horses, indicating genetic variation, but scientific literature on this topic is scarce. In nonscientific articles, the Thoroughbred is perceived as a breed with poor hoof quality [20, 21], while Standardbred trotters are believed to have good

Table 6 Mean and range of accuracies[a] of estimated breeding values for the proportion of barefoot races and barefoot status for Swedish Standardbred (SB) and Swedish- Norwegian Coldblooded (CB) stallions with at least 10 progeny with data

Breed	Trait	Birth years	Number of stallions	Average number of offspring	Accuracy range	Mean accuracy
SB	Prop. barefoot races I	1992–2013	285	78.4	0.71–0.97	0.87
	Prop. barefoot races II	1992–2013	270	71.5	0.63–0.96	0.84
	Barefoot status	1992–2013	289	80.2	0.49–0.89	0.79
CB	Prop. barefoot races I	1992–2011	69	53.1	0.55–0.92	0.75
	Prop. barefoot races II	1992–2011	49	38.2	0.54–0.91	0.74
	Barefoot status	1992–2011	60	54.9	0.45–0.89	0.67

[a] Accuracy (r_{TI}) of the estimated breeding values (EBV) presented as range and mean for breeding stallions born in 1992 and later with at least ten offspring with data in Swedish Standardbred trotters (SB) and Swedish-Norwegian Coldblooded trotters (CB)

hoof quality [22]. Standardbred trotters descend from Thoroughbreds but race on harder race tracks. Thus, it is reasonable to believe that Standardbreds have been indirectly selected for durable hooves. In a subpopulation of a Chinese-Mongolian horse breed adapted for life in the mountains and known for its strong and durable hooves, several candidate genes that could be important for hoof quality have been found [23], indicating genetic effects. In Swedish Standardbred trotters, individuals which are reported to have hooves that can tolerate racing barefoot repeatedly, have been found to have lower concentrations of copper and higher concentrations of arginine in the hoof wall compared with individuals that cannot race barefoot repeatedly, which could be linked to the hardness of the hoof [5]. In the present study, genetic parameters estimated for the proportion of barefoot races and barefoot status in Swedish trotters showed within-breed genetic variation for both traits for SB and CB.

Trait definitions and environmental factors

The ability to race barefoot is a complex trait that is affected by the horse's genes in combination with environmental factors and the trainer's decisions. Due to the nature of the trait proportion of barefoot races, we could not adjust for the effect of the trainer. In our statistical analyses, we could only adjust for sex (mare or gelding/stallion) and year of birth, which were both the same for each horse across its racing years.

In the definition of the trait proportion of barefoot races I, we included horses that never raced barefoot. This trait has the advantage of covering a larger proportion of the population and the results are easier to interpret as no transformation was applied. For the trait proportion of barefoot races II, horses that had never started unshod hind were removed to help create a normally distributed trait as the proportion barefoot races I was zero-inflated, and to ensure that the included horses had the opportunity to race barefoot. In the end, both trait definitions gave similar results and, thus, the definition that includes more horses (I) is preferred.

The binary trait barefoot status defined in this study had the advantage of being based on repeated measurements, which made it possible to correct individual races for environmental effects of importance. This trait definition allowed more horses and observations to be retained for the analysis than for the traits based on the proportion of barefoot races. The trainer's perception of barefoot racing could be an important factor in the decision to race barefoot or not. Therefore, observations from trainers who never raced with a barefoot horse in the data were removed to avoid that horses with the ability to race barefoot that never got the chance to do so, impact the results. The trainer of the trotting horse has been shown to explain more variation in racing performance than, for example, the driver of the horse [14]. Variation in the trait explained by the trainer may also cover yard-specific management routines such as feeding, housing, and farriery (hoof care). The trainer effect explained 11% and 14% of the phenotypic variance (defined as the sum of the variance components for all random effects in the model for genetic analysis) in SB and CB, respectively. However, the permanent environment effect for barefoot status was almost twice as large and represented 19% of the phenotypic variance for SB and 29% for CB. This effect accounts for factors not covered by the trainer effect, such as the horse's history, including its rearing period, as well as for example previous training and injuries, but also variation that comes from trainers that only had one horse (more common in CB).

The amount of phenotypic variance explained by the random effect of year-season was 30% for SB but only 0.4% for CB. The probability of racing barefoot was relatively stable across years and seasons for CB compared with SB, for which the probability of racing barefoot varied more over years as well as over seasons.

There was a very small difference in the least squares mean for the proportion of barefoot races between sexes for both SB and CB. For barefoot status, the least squares mean from the preliminary analyses in SAS showed that SB mares had only a slightly higher probability of racing barefoot than SB geldings/stallions. This could be because mares are, on average, slower than geldings/stallions in trotting races [14], and removing the shoes could help to even out the differences in mixed races. A study on hoof strength and mineral content in different horse breeds reported no differences between sexes [24], which is in line with the findings of our study.

For barefoot status, easy track conditions resulted in a higher probability of racing unshod (SB and CB), followed by somewhat heavy (SB and CB) and heavy track conditions (SB). There was also a higher probability of racing unshod in short races than in longer races for both breeds. This could be due to smaller margins in shorter races that favor barefoot horses but also a potential increase of wear and tear of hooves for longer races.

The level of the race, which in this study was defined as the prize money for the winner, was shown to have a large impact on whether the horse raced barefoot or not. In SB races, prize money > 1 M SEK to the winner considerably increased the probability of racing barefoot, with a least squares mean as high as 60%. This shows the impact of prize money on the trainer taking the risk of racing barefoot. In CB races, for the class with the highest prize money to the winner the least squares mean for barefoot racing was only 13%. Possibly, the increased risk of disqualification associated with barefoot racing outweighs the benefit of increased speed when unshod.

