University of Veterinary Medicine Budapest
Department of Animal Breeding and Genetics

Current genomic Data of Health and Performance of German showjumping horses (Holsteiner, Hannoverian)

Virág Viktoria Reichert

Supervisor:
Professor Dr. Zöldág László
Departement of Animal Breeding and Genetics

Budapest 2023

Table of contents

1. INTRODUCTION 6

2. GENOMICS AND ITS APPLICATION IN EQUINE HEALTH AND PERFORMANCE 8

2.1. Genetic models and techniques 9

2.2. Significance in Equine Breeding 11

3. HEALTH AND PERFORMANCE ASSESSMENTS 13

3.1 Genomic Variation and Health 14

3.1.1 Genetic Markers for Health Conditions 14

3.1.2 Insights into Hereditary Health Issues and breed-specific health conditions in Holstein and Hanoverian horses 20

3.2. GENOMIC VARIATION AND PERFORMANCE 22

3.2.1. Genetic markers for Athletic Performance 22

3.2.2. Training and Performance Optimisation 25

4. OVERVIEW OF THE SUCCESSFUL BREEDS IN SHOWJUMPING 26

4.1. Holsteiner 26

4.1.1 History 26

4.1.3 The most Important Bloodlines 28

4.2. Hanoverian 32

4.2.1. History 32

4.2.2 Description of the Breed 33

4.2.3. The Most Important Bloodlines 35

5.CONCLUSION 38

6. ACKNOWLEDGEMENT 39

7. BIBLIOGRAPHY 40

8. LIST OF FIGURES..... 47

Abbreviation

DNA	Deoxyribonucleic acid
WBFSH	World Breeding Federation for Sport Horses
SNP	Single-nucleotide polymorphism
e.V.	eingetragenen Verein
PSSM2	Muscle Integrity Myopathy
MRI	Magnetic Resonance Imaging
HYPP	Hyperkalemic Periodic Paralysis
GYS1	Glycogen synthase 1
SCID	Severe Combined Immunodeficiency
PSSM1	Polysaccharide Storage Myopathy
DNA-PK	Deoxyribonucleic acid proteinkinase gene
CA	Cerebellar Abiotrophy
EGR1	Early growth response protein 1
B4GALT7	Beta-1,4-galactosyltransferase 7
OC	Osteochondrosis
OCD	Osteochondrosis dissecans
QTL	Quantitative trait locus
ERU	Equine Recurrent Uveitis
RAO	Recurrent Airway Obstruction
RLN	Recurrent laryngeal neuropathy
WFFS	Warmblood fragile foal syndrome
PLOD 1	Procollagen lysine-2-oxoglutarate 5-dioxygenase 1 gene
CO2	Carbon dioxide
MSTN	Myostatin
COL9A2	Collagen alpha-2(IX) chain
ACE	Angiotensin-converting enzyme
cm	centimeter

1. Introduction

Genomic data has revolutionized the world of horse breeding and performance, and German showjumping horses are no exception. In recent years, the integration of cutting-edge genomics into the equine industry has opened exciting possibilities for enhancing the health and performance of these remarkable athletes. This introduction delves into the realm of current genomic data in the context of German showjumping horses, exploring how this scientific breakthrough is reshaping the way we understand, select, and nurture these equestrian stars.

German showjumping horses have long been celebrated for their exceptional agility, power, and grace in the demanding sport of showjumping. However, achieving peak performance and maintaining the health and longevity of these equine athletes is a complex endeavor. Traditional breeding methods, although effective to some extent, have inherent limitations, such as the unpredictability of genetic inheritance and the long generational cycles required to observe results.

Enter genomics, a game-changer that is helping breeders and trainers unlock the secrets hidden within the Deoxyribonucleic acid (DNA) of German showjumping horses. By analyzing the genomic data of these horses, scientists and equine enthusiasts can gain invaluable insights into the genetic underpinnings of various traits, including athleticism, temperament, and susceptibility to certain health conditions. This knowledge empowers stakeholders to make informed decisions about breeding, training, and healthcare.

Genomic data has enabled researchers to identify specific genes and genetic markers associated with showjumping ability and other performance-related traits. With this information, breeders can make more precise breeding selections, pairing horses with the most favorable genetic profiles to increase the likelihood of producing exceptional offspring. This targeted breeding strategy has the potential to accelerate the development of top-tier showjumping horses.

Moreover, genomic data plays a pivotal role in improving the overall health and well-being of German showjumping horses. Understanding the genetic predispositions to certain diseases and conditions allows for early intervention and preventive measures. Equine genomics can also aid in tailoring training and nutrition programs to individual horses, ensuring they reach their full potential while minimizing the risk of injury.

In this rapidly evolving field, German showjumping horse enthusiasts, breeders, and trainers are increasingly relying on genomic data to shape the future of their beloved sport. As our

knowledge of equine genomics continues to grow, we can anticipate even more breakthroughs and innovations that will further enhance the health and performance of these magnificent athletes. The fusion of science and tradition is creating a bright and promising path for German showjumping horses, where genetic insights are propelling them to new heights of excellence.

2. Genomics and its Application in Equine Health and Performance

Equine genomics is the study of the genetic makeup of horses, including their DNA sequences, gene expression patterns, and how these genetic factors influence various traits and characteristics in horses. It involves using advanced genomic technologies and bioinformatics tools to analyse the entire genome of horses and understand the genetic basis of various traits, such as coat colour, size, athleticism, disease susceptibility, and more.

"A genome represents the genetic material or the core regulatory and functional machinery of any organism. In the horse, as is typically in most mammals, the genetic material largely resides in the cell's nucleus, while a fractionally vital component is present in the cytoplasm. The former is packaged in the form of chromosomes and the latter in the form of mitochondria"[1*]*.

The genome of the horse, specifically the domestic horse (Equus Ferus caballus), is relatively large, consisting of about 2.7 billion base pairs. In a horse, we can find 32 pairs of chromosomes as ladder-shaped DNA strands. These are composed of only four different building blocks (G, C, A, T) in alternating combinations (base pairs), which form the code for the respective composition of the 23000 genes (one gene= one protein). [2]

Different horse breeds have specific genetic characteristics shaped through selective breeding. The genomic information of various horse breeds is studied to understand their unique features and to improve breeding programs.

Genomic research in horses has led to a better understanding of various equine diseases, such as genetic disorders and hereditary conditions. It has also contributed to advancements in equine sports performance and horse health.

In recent years, advances in genomics and genetic sequencing have allowed for more precise and efficient breeding practices and the identification of genetic markers for specific traits. These developments have been instrumental in equine science, helping horse breeders, veterinarians, and researchers make informed decisions about horse health, performance, and breeding strategies.

2.1. Genetic models and techniques

Genetic models and techniques in horses are crucial in improving equine health, performance, and breeding. These methods are used to understand the inheritance of traits, identify genetic diseases, and make informed breeding decisions.

The simplest method is, of course, pedigree analysis, where the horse's ancestry can be traced back to determine its genetic heritage. Stud books and pedigrees provide information about a horse's ancestry and help breeders make informed decisions about mating choices. Nevertheless, they are not only helpful for breeders; horse owners and potential buyers can also learn about the history of the bloodline or potential character traits and performance characteristics of their horse [3]. To give an overview of such a pedigree, the pedigree of Chacco-Blue is included (**Fig.1**), who was number 1 in the World Breeding Federation for Sport Horses (WBFSH) ranking in 2022 [4].

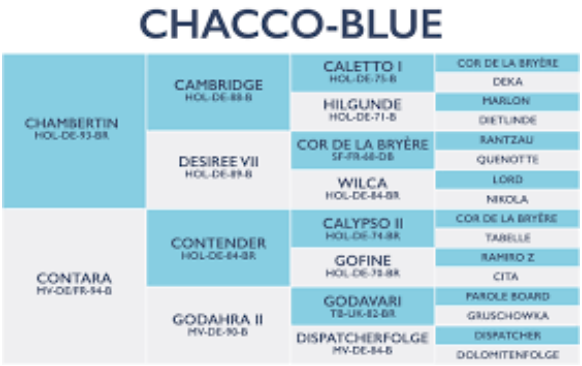

Figure 1: Chacco-Blue Pedigree [5]

However, genetic tests are also widely used. These began in the 1960s with ancestry testing through blood tests (blood group and protein polymorphism tests).

Methods to identify and evaluate genetic variants at the DNA level became available in the late 1990s, and parentage testing subsequently shifted to using DNA markers *[6]*.

DNA testing is a powerful tool in equine genetics. It can be used to determine the genetic makeup of a horse, identify parentage, and detect genetic diseases and traits. DNA tests are available for coat colour, disease susceptibility, and performance-related genes. This test is viral and is offered by many laboratories worldwide, so it is easily considerable for breeders, horse owners and veterinarians.

