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Radiographic findings in the limbs of Hanoverian Warmblood horses: Genetic analyses and relationships with performance in sports

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For my parents

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Introduction

Epidemiological studies as well as statistical analyses of insurance companies have substantiated the predominant role of locomotory diseases in respect of premature retirement and culling of horses (CLAUSEN et al. 1990, PHILIPSSON et al. 1998, SEIDENSTICKER 1999, WALLIN et al. 2000). Racing and riding horses appeared to be concerned in comparable measures. Furthermore, orthopedic problems are significantly involved in the complex etiology of the performance loss syndrome of the sports horse (ROSSDALE et al. 1985). Radiographic findings are often considered to be useful predictors for the future soundness of the individual horse. Therefore, the radiological examination of the equine limbs has become an integral part of pre-purchase examinations, and has a considerable impact on the outcome of sale and the sale value of a horse (VAN HOOGMOED 2003).

Most equine musculoskeletal problems can be localized in the lower limbs. The main locations of alterations vary in dependence on the horses' use corresponding to the distribution of load and wear. Sites exposed to the greatest mechanical stress are regarded as predisposed to develop relevant pathology. However, some common orthopedic problems become clinically or at least radiographically manifest at a very young age. Among these, alterations ranked among the osteochondrosis syndrome, different types of juvenile degenerative joint disease, and navicular disease appear to be of utmost importance in the Warmblood horse. Nevertheless, controversy persists about disease definition and classification. Therefore, epidemiological studies should be based on well-defined radiographic findings that fit into the major disease complexes.

Intra-articular osseous fragments

Osseous fragments are frequently observed in the joints of young horses. The main sites of occurrence seem to depend on the breed and/or the use of the horse. In general, fetlock joints (metacarpo- and metatarsophalangeal joints) and hock joints (tarsocrural joints) were found to be more often affected than stifle and shoulder joints, proximal and distal interphalangeal joints, and vertebral joints. The possible pathogeneses of osseous fragments vary in dependence on the affected joint, and even in dependence on the location in the affected joint. On the one hand, traumatic fragmentation (chip fracture) is more likely in carpal and phalangeal joints than in less exposed joints. On the other hand, osseous fragments located dorsally in fetlock joints are often interpreted as signs of osteochondrosis, whilst the classification of palmar/plantar osseous fragments in fetlock joints as osteochondrotic or non-osteochondrotic is controversial. In hock joints, osseous fragments are almost universally considered to be of osteochondrotic genesis (JEFFCOTT 1991, GRØNDAHL 1991, 1992, CARLSTEN et al. 1993, DALIN et al. 1993).

Osteochondrosis (OC) is a developmental disease that occurs in many different species (SAMY 1977). In the horse, it is ranked among the equine developmental orthopedic diseases (DOD) besides physistis/epiphysitis, angular limb deformities, osseous cyst-like lesions and the Wobbler syndrome (JEFFCOTT 1991, PAGAN and JACKSON 1996). According to the leading characteristics of the disease, i.e., failure or malfunction of normal cartilage maturation, the term dyschondroplasia might be preferred to the common term osteochondrosis (JEFFCOTT and SAVAGE 1996, JEFFCOTT and HENSON 1998).

Radiographical diagnosis of osteochondrosis in the horse may be possible at an age of less than 6 months (HOPPE 1984, GRØNDAHL 1991, CARLSTEN et al. 1993, DIK et al. 1999, KROLL et al. 2001). Depending on the affected joint, the so-called point of no return has been defined at between 6 and 9 months of age. After this time both the resolution of existing alterations and the formation of new alterations are very unlikely. Radiological signs may be confined to discreet irregularities of the joint surface, i.e., of joint cartilage and subchondral bone. However, developing cartilage flaps may partly or totally detach. If mineralization occurs, loose or at least apparently loose particles (“free joint bodies”, “joint mice”, “chips”) may become visible radiographically, specifying the condition as osteochondrosis dissecans (Latin: dissecare = to cut apart). But the origin of such mineralized particles in the joint cavity cannot be determined doubtlessly in any case. After complete separation, osteochondral fragments may float freely in the synovial space, departing from their detachment sites. In such cases, they may not always be clearly distinguishable from osseous fragments of non-osteochondrotic genesis (e.g., mineralized remnants of previous inflammation, chip fracture).

Nutrition, growth parameters, trauma and exercise are the main environmental factors considered to influence the formation of dyschondroplastic alterations in the growing individual. Furthermore, there is virtually no doubt that genetic components play some role in the etiology of the osteochondrosis syndrome (JEFFCOTT 1991). However, despite the considerable number of genetic studies that have been performed, conclusive heritability estimates for this condition in the Warmblood horse are still missing. The range of published heritability estimates is disconcertingly wide (h^2 = 0.02-0.64), and in many cases the estimates were afflicted with high standard errors (SCHOUGAARD et al. 1987, GRØNDAHL and DOLVIK 1993, PHILIPSSON et al. 1993, KWPN 1994, WINTER et al. 1996, WILLMS et al. 1999a, PIERAMATI et al. 2003; Table 1).

Deforming arthropathy

Acute and chronic joint diseases (arthropathies) are made responsible for a bigger part of locomotory problems in the horse. However, chronic conditions do not necessarily involve signs of lameness, but performance might be impaired at least subclinically.

Contrary to the widespread belief that radiographic findings fitting in the comprehensive arthrosis concept primarily affect older horses, high proportions of young horses have been found to show chronic joint alterations (Böhm and Nagel 1980, Münzer et al. 1984). In this connection, the term juvenile degenerative joint disease might be used. The horse's age and its use are not the only and probably not even the main determinants for time and extent of joint pathology. The general constitution and some disposition of the individual horse appear to be more decisive (Haakenstad 1968, KWPN 1994, Winter et al. 1996, Eksell et al. 1998, Willms et al. 1999b, Axelsson et al. 2001).

Bone is a remarkably active and variable supporting tissue, resulting in a continuous adjustment of existing bone structures. If load configuration changes, responsive bone remodeling will become visible radiographically after only a few weeks. Attachment sites of joint capsules and ligaments as well as prominent parts of bones are most likely to show osseous reactions to excessive and irregular traction and pressure forces. However, trauma or infectious joint diseases might also result in noticeable bone responses. In joint regions, productive changes might vary from subchondral sclerosis to so-called spurs and up to bony bridging of the joint space. If osteolytic activity prevails, bone contours might appear blurred or eroded. Furthermore, un-physiological load and wear of joints will impair the cartilage supply so that narrowing of the joint space might become visible radiographically (Van Suntum 1983, Ueltschi 2002).

The detection of contour changes might be demanding in complex joints such as the hock joint. Furthermore, there is some controversy about the valuation of particular radiographic findings. For example, a prominent processus extensorius at the dorso-proximal aspect of the third phalanx might be interpreted as variation within the physiological range of joint appearance or as pathological condition. The distinction has to be drawn in each individual case. However, if extensive reshaping of bone contours has occurred there should be no doubt about the pathological character of this condition.

Among the diverse etiological factors some genetic disposition appears to be involved in the development of equine deforming arthropathy. However, the reported heritability estimates for arthrotic conditions in the phalangeal joints and in hock joints ("bone spavin") vary considerably (h^2 = 0.02-0.65; KWPN 1994, WINTER et al. 1996, WILLMS et al. 1999a, BJØRNSDÓTTIR et al. 2000; Table 1). Some authors hypothesized that not the development of the condition itself, but primarily the age of onset of radiologically visible bone remodeling in the hock is predetermined genetically (ÁRNASON and BJØRNSDÓTTIR 2003).

Radiographic changes in navicular bones

The equine podotrochlea is a species specific feature comprising bony (os sesamoideum distale), tendon (distal end of the deep digital flexor tendon) and synovial (bursa podotrochlearis) components. Chronic, degenerative and in many cases progressive conditions in the navicular region are usually subsumed under the term navicular disease/navicular syndrome or podotrochlosis (first description in 1802 by EDWARD COLEMAN),

Pathologic conditions might primarily affect the osseous or the non-osseous parts. However, the main concern usually refers to the navicular bone which is the only part of the podotrochlea that is accessible via diagnostic radiography. Several special projections have been developed for the scrutiny of the diagnostic criteria regarding the canales sesamoidales (quantity and location, size, shape) and the structure and contour of the navicular bone as a whole (OXSPRING 1935, LANGFELDT 1986, LEUENBERGER 1989, DIK 1992). Several radiographic findings (e.g., branched or lollypop-shaped canales sesamoidales) have been related to navicular bone pathology (OXSPRING 1935, BRUNKEN 1986, HERTSCH and STEFFEN 1986, KASER-HOTZ and UELTSCHI 1992, WRIGHT 1993b). Nevertheless, the radiological examination and evaluation of the equine navicular bone is ranked among the most demanding and the most disputed tasks of veterinarian radiologists. Radiographic alterations in the navicular bones considered to be pathological do not necessarily involve lameness problems or constrained gates, but have also been observed in clinically healthy horses of all ages (including foals; BRANSCHEID 1977, TURNER et al. 1986, AMMANN 1987, RÖSTEL-PETERS 1987, LEUENBERGER 1989, KASER-HOTZ and UELTSCHI 1992, HORNIG 1993). Given the varying pattern of progress, prognostic statements are always arguable if they are based on the results of only a single radiological examination (BRUNKEN 1986, GRUNDMANN 1993, SEYREK-INTAS 1993). The extent and persistence of impact and pressure load acting on the navicular region appear to be determinants for the time of clinical manifestation. Accordingly, clinical manifest navicular disease, i.e., lameness relating to podotrochlear pathology, appears to be mainly a problem of middle-aged riding horses (ACKERMANN et al. 1977, AMMANN 1987, BODENMÜLLER 1983, BRUNKEN 1986, WRIGHT 1993a). Podotrochlosis is one of the major reasons for premature retirement of riding horses (PHILIPSSON et al. 1998, SEIDENSTICKER 1999, WALLIN et al. 2000).