Heritability estimates

The estimated heritability for the proportion of barefoot races I and II was moderate (0.2–0.3) for both SB and CB. For these traits, the definition required at least 10 races for SB horses and 5 for CB horses, which may have influenced the estimate [25]. For barefoot status, the heritability estimate was low (< 0.1), although it was significant for both breeds and stable for different models and settings for Gibbs sampling and post-Gibbs analyses.

Variance component estimation for barefoot status with a threshold model required a relatively long computational time, especially for SB. However, the use of threshold models for a binary trait generally results in higher heritability than if it was treated as a linear trait [26, 27] because threshold models estimate the heritability on the underlying continuous scale. Threshold models also have the benefit of giving less biased heritability estimates for traits that are not normally distributed [28]. Despite the binary nature of barefoot status and the low heritability estimates, the large number of repeated observations led to moderate to high accuracy of EBV of breeding stallions, similar to the proportion of barefoot races.

Hoof quality and racing performance

We considered the possibility that the proportion of barefoot races may be a too simplified measurement of the ability to race barefoot, as we could not take into account factors such as the level of the race, which appears to be of importance for the incentive to have the horse race barefoot. For barefoot status, factors such as prize money could be adjusted for, which would make this trait more independent from racing performance. The genetic correlation between the proportion of barefoot races and barefoot status could not be estimated because of convergence problems. However, the correlation between EBV for breeding stallions for the proportion traits and barefoot status trait was moderately strong and the corresponding genetic correlation can then be expected to be even higher. The simpler proportion traits thus seem to be rather closely related to the more strictly defined barefoot status trait, and thus useful as measures of the ability to race barefoot.

The difference in the popularity of racing barefoot for SB compared with CB horses may be due to reasons other than a difference in hoof quality. The low proportion of barefoot races for CB compared with SB horses is possibly partly due to genetic differences between the breeds in their ability to balance in trot at high speed. In Standardbred trotters, individuals that are homozygous for the A allele at the doublesex and mab-3 related transcription factor 3 (*DMRT3*) gene have been shown to be better at keeping trot at high speed and perform better in trotting races [29]. In the Coldblooded trotter, the benefit of the mutation in *DMRT3* on racing performance is less clear [30]. In Swedish Standardbred trotters, the favorable A allele is close to fixation, but in Coldblooded trotters the frequency of the A allele has been estimated to be 45% [31]. In Coldblooded trotters, often referred to as less good "natural trotters", shoes still seem to play an important role in balancing the trot at high speed.

Implications

This study presents the first estimates of the genetic contribution to the ability to race barefoot. Despite the low heritability for barefoot status for both breeds, it had the advantage of many repeated observations and that factors shown to be important for the trait, such as age, season, and prize money, could be accounted for. However, before implementing a trait that measures the ability to race barefoot in routine genetic evaluation, genetic correlation with performance traits must be estimated. Also, the welfare aspect of racing barefoot and its impact on the durability and longevity of trotting horses need to be studied, especially how shoeing condition in a horse's early career impacts its future racing career. Today, European trotting associations have different regulations regarding barefoot racing for young horses [32] but there is a lack of published research to base new regulations and standards on.

Although the traits in this study were based on data that is already routinely recorded for both trotter breeds in Sweden, there are some practical concerns. During the part of the year when racing barefoot is allowed, the sole of the hoof can for instance be covered with plastic for protection and still be registered in the system as barefoot. If any of the traits studied in this paper were included in genetic evaluation of the two breeds, one would need to consider implementing a differentiation between barefoot and plastic covered soles in the registration. For the current study, information about this could have helped to verify that the information on shoeing condition was correctly interpreted.

Conclusions

In this study, genetic parameters were estimated for the ability to race barefoot for Swedish Standardbred trotters and Swedish-Norwegian Coldblooded trotters, including two traits related to the proportion of barefoot races and the binary trait barefoot status. Heritability estimates ranged from 0.17 to 0.28 for the proportion of barefoot races I and II and from 0.07 to 0.08 for the barefoot status. Due to repeated observations for barefoot status, its average accuracy of EBV for breeding stallions was similar to that for the proportion of barefoot races traits. The Pearson correlation coefficient between the EBV of the proportion traits and barefoot status traits was 0.63 and 0.64 in SB and 0.82 and 0.76 in CB. These results indicate that it would be possible to select for the ability to race barefoot in trotters. However, further studies are needed to estimate the genetic correlation of these traits with performance and career length.

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Author contributions
PB, SA, ES, and SE initiated the study. TL and CO provided the data material used for the study and helped with its interpretation. TL, CO and AJ advised on the data editing and interpretation of the results. PB performed the statistical analyses and drafted the manuscript under supervision from SA, ES, and SE. All the authors have read, edited and approved the final version of the manuscript.

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Availability of data and materials
The data used for this study were obtained from the Swedish Trotting Association and used under license. To access the data, permission is required from the Swedish Trotting Association.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
CO and TL are employed by the Swedish Trotting Association, and SE and SA have commitments to the Swedish Trotting Association, regarding development of the genetic evaluation.

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This thesis aimed to study the genetic background of novel traits related to distance-specific performance and the ability to race barefoot in Swedish trotters. The results showed that racing time can be treated as one trait over all distances in trotting races. The ability to race barefoot was found to be partly explained by genetics and showed potential for inclusion in the genetic evaluation. However, racing barefoot at a young age was found to be negative for career length.

Paulina Berglund received her doctoral education at the Department of Animal Biosciences, Swedish University of Agricultural Sciences (SLU). She received her MSc in Agricultural Science – Animal Science from SLU.

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