Another way for breed identification verification of pedigree, disease susceptibility, and performance traits is genetic markers. These are specific polymorphic regions of DNA that

are associated with certain traits or characteristics in horses. Markers are often located in intergenic or non-coding genic regions, as those regions are presumed to be selectively neutral and comprise most of the genome. There are different marker types, such as microsatellites or single nucleotide polymorphisms (SNPs*)* [7].

For more than two decades, parentage testing of horses has been carried out in Germany, for example, using molecular genetic diagnostics in the laboratory. Till 2021, mainly the so-called microsatellite marker has been investigated.

Microsatellites are sequences of DNA where a short sequence of nucleotides is repeated multiple times. These markers are highly variable, and the motif number differs between animals and can vary, for example, between two and twenty. In order to check the pedigree, a hair sample is usually taken, and the cell nucleus of the hair roots contains the genetic information. Since 1997, a set of 17 microsatellites has been agreed upon for horses, including 12 standard markers and five markers for extended examinations.

Thus, during the parentage control, it is checked whether the variants (i.e., the number of motif repetitions) in each of the examined microsatellite markers present in the foal match those of the parents. If the foal shows a variation, it cannot be inherited from its parents; the parentage is doubted. The results are communicated directly to the responsible horse breeding association and entered into the database *[8].*

The other marker we mentioned earlier is SNPs (Single Nucleotide Polymorphisms).

Since the 1st of January 2021, the first breeding associations in Germany have changed the parentage control of riding horses from a microsatellite-based procedure to an SNP-based procedure. A SNP is a single site in DNA where individuals differ. While microsatellites can occur in many variants, each SNP can usually only exist in two different variants. In contrast to microsatellites, however, there are millions of SNPs in the genetic material of a horse. A set of several dozen to a few hundred SNPs is sufficient to create an individual genetic fingerprint for an animal. For routine diagnostics, so-called SNP chips are offered, with the help of which the variants of tens of thousands or even hundreds of thousands of SNPs in the genetic material of an animal can be examined in parallel *[8].*

In 2017, five associations joined forces, namely the "Verband der Züchter des Oldenburger Pferdes eingetragener Verband (e.V.)", the "Springpferdezuchtverband Oldenburg-International e.V.", the "Westfälisches Pferdestammbuch e. V.", the "Trakehner Verband e. V." and the "Verband der Züchter des Holsteiner Pferdes e. V.". They aim is to create a database and to develop an evaluation procedure that can be used to conclude specific horse characteristics from genetic markers. They have already registered 5000 horses and,

in addition to checking their pedigree, they have been able to query the entire spectrum of performance, conformation and behavioural characteristics since this year. Nevertheless, health data can also be analysed, such as Muscle Integrity Myopathy (PSSM2), a hereditary degenerative muscle disease [9].
Using the methods shown so far, breeders can use selective breeding to choose horses with desired traits and produce improved characteristics. Of course, these methods are also used nowadays to clarify hereditary diseases in horses and to detect and limit these hereditary disease carriers before they are used for breeding. However, later in this paper, there will be more details about this topic [6].

2.2. Significance in Equine Breeding

Genomics plays a significant role in equine breeding, just as it does in the breeding of other species. They allow breeders to select horses with desirable traits at a much earlier age. Instead of waiting for observable characteristics, such as performance or conformation, genetic testing can reveal information about a horse's potential traits, including disease resistance, athletic ability, and temperament. By analysing an individual horse's genome, breeders can identify genetic markers for certain diseases or conditions, allowing for more informed breeding decisions to reduce the risk of passing these conditions to offspring. Genomics can provide valuable insights into an individual horse's pedigree and its genetic ancestry. This information can help breeders decide which mares and stallions to pair for optimal genetic diversity and quality [6].

Another critical point is using genomic data to calculate inbreeding coefficients, which measure the degree of relatedness between two horses. After common ancestors are identified, the relationship between the parents of the individual in question can be calculated. This helps breeders avoid excessive inbreeding, which can lead to the expression of undesirable recessive traits and health issues, like inbreeding depression. This commonly manifests in poor performance of complex traits (due to contributions of many different genes), such as fertility and athleticism [10].
Performance Prediction is also a pivotal point in breeding, and genomic information can help predict a horse’s potential performance in various equestrian disciplines. It can provide insights into speed, endurance, jumping ability, and more, allowing breeders to match horses with the desired performance attributes.

Furthermore, the appearance of the horse is equally important, so by studying the genetics of specific traits such as coat colour, gait or size, breeders can work to improve or change these traits within a breed if desired [9].
Another important area of application, which must be remembered, is the preservation of rare breeds. For rare or endangered horse breeds, genomics can be used to assess genetic diversity and to guide breeding programmes for the conservation of these breeds [11].

An example of such a breed is the “Altwürttemberger” (**Fig. 2**). Since 2013, the studbook has been closed, and the primary breeding objective is to preserve the remaining genes and to concentrate them in order to achieve the highest and most uniform gene content possible [12].

Figure 2: Altwürttemberger [13]

Genomics can significantly speed up breeding programs by identifying promising candidates at a young age and reducing the need for lengthy trial-and-error processes. Research in equine breeding continues to advance our understanding of horse genetics and genomics, leading to potential breakthroughs in disease resistance, performance enhancement, and animal welfare.
Overall, genomics in equine breeding empowers breeders to make more informed decisions, improve the health and performance of horses, and contribute to the sustainability and quality of horse breeds. It has the potential to enhance both the economic and sporting aspects of the equine industry [14].

3. Health and Performance Assessments

Health and performance assessments for showjumpers are essential to ensure the well-being of the horse and the rider, as well as to maximise their performance in this physically demanding sport. The competition career of a horse is relatively short but can be positively influenced by good management, a team of veterinarians, health experts and trainers [15]. Many riders have their horses checked annually before each upcoming season to ensure their sporting partners are in the best possible health. On the one hand, regular veterinary examinations are essential to monitor the general health of the horse. This includes vaccinations, dental care and routine physical examinations. Other examinations may include assessing the horse's heart and lung function to ensure it meets the demands of show jumping. Blood sampling can also be helpful to obtain a baseline sample or to investigate underlying problems. An essential aspect is any lameness problem, which should be detected through physical examinations and diagnostic tools such as X-rays, ultrasound or Magnetic Resonance Imaging (MRI) scans and treated accordingly. Hand trotting on hard and soft ground and a standard limb flexion test should be included in a physical examination. Also, working with an equine physiotherapist and chiropractor to keep the movement part of the horse strong and flexible shows positive effects. In this way, not only tensions in the musculature but also blockages can be eliminated [16].

Optimal feeding so that sufficient nutrients are available for their energy balance and an optimal metabolism also makes a significant contribution to the achievement of maximum performance. Horses belong to a group of animal species that base their digestion on a constant, slow, and not primarily carbohydrate based nutrient intake. This, in turn, means that the basis of optimal feeding should be sufficient access to quality roughage.

Another source of protein and energy is the administration of concentrated feed, but care should be taken not to overestimate this and to adapt it to the type and needs of the horse. Optimal feed management can also have a preventive effect on stomach ulcers, which can be observed more and more frequently in horses *[17].*

As we have already seen, many different aspects contribute to the success of a sport horse. In the following sections of this paper, various common diseases will be illustrated, as well as ways to prevent them. In addition, the performance of a sport horse will be discussed, and genetic ways to optimise it will be discussed, for example, in breeding [18].

3.1 Genomic Variation and Health

3.1.1 Genetic Markers for Health Conditions

Genetic markers for health conditions in sport horses can be crucial in identifying and managing potential risks or issues that may affect their performance and overall well-being. These markers can be used for both diagnostic and preventive purposes.

In recent centuries, intensive selection in horse breeding has led to a decline in genetic diversity, possibly through the inclusion of a limited number of influential stallions [19]. This decline is due to a substantial increase in deleterious alleles, also defined as mutational load, attributable to intensive selection. This intensive selection also includes the mating of related horses, called "inbreeding". The result can be inbreeding depression, i.e., reduced fitness of individuals due to deleterious recessive mutations present in the homozygous state./20].

This accumulation of deleterious alleles is an undesirable side effect of intensive selection in horse breeding. Genetic tests and thus also "marker tests" are important for the foundations of responsible breeding management and for finding and determining these carrier animals. Another important reason for using genetic markers is identifying genotypes responsible for certain inherited traits or diseases [21].

Hereditary diseases (syn. genetic disease, hereditary defect, hereditary defect) are diseases or peculiarities caused by changes in the hereditary makeup. A change in individual chromosomes (carriers of hereditary traits) or chromosome sections (genes) is responsible. Each chromosome and each gene can be changed. If the germ cell (egg or sperm cell) is affected by the DNA change (mutation), the mutation is passed on from one generation to the next. However, a hereditary defect can also occur spontaneously due to new mutations [13]. In general, a distinction can be made between monogenic and polygenic hereditary diseases, whereby they exhibit monogenic characteristics in the classical sense, which are inherited according to Mendelian rules. There are 28 known monogenetic diseases in the horse, of which 21 are recessively inherited [13].