Despite the long and extensive research on the pathogenesis of navicular pathology, little is known about etiological factors yet. Mechanical stress (BRANSCHEID 1977, ØSTBLOM et al. 1982) or some perfusion disorder (COLLES and HICKMAN 1977, FRICKER et al. 1982, SVALASTOGA 1983) have been held responsible for the initiation of structural remodeling in the navicular bone. However, conclusive results concerning definite risk factors or the course of the disease process have not been obtained. Therefore, much importance should be attached to the findings that indicated a relevant hereditary disposition to develop presumably pathologic alterations of the navicular bones (BOS et al. 1986, DIK and VAN DER BROEK 1995, HORNIG 1993, PHILIPSSON et al. 1998, KWPN 1994, WILLMS et al. 1999a, WINTER et al. 1996).

Early authors already assumed some relevant influence of genetic factors on the development of navicular bone pathology (ACKERMANN et al. 1977). This assumption was substantiated in multiple studies later on. However, the heritability estimates determined for this common condition in Warmblood horses ranged from $h^2 = 0.06$ to $h^2 = 0.31$ (KWPN 1994; WINTER et al. 1996; WILLMS et al. 1999a; Table 1), representing no conclusive guide to develop preventive breeding schemes.

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Table 1 Heritability estimates (with their standard errors) for selected joint and bone diseases in the equine limbs, provided by literature

Author: Population and number of investigated horses	**Radiographic finding**	**Heritability estimate**	**Method of analysis**
Schougaard et al. 1987: Danish trotters (n = 325)	OCD (hock)	$0.26^{0.14}$	STM (χ²-heterogeneity test[1])
Grøndahl and Dolvik 1993: Norwegian trotters (n = 644)	OCD (fetlock) OCD (hock)	0.52 0.21	STM (REML[2])
Philipsson et al. 1993: Swedish Standardbred trotters (n = 793)	OCD (fetlock)	0.09 -> 0.19 0.09 -> 0.24	LSM (χ²-heterogeneity test[1] -> transformation[3])
	OCD (hock)	0.08 -> 0.17 0.09 -> 0.27	LSM (Henderson III[4] -> transformation[3])
Pieramati et al. 2003: Maremmano horses (n = 350)	OCD	$0.13\text{-}0.14^{0.22\text{-}0.23}$ $0.08\text{-}0.09^{0.23\text{-}0.24}$	LAM (REML[5], transformation[3]) ATM (Average Information REML[6])
KWPN 1994: Dutch Warmblood horses (mares; n = 590)	OCD (hock)	$0.14^{0.17}$ $0.01^{0.06}$ -> $0.02^{0.14}$ $0.02^{0.06}$	LAM (REML, transformation[7]) LSM (REML -> transformation[7]) STM (REML[8])
	Fetlock joint arthrosis	$0.26^{0.15}$ $0.16^{0.09}$ -> $0.24^{0.14}$ $0.24^{0.11}$	LAM (REML, transformation[7]) LSM (REML -> transformation[7]) STM (REML[8])
	Bone spavin	$0.31^{0.14}$ $0.20^{0.10}$ -> $0.26^{0.15}$ $0.31^{0.12}$	LAM (REML, transformation[7]) LSM (REML -> transformation[7]) STM (REML[8])
	Pathologic changes in navicular bones	$0.30^{0.14}$ $0.26^{0.11}$ -> $0.32^{0.14}$ $0.31^{0.12}$	LAM (REML, transformed[7]) LSM (REML -> transformation[7]) STM (REML[8])
Winter et al. 1996: German Riding Horses (n = 2407 resp. 3566)	OCD	$0.07^{0.03}$ $0.06^{0.04}$	LAM (REML) LSM (Henderson III[4])
	Arthropathia deformans (ph.j.)	$0.05^{0.03}$ $0.07^{0.04}$	LAM (REML) LSM (Henderson III[4])
	Bone spavin	$0.04^{0.03}$ $0.02^{0.04}$	LAM (REML) LSM (Henderson III[4])
	Podotrochlosis	$0.06^{0.03}$ $0.06^{0.04}$	LAM (REML) LSM (Henderson III[4])
Willms et al. 1999a: German Riding Horses (mares; n = 401 resp. 456)	OCD	$0.45^{0.23}$ 0.64 $0.34^{0.06}$	LSM (GS) STM (REML-type algorithm[9]) ATM (GS)
	Arthrosis (ph.j.)	$0.36^{0.22}$ 0.21 $0.29^{0.04}$	LSM (GS) STM (REML-type algorithm[9]) ATM (GS)
	Bone spavin	$0.53^{0.20}$ 0.65 $0.35^{0.06}$	LSM (GS) STM (REML-type algorithm[9]) ATM (GS)
	Podotrochlosis	$0.20^{0.12}$ 0.24 $0.31^{0.05}$	LSM (GS) STM (REML-type algorithm [9]) ATM (GS)

Willms et al. 1999a: German Riding Horses (foals; n = 144)	OCD	$0.58^{0.15}$ $0.19^{0.02}$	LSM (GS) ATM (GS)
	Arthrosis (ph.j.)	$0.19^{0.14}$ $0.18^{0.03}$	LSM (GS) ATM (GS)
	Bone spavin	$0.16^{0.15}$ $0.19^{0.03}$	LSM (GS) ATM (GS)
	Podotrochlosis	$0.20^{0.29}$ $0.25^{0.04}$	LSM (GS) ATM (GS)
Bjørnsdóttir et al. 2000: Icelandic Horses (n = 614)	Bone spavin	0.06 -> $0.10^{0.06}$ $0.09^{0.11}$	LAM (REML -> transformation[3]) STM (REML[8])
	Bone spavin and lameness	0.10 -> $0.22^{0.08}$ $0.28^{0.19}$	LAM (REML -> transformation[3]) STM (REML[8])
Árnason et al. 2003: Icelandic Horses (n = 439)	Age at onset of bone spavin	0.26 0.33	STM (Weibull regression model[10]) STM[11]

ATM – animal threshold model; STM – sire threshold model; LAM – linear animal model; LSM – linear sire model; REML – restricted maximum likelihood; GS – Gibbs Sampling; OCD – osteochondrosis dissecans; ph.j. – phalangeal joints

[1] Robertson and Lerner 1949; [2] Gianola and Foulley 1983; [3] Dempster and Lerner 1950; [4] Harvey 1985; [5] Boldman et al. 1993; [6] Wang 1994; [7] Gianola 1982; [8] Misztal et al. 1989; [9] Misztal 1989; [10] Ducrocq and Sölkner 1999; [11] Prentice and Gloeckler 1978

Intention of the present study

First of all, the importance of different radiographic findings in the limbs of young and clinically healthy Warmblood riding horses should be determined. Factors influencing the prevalences of the quantitatively most important radiological alterations were to be identified. Following the investigation of non-genetic influences, the relevance of genetic components should be ascertained (Papers I to V). The definition of the main radiological traits in the Warmblood horse had to be based on their prevalences as well as on their heritabilities and additive genetic correlations, estimated in a sufficiently large population of horses (Paper VI). Given the relevantly heritable character of the considered radiological conditions, the feasibility and efficiency of breeding measures should be tested that aim at an improvement of the radiological state in the whole Warmblood horse population (Papers VII and VIII).

In order to assess the long-term effect of radiographic findings in the equine limbs, the development of Warmblood riding horses with and without radiological alterations was investigated in terms of usability and sports performance (Paper IX). The analysis of genetic correlations between the most important radiological conditions and particular performance parameters should provide further indications for future breeding schemes that account for orthopedic health traits (Paper X).

Parts of this work are intended for publication:

List of papers

I. Stock, K.F.; Hamann, H.; Distl, O., 2004a: Prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses. J. Vet. Med. A (submitted).

II. Stock, K.F.; Hamann, H.; Distl, O., 2004b: Influence of systematic effects on the prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses. Vet. J. (submitted).

III. Stock, K.F.; Hamann, H.; Distl, O., 2004c: Estimation of genetic parameters for the prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses. J. Anim. Breed. Genet. (in press).

IV. Stock, K.F.; Hamann, H.; Distl, O., 2004d: Variance component estimation on the frequency of deforming arthropathies in limb joints of Hanoverian Warmblood horses. J. Anim. Breed. Genet. (in press).

V. Stock, K.F.; Hamann, H.; Distl, O., 2004e: Variance component estimation on the frequency of pathologic changes in the navicular bones of Hanoverian Warmblood horses. J. Anim. Breed. Genet. (in press).

VI. Stock, K.F.; Distl, O., 2004a: Estimation of genetic parameters for osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in navicular bones of Warmblood riding horses. Equine Vet. J. (submitted).

VII. Stock, K.F.; Distl, O., 2004b: Prediction of breeding values for osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in navicular bones of Hanoverian Warmblood horses. Livest. Prod. Sci. (in press).

VIII. Stock, K.F.; Distl, O., 2004c: Expected response to selection when accounting for orthopedic health traits in a population of Warmblood riding horses. Am. J. Vet. Res. (submitted).

IX. Stock, K.F.; Distl, O., 2004d: Survey on the development of Hanoverian Warmblood horses selected for sale at auction in 1991 to 1998. J. Equine Vet. Sci. (submitted).

X. Stock, K.F., Distl, O., 2004e: Analysis of the correlations between sport performance and different radiographic findings in the limbs of Hanoverian Warmblood horses. Equine Vet. J. (submitted).

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Prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses

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With 1 figure and 3 tables

Summary

The prevalence of osseous fragments in different limb joints was analysed in a population of 3,749 young Warmblood riding horses. The horses were selected for sale at auction from 1991 to 1998 by the Association of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V.) in Verden (Aller), Germany. For this purpose, all horses underwent a standardised radiological examination, the results of which were used for the present study. The presence of at least one osseous fragment in distal interphalangeal, proximal interphalangeal, fetlock or hock joints was documented for 32% of the horses. Hock joints were affected in 9.6% of the horses and fetlock joints in 20.7%. The percentage of horses affected in the hind fetlock was significantly higher (13.7%) than that of horses affected in the front fetlock (9.5%). The prevalences of osseous fragments were considerably lower in distal (4.5%) and proximal interphalangeal joints (0.9%). Osseous fragments occurred in only one type of joint in 87% of the affected horses. Depending on the joint type, analogous joints showed osseous fragments in the forehand and the hindquarters in up to 26% of the affected horses, and between 10% and 46% of the horses were affected bilaterally. There was no significant difference in the distribution of osseous fragments in the limb joints investigated here between male and female horses. There was a significant increase in the percentage of horses with osseous fragments in fetlock joints during the study period. The results of this study indicate the need to act against the high prevalences of radiographic findings in the limbs of young Warmblood riding horses.