Common examples of monogenic hereditary diseases are, for example:

1. *Hyperkalemic Periodic Paralysis (HYPP):* HYPP is a muscular disease caused by genetic mutation in the skeletal muscle sodium channel gene. It is inherited as an autosomal dominant trait; most affected horses are heterozygotes [22].

The clinical signs are muscle tremors or paralysis, which in severer cases can lead to collapse and sudden death due to cardiac arrest or respiratory failure *[23]*. However, horses with two copies of the genetic mutation (homozygous) are usually more affected than horses that have only one copy (heterozygous). A DNA test can find out how many copies of the HYPP mutation (H) and the "normal" (N) gene can be identified [23].

2. *Polysaccharide Storage Myopathy Type 1 (PSSM1):* PSSM is a degenerative muscle disease caused by a disorder of the sugar metabolism and a mutation of the Glycogen synthase 1 (GYS1) gene. Mostly horses with strong muscles are affected, such as Quater Horse, Paint Horse etc. They show symptoms such as reluctance to move, muscle tremors and tension.

   The disease occurs in many breeds and is inherited in an incomplete autosomal dominant manner [24].
3. *Severe Combined Immunodeficiency (SCID):* In SCID, foals are born with a severely weakened immune system. Affected foals have been found to have a mutation in the DNA-dependent protein kinase gene (DNA-PK), which codes for an enzyme that is crucial for the development of the immune system and the ability to protect against infection *[25]*. This disease is also inherited in an autosomal recessive manner and affected foals are unable to produce B and T lymphocytes and thus cannot develop a proper immune response. Unfortunately, there is no cure for these foals and due to their susceptibility to bacterial, viral, fungal and protozoal infections[21].
4. *Cerebellar Abiotrophy (CA):* CA is a genetic neurological condition of young horses, mainly Arabian breeds, and an autosomal recessive trait, which affects the cerebellum and causes a progressive death of neurons. Clinical signs generally recognized by six month of age and include head tremor, ataxia. The mutation of the target of Early growth response protein 1 (EGR1) is associated with CA and genetic tests are available for testing*[26]*.

The next figure shows all monogenic hereditary diseases in horses.

	Gene	Breeds
Androgen intensitivity syndrome	AR	Quarter Horse, Tennessee Walking Horse, Thoroughbred, Warmbloods

Cerebellar abiotrophy	MUTYH, TOE1	Arabian, Bashkir Curly Horse, Trakehner, Welsh Pony
Dwarfism	B4GALT7	Friesian Horse
Dwarfism, ACAN related	(ACAN)	Miniature Horse, Shetland Pony
Foal immunodeficiency syndrome	SLC5A3	Dales Pony, Fell Pony
Glycogen branching enzyme deficiency	GBE1	American Quarter Horse
Hereditary equine regional dermal asthenia	PBIB	American Quarter Horse
Hoof wall seperation disease	SERPINB1 1	Connemara pony
Hydrocephalus	B3GALT2	Belgian draft horse, Friesian horse
Hyperkalemic periodic paralysis	SCN4A	American Quarter Horse
Idiopathic hypocalcaemie / Hypoparathyroidism	RAPGEF5	Thoroughbred
Immune – mediated myositis	MYH1	American Quarter Horse
Junctional epidermolysis bullosa	LAMC2	Belgian, Italian draft horse, Trait Breton, Trait Comtois
Junctional epidermolysis bullosa	LAMA3	American Saddlebred
Malignant hyperthermia	RYR1	American Quarter Horse
Myotonia	CLCN1	New Forest pony
Naked foal syndrome	ST14	Akhal - Teke
Occipitoatlantaoaxial malformation	HOXD3	Arabian
Ocular squamous cell carcinoma	DDB2	Belgian, Haflinger, Percheron

Polysaccharide storage myopathy type 1	GYS1	American Paint Horse, Appaloosa, Draft, Quarter Horse, Warmblood
Severe combined immunodeficiency disease	PRKDC	Arabian
Skeletal atavism	SHOX	Shetland Pony
Warmblood fragile foal syndrome	PLOD1	Warmblood,Thoroughbred, Haflinger,Knapstrupper, American Sport Pony
Congenital stationary night blindness / Leopard Complex Spotting	TRPM1	AmericanMiniature Horse, Appaloosa, Australian Spotted Pony, British Spotted Pony, Knabstrupper, Noriker, Pony of the Americans, Thoroughbred
Lavender foal syndrome	MYO5A	Arabian
Melanoma / Gray	STX17	Many
Multiple Congenital Ocular Anomalies (MCOA) / Silver	PMEL	American Miniature Horse, Icelandic, Rocky Mountain
Overo lethal white syndrome (OLWS)	EDNRB	American Paint Horse, Miniature Horse, Pinto Horse, Quarter Horse, Thoroughbred

Figure 3: monogenic hereditary diseases

The table shows an overview of the most widespread polygenic diseases and in the following part of this work we will also go into more detail about individual diseases which are of great importance in show jumping.

Name	Clinical Signs	Pathogenesis	Hereditary, genetic defect
Osteochondrosis (OC)	(fast)growing horses filled joints and intermittent lameness	Disruption of ossification; thickening of cartilage; loosening	Breed, sex, feeding, growth, biomechanics. Estimated

		of pieces of cartilage or bone.	heritability varies between 0.01 and 0.52 and depends on localisation
Navicular Syndrome	Forehand lameness; relieving position, shortened gait	Two different approaches: ischaemia as the basic problem and degenerative disease	Breed, position. Estimated heritability ranges from 0.02-0.3
Bone spavin	Hind lameness. Very common in trotters and western horses.	Osteoarthrosis of the distal parts of the ankle joint	Positional defects (sabre-legged, steep stance). Heritability is estimated at 0.2-0.35
Wobblers syndrome	Increasingly male thoroughbreds affected. Weakness, spasticity, ataxia, incoordination and even falls.	Cervico-vertebral malformation leads to compression of the spinal cord	Breed, gender, growth and sometimes trauma
Equine Degenerative Myeloencephalopathy	Neurological disease of young horses, showing Ataxia	Degeneration of axons in the spinal cord and brainstem	Familial accumulation, Vit. E deficiency
„Tying up“	Myopathy, which mainly affects young thoroughbred mares	Abnormal muscle contraction possibly triggered by a disturbance of the intracellular calcium regulation.	Familial clustering in thoroughbreds, sex, work. Autosomal-dominant inheritance with variable

			expressivity suspected
Cribbing	Oral stereotypy. Thoroughbreds more often affected than warmbloods. Dressage and show jumping horses more often than endurance horses.	Sucking air into the cricopharynx produces what is known as cribbing	Breed, certain bloodlines, boredom, lack of social contact, stress
Recurrent airway obstruction (RAO)	Strained breathing, coughing, nasal discharge, especially in animals that are kept indoors most of the time.	Hypersensitivity reaction to fungal spores from hay and straw dust and other allergens	Hay feeding, bedding (allergenic). Genetic background confirmed.
Equine recurrent uveitis (ERU)	More common in trotters, warmbloods and appaloosas. Recurrent inflammation of the middle eye skin, can lead to blindness.	Autoimmune reaction against retinal autoantigens	Breeds
Sweet itch	Imported Icelandic horses most frequently affected. Seasonal pruritus especially on tail and mane.	Dermatitis based on a hyper-sensitivity reaction to insect bites	Familial cluster, breed
Equine sarcoid	Most common skin tumour.	Bovine papillomaviruses	Race, familial accumulation,

	QH Appaloosas and Arabians more frequently affected than warm-blooded horses.	type 1 and 2 are involved in the disease	deficient immune system
Melanoma	Tumour affecting about 80% of older grey horses. Often perianal and in the nuchal crest	Originate from melanocytes, but pathogenesis largely unclear	Connection with the progressive greying of grey horses

Figure 4: widespread polygenic diseases

3.1.2 Insights into Hereditary Health Issues and breed-specific health conditions in Holstein and Hanoverian horses

Holstein and Hanoverian horses are two distinct breeds, and they may be prone to different hereditary health issues and breed-specific conditions. However, there are also genetic diseases that affect both breeds. These may be more common in sport horses.
The previous part of the paper has already covered general information about genetic diseases and the categorisation of monogenetic and polygenetic hereditary diseases. This part is primarily concerned with highlighting the diseases that frequently occur in these breeds, but also deals with sport horses in general. The breed-specific diseases are then described [13].

The following diseases are among the most common polygenic hereditary diseases:

1. *Osteochondrosis (OC)*: Osteochondrosis is a group of developmental orthopedic diseases. One of the most common forms of osteochondrosis is Osteochondrosis dissecans (OCD), which is thought to be associated with a failure of cell differentiation in the growing cartilage, which can lead to thickening, retention and cracking. This combination then leads to a focal loss of cartilage flaps into the joint cavity and later these fragments can impede the horse's movement and, in the worst case, lead to severe joint inflammation which can later lead to osteoarthritis [27]. This process is usually only active in horses in the first year after birth. In warmbloods, these fragments are usually found in the tarsocrural joint and occur

when young horses are challenged in sport for the first time. OCD is not only a health risk but also an economic loss as it drastically reduces the athletic performance of competition horses. For this reason, attention is paid to the detection of OCD when selecting horses for breeding [27]. There is evidence of inheritance with frequencies between 0.2 and 0.64 depending on the localisation of the osteochondrosis lesion and the breed of horse [28]. In one study, data were collected from 211 Hanoverian horses from 14 paternal half-siblings to identify a quantitative trait locus (QTL) for OC and OCD. QTLs were found on equine chromosomes two, four, five and 16, and the QTLs for fetlock OC and hock OC partially overlapped on the same chromosome, which may indicate a tendency for genetic correlation[29].

2. *Navicular Disease*: This disease is a bilateral, chronic, progressive lameness of the forelimbs [30].The average clinical age of these horses is usually between seven and nine years, with geldings more commonly affected than mares and stallions. There appears to be a breed specific predisposition to Navicular disease in warmbloods and American Quarter Horses in particular. The prevalence in warmbloods ranges from 14.9% to 87.6%, with Bavarian, Hessian, Holstein and Trakehner warmbloods being more affected than Hanoverian and Oldenburg. Again, a polygenic familial predisposition is suggested [31].
3. *Bone spavin*: This disease is also known as hock osteoarthritis and is a common degenerative joint disease that primarily affects the hock joint. This condition can cause lameness and pain in affected horses. Bone spavin usually develops as a result of gradual degeneration of the hock joint over time. The exact cause can be multifactorial, including genetic predisposition, deformity, high physical activity, trauma and chronic wear and tear [32]. A polygenic predisposition with a heritability of 0.2 to 0.25 is known. In addition, not only sport horses are affected, but also many other breeds [31]. These horses show several signs and symptoms, including lameness, which usually increases with movement or turning, especially on hard or uneven surfaces. Other signs may include swelling, hyperthermia and pain around the affected hock, as well as limited mobility [32].

Other polygenic diseases are e.g., Equine Recurrent Uveitis (ERU), Recurrent Airway Obstruction (RAO), Wobbler syndrome, Recurrent laryngeal neuropathy (RLN) and Equine sarcoid.

But there is another important disease that must not be forgotten, and that is the Warmblood fragile foal syndrome (WFFS). WFFS is a monogenetic autosomal recessive disorder caused

by a mutation in the procollagen lysine-2-oxoglutarate 5-dioxygenase 1 gene (PLOD1) that results in the production of structurally abnormal type 1 collagen, a protein essential for the development of connective tissues such as skin, tendons, ligaments and other organs in the body [33]. Foals affected by WFFS (**Fig.5**) are born with extremely fragile and thin skin that is prone to tearing and blistering at the slightest physical contact or pressure. These foals often suffer from severe wounds and skin lesions, making it extremely difficult for them to survive. In addition to skin problems, the condition can affect the connective tissue in other parts of the body, causing problems with joints, tendons and ligaments [34]. To prevent the birth of affected foals, responsible breeding practices in warmblood and related breeds include genetic testing of potential breeding animals to identify carriers of the WFFS mutation. By avoiding the pairing of two carriers, breeders can reduce the risk of producing foals with this debilitating disorder. Education and awareness among breeders have played a significant role in managing and preventing WFFS in affected horse populations[34].

Figure 5: WFFS [7]

3.2. Genomic variation and performance

3.2.1. Genetic markers for Athletic Performance

Genetic markers for equine athletic performance are the subject of ongoing research, and our understanding of the genetic factors that influence equine athletic performance continues to

evolve. The phenotype of the domestic horse (Equus caballus) has been modified by intensive selection for speed, endurance, or traction, resulting in a variety of adaptive changes necessary for peak athletic performance.

For exceptional athletic performance, horses have several functional and structural adaptations, including the development of muscle mass, increased blood oxygen-carrying capacity, buffering and transport capacity for CO2, intramuscular storage of energy substrates (especially glycogen), lactate removal capacity of the liver and muscles, and effective utilisation of evaporation for thermoregulation.

So far, however, only little research has been carried out using molecular genetic analyses. Although there is no single "athleticism gene" for horses, several genetic markers and factors have identified that may contribute to a horse's athletic potential [35].

1. *Muscle Fiber Type*: Different types of muscle fibers can affect a horse's performance. Fast-twitch muscle fibers are associated with explosive power and are important for jumping. Genetic variations in genes like Myostatin (MSTN) can influence muscle fiber composition. The MSTN gene regulates muscle growth. The muscle mass and strength of a horse can be influenced by variations in the MSTN gene. Sprinting ability and endurance are different variations. For example, MSTN polymorphisms in thoroughbred horses are associated with their ability to run certain race distances [31]. A 2010 in 2010, was the first to find an MSTN sequence polymorphism in these horses. This polymorphism correlated in particular with the speed and the best racing distance of top horses [36].
2. *Joint Health Genes*: Genes associated with joint health and soundness are crucial for showjumping horses to minimize the risk of injuries. Variations in genes affecting joint integrity may indirectly influence a horse's performance. For example, The Collagen alpha-2(IX) chain (COL9A2) gene in horses is responsible for a specific type of collagen. It's found on horse chromosome 2p16-->p14, and it's linked to a trait called osteochondrosis. In a study they obtained a clone of this gene and analysed its complete genetic structure [37]. By analysing eight unrelated Hanoverian warmblood stallions, they found 32 tiny genetic variations (SNPs) scattered throughout the gene. One of these variations alters the structure of the protein. They compared the COL9A2 gene in horses with the same gene in humans, mice, and rats. The location of the gene in the horse chromosomes is consistent with what they know about genetic relationships in different species. When they looked at the structure and instructions of the gene, they found that it is quite like the same

gene in other mammals. To understand how this gene is related to osteochondrosis in horses, they selected three specific genetic variations (SNPs) that they tested in 44 to 75 Hanoverian warmblood horses from different families. Unfortunately, the results showed no significant association between COL9A2 and osteochondrosis in these horses. Although this study was not successful, it shows that there are many attempts to recognise problems such as OC using genetic markers and to solve them prematurely. Although this study was not successful, it shows that there are many attempts to recognise problems such as OC using genetic markers and to solve them prematurely [37].

3. *Cardiorespiratory Fitness:* A horse's ability to oxygenate its muscles during exercise is critical for endurance and jumping. Genes related to oxygen carrying capacity and cardiovascular health may be important. The horse's aerobic capacity and oxygen uptake are outstanding compared to other species of similar size and are characterised by a remarkable oxygen transport capacity and supply. Elevated VO2max levels, substantial cardiac output, expansive stroke volumes, and elevated haemoglobin concentrations are indicative of the robust aerobic capacity exhibited by equine [35]. Another study focused on angiotensin-converting enzyme (ACE), comparing horses and humans, as circulating ACE levels are similar. Angiotensin-converting enzyme (ACE) plays a central role in the renin-angiotensin system and has a significant influence on the regulation of blood pressure, renal function and male reproductive potential [38].
4. *Tendon and Ligament:* The equine distal limb is predominantly characterised by a single digit, a feature that simplifies the anatomical configuration of tendons and ligaments. In this context, the extensor tendons are subjected to relatively modest loads, whereas the flexor tendons are subjected to significant weight-bearing demands. This adaptation of tendon and ligament structures facilitates fast and efficient locomotion, resulting in a longer stride length and reduced energy expenditure during hind limb extension. Collagen is an essential component of tendons and ligaments. Variations in genes related to collagen production and quality could influence a horse's susceptibility to injury and, indirectly, its performance in show jumping [39].

3.2.2. Training and Performance Optimisation

Genomic variations in show jumping horses can play an important role in their training and performance optimisation. These variations can influence factors such as agility, speed, strength, endurance and even their susceptibility to certain health problems. The following approaches are conceivable to utilise this genetic information for training and performance enhancement. Firstly, as mentioned above, DNA testing can be used to identify specific variations associated with athletic performance in horses. Some companies offer genetic tests that can identify traits relevant to show jumping, such as muscle development, endurance and bone density [40]. It is also useful to consider different breeding strategies, such as selective breeding. This genetic information can be used to make informed breeding decisions. Breeding horses with favourable genetic variation for jumping can increase the chances of producing offspring with increased performance potential. Analysing the pedigree of horses to understand genetic ancestry and heritable traits can also help to breed successful bloodlines. This can help to identify successful bloodlines and make better breeding decisions [9]. Optimum training and conditioning can help trainers understand a horse's genetic make-up and develop tailored training programmes. For example, if a horse has genetic traits that indicate agility, the focus should be on exercises that promote these traits. Diets also play an important role as genomic variations can affect a horse's nutritional needs. Therefore, feeding should be adjusted based on genetic data to optimise muscle development and overall health [17]. Using genetic information to track a horse's progress and adjust training strategies where necessary. Genomic data can help trainers and riders better understand the potential and limitations of their horses.