Keywords: Horse; radiographic findings; prevalence; osseous fragments; limb joints.

Introduction

Diseases of the locomotory system are the most important causes of premature retirement and culling of racing, riding and working horses (Philipsson et al., 1998; Rossdale et al., 1985; Wallin et al., 2000). This applies not only to older horses used extensively for years, but also to young horses right at the beginning of their careers. Radiologically manifesting joint alterations in particular may significantly reduce the performance of affected horses and jeopardise their further use (Storgaard Jørgensen et al., 1997). Although the predictive value of certain radiographic findings is somewhat controversial, radiography has become an integral part of pre-purchase examinations and substantially affects the outcome of sale and the sale value of the horse (Van Hoogmoed et al., 2003). In addition to use-specific performance characteristics, the presence or absence of radiological abnormalities has become an important economic factor in the horse business.

Osteochondrosis constitutes a classic disease of growing individuals. It has been known in humans since the late 19th century (Paget, 1870); it was first described in the horse about 100 years later (Nilsson, 1947: stifle joint; Baker, 1963). Increasing use of radiography in equine medicine has brought to light the great importance of this disease in that species. Disturbed differentiation of growing cartilage leads to radiologically detectable joint pathology. Irregularities of the joint contour (indentations of the articular surfaces) and subchondral bone cysts (Trotter and McIlwraith, 1981) may occur. The presence of intra-articular osseous fragments (free joint bodies, joint mice, chips, corpora libera) permits characterisation of the underlying disease as osteochondrosis dissecans (OCD).

Various studies have documented high prevalences of osteochondrotic lesions in the horse. However, many reports refer either to radiographic surveys in limited numbers of very young horses (two years old or younger), i.e. to horses not yet in use, or to clinical studies in patients of veterinary clinics. Although rare, epidemiological studies comprising significant numbers of adult Warmblood horses have been performed in Dutch (KWPN, 1994) and German (Willms et al., 1999; Winter et al., 1996) horse populations. However, no detailed information is available about the distribution of particular alterations and of specific predilection sites in riding horses.

For this reason, the results of a standardised radiological examination of young Warmblood riding horses selected for sale at auction were used to investigate the prevalence of osseous fragments in different limb joints. Prevalences of radiographic findings were compared in joints of front and hind limbs, and in limb joints of male and female horses.

Material and methods

Information on 3,749 Hanoverian Warmblood horses (probands) was used for this investigation. All horses were selected for sale at auction as riding horses from 1991 to 1998 by the Association of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden (Aller), Germany. Of the selected horses, 3,502 were actually offered at one of the 42 auctions held during this period. The remaining 247 horses had also been selected, but were then not auctioned (i.e. pulled out of auction) for a variety of reasons. The basic data on the auctioned horses (animal number, sex, age, height at withers, anticipated suitability, breeder, exhibitor; date of auction) were drawn from the official auction catalogues of the VHW. Pedigree data were taken from a unified animal ownership database (Vereinigte Informationssysteme Tierhaltung w.V., VIT) maintained in Verden (Aller), Germany.

In the study period, there was a trend toward selection of more horses for sale at riding horse auctions (383 horses in 1991, 635 horses in 1998). Up to 122 horses were offered at one auction. By far the most horses were advertised as suited for future use in dressage (58%). Only 23% of the probands were advertised as having special jumping talent and another 19% as suitable for both dressage and show-jumping. The ratio of male to female probands was 2 to 1 (2,508 males and 1,241 females). The age of the probands was between three and seven years. Most horses were selected for auction sale at three (30.5%) or four (50.8%) years of age. On average, the female probands were older (mean age: 4.00 ± 0.84) than the males (mean age: 3.88 ± 0.74). The mean height at withers was 167.4 ± 3.7cm (ranging between 156 and 183cm) in the male, and was 166.2 ± 3.6cm (ranging between 152 and 178cm) in the female probands.

Each horse listed as a potential auction candidate by the selecting commission of the VHW underwent a standardised veterinary examination. This included a clinical and a radiological examination and was comparable to a common pre-purchase veterinary medical examination. Ten radiographs of the horses' limbs were routinely taken:

- toe laterolateral (90°), left and right leg in forehand and hind quarters, respectively;
- region of navicular bone dorsopalmar (DP) according to the method described by Oxspring, both front limbs;
- hock joint laterolateral (90°), both hind legs;
- hock joint dorsolateral-plantaromedial-oblique (45°), both hind legs.

In the case of questionable radiographic findings, special X-ray projections were used to clarify the orthopaedic status of the horse.

The orthopaedic findings collected prior to the respective auctions were taken from the medical records of the responsible veterinarian. Subsequently they were transformed to a numeric code that made it possible to distinguish locations not investigated or without pathological findings and to specify the forms of pathological findings for each joint of each limb. In this way, it was possible to take into consideration both single and multiple affections of every limb joint. If a horse was shown more than once and there was some repetition in the veterinary examination, all relevant findings were taken into account. If it was known that a horse had been operated on, the preoperative (i.e. diseased) state was used in our data set.

In the following, we consider only osseous fragments in the routinely investigated limb joints, i.e., in distal interphalangeal (DIJ), proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ). The exact location of the osseous fragment(s) was not generally specified in the medical records. Therefore, for the present investigation distinctions were made only between the affected joints in the particular limbs (e.g. FJ front left) and in the forehand and the hindquarters (e.g. FJ front). The prevalences of osseous fragments were analysed as binary traits: 0 = no indication of an osseous fragment, 1 = presence of at least one osseous fragment in the specified joint(s). Binary coding was used even if there was more than one radiographic finding per joint and limb.

Following the joint-specific prevalence analyses of osseous fragments, prevalences in males (stallions and geldings) were compared with those in females (mares) using Fisher's exact test. The significance limit was set to $P < 0.05$.

Results

The prevalences of osseous fragments in DIJ, PIJ, FJ and HJ for all horses and by sex are given in Table 1. Osseous fragments were most often diagnosed in the FJ (in 777, or 20.7%, of the probands), and particularly in the hind FJ (metatarsophalangeal joints; in 513, or 13.7%, of the probands). Osseous fragments were found in front FJ (metacarpophalangeal joints) and HJ in comparable numbers of horses (356, or 9.5%, in FJ vs. 360, or 9.6%, in HJ). Osseous fragments were rarely found in DIJ (in 168, or 4.5%, of the probands) and/or PIJ (in 34, or 0.9%, of the probands). Osseous fragments in DIJ tended to be more prevalent in the forehand than in the hindquarters. No significant sex differences were determined for any of the types of joints considered here ($P > 0.05$).

The development of the prevalences of osseous fragments in the study period was investigated separately for DIJ, PIJ, FJ and HJ (Fig. 1). Apart from some undirected fluctuation, the percentages of probands with osseous fragments in DIJ, PIJ and HJ were almost constant from 1991 to 1998. However, the prevalence of osseous fragments in FJ increased significantly over the years from 14.4% in 1991 to 26.9% in 1998.

Table 2 shows the distribution of osseous fragments among the types of joints in question. Almost one-third (31.6%) of the probands had at least one osseous fragment in DIJ, PIJ, FJ or HJ. However, osseous fragments were detected in only one type of joint in 87% of the affected horses, corresponding to 28% of all probands. Two types of joints showed osseous fragments in 12% of the affected horses and in 4% of all probands. Only four horses had osseous fragments in three types of joints, and no horse had osseous fragments in all four types of joints. The following frequencies of co-affected types of joints were found: osseous fragments in FJ occurred in 32.4% of the horses affected in PIJ, in 22.5% of the horses affected in HJ and in 22.0% of the horses affected in DIJ. Reversely, only 1.4% of the horses affected in FJ had also osseous fragments in PIJ, 10.4% also had osseous fragments in HJ and 4.8% also had osseous fragments in DIJ. Of the horses with osseous fragments in DIJ, 14.9% had also osseous fragments in HJ, and of the horses with osseous fragments in HJ, 6.9% had also osseous fragments in DIJ.

Differentiation between the individual joints revealed that 327 horses had osseous fragments in two different joints (e.g., DIJ front left and FJ front right), 75 horses in three, 16 horses in four, four horses in five and one horse in six different limb joints.

Between 20.0% and 45.6% of the horses with osseous fragments in DIJ, PIJ, FJ or HJ showed the same kind of radiographic finding in the same location of the contralateral limb (e.g. osseous fragments in FJ front left and front right). The few probands with osseous fragments in hind PIJ (n = 20) were the only exception, with only 10% of the horses affected bilaterally. On the other hand, there was less coincidence of osseous fragments in analogous joints of the forehand and the hindquarters (in between 1.3% and 26.4% of the affected horses). The highest coincidence emerged for FJ: about one horse in four (26.4%) with an osseous fragment in front FJ also had an osseous fragment in hind FJ; and almost one horse in five (18.25%) with an osseous fragment in hind FJ also had an osseous fragment in front FJ.

Discussion

The objective of this study was to determine the prevalence of osseous fragments in limb joints of clinically healthy Warmblood horses at the beginning of their careers as riding horses. Differences regarding the occurrence of osseous fragments in male and female horses, and in joints of front and hind limbs should be investigated.

The present study was based on the results of standardised radiological examinations of a population of clinically healthy Hanoverian Warmblood horses intended for sale at riding horse auctions. Therefore, all horses were selected chiefly according to performance criteria such as quality of gaits, natural ability for dressage, show jumping, eventing or driving, rideability and temperament. However, since the breeding aim of the Hanoverian Warmblood horse requires what is known as a noble, correct and large-framed horse, suitable for use in sports as well as for pleasure riding, exterior parameters have also played a role in selection. Consequently, approximate homogeneity can be assumed for this horse population. Furthermore, the thorough clinical and radiographic veterinary examinations of the auction candidates had been performed in a standardised way (routine projections of the limbs, uniform scrutiny of radiographs), which thus provides a certain degree of consistency of the data analysed here.