It is also helpful to keep up to date with the latest research and development. New scientific findings can provide new insights into the genetic factors that influence show jumper performance. It is important to note that while genetic information can be a valuable tool in optimising the performance of show jumpers, other factors such as training, environment and rider ability are equally important. The genetic component is only one piece of the puzzle, and a holistic approach is required for success in the sport [41].

4. Overview of the successful breeds in showjumping

4.1. Holsteiner
4.1.1 History

The Holsteiner horse is a warmblood breed known for its athletic ability, strength, and versatility. It has a rich history dating back centuries in the Holstein region of northern Germany. The story begins in 1225, when Gerhard I, count of Schleswig-Holstein and Stormarn, granted the monastery of Uetersen the right to graze its horses on the pasture of the county of Pinneberg [9]. Since jousting tournaments were very popular at that time, the horses were not only kept in the pastures, but they also began to breed. The horses were initially used as work animals in agriculture, which means that surefootedness and a muscular physique were essential prerequisites for being able to work in the marshes along the Elbe *[4*3].
These properties were then also recognised and used by the military. The coat colour of the Holsteiner at that time was predominantly brown. In the 18th century, they were not only known for their willingness to perform but also caused a sensation as luxury carriage horses with their outstanding gaits (**Fig.6**) *[*44].

Figure 6: Luxury carriage [44]

Only in the 19th century, the Elbe marshes began to select horses in order to breed the best possible heavy warmblood horses for agriculture and the army. Yorkshire Coach horses, for example, were used to achieve this*[*44*]*. The “Verband der Pferdezuchtvereine in den Holsteiner Marschen” was founded in 1883 and then merged in 1935 with the "Verband des

Schleswig-Holsteiner Geestlandes", founded in 1896, to form the "Verband der Züchter des Holsteiner Pferdes" who is still present nowadays (**Fig.7**) *[42]*.

In 1944, the Brand mark was introduced. Until 1960, the breeding objective was to breed intense riding and driving horses. However, times changed, and in the 1950's, modernisation changed everything. Machines replaced the working horses, and the number of Holstein mares decreased to 1311, which is why the Schleswig-Holstein state parliament dissolved the Traventhal State Stud. Over the years, a stallion depot was built up in Elmshorn from the stallion stock taken over from Traventhal [42]. In the 20th century, the focus was on refining the breed's characteristics to create a horse that excels in show jumping and dressage. To do this, Holsteins were crossed with Thoroughbreds, Anglo-Arabians and other warmblood breeds to introduce speed, agility and refinement while maintaining the breed's strength and resilience. One of these famous thoroughbreds was Ladykiller xx, born in England [44]. In the following sections, there will be more details about this and other remarkable horses from this breed [44].

Figure 7: Holsteiner Verband logo [44]

4.1.2 Description of the Breed

To ensure that the Holstein breed remains pure breeding, the Holsteiner Breeders' Association keeps a studbook on the origin of the Holsteiner horse breed. The breeding program of the Holstein horse comprises all measures which are suitable to achieve breeding progress regarding the breeding objective and the characteristics of the breed, as far as they comply with the Animal welfare regulations.

The Breeding goal of the "Holsteiner Verband" includes a rideable, versatile, willing and capable riding horse, which is mainly suitable for show jumping but also has a talent for dressage and eventing [45].

To recognise these performance predispositions in the stallions, the following characteristics are checked and evaluated before entry in the stud book. These characteristics are character and temperament, rideability, basic gaits and jumping.

According to the Statutes of the "Verbandes der Züchter des Holsteiner Pferdes e. V.“, a Holsteiner is at least 164 cm tall, has predominantly bay horses and shows a large frame, with an athletic appearance, a correct build, with a raised posture and good neck carriage [46]. Due to the influence of the thoroughbred, an impressive head with large eyes and good muscling is desired, whereas a clumsy or unathletic appearance and a coarse head are undesirable [46]. When jumping, a Holsteiner should be wealthy, elastic, and deliberate, showing composure and intelligence.

With these characteristics and traits, it is not surprising that this breed is highly recognised by riders and breeders worldwide and that we see them every weekend at top international shows [46].

4.1.3 The most Important Bloodlines

The Holsteiner horse breed is known for its solid and influential bloodlines that have contributed to its success in show jumping and other equestrian disciplines. While there are many important bloodlines within the Holsteiner breed, it is essential to note that the importance of a bloodline can vary depending on the specific discipline and the goals of a breeder or rider.

Nevertheless, there are a few historically significant and influential Holsteiner bloodlines which should be mentioned [47]

Figure 8: Ladykiller xx [48]

As already mentioned in the history of the Holsteiner, the stallion *Ladykiller xx* **(Fig.8)** belongs to one of the most influential sires of this breed, which not only played an essential role in the past but also still today and, as a thoroughbred, contributed to the modernisation of the formerly heavy workhorse to a modern sport partner. He was born in England in 1961 and approved in Holstein in 1965. He sired 35 state premium mares and the same number of approved stallions, among them *Landgraf I*, who was awarded a statue before the stables at Elmshorn and is one of the most renowned Holsteiner stallions, known for producing top-level show jumpers, like Libero H, Landadel and Landor S (**Fig.9)**[45].

Furthermore, his bloodline has had a lasting impact on the Holsteiner breed and the world of show jumping. His descendants continue to be sought after for their jumping ability and athleticism, making him a key figure in the history of Holsteiner horse and equestrian sport [45].

Figure 9: Landgraf [49]

Until today, *Ladykiller's xx* offsprings have won more than 7 million marks in the sport, and his numerous sons and daughters are passing on the precious blood [45].

Lord, the second outstanding offspring of *Ladykiller xx* and a *Cottage-Son xx* dam, competed in the first years under Herbert Blöcker not only in breeding but also in heavy hunter jumping and the international military. He also produced numerous internationally successful sons for show jumping, such as *Livius,* who was successful under Peter Luther *[50].*

In the last part of the work, we talked about the L-line, but one must also keep an eye on the so-called L-line.

The basis of this line is the French-bred dark bay stallion *Cor de la Bryere*, born in France in 1968 by *Rantzau xx* out of the dam *Quenetto* by *Lurioso-Furioso xx*.

At the beginning of the 1970s, the crossing of thoroughbreds in Holstein breeding peaked. At that time, France was very successful in international show jumping, and many of these successful horses were in the 2nd and 3rd generation of Thoroughbred stallions, which had the same blood as *Ladykiller xx* or *Cottage Son xx*, for example. As the Holsteiner breeding management was looking for a sire who would improve the jumping manner, they got the opportunity to go to France through the mediation of Alwin Schockemöhle and Francois Mathy and to look at and lease *Urioso,* a son of *Furioso xx.* During this journey, a three-year-old stallion was discovered, which was not yet well developed but already showed much quality. This stallion was *Corde (***Fig.10***),* as he was affectionately called, and so he was licensed in Holstein in 1971 and was one of the best in his age group. To this day, he is regarded as a stallion of the century of unique breeding quality and inspired by his elegance, very good muscling, and excellent jump, but also his enormous ability to learn and his willingness to perform. *Corde* died in 2000 but left 1456 foals, 85 approved sons, and 569 mares in the first studbook, from which 84 were recognised Elite. Around 80 % of all Holsteiner pedigrees enclose the genes of *Cor de la Bryère [*51*].*

Figure 10: Cor de la Bryére [52]

At the same time, his sons greatly influenced sport horse breeding, such as *Caletto I*, who won many successes at international shows and the team bronze medal at the European Championships in 1983. However, he was also essential as a stallion, producing 19 licensed sons and 103 registered broodmares. Well-known names are, for example, *Cambridge and* his genetics, who are also responsible for *Chambertin* and his son *Chacco Blue,* who is now a current sire of many horses in Oldenburg and is an indispensable part of the breeding programme.

An even more successful offspring of *Cor de la Bryere* was *Caletto II*, who produced the elite stallion *Cadillac*, born in 1984, and *Caretino,* who was ridden by one of the most successful show jumpers, Ludger Beerbaum. His most famous offspring *is Casall,* who celebrated many victories and placings in international 5-star competitions, such as the Global Champions Tour, under Rolf-Göran Bengtsson (**Fig.11**) [53].

The mare *Tabelle* brought another brother dynasty to light, namely *Calypso I to V.* Especially *Calypso II* should be mentioned, who also built up his own man line through his son *Contender.* However, these were not isolated cases, and he was also able to produce the two very successful stallions *Corrado I and II* with the mare *Soleil by Capitol*. *Corrado I*, found a new line with his jumping ability, especially with his grandson *Cornet Obolensky [54].*

Figure 11: Casall [53]

4.2. Hanoverian

4.2.1. History

The history of the Hanoverian can be traced back to the 16th century and originally comes from the state of Lower Saxony, whose capital city is Hanover. As in the history of the Holsteiner, this breed was also initially bred for agriculture and military purposes. King George II founded the Celle State Stud in 1735. Not only were stallions made available to the rural breeders in Hanover, but all studs were registered, and foal certificates were issued. In addition, until about 1870, the focus was on the refinement of the Hanoverian by crossing with English thoroughbreds and half-breeds [55].

The predecessor of the Hanoverian Association was the "Hannoversche Stutbuch für Edles Warmblut ", which was only founded in 1888, and the structure of district associations and delegates has remained until today. Gradually, the Association of Hessian Horse Breeders and a part of the Reihnian horse stud book joined this Association. Today, the main office is in Verden, where the stud books are kept, and all equine passports are issued.

Remarkably, no European association has as many registered associations as the Hanoverian Association (**Fig.12)** [56].

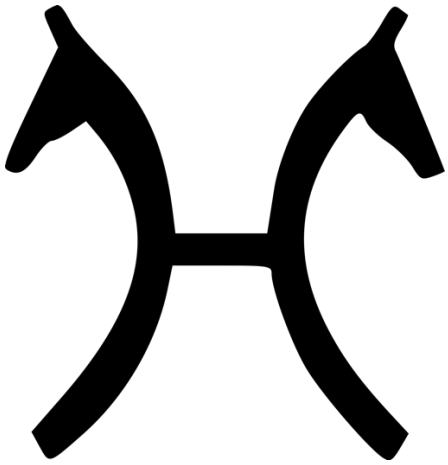

Figure 12: Branding of the hanoverian [57]

During the industrialisation, the horses were replaced as working animals. The focus was put on the breeding of sport horses by using thoroughbreds. This time also, Trakehners and those further refinements of the genetic pool progressively produced the modern Hanoverian horse we know today. The aim was to breed an elegant horse with a trainable temperament, a strong back and athletic movements *[58].*

An excellent example for many other breeding associations and marketers is the Verden auctions, which have existed since 1949, and Joachim Köhler was the one who laid the foundation stone. They still take place in the Niedersachsen Halle, and around 900 horses are auctioned here every year. Nevertheless, not only breeding and marketing but also consulting, science and research are essential activities of the Association. Therefore, it is not surprising that this breed is sought after worldwide. They have also been placed in the top five internationally in show jumping and third in eventing, as ranked by the WBFSH (World Breeding Federation for Sport Horses) and the Fédération Équestre Internationale (FEI) since standings began to be published in 2001 [58] . "Everyday life is about being an important support for our breeders, and our members drive their breeding forward with passion, love for horses, tact and individual ideas!" Says the President of the Hanoverian Association, Dr. Hinni Lührs-Behnke [56].

4.2.2 Description of the Breed

The Hanoverian horse is a warmblood breed that originated in Germany and is renowned for its exceptional qualities as a sport horse. This breed is highly regarded for its athleticism, temperament, and versatility, making it a popular choice in various equestrian disciplines.

The Hanoverian Association keeps the stud book on the origin of the Hanoverian breed to the requirements of the EU and the German animal breeding law*[59]*.

In order to ensure that breeding progress is made towards the breeding objective, the Association's breeding programme, like that of the Holstein, covers all measures.

A horse must be bred, suitable as a performance and leisure horse due to its inner qualities, rideability, outer appearance, movement, jumping disposition and health.

A Hanoverian should be around 168cm tall. A noble and performance-ready type with precise contours and great lines is desired. They have a well-shaped head with expressive eyes, and the neck is long and muscular, blending smoothly into well-sloped shoulders. Moreover, the body is deep and compact, with a strong back and well-muscled hindquarters, and the legs are sturdy and have a robust and dense bone structure, which provides durability and support for athletic endeavours.

The temperament of this breed is described as willing, intelligent and cooperative, making them easy to train and handle. They have a good work ethic and are calm and level-headed in various situations.

Due to their great movement, it is no wonder that they are not only prevalent in show jumping but are also indispensable in dressage. Fluid gaits characterise this with a particular emphasis on the trot and canter. They have a ground-covering trot with good suspension and an elegant, expressive canter.

If one looks at the breeding objective of the Hanoverian Association, the horse should show a balanced, elastic, courageous and capable jumping manner. Over the jump, it is essential to have a quick footing, a pronounced bending of the limbs and good reflexes.

Of course, over the jump, the back should arch up, and the hindquarters should open *[59]*.

In summary, Hanoverian horses are known for their attractive appearance, exceptional temperament, impressive movement, and versatility in equestrian sports. They are a sought-after breed for riders and competitors looking for a capable and willing equine partner [59].

4.2.3. The Most Important Bloodlines

As mentioned in the Description of the breed, the Hanoverian is known for its many successes in various disciplines, such as dressage, eventing or show jumping. Although it is difficult to identify a single "most important" bloodline within the Hanoverian breed, there are several influential bloodlines that have made a significant contribution. These bloodlines are often characterised by outstanding sires and mares that have produced exceptional offspring.

In order to represent these lines more efficiently, they can be divided into different categories.

The first category describes the classical, old Hanoverian lines: A/E-Line, F-Line, D-Line and G-Line*[60]*.

The A-line was founded by the thoroughbred *Adeptus XX*, who was used in breeding from 1884-1904 and produced the stallion, *Alderman*. However, this line lost importance after 1950 and changed to the E-line. One of the most famous sires of this line is *Escudo I*, primarily through his offspring in show jumping. A good example is *Embassy II*, which collected several successes in show jumping under Hans Dieter Dreher. This line is also successful in eventing. For example, *SAP Escada FRH*, a daughter of *Embassy* under Ingrid Klimke, became the European team champion in 2013 and the team world champion in 2014. For a while, the E-line had also lost its importance. However, in the world of dressage breeders, there is talk about the stallion *Escolar*, who descends from another old Hanoverian line that established itself in Westphalia (**Fig.13**) [60].

Figure 13: New breeding star Escolar [61]

The D-line is one of the most widespread dressage lines in the world. Due to its great popularity, a few words must be devoted to this line, although this work is more concerned with showjumping and its horses. This line was founded by a thoroughbred *Devil's own xx*, who stood in Celle from 1894 to 1906. Every pardoned dressage rider has heard of the name *Donnerhall*. A son of *Donnerwetter* by *Disput/matador* (**Fig.14*).* This is not surprising, as he was one of the most successful dressage horses in the world in his time and could collect gold medals in European and world championships. Together with his son *De Niro*, they made this line the most successful worldwide *[62].*

Figure 14: Donnerhall [63]

Although this line is more known for its offspring in dressage, it also has good jumping sires such as the stallion *Diskus* or *Dynamo.*

The thoroughbred stallion *Goldschaum xx* born in 1891 founded the G-line. This line produces horses with an enormous willingness and ability to work and are highly successful in show jumping and dressage. The two stallions, Grande and Gotthard, dominated the world of competition in the 50s to 70s. Not only Gotthard was a vital sire of highly successful jumpers such as *Glückstern* and *Glückspilz*. *Goldfever* is a well-known name (**Fig.15),** and with his rider, Ludger Beerbaum, he collected unforgettable successes and lifetime earnings of more than 2.3 million Euros. However, Grande should not be forgotten with his grandson, *Grannus,* who was once the most essential jumping sire in the world *[62].*

After the Second World War, original Trakehner stallions were used to improve the breed and founded a new stallion line that still exists today. The best-known descendant of this line is *Stakkato,* who can be traced back to *Semper Idem* and belonged to one of these Trakehner

stallions. *Stakkato* is an absolute sire legend and had his breakthrough in 1998 at the "Bundeschampionat", which he won at the age of five.

In 2019, at 30, he died by his rider, Eva Bitter. She collected titles with him at the German Championships and many national and international victories.

His breeding achievements include 76 licensed stallions, 104 state premium mares and 246 successful offspring in advanced (S) level show jumping competitions. Since 2001, *Stakkato* has been part of the top show jumpers of the integrated breeding value assessment. His offspring include names such as *Stolzenberg* and *Stakkato Gold [64].*

An already well-known name is also found in Hanoverian blood, the stallion *Cor de la bryere*, already mentioned in the bloodline of the Holsteiner.

In the 1980's, Holstein genetics was approved for Hanoverian breeding. *Calypso II,* a son of the famous *Cor de la Bryere*, was the first Holstein stallion to enter the Celle State Stud, and his blood is still widespread in Hanoverian breeding, as *are Chacco-blue, Calido* and *Cornet Obolensky.*

The French thoroughbred stallion *Furioso xx* is one of the founders of the F-line. His most famous son is *Furioso II*, who first came to Oldenburg as a refinement stallion but was later recognised and used in Hannover. One of his most famous offspring is *For Pleasure*, who descends from a dam by *Grannus.* The stallion *Voltaire,* another offspring of *Furioso II,* founded a stallion line in the Netherlands and produced the successful *Kannan [62].*

Figure 15: Goldfever [65]

5.Conclusion

The examination of the current genomic data of health and performance in German show jumping horses is a culmination of the extensive research and analysis presented in this study. Through the exploration of genomic models and techniques in the context of equine health and performance, we have been able to delve into the intricate details of this topic.