The presence of intra-articular osseous fragments was found to be the most prevalent radiographic diagnosis in our probands; it was documented in the medical records of almost one in three horses (31.6%). In the same population of Warmblood horses, radiological signs of deforming arthropathy occurred in about one in four horses (17.7%; Stock et al., 2004a) and radiographic changes of navicular bones occurred in about one in five horses (21.6%; Stock et al., 2004b). These findings clearly substantiate the great importance of osseous fragments among the radiographic findings in the limbs of clinically healthy young horses.

For the present study, an osseous fragment was defined as an intra-articular radio-dense particle visible on at least one of the available radiographs of the equine limbs. In principle, these particles might have been attributable to trauma or to the osteochondrosis syndrome, i.e. to a failure of cartilage maturation and enchondral ossification at articular/epiphyseal growth cartilage (dyschondroplasia; Jeffcott, 1991; Jeffcott and Henson, 1998). Osteochondrosis dissecans (OCD) is a well-defined pathological feature of the equine tarsocrural joint. However, acquired lesions might be as important as or even more important than osteochondral fragmentation in the distal limb joints (including fetlock joints; Dalin et al., 1993, Pool, 1993). Furthermore, the classification of an osseous fragment as of presumably traumatic origin or as osteochondrosis-related might depend on its location in the particular joint. For example, osseous fragments in fetlock joints are usually considered to be of osteochondrotic origin if they are located dorsally at the sagittal ridge of the metacarpo- or metatarsophalangeal bones, but not if they are located at the dorsoproximal aspect of the third phalanx or in the palmar or plantar region of the fetlock joint (Yovich et al., 1985; Grøndahl, 1992). Most literature on this subject refers to tarsocrural osteochondrosis (hock OC) and/or to palmar/plantar osteochondral fragments in fetlock joints (POF). Osteochondrosis has been rarely described in the interphalangeal joints. Trauma was considered to be the major factor for the development of osseous fragments in these joints. Nevertheless, it seemed reasonable to include these joints in our study because the expected consequences of free joint bodies (irritation of synovialis, abrasion of joint cartilage) are largely independent of the cause of their existence. The type of the affected joint, the size of the fragment and its location in the affected joint have been regarded as decisive factors for the time and extent of the clinical relevance of an intra-articular fragment. However, the present investigation was based on radiographic findings documented in official medical records. Because details were frequently missing in the documentation, no distinction could be made between the size, the number and the exact location of osseous fragments in the different joints. Consequently, the prevalence of osseous fragments was analysed separately in the different limb joints investigated here, but all osseous fragments detected in one particular joint were analysed jointly. The application of this more general definition has to be borne in mind when reported prevalences of osteochondrosis or osteochondrosis dissecans are compared with the results of the present study that cannot be directly attributed to osteochondrosis.

Overall, prevalences of between 8% and 79% have been quoted in the literature for osseous fragments and osteochondral lesions in general, depending on the horse population investigated (foals, adult horses; trotters, racehorses, draft horses, riding horses; Thoroughbreds, Standardbreds), and on the joints in question (Table 3). However, in populations comparable to our probands with respect to breed (Warmblood horses), age (3 to 8 years of age) and use (riding horses), prevalences in the range of 5.0%, 0.2%, 9.0% and of more than 11.0% have been determined for osseous fragments in distal interphalangeal, proximal interphalangeal, fetlock and hock joints, respectively. Our results generally agree quite well with those figures.

Fetlock and hock joints are regarded as predilection sites of osteochondrosis in the horse (Jeffcott, 1991). Accordingly, osseous fragment were most often diagnosed in fetlock and hock joints of our probands. Several authors regard the hock as the joint most often affected by osteochondrosis (apart from the stifle, which was not included in the present investigation; Hoppe, 1984a, b; Alvarado et al., 1989; Schougaard at al., 1990; Wagner and Watrous, 1990; McIlwraith at al., 1991). However, our results differ from those of some previous studies. Osseous fragments occurred less often in the hock joints than in the fetlock joints of our probands, as was the case in other investigations on young Warmblood riding horses (Leonhardt, 1986; Merz, 1993; Müller, 1994; Kahler, 2001). This might be explained by the fact that tibiotarsal osteochondrosis is likely to cause clinical signs such as synovial effusion or pain earlier than affections of the fetlock or other joints (Jeffcott, 1991). Horses with marked exterior faults or symptoms of orthopaedic problems do not pass selection for riding horse auctions. Accordingly, the incidence of osteochondrotic lesions in hock joints in the whole population of the Hanoverian Warmblood horse might be even greater than that in the auction candidates investigated here. Prevalences of osseous fragments in the range of between 10% and 15% as determined for metacarpophalangeal, metatarsophalangeal and tarsocrural joints support previous indications that radiographic findings of this kind are not infrequently detectable in (hitherto) clinically sound horses (Müller, 1982; Petterson and

Ryden, 1982; Yovich et al., 1985; Harfst, 1986; Stäcker, 1987; Carlsten et al., 1993; Sandgren et al., 1993a, b; Leonhardt,. 1996).

Depending on the type of joint, between one in five and one of two horses with an osseous fragment was affected bilaterally. Other investigators found between 30.8% and 72.7% of diseased horses with bilateral osteochondrotic lesions (Grøndahl, 1991; Hoppe, 1984a, b; McIlwraith, 1993; McIlwraith et al., 1991; Riley et al., 1998; Schougaard et al., 1990). In view of the frequent bilateral nature of lesions and the less frequent involvement of different types of joints, one might consider the development of osseous fragments to be a joint-specific condition. Accordingly, osteochondrosis could be considered to represent a joint-specific developmental orthopaedic disease. In light of the slightly differing age of manifestation of osteochondral lesions (development of definite, radiographically visible alterations in fetlock, hock and stifle joints up to the age of four, five and eight months, respectively; Dik et al., 1999; Kroll et al., 2001), McIlwraith (1993) hypothesised a connection with some joint-specific ‘window of vulnerability’ in enchondral ossification.

As far as possible sex differences are concerned, males seemed to be affected more often by developmental diseases than females (Alvarado et al., 1989; Philipsson et al., 1993; Sandgren et al., 1993a). This might be explained by hormonal effects or by fact that males usually tend to grow faster and be larger than female horses (Jeffcott, 1991). However, some investigators have not been able to determine any sex differences (Hoppe, 1984b; Yovich et al., 1985; Grøndahl 1991, 1992), and this was the case in the present study.

The prevalences of osseous fragments in distal and proximal interphalangeal and in hock joints were largely constant during the study period. However, the proportion of horses with osseous fragments in fetlock joints increased almost continuously, reaching a prevalence of 26.9% in 1998. There is some controversy about the clinical relevance of these radiographic findings, even in racehorses (Laws et al., 1993; Storgaard Jørgensen et al., 1997). However, the presence of intra-articular osseous fragments involves the risk of irreversible cartilage damage and predisposes the affected individual to developing degenerative joint alterations. The arthroscopic removal of osseous fragments might prevent at least some of their aftereffects. But therapeutic measures and convalescence periods cause economic losses in addition to (at least temporary) losses of training and competing capacity (Rossdale et al., 1985). Accordingly, the current sale value of a horse reflects not only its sports or racing ability, but is relevantly dependent on its radiological state (Van Hoogmoed et al., 2003). Therefore, efforts should be made to lower the prevalences of radiographic findings in the equine limbs.

Effective prophylactic measures have to address the significant causative factors. However, the details of the pathogenesis of osteochondrosis are still unknown. Further research is needed that focuses on parameters that influence the prevalence of radiographic findings in the limbs of Warmblood riding horses. According to previous studies, both genetic as well as non-genetic factors should be taken into account. Information on large numbers of horses subjected to standardised radiological examinations are needed in order to perform reliable analyses. In light of the high costs of extensive radiological surveys, further use should be made of data on auction horses or prospective sires that are collected routinely and uniformly.

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Table 1. Prevalences of osseous fragments in distal interphalangeal (DIJ), proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ) by sex in the probands of this study

Limb joint	Prevalences of osseous fragments		
	Males (n = 2,508)	Females (n = 1,241)	Total (n = 3,749)
DIJ (front and/or hind limbs)	120 (4.78%)	48 (3.87%)	168 (4.48%)
front DIJ	111 (4.43%)	39 (3.14%)	150 (4.00%)
hind DIJ	10 (0.40%)	10 (0.81%)	20 (0.53%)
PIJ (front and/or hind limbs)	26 (1.04%)	8 (0.64%)	34 (0.91%)
front PIJ	16 (0.64%)	0 (0.00%)	16 (0.43%)
hind PIJ	12 (0.48%)	8 (0.64%)	20 (0.53%)
FJ (front and/or hind limbs)	516 (20.57%)	261 (21.03%)	777 (20.73%)
front FJ	250 (9.97%)	106 (8.54%)	356 (9.50%)
hind FJ	326 (13.00%)	189 (15.23%)	513 (13.68%)
HJ (hind limbs)	249 (9.93%)	111 (8.94%)	360 (9.60%)

Table 2. Distribution of osseous fragments among the limb joints of the probands (n = 3,749) in this study

Number of different types of joints affected with osseous fragments	Number (proportion) of horses		DIJ	PIJ	FJ	HJ
0	2,563 (68.4%)		–	–	–	–
I	1,037 (27.7%)	110	+	–	–	–
		20	–	+	–	–
		652	–	–	+	–
		255	–	–	–	+
II	145 (3.9%)	0	+	+	–	–
		33	+	–	+	–
		21	+	–	–	+
		11	–	+	+	–
		3	–	+	–	+
		77	–	–	+	+
III	4 (0.1%)	0	+	+	+	–
		0	+	+	–	+
		4	+	–	+	+
		0	–	+	+	+
IV	0 (0.0%)		+	+	+	+
0 - IV	3,749 (100%)		168 (4.48%) affected horses	34 (0.91%) affected horses	777 (20.73%) affected horses	360 (9.60%) affected horses

DIJ: distal interphalangeal joint; PIJ: proximal interphalangeal joint; FJ: fetlock joint; HJ: hock joint; +: presence of an osseous fragment; –: absence of an osseous fragment

Table 3. Reported prevalences of osseous/osteochondral fragments in the limb joints of horses by breed and age

Horse population	Age	Sites of osseous fragments	% affected horses	Authors
German WB	6 months to 3 years	DIJ PIJ FJ HJ	0.0 - 10.7 0.0 - 0.9 10.2 - 30.1 4.4 - 78.8	Harfst 1986; Leonhardt, 1986; Heinz, 1993; Müller, 1994; Thomsen, 1995; Kirchner, 1996; Willms et al., 1999; Kahler, 2001
German WB	3 to 8 years	DIJ PIJ FJ HJ	4.9 - 5.7 0.2 9.2 - 9.3 6.5 - 11.0	Müller, 1982; Merz, 1993; Winter et al., 1996
Dutch WB	3 years	HJ	13.7	KWPN, 1994
Swedish WB	< 1 month to 3 years	HJ	26.0	Hoppe, 1984a, b
WB	< 1 month to 18 years	FJ HJ FJ and/or HJ and/or SJ	8.1 11.0 15.7 - 31.5	Zeller et al., 1978; Stäcker, 1987; Alvarado et al., 1989
Maremmano horses	2 to 3 years	FJ HJ	2.8 9.2	Pieramati et al., 2003
Norwegian trotters	< 1 month to 2 years	FJ HJ	11.8 14.3	Grøndahl, 1991, 1992
Swedish trotters	< 1 month to 3 years	FJ HJ FJ and/or HJ	14.3 - 31.0 9.7 - 15.0 35.9	Hoppe, 1984a,b ; Carlsten et al., 1993 ; Sandgren et al., 1993a
Danish trotters	< 1 month to 3 years	HJ	12.0	Schougaard et al., 1990
American Draught horses	< 1 month to 3 years	FJ HJ	5.2 64.7	Riley et al., 1998

WB – Warmblood horse; DIJ – distal interphalangeal joint; PIJ – proximal interphalangeal joint; FJ – fetlock joint; HJ – hock joint; SJ – stifle joint

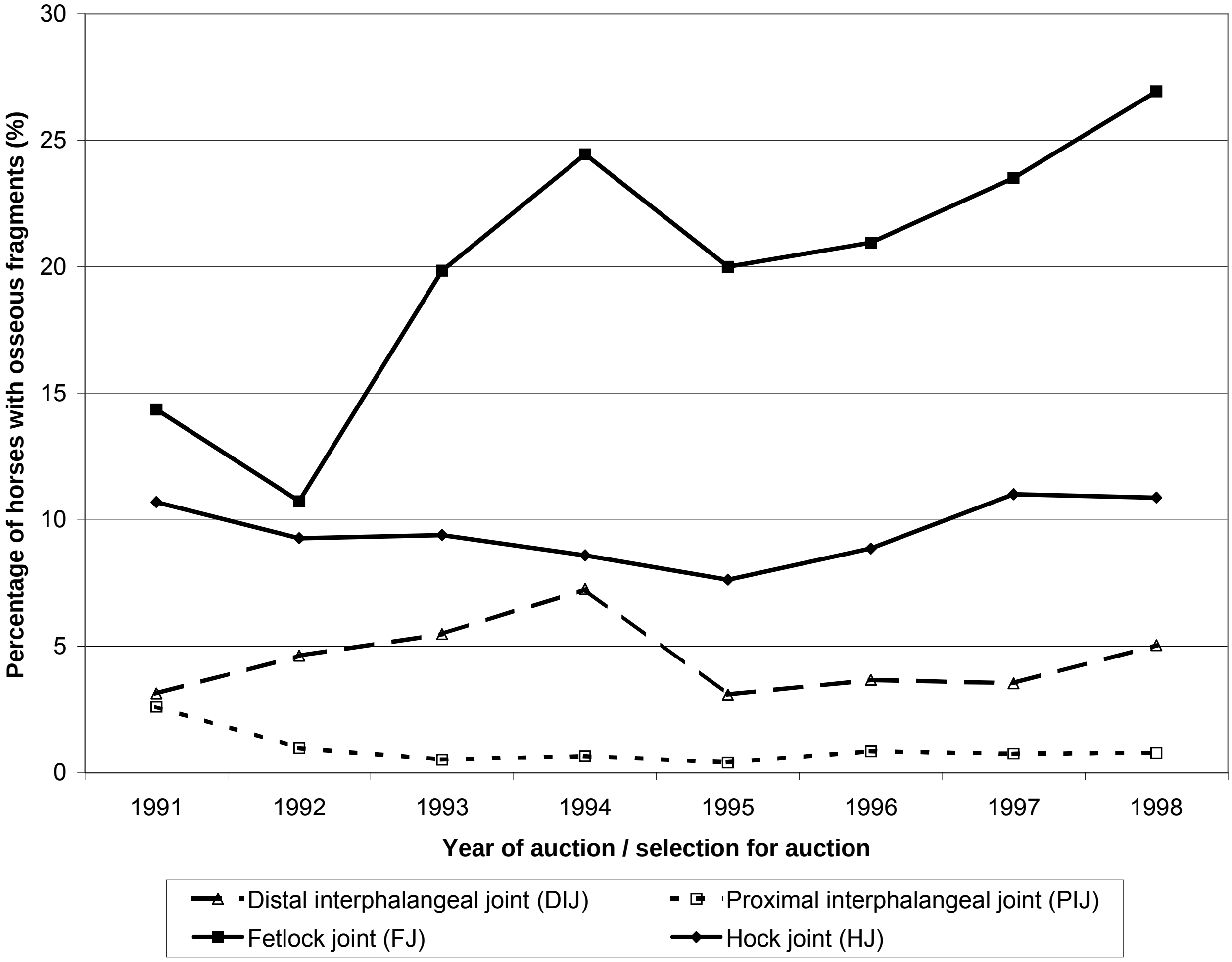

Fig. 1. Development of the prevalences of osseous fragments in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ) in the study period (1991-1998)

Influence of systematic effects on the prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses

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Abstract

The influence of systematic effects on the prevalence of osseous fragments (OF) in fetlock and hock joints was investigated in a population of young Hanoverian Warmblood horses selected for sale at auction from 1991 to 1998. The study was based on the results of a standardized radiological examination of 3,127 horses. The prevalences of OF in fetlock and hock joints were significantly dependent on date, type and quality of auction, and on the region of origin and the anticipated suitability of the auction horses. The probability of an OF in the joints in question increased with withers height. Furthermore, there was a significant influence of the individual sire on the prevalence of OF in both fetlock and hock joints, and of the maternal grandsire on the prevalence of OF in hock joints. Consequently, both systematic environmental and genetic parameters should be taken into account in order to lower the prevalence of OF in young Warmblood riding horses.

Keywords: Horse; radiological examination; osseous fragments; systematic effects; sire effect.

1. Introduction

Locomotory problems are among the major reasons for premature retirement and culling of horses (Philipsson et al., 1998; Wallin et al., 2000). Many chronic conditions of the bones and joints can be visualised via diagnostic radiography. Recent studies have revealed high prevalences of abnormal radiographic findings in the limbs of active sport horses. However, several studies could not verify the clinical relevance of particular radiographic findings and any negative effect on performance (Grøndahl and Engeland, 1995; Storgaard Jørgensen et al., 1997). Nevertheless, there is no doubt that horses with radiologically visible alterations are at a higher risk of developing orthopaedic problems than unaffected horses, at least in the long term. Even subtle gait irregularities caused by musculoskeletal pain will interfere with equine performance. Manifest lameness might even jeopardise the horse's further use in sports or racing. Therefore, economic aspects are not confined to the direct costs of therapeutic measures, but also include the costs of lost training days and impaired competing capacity (Rossdale et al., 1985). Accordingly, the radiological state of a horse has in many cases a significant influence on its sale value (Van Hoogmoed et al., 2003).

Intra-articular osseous fragments have a predominant role among those radiographic findings that occur in many clinically healthy horses. In many cases, the development of osseous fragments has been attributed to the osteochondrosis syndrome. Some failure of the normal cartilage maturation might result in the formation of cartilage flaps. After the partial or complete detachment of such flaps secondary calcification and ossification might take place, characterizing the condition as osteochondrosis dissecans (OCD). However, there is no uniform aetiology of osseous fragments in the equine limb joints, i.e., not all osseous fragments are attributable to osteochondrosis. Depending on the affected joint and on the site of manifestation, trauma might be just as or even more important as a causative factor. Regardless of their origin, intra-articular osseous fragments will cause comparable secondary changes (synovial effusion, formation of so-called wear-lines in the joint cartilage). The extent of such changes and the time of their occurrence largely depends on the type of the affected joint (radius of motion), the specific affection site in the particular joint (load distribution) and the size and/or number of fragments present in the joint.

Arthroscopic removal of free joint bodies might prevent some or even most of the aftereffects of the presence of intra-articular osseous fragments. However, affections of the joint cartilage have to be considered irreversible. Therefore, primary effort should focus on prophylactic measures to reduce the prevalence of osseous fragments in equine limbs. But effective precaution implies detailed knowledge of the aetiopathology of osseous fragments. Despite extensive research on osteochondrosis in general, and on equine osteochondrosis in particular, its aetiology is still not completely understood. Environmental effects such as rearing conditions, feeding and exercise have been considered as relevant aetiological factors, as have genetic influences (Jeffcott 1991).

The objective of the present study was to investigate the influence of systematic effects on the prevalence of osseous fragments in the limb joints of young Warmblood riding horses. In this context, environmental effects as well as the effect of the sire and the maternal grandsire were to be accounted for.

2. Material and methods

2.1. Sample population

The present study was based on information on 3,749 Hanoverian Warmblood horses selected for sale at auction as riding horses from 1991 to 1998 by the Association of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden (Aller), Germany. All horses underwent a standardised veterinary examination in the course of which ten radiographs were routinely taken (latero-lateral projections of the four distal limbs, dorso-palmar projections of the navicular bones of the front limbs, latero-lateral and dorsolateral-plantaromedial-oblique projections of the hocks). The results of the radiographic examinations including notation of previous surgery were documented in the medical records by the responsible veterinarian.