In this journey, we have uncovered the significance of genomics in equine breeding, emphasizing its transformative potential for the industry. The assessment of genomic variation in equine health has not only identified genetic markers for health conditions but also shed light on hereditary health issues, including breed-specific conditions in Holstein and Hanoverian horses.

Furthermore, we have closely examined the genomic variation in equine performance, dissecting the genetic markers associated with athletic success, specifically in showjumping. This has not only provided insights into the genetic foundations of performance but also the prospects for optimizing training and enhancing overall equine performance.

To put the German show jumping horses into perspective, we have offered an overview of the most successful breeds, Holsteiners and Hanoverians, highlighting their historical backgrounds, breed descriptions, and the vital bloodlines that have contributed to their prominence in the show jumping world.

The culmination of this content-rich exploration has allowed us to gain a deeper understanding of the role genomics plays in the health and performance of German show jumping horses, providing valuable insights for breeders, trainers, and researchers as they seek to unlock the full potential of these remarkable equine athletes.

6. Acknowledgement

I thank my supervisor, Dr.Zöldag Laszlo, for his continuous support and feedback throughout this process. I would also like to thank the University of Veterinary Medicine in Budapest for the last 6,5 years, allowing me to live my dream and work as a vet. Finally, I would like to thank my Family, especially my mother and father, without whom these study years would never been possible.

7. Bibliography

Polygenic diseases in horses are health conditions that result from the interaction of multiple genes (polygenic traits), as well as environmental factors (multifactorial traits), which additionally influence the phenotypic expression of a trait. For these reasons, the Mendelian principles of inheritance can no longer be directly observed in the phenotype of quantitative traits. These diseases often have a complex inheritance pattern, making it challenging to predict their occurrence or severity 1. Chowdhary BP (2013) Defining the Equine Genome: The Nuclear Genome and the Mitochondrial Genome. In: Chowdhary BP (ed) Equine Genomics, 1st ed. Wiley, pp 1–9

2. Barrey E (2010) Reviewe: Genetics and genomics in equine exercise physiology: an overview of the new applications of molecular biology as positive and negative markers of performance and health. Equine Vet J 42:561–568. https://doi.org/10.1111/j.2042-3306.2010.00299.x

3. G N Breeding Basics: Understanding the Equine Pedigree. https://horserookie.com/horse-pedigree-terminology/. Accessed 23 Oct 2023

4. Sire Rankings. https://wbfsh.com/sire-rankings. Accessed 21 Oct 2023

5. Chacco-blue. https://www.horsemagazine.com/thm/2022/09/chacco-blue/. Accessed 2 Nov 2023

6. Bellone RR, Avila F (2020) Genetic Testing in the Horse. Vet Clin North Am Equine Pract 36:211–234. https://doi.org/10.1016/j.cveq.2020.03.003

7. Reiter SV (2022) Mendelian traits in horse breeding: studying the background of roan coat color and the distribution and origin of the allele causing Warmblood Fragile Foal Syndrome (WFFS). Ludwig-Maximilians-Universität München

8. Umstellung der Abstammungskontrolle beim Reitpferd

9. Szymanski N (2022) Das Pferde-Genom. https://www.cavallo.de/medizin/genomische-selektion-in-der-pferdezucht/. Accessed 23 Oct 2023

10. Bailey E, Kalbfleisch T (2020) Inbreeding and Genomics. https://equine.ca.uky.edu/index.php/content/inbreeding-and-genomics. Accessed 21 Oct 2023

11. Dell A, Curry M, Hunter E, Dalton R, Yarnell K, Starbuck G, Wilson PB (2021) 16 Years of breed management brings substantial improvement in population genetics of the endangered Cleveland Bay Horse. Ecol Evol 11:14555–14572. https://doi.org/10.1002/ece3.8118

12. Krumbiegel DrC Der Altwürttemberger. https://hul.landwirtschaft-bw.de/pb/,Len/About+Marbach+State+Stud/Erhaltungszucht+Altwuerttemberger. Accessed 20 Oct 2023

13. Mele M, Ramseyer A, Burger D, Brehm W, Rieder S, Marti E, Straub R, Gerber V (2008) Erbkrankheiten beim Pferd: II. Polygen vererbte oder multifaktorielle Erkrankungen. Schweiz Arch Für Tierheilkd 150:173–180. https://doi.org/10.1024/0036-7281.150.4.173

14. Veerkamp RF, Haas Y de (2022) Proceeding of 12th World Congress on Genetics Applied to Livestock Production (WCGALP): Technical and species orientated innovations in animal breeding, and contribution of genetics to solving societal challenges. Wageningen Academic Publishers, The Netherlands

15. Rogers C, Bolwell C, Gee E (2012) Proactive Management of the Equine Athlete. Animals 2:640–655. https://doi.org/10.3390/ani2040640

16. Schroller D (2022) Physiotherapie, Osteopathie und Chiropraktik: Was wann wirkt. https://www.equitana.com/essen/de-de/blog/gesundheit/sprechstunde-manuelle-therapien.html. Accessed 21 Oct 2023

17. (2020) Hilfe vom Tierarzt: «Wie füttere ich mein Sportpferd?». https://www.ufarevue.ch/nutztiere/wie-fuettere-ich-mein-sportpferd#:~:text=Basis%20einer%20erfolgreichen%20Fütterung%20ist,gar%20eine%20ad%20libitum%2DHeufütterung. Accessed 21 Oct 2023

18. Szmatoła T, Gurgul A, Jasielczuk I, Oclon E, Ropka-Molik K, Stefaniuk-Szmukier M, Polak G, Tomczyk-Wrona I, Bugno-Poniewierska M (2022) Assessment and

Distribution of Runs of Homozygosity in Horse Breeds Representing Different Utility Types. Anim Open Access J MDPI 12:3293. https://doi.org/10.3390/ani12233293

19. Fages A, Hanghøj K, Khan N, Gaunitz C, Seguin-Orlando A, Leonardi M, McCrory Constantz C, Gamba C, Al-Rasheid KAS, Albizuri S, Alfarhan AH, Allentoft M, Alquraishi S, Anthony D, Baimukhanov N, Barrett JH, Bayarsaikhan J, Benecke N, Bernáldez-Sánchez E, Berrocal-Rangel L, Biglari F, Boessenkool S, Boldgiv B, Brem G, Brown D, Burger J, Crubézy E, Daugnora L, Davoudi H, De Barros Damgaard P, De Los Ángeles De Chorro Y De Villa-Ceballos M, Deschler-Erb S, Detry C, Dill N, Do Mar Oom M, Dohr A, Ellingvåg S, Erdenebaatar D, Fathi H, Felkel S, Fernández-Rodríguez C, García-Viñas E, Germonpré M, Granado JD, Hallsson JH, Hemmer H, Hofreiter M, Kasparov A, Khasanov M, Khazaeli R, Kosintsev P, Kristiansen K, Kubatbek T, Kuderna L, Kuznetsov P, Laleh H, Leonard JA, Lhuillier J, Liesau Von Lettow-Vorbeck C, Logvin A, Lõugas L, Ludwig A, Luis C, Arruda AM, Marques-Bonet T, Matoso Silva R, Merz V, Mijiddorj E, Miller BK, Monchalov O, Mohaseb FA, Morales A, Nieto-Espinet A, Nistelberger H, Onar V, Pálsdóttir AH, Pitulko V, Pitskhelauri K, Pruvost M, Rajic Sikanjic P, Rapan Papeša A, Roslyakova N, Sardari A, Sauer E, Schafberg R, Scheu A, Schibler J, Schlumbaum A, Serrand N, Serres-Armero A, Shapiro B, Sheikhi Seno S, Shevnina I, Shidrang S, Southon J, Star B, Sykes N, Taheri K, Taylor W, Teegen W-R, Trbojević Vukičević T, Trixl S, Tumen D, Undrakhbold S, Usmanova E, Vahdati A, Valenzuela-Lamas S, Viegas C, Wallner B, Weinstock J, Zaibert V, Clavel B, Lepetz S, Mashkour M, Helgason A, Stefánsson K, Barrey E, Willerslev E, Outram AK, Librado P, Orlando L (2019) Tracking Five Millennia of Horse Management with Extensive Ancient Genome Time Series. Cell 177:1419-1435.e31. https://doi.org/10.1016/j.cell.2019.03.049

20. Hill EW, Stoffel MA, McGivney BA, MacHugh DE, Pemberton JM (2022) Inbreeding depression and the probability of racing in the Thoroughbred horse. Proc R Soc B Biol Sci 289:20220487. https://doi.org/10.1098/rspb.2022.0487

21. Brain DrM (2021) The benefits of genetic testing. https://eqlifemag.com.au/issues/65/the-benefits-of-genetic-testing/. Accessed 21 Oct 2023

22. Naylor JM (1994) Equine hyperkalemic periodic paralysis: review and implications. Can Vet J Rev Veterinaire Can 35:279–285