Pedigree data was taken from a unified animal ownership database (Vereinigte Informationssysteme Tierhaltung w.V., VIT) maintained in Verden (Aller), Germany. Data were available for 3,725 of the auction candidates. These horses were sired by 462 different stallions and descended from 641 different maternal grandsires. The distribution of horses among the sires and maternal grandsires is given in Table 1. On the average the sires were represented by 8.1 radiographed horses (range 1-102), the maternal grandsires by 5.8 (range 1-68). For the investigation of the effects of the individual sire and maternal grandsire, only those stallions were considered that had at least three offspring included in this investigation. This applied to 60% of the sires (n = 278, which sired 94% of the probands) and to 51% of the maternal grandsires (n = 325, which anteceded 89% of the probands). After all, analyses of variance were performed for those 3,127 auction candidates (probands) that had two or more paternal half-siblings included in this investigation and descended from maternal grandsires with at least three radiographed offspring. The mean numbers of such probands per sire or maternal grandsire were 12.5 and 10.2, respectively.

The basic data for the auctioned horses – animal number, sex, age, withers height (WH), anticipated suitability, breeder, exhibitor, date of auction – were drawn from the official auction catalogues of the VHW. The results of the radiological examinations and information on the horses pulled out of auction were taken from the medical records.

In the study period the number of horses selected for sale at auction increased almost linearly from 302 in 1991 to 502 in 1998. Between 35 and 156 riding horses were offered for sale at each auction, amounting to 2,925 horses actually offered at one of the 42 auctions held from 1991 to 1998. The remaining 202 horses had been pulled out of auction for various reasons. At the time of auction selection the probands were on average 3.91 ± 0.77 years old (between three and seven years) and had a mean WH of 166.98 ± 3.73 cm (between 152 and 183 cm). There were twice as many males than females among the auction candidates (2,091 stallions and geldings, 1,036 mares). The mares were slightly older (mean age of 3.97 ± 0.84 years) and smaller (mean WH of 166.21 ± 3.66 cm) than the stallions and geldings (mean age, 3.88 ± 0.73 years; mean WH, 167.36 ± 3.71 cm). Most auction horses were offered as particularly suited for dressage riding (n = 1,711; 58.5% of all the auction horses). Remarkable jumping-talent was mentioned for 682 horses (23.3%). A further 532 horses (18.2%) were advertised as suitable for both show-jumping and dressage.

2.2. Radiographic findings

The radiographic findings were taken from the documentation of the responsible veterinarian. If it was known that the horse had been operated on, the preoperative (i.e. diseased) state was used for our analyses.

Intra-articular osseous fragments (OF) were the most prevalent radiographic finding among the auction candidates, occurring in the limb joints of about one-third of the probands (981 singularly or multiply affected horses). OF were most often diagnosed in fetlock joints, in one in five auction candidates. Hind fetlock joints showed at least one OF in 13.4% of the probands. OF in front fetlock joints were as prevalent as OF in hock joints (9.4%). Distal and proximal interphalangeal joints were affected in only 4.5% and 0.8% of the horses, respectively. Analyses of variance were confined to the joints more frequently affected with OF, i.e. the fetlock and hock.

2.3. Statistical analysis

Binary coding was used for the analysis of the prevalences of OF with “0” denoting the absence of radiographic signs of an OF on the available X-rays, and “1” denoting the presence of at least one OF in a joint. All analyses were performed separately for fetlock and hock joints.

The following factors were tested for their influence on the prevalence of OF in fetlock and hock joints: sex (Sex: male, female); age group (Age: 3 years old, 4 years old, 5 years old and older); withers height (WH: up to 163 cm, 164-165 cm, 166-167 cm, 168-169 cm, 170-171 cm, 172 cm and larger); anticipated suitability of the horse (Suit: dressage, show jumping, dressage and show jumping); region of breeder (RegB) and exhibitor (RegE); individual date of auction (Auct: 42 auctions of young riding horses); year of selection for auction (Year: 1991 – 1998), type of auction (Type: winter auction, elite auction in the spring, Equitop auction in May, summer auction, elite auction in the autumn, Equitop auction in November); quality of auction (Qual: elite auction, subsidiary auction, Equitop auction); sire and maternal grandsire (MGS). Furthermore, the interactions between sex and age (Sex * Age), sex and withers height (Sex * WH) and year and quality of auction (Year * Qual) were tested for significance.

The influence of the individual breeder or exhibitor could not be included in the analyses because most of the breeders and exhibitors had only one horse selected for an auction in the relevant years (67.2% of the breeders, 66.8% of the exhibitors). Varying rearing conditions were therefore taken into account by the region where the breeder and exhibitor of the horse were located. For this, Germany was divided into three parts corresponding to the first two digits of the postal code: region 1, Bremen and Bremerhaven (postal codes 27 and 28); region 2, north and northeast Germany (postal codes 01-25 and 29-39); region 3, west and south Germany (postal codes 26 and 40-99). In many cases, breeder and exhibitor were not identical. Furthermore, the regions of the breeder and the exhibitor of a horse were frequently not the same, indicating that there had obviously been no regional limitation of sales. Therefore, confounding was assumed to be minor, and the regions of breeder and exhibitor were considered separately. Sex, age, WH, anticipated suitability, region of breeder and exhibitor, date, year, type and quality of auction were considered as fixed effects. The sire and the maternal grandsire were tested as random effects.

Generalised linear mixed models were used for the analysis of variance, including a dependent variable (y), a systematic component (μ) and an error component (e). For modelling of the systematic component, a link function can be chosen corresponding to the function of distribution of the trait values. For the traits analysed here, the ML (maximum likelihood) approach was employed, the function of distribution was considered binomial, and the probit function was used as the link function ($g(\mu)$):

$$y = \mu + e \qquad \text{with} \qquad g(\mu) = \Phi^{-1}(\mu).$$

The inverse of the link function was employed to transform the resulting estimates into relative frequencies. The analyses were performed with the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, USA, 2002). Threshold models were employed for the analysis of variance and the estimation of least square means, using the procedure MIXED (Mixed Model) and the macro GLIMMIX. The Wald test was used to assess the significance of random effects. The significance limit was set to P = 0.05.

First, each of the considered systematic effects was tested individually for its influence on the prevalence of OF in fetlock and hock joints. Investigation of the individual systematic effects was followed by analysis of different combinations of systematic effects (basic model, Model 1). If the sire or the maternal grandsire was significant in the basic analyses, the simple models were subsequently augmented with the random sire effect (random sire model, Model 2), the random maternal grandsire (MGS) effect (random MGS model, Model 3), or both the random sire and the random MGS effect (random sire-random MGS model, Model 4).

Model 1 $\quad y_{il} = \mu + F_{(1)i} + e_{il}$

with y_{il} = radiographic finding of an OF in the ilth horse, μ = model constant, $F_{(1)I}$ = systematic effect component (fixed and/or random effects), e_{il} = residual error,

Model 2 $\quad y_{ijl} = \mu + F_{(2)i} + S_j + e_{ijl}$

with y_{ijl} = radiographic finding of an OF in the *ijl*th horse, μ = model constant, $F_{(2)i}$ = systematic effect component (fixed and/or random effects except for random sire effect), S_j = random effect of the *j*th sire, e_{ijl} = residual error,

Model 3 $y_{ikl} = \mu + F_{(3)i} + MGS_k + e_{ikl}$

with y_{ikl} = radiographic finding of an OF in the *ikl*th horse, μ = model constant, $F_{(3)i}$ = systematic effect component (fixed and/or random effects except for random MGS effect), MGS_k = random effect of the *k*th maternal grandsire, e_{ikl} = residual error,

Model 4 $y_{ijkl} = \mu + F_{(4)i} + S_j + MGS_k + e_{ijkl}$

with y_{ikl} = radiographic finding of an OF in the *ijkl*th horse, μ = model constant, $F_{(4)i}$ = systematic effect component (fixed effects), S_j = random effect of the *j*th sire, MGS_k = random effect of the *k*th maternal grandsire, e_{ijkl} = residual error.

Finally, for each of the four model variants (basic, random sire, random MGS, random sire-random MGS model) models were developed that included different combinations of systematic effects. As the individual auction effect was confounded with the effects of year, type and quality of auction and with the interaction of year and quality of auction, these effects could not be included in models simultaneously. The definition of final models was based on two conditions: all individual systematic effects included in the model had to be significant ($P < 0.05$), and least square means had to be estimable for all variance components considered in the model. The final model estimates were then used to calculate relative frequencies for the relevant systematic effects.

3. Results

The results of the simple and multiple analyses of variances for OF in fetlock joints are given in Tables 3 and 4. The simple analyses of variance in the basic model (Model 1) revealed that the individual date of auction had a significant influence on the prevalence of OF in fetlock joints, as did the fixed effects of year, type and quality of auction and the interaction between year and quality of auction. None of the following were significant for this trait: sex, age, the interaction between sex and age or between sex and WH. However, the prevalence of OF in fetlock joints was significantly dependent on the size of the horse, its anticipated suitability and its region of origin (breeder, exhibitor). Furthermore, the prevalence of OF in fetlock joints was significantly influenced by the random sire effect, but not by the random effect of the MGS. Accordingly, further analyses of variance were performed using random sire effect models (Model 2). Despite the slightly attenuated significance of WH, almost identical results were obtained under the two model variants.

The final models for the prevalence of OF in fetlock joints included the interaction of year and quality of auction (Year * Qual), age (Age) and height at withers (WH) as fixed effects. They were significant ($\chi^2 = 2.93\text{-}3.73$, $P \leq 0.03$) whether the probands' sire was (Model 2) or was not considered as a random effect (Model 1). The relative frequencies estimated for the combined effect of year and quality of auction ranged between 3.8% and 33.9% under the basic model (Model 1) and between 3.6% and 32.8% under the random sire effect model (Model 2). Three- or four-year-old horses were at a significantly higher risk (with relative frequencies between 20.6% and 22.3%) of OF in fetlock joints than older horses (relative frequencies between 16.2% and 16.6%). Furthermore, the probability of fetlock joint OF increased almost linearly with WH, namely from 15.8% to 16.2% in the smallest horses (WH 152-163 cm) to between 25.4% and 26.1% in the tallest horses (WH 172-183 cm). In all cases the correlation between the basic and the random sire effect model estimates was close to unity ($r > 0.99$). The estimates drawn from the random sire effect model were generally slightly lower than the estimates drawn from the basic fixed effect model.

The results of the analyses of variance for the prevalence of OF in hock joints are given in Tables 5 and 6. The prevalence of OF in hock joints was significantly dependent on date, and type and quality of auction, but not on the auction year. There was no significant sex difference in respect to this radiographic finding. However, the horse's age and size (WH) was found to be significant, as was the interaction between sex and age and between sex and WH. The prevalence of OF in hock joints was also significantly related to the anticipated suitability of the horse and to its region of origin (breeder, exhibitor). As both, the random effect of the sire and of the MGS were significant for hock joint OF, all four model variants were used for the analyses of variance. However, the results obtained under the basic model (Model 1) were confirmed in all cases by random sire (Model 2), random MGS (Model 3) and random sire-random MGS effect model (Model 4) analyses.

The final models defined for the prevalence of OF in hock joints included only two fixed effects, i.e. age (Age) and withers height (WH). Whether the random sire and/or MGS effect were included or not, these effects were significant or almost significant with $\chi^2 = 2.75\text{-}5.99$ and $P \leq 0.06$. The presence of a hock joint OF was most likely in four-year-old horses (relative frequencies between 9.4% and 10.4%). Three-year-olds were at the lowest risk of showing this radiographic finding (relative frequency between 6.4% and 7.6%). The probability of an OF in hock joints increased with the size of the horse. The relative frequencies were estimated at between 4.9% and 5.6% in the smallest horses, but at between 10.3% and 12.6% in horses with WH of 170 cm or larger. The correlations between the estimates drawn from the basic, the random sire, random MGS and random sire-random MGS effect models were almost unity (r > 0.99). The inclusion of random effects in the model resulted in lower estimates of least square means, with estimated values decreasing with an increasing number of systematic effect levels (Model 1 > Model 2 > Model 3 > Model 4).

4. Discussion

The objective of this study was to investigate the influence of different systematic effects on the prevalences of osseous fragments in the limb joints of young Warmblood riding horses. Given the low prevalences of osseous fragments in distal and proximal interphalangeal joints, the analyses of variance was confined to the main sites of intra-articular osseous fragments, i.e. to fetlock and hock joints.

The probands of this study were Hanoverian Warmblood horses selected for sale at riding horse auction at between three and seven years of age. After some pre-selection based mainly on performance, the auction candidates had to pass a thorough veterinary examination. This included a standardised clinical and radiological examination of the locomotory system, the results of which were related to available background information on the horses. The inclusion of horses that had been allotted for auction sale, but subsequently not auctioned (horses pulled out of auction), was intended to alleviate the effect of the selection that had previously taken place, since the failure to be offered at auction was at least partly due to unsatisfactory radiographic findings or to locomotory problems that appeared in the training period prior to auction. Therefore the level of performance for the population of horses investigated here could be assumed to be high and quite uniform, although there was some variation of the radiological state of the horses.

High prevalences of osseous fragments have been determined in the limbs joints of clinically healthy young riding horses (KWPN, 1994; Merz, 1993; Müller, 1982; Winter et al., 1996). The results of the present study largely agree with the figures reported in literature. However, osseous fragments in fetlock joints were to some extent an exception inasmuch they were about twice as prevalent in our auction candidates than in the German or Dutch Warmblood horses investigated previously.

There is no uniform aetiology of osseous fragments. In fetlock and hock joints, many of the radio-dense particles radiographically visible might be attributable to the osteochondrosis syndrome (osteochondrosis dissecans, OCD). However, other aetiological factors also have to be considered even in those joints considered to represent predilection sites of this developmental orthopaedic disease (i.e. stifle, hock, metacarpo- and metatarso-phalangeal joints; Jeffcott, 1991). The importance of non-osteochondrotic causes such as trauma, rapid growth or unbalanced nutrition depends on the type of the joints affected and on the sites of manifestation in the particular joints (Dalin et al., 1993; Pool, 1993). However, the medical records of the prospective auction horses were utilised for the present investigation. Given the limited specificity of documentation, only joint-specific analyses could be performed, but no site-specific analyses. The comprehensive term osseous fragments was chosen to allow for this more general definition of traits as opposed to trait definition in many previous studies.

Despite long research, details of the pathogenesis of osteochondrosis are as yet unknown. Nevertheless, there is quite an extensive literature on potential etiological factors (see Jeffcott, 1991 for a review), some of which could be considered in the present study.

Though about 20% of the probands' sires and maternal grandsires were represented by more than ten radiographed horses, the distribution of sires and maternal grandsires among the individual auctions was not balanced. Considerable inter-sire variations have been reported for the prevalences of osseous fragments among their progeny in trotters (between 0% and 44% OF in fetlock joints; between 0% and 69% and between 3% and 30% OF in hock joints; Grøndahl and Dolvik, 1993; Philipsson et al., 1993; Schougaard et al., 1990). As indicated by the significance of the sire and the maternal grandsire in the present study, a similar effect might apply to the Warmblood riding horse. The significance of the temporal effects of date and year of auction or the interaction between year and quality of auction could therefore be related to the specific representation of sires and maternal grandsires. Furthermore, the probands' regional origin, as well as their anticipated suitability and size (withers height) were found to be significant for both main locations of osseous fragments. It is quite likely that these parameters relate to some extent to the horses' pedigrees. In light of the young age of the probands, the type and amount of stress experienced in previous discipline-specific training might have played only a minor role for the significance of anticipated suitability. Height at withers represents a type trait of moderate heritability in the German Warmblood horse ($h^2 = 0.25$; Von Butler and Krollikowsky, 1986). However, the results of the analyses of variance did not change when the sire and/or the maternal grandsire were included as random effects in the model. Consequently, there does not seem to be a very close direct relation between the sire or maternal grandsire and some of the fixed effects considered here. Clearly, other factors are responsible for the significance of particular fixed effects found here.

Various studies have substantiated the influence of growth parameters such as growth rate, above-average height at withers or bone diameter, as well as the influence of aspects of feeding on the prevalence of developmental orthopaedic diseases (excessive energy and/or protein intake, mineral imbalances; Bridges and Harris, 1988; Glade and Belling, 1986; Hoppe, 1984b; Jeffcott, 1991; Jeffcott and Henson, 1998; Jeffcott and Savage, 1996; KWPN, 1994; Mohammed, 1990; Sandgren et al., 1993a, b; Savage et al., 1993; Winter et al., 1996; Willms et al., 1999). The predisposition of taller horses that we determined for osseous fragments in fetlock and hock joints agrees with findings in the literature on OCD for German, Dutch and Swedish horse populations (KWPN, 1994; Sandgren et al., 1993a, b; Winter et al., 1996). Importance should therefore be attached to the rearing conditions of the horses as decisive for their growth and maturation. However, little is known about the circumstances of rearing of our probands. Their origins could be taken into account only by the makeshift variables of the regions of breeder and exhibitor, both of which had a significant influence on the prevalences of osseous fragments in both fetlock and hock joints. The extensive use of artificial insemination in the breeding of Warmblood horses has largely abolished regional restrictions of mating. The specific causes of regional differences remain unclear, as their significance persisted in the random sire and random maternal grandsire models.

Several authors found higher prevalences of developmental diseases in male horses than in females (Mohammed, 1990; Philipsson et al., 1993; Sandgren et al., 1993a), which was explained by hormonal effects or sex-dependent growth rates (Jeffcott, 1991). However, some investigators did not find any sex differences in the prevalences of osteochondrosis (Hoppe, 1984b; Grøndahl, 1991, 1992; Yovich et al., 1985). Similarly, we found no sex-related differences in the prevalences of intra-articular OF.

The significance of the effect of type and quality of auction and of the interaction of year and quality of auction on the prevalences of osseous fragments is likely to depend at least partly on the selection procedure of the VHW. The decision as to at which auction a horse will be offered may not depend only on performance criteria, but also on health aspects. Higher standards will be applied for elite auctions than for subsidiary auctions. The presence of extensive radiological alterations will ultimately bar a horse from being offered for auction sale, even if it currently performs well. The significant differences in prevalences between the actual auction horses and those selected but not auctioned are therefore plausible.

The prevalence of osseous fragments in fetlock joints increased significantly and almost continuously during the eight years of the study period. Given the constancy of technical conditions and the unchanged mode of examination, improvement of radiographic diagnostics can not be assumed to account for this increase in the frequency of documented radiographic findings. Routine radiological examination of two-year-olds has become more and more common among professional horse breeders. Where required, surgical intervention can be arranged before training under saddle is begun. After another season on pasture not even a thorough examination might reveal signs of a previous operation. Economic aspects (sales prospects) restrict the general availability of complete medical preliminary records for all horses, which would allow the correct classification of horses that have been operated on. Therefore, the proportion of affected horses might have been somewhat higher than it was possible to determine in the present study. Given the increased availability and acceptance of arthroscopy, it is quite likely that the proportion of horses previously operated on and therefore falsely classified as negative increased during the study period. Nevertheless, the prevalence of osseous fragments in fetlock joints increased. Consequently, it is clear that the factors promoting the development of intra-articular osseous fragments have remained in effect and have even been intensified despite progress in the keeping and management of horses.

Multiple systematic effects have been found to influence the prevalence of osteochondrosis and osteochondrosis dissecans in the horse. However, it has long been surmised that there is some genetic determination of this widespread developmental disease (Hoppe, 1984a, b; Mohammed, 1990). More recently, the relevant role of genetics has been substantiated in several studies on equine osteochondrosis (Grøndahl and Dolvik, 1993; KWPN, 1994; Philipsson et al., 1993; Pieramati et al., 2003; Schougaard et al., 1990; Willms et al., 1999; Winter et al., 1996). This agrees with our results and indicates a significant influence of the sire and the maternal grandsire on the prevalences of osseous fragments in fetlock and hock joints. Preventive measures should therefore take into account systematic environmental as well as genetic determinants. Further research is needed to develop strategies compatible with current practices of horse breeding and keeping in order to improve the radiological state of the Warmblood riding horse.