23. Young A (2019) Hyperkalemic periodic paralysis (HYPP). https://ceh.vetmed.ucdavis.edu/health-topics/hyperkalemic-periodic-paralysis-hypp. Accessed 22 Oct 2023

24. (2022) Equine Myopathien – PSSM1 und MIM („PSSM2“). https://www.st-hippolyt.de/wissen/wissenswertes/equine-myopathien-pssm1-und-mim-pssm2. Accessed 23 Oct 2023

25. Young A (2020) Severe Combined Immunodeficiency (SCID). https://ceh.vetmed.ucdavis.edu/health-topics/severe-combined-immunodeficiency-scid. Accessed 23 Oct 2023

26. Young A (2020) Cerebellar Abiotrophy (CA). https://ceh.vetmed.ucdavis.edu/health-topics/cerebellar-abiotrophy-ca#:~:text=Equine%20Cerebellar%20Abiotrophy%20(CA)%20is%20a%20genetic%20neurological%20condition%20of,the%20cerebellum%20of%20affected%20foals. Accessed 23 Oct 2023

27. Bourebaba L, Röcken M, Marycz K (2019) Osteochondritis dissecans (OCD) in Horses - Molecular Background of its Pathogenesis and Perspectives for Progenitor Stem Cell Therapy. Stem Cell Rev Rep 15:374–390. https://doi.org/10.1007/s12015-019-09875-6

28. Bates JT, Jacobs JC, Shea KG, Oxford JT (2014) Emerging genetic basis of osteochondritis dissecans. Clin Sports Med 33:199–220. https://doi.org/10.1016/j.csm.2013.11.004

29. Dierks C, Löhring K, Lampe V, Wittwer C, Drögemüller C, Distl O (2007) Genome-wide search for markers associated with osteochondrosis in Hanoverian warmblood horses. Mamm Genome 18:739–747. https://doi.org/10.1007/s00335-007-9058-9

30. Rose RJ (1996) Navicular disease in the horse. J Equine Vet Sci 16:18–24. https://doi.org/10.1016/S0737-0806(96)80061-X

31. Mählmann C (2007) Erbliche Defekte und Dispositionen beim Pferd – eine Bewertung unter tierschutzrechtlichen Gesichtspunkten

32. Midlothian R Bone spavin fact sheet. https://www.ed.ac.uk/sites/default/files/atoms/files/bone_spavin.pdf. Accessed 20 Oct 2023

33. Rowe Á, Flanagan S, Barry G, Katz LM, Lane EA, Duggan V (2021) Warmblood fragile foal syndrome causative single nucleotide polymorphism frequency in horses in Ireland. Ir Vet J 74:27. https://doi.org/10.1186/s13620-021-00206-1

34. WBFSH Warmblood Fragile Foal Syndrome WFFS. https://www.wbfsh.com/wffs

35. Schröder W, Klostermann A, Distl O (2011) Candidate genes for physical performance in the horse. Vet J 190:39–48. https://doi.org/10.1016/j.tvjl.2010.09.029

36. Hill EW, McGivney BA, Gu J, Whiston R, MacHugh DE (2010) A genome-wide SNP-association study confirms a sequence variant (g.66493737C>T) in the equine myostatin (MSTN) gene as the most powerful predictor of optimum racing distance for Thoroughbred racehorses. BMC Genomics 11:552. https://doi.org/10.1186/1471-2164-11-552

37. Böneker C, Kuiper H, Drögemüller C, Chowdhary BP, Distl O (2006) Molecular characterization of the equine collagen, type IX, alpha 2 (COL9A2) gene on horse chromosome 2p16→p15. Cytogenet Genome Res 115:107–114. https://doi.org/10.1159/000095229

38. Hamilton NA, Tammen I, Raadsma HW (2013) Multi-species comparative analysis of the equine ACE gene identifies a highly conserved potential transcription factor binding site in intron 16. PloS One 8:e55434. https://doi.org/10.1371/journal.pone.0055434

39. Gallo N, Natali ML, Sannino A, Salvatore L (2020) An Overview of the Use of Equine Collagen as Emerging Material for Biomedical Applications. J Funct Biomater 11:79. https://doi.org/10.3390/jfb11040079

40. Leistungen für Pferde. https://generatio.de/leistungen/leistungen-fuer-pferde

41. Williams J, Tabor G (2017) Rider impacts on equitation. Appl Anim Behav Sci 190:28–42. https://doi.org/10.1016/j.applanim.2017.02.019

42. Verband der Züchter des Holsteiner Pferdes e. V. Eine über achthundertjährige Erfolgsgeschichte. https://holsteiner-verband.de/de/verband/das-holsteiner-pferd/die-geschichte. Accessed 15 Oct 2023

43. Rottmann A (2022) Holsteiner – 7 Fakten zu den „Bauernpferden". https://www.pferde.de/magazin/holsteiner-7-fakten-zu-den-bauernpferden/. Accessed 15 Oct 2023

44. Holsteiner Pferd. https://geschichte-s-h.de/sh-von-a-bis-z/h/holsteiner-pferd/. Accessed 15 Oct 2023

45. Holstein – a breeding concept has established itself. https://web.archive.org/web/20110719041618/http:/www.holsteiner-verband.de/cms/front_content.php?idcat=39&lang=2. Accessed 15 Oct 2023

46. Holsteiner Verband Satzung des Verbandes der Züchter des Holsteiner Pferdes e. V.

47. Successful Sporthorses in all Disciplines. https://www.holsteiner-verband.de/en/verband/das-holsteiner-pferd/erfolgreiche-sportpferde

48. Ladykiller xx. https://www.pferdezucht-oesterdiekhoff.de/hengstportraits/ladykiller-xx.html

49. Landgraf. https://www.horsemagazine.com/thm/2010/08/landgraf/

50. (2014) LADYKILLER XX - HENGSTPORTRAIT. https://www.pferdezucht-oesterdiekhoff.de/hengstportraits/ladykiller-xx.html#nachkommen. Accessed 16 Oct 2023

51. Cor de la Bryere. https://holsteiner-verband.de/verband/holsteiner-pferd/geschichte/Cor%20de%20la%20Bryere.pdf

52. cor de la bryere. http://www.sportpferde-angerer.at/cor%20de%20la%20bryere.htm

53. Casall. https://www.holsteiner-verband.de/de/hengsthaltung/hengste/pferd/casall

54. Corrado 1. https://www.holsteiner-verband.de/de/hengsthaltung/hengste/pferd/corrado-i

55. Der Hannoveraner im Rasseportrait: Das macht diese Pferderasse so erfolgreich. https://www.wehorse.com/de/blog/hannoveraner/#:~:text=Die%20Geschichte%20der%20Hannoveraner%20lässt,den%20Beginn%20der%20organisierten%20Zucht. Accessed 17 Oct 2023

56. Dr. Hinni LB 100 Jahre Hannoveraner Verband. https://www.hannoveraner.com/hannoveraner-verband/news/artikel/100-jahren-hannoveraner-verband/. Accessed 17 Oct 2023

57. Die letzte chance nutzen. https://www.kn-online.de/sport/regional/die-letzte-chance-nutzen-NYXYOMW55SMNYDZKJM7W6JLUEQ.html

58. Hanoverian Horse Society of Australia THE HANOVERIAN. https://www.hanoverian.org.au/the-hanoverian/. Accessed 18 Oct 2023

59. Hannoveraner Verband Zuchtprogramm. https://www.hannoveraner.com/pferdezucht/zuchtprogramm/. Accessed 17 Oct 2023

60. Hector C (2018) The return of the E line. https://www.horsemagazine.com/thm/2020/11/the-return-of-the-e-line/. Accessed 16 Oct 2023

61. Escolar. https://horse-gate.com/escolar/

62. Hannoveraner Stallion Lines. . https://www.horsemagazine.com/thm/2018/10/hannoveraner-stallion-lines/. Accessed 16 Oct 2023

63. Donnerhall. https://horse-gate.com/donnerhall/

64. FN (2023) Alte Helden: Stakkato ✝ Vererber-Legende in der Springpferdezucht. https://www.pferd-aktuell.de/altehelden/stakkato. Accessed 18 Oct 2023

65. Goldfever. https://www.st-georg.de/news/zucht/coupe-de-coeur-und-goldfever-ziehen-nach-italien-monte-bellini-nach-frankreich/

8. List of Figures

Figure 1: Chacco-Blue Pedigree [5] 9
Figure 2: Altwürttemberger [13] 12
Figure 3: monogenic hereditary diseases 17
Figure 4: widespread polygenic diseases 20
Figure 5: WFFS [7] 22
Figure 6: Luxury carriage [44] 26
Figure 7: Holsteiner Verband logo [44] 27
Figure 8: Ladykiller xx [48] 29
Figure 9: Landgraf [49] 29
Figure 10: Cor de la Bryére [52] 31
Figure 11: Casall [53] 32
Figure 12: Branding of the hanoverian [57] 33
Figure 13: New breeding star Escolar [61] 35
Figure 14: Donnerhall [63] 36
Figure 15: Goldfever [65] 37