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Table 1. Distribution of auction candidates with available pedigree information (n = 3,725) among the sires (n = 462) and maternal grandsires (MGS; n = 641)

Number of descendants per sire or MGS	Number of sires (Number of probands)	Number of MGS (Number of probands)
1	128 (128)	232 (232)
2	56 (112)	84 (168)
3	48 (144)	62 (186)
4	29 (116)	45 (180)
5	24 (120)	32 (160)
6 - 10	77 (608)	87 (643)
11 - 20	57 (810)	61 (884)
21 - 50	34 (1,050)	33 (976)
≥ 51	9 (637)	5 (296)

Table 2. Prevalences of osseous fragments in distal interphalangeal, proximal interphalangeal, fetlock and hock joints of the probands (n = 3,127)

	Prevalences of osseous fragments	
	absolute	relative
Distal interphalangeal joint	141	4.51%
Proximal interphalangeal joint	26	0.83%
Fetlock joint	641	20.50%
Front fetlock joint	294	9.40%
Hind fetlock joint	420	13.43%
Hock joint	294	9.40%

Table 3. Results of the simple analyses of variance for each of the considered systematic effects concerning the prevalence of osseous fragments in fetlock joints, using singular effect models (Model 1) and random sire effect models (Model 2)

	DF	Model 1		Model 2	
		χ^2	P	χ^2	P
Auct	44	2.31	< 0.001	2.24	< 0.001
Year	7	6.36	< 0.001	5.60	< 0.001
Type	6	4.52	< 0.001	3.97	< 0.001
Qual	3	8.82	< 0.001	7.68	< 0.001
Year * Qual	22	3.43	< 0.001	3.25	< 0.001
Sex	1	0.12	0.733	0.05	0.815
Age	2	1.72	0.179	1.47	0.230
Sex * Age	5	0.97	0.436	0.80	0.547
WH	5	2.34	0.040	2.23	0.049
Sex * WH	11	1.66	0.077	1.61	0.089
Suit	3	4.26	0.005	4.04	0.007
RegB	3	5.01	0.002	4.41	0.004
RegE	3	4.84	0.002	4.23	0.005
Sire	277	3.61	< 0.001	3.16-3.60	< 0.001
MGS	324	0.006	0.477	n.e.	n.e.

DF: degrees of freedom; Auct: individual date of auction; Year: year of auction; Type: type of auction; Qual: quality of auction; WH: Withers height; Suit: anticipated suitability; RegB: region of breeder; RegE: region of exhibitor; MGS: maternal grandsire; n.e.: not estimable

Table 4. Results of the simple analyses of variance for each of the considered systematic effects concerning the prevalence of osseous fragments in hock joints, using singular effect models (Model 1), random sire effect models (Model 2), random maternal grandsire (MGS) effect models (Model 3) and random sire-random MGS effect models (Model 4)

	DF	Model 1		Model 2		Model 3		Model 4	
		χ^2	P	χ^2	P	χ^2	P	χ^2	P
Auct	44	1.40	0.043	1.50	0.018	1.59	0.008	1.79	0.001
Year	7	1.18	0.313	1.28	0.257	1.38	0.210	1.57	0.141
Type	6	3.71	0.001	4.14	< 0.001	3.95	0.001	4.49	< 0.001
Qual	3	4.82	0.002	5.20	0.001	4.79	0.003	5.35	0.001
Year * Qual	22	1.54	0.051	1.68	0.024	1.69	0.024	1.91	0.006
Sex	1	1.20	0.272	1.68	0.195	1.67	0.196	2.25	0.134
Age	2	3.20	0.041	3.31	0.037	3.60	0.027	3.64	0.027
Sex * Age	5	2.23	0.049	2.45	0.032	2.54	0.027	2.77	0.017
WH	5	4.62	< 0.001	5.51	< 0.001	5.08	< 0.001	6.20	< 0.001
Sex * WH	11	2.40	0.006	2.88	< 0.001	2.68	0.002	3.32	< 0.001
Suit	3	7.08	< 0.001	6.73	< 0.001	6.88	< 0.001	6.71	< 0.001
RegB	3	6.34	< 0.001	6.24	< 0.001	6.32	< 0.001	6.68	< 0.001
RegE	3	4.71	0.003	5.09	0.002	4.80	0.002	5.36	0.001
Sire	277	3.07	0.001	2.88-3.25	≤ 0.002	3.35	< 0.001	3.23-3.60	< 0.001
MGS	324	2.89	0.002	3.26	0.001	2.61-3.06	≤ 0.005	3.09-3.75	< 0.001

DF: degrees of freedom; Auct: individual date of auction; Year: year of auction; Type: type of auction; Qual: quality of auction; WH: Withers height; Suit: anticipated suitability; RegB: region of breeder; RegE: region of exhibitor; MGS: maternal grandsire; n.e.: not estimable

Table 4. Means and 95% confidence intervals (CI) of the relative frequencies of osseous fragments in fetlock joints for the fixed systematic effects included in final models without random effects (Model 1) and with random sire effect (Model 2)

Fixed effect / Fixed effect level	n	Model 1 $\bar{x}$	Model 1 95% CI	Model 2 $\bar{x}$	Model 2 95% CI
Year * Quality of auction (Year * Qual)					
		P < 0.001 (χ^2 = 3.60)		P < 0.001 (χ^2 = 3.49)	
1991 – I	137	17.00	(11.48-23.98)	16.44	(10.98-23.41)
1991 – II	150	13.33	(8.60-19.60)	13.06	(8.36-19.34)
1992 – I	156	3.81	(1.69-7.73)	3.55	(1.56-7.27)
1992 – II	181	15.51	(10.79-21.42)	15.46	(10.71-21.43)
1993 – I	133	16.61	(11.09-23.63)	15.77	(10.41-22.69)
1993 – II	180	18.01	(12.87-24.29)	17.60	(12.49-23.85)
1994 – 0	46	25.01	(13.85-39.69)	25.31	(14.07-40.03)
1994 – I	120	24.71	(17.65-33.04)	24.46	(17.39-32.84)
1994 – II	182	23.04	(17.29-29.73)	22.54	(16.79-29.26)
1994 – III	76	28.99	(19.69-39.96)	27.30	(18.32-38.04)
1995 – I	139	13.56	(8.69-20.03)	12.83	(8.14-19.12)
1995 – II	166	21.82	(15.98-28.74)	22.41	(16.41-29.50)
1995 – III	94	18.73	(11.86-27.63)	18.00	(11.32-26.74)
1996 – I	110	20.85	(14.09-29.21)	20.83	(14.03-29.28)
1996 – II	161	16.00	(10.90-22.45)	14.99	(10.09-21.28)
1996 – III	96	21.23	(13.97-30.30)	21.10	(13.87-30.16)
1997 – I	109	18.09	(11.78-26.16)	17.63	(11.43-25.62)
1997 – II	187	19.94	(14.61-26.31)	20.43	(14.95-26.95)
1997 – III	129	32.61	(24.89-41.15)	31.60	(23.96-40.11)
1998 – 0	156	33.86	(25.78-42.75)	32.84	(24.82-41.73)
1998 – I	129	27.04	(19.95-35.21)	25.59	(18.60-33.75)
1998 – II	176	23.33	(17.48-30.13)	22.77	(16.92-29.62)
1998 – III	114	25.80	(18.37-34.55)	24.96	(17.60-33.69)
Age					
		P = 0.027 (χ^2 = 3.62)		P = 0.024 (χ^2 = 3.73)	
3 years old	961	22.32	(19.58-25.27)	21.95	(18.99-25.15)
4 years old	1,607	21.28	(19.20-23.47)	20.63	(18.34-23.09)
5-8 years old	559	16.64	(13.66-20.02)	16.16	(13.11-19.63)
Withers height (WH)					
		P = 0.012 (χ^2 = 2.93)		P = 0.008 (χ^2 = 3.12)	
152-163 cm	539	16.22	(13.13-19.74)	15.75	(12.63-19.34)
164-165 cm	522	18.91	(15.57-22.64)	18.42	(15.04-22.24)
166-167 cm	807	18.25	(15.41-21.39)	17.55	(14.64-20.80)
168-169 cm	512	18.69	(15.35-22.46)	18.16	(14.78-21.99)
170-171 cm	418	22.64	(18.63-27.10)	22.51	(18.40-27.10)
172-183 cm	329	26.10	(21.34-31.36)	25.42	(20.59-30.79)

I: elite auction; II: subsidiary auction; III: Equitop auction; 0: pulled out of auction

Table 5. Means and 95% confidence intervals (CI) of the relative frequencies of osseous fragments in hock joints for the fixed systematic effects included in final models without random effects (Model 1), with random sire effect (Model 2), random maternal grandsire (MGS) effect (Model 3) and with both random sire and random MGS effect (Model 4)

Fixed effect Fixed effect level	n	Model 1 $\bar{x}$ 95% CI	Model 2 $\bar{x}$ 95% CI	Model 3 $\bar{x}$ 95% CI	Model 4 $\bar{x}$ 95% CI
Age					
		P = 0.064 (χ^2 = 2.75)	P = 0.058 (χ^2 = 2.86)	P = 0.046 (χ^2 = 3.09)	P = 0.044 (χ^2 = 3.14)
3 years old	961	7.64 (6.06-9.53)	7.61 (5.97-9.56)	7.18 (5.66-9.01)	6.43 (5.37-8.82)
4 years old	1,607	10.40 (8.95-12.00)	10.27 (8.72-12.01)	9.88 (8.39-11.54)	9.44 (7.85-11.25)
5-8 years old	559	8.83 (6.69-11.44)	8.59 (6.49-11.16)	8.47 (6.42-10.98)	7.98 (5.99-10.44)
Withers height (WH)					
		P < 0.001 (χ^2 = 4.43)	P < 0.001 (χ^2 = 5.32)	P < 0.001 (χ^2 = 4.89)	P < 0.001 (χ^2 = 5.99)
152-163 cm	539	5.58 (3.88-7.82)	5.37 (3.73-7.53)	5.31 (3.71-7.42)	4.94 (3.43-6.94)
164-165 cm	522	6.22 (4.39-8.60)	5.99 (4.23-8.29)	5.77 (4.07-7.98)	5.29 (3.70-7.36)
166-167 cm	807	10.17 (8.20-12.47)	9.97 (7.98-12.30)	9.54 (7.64-11.76)	9.02 (7.12-11.27)
168-169 cm	512	9.80 (7.43-12.67)	9.54 (7.22-12.37)	9.53 (7.23-12.33)	9.09 (6.84-11.85)
170-171 cm	418	12.42 (9.50-15.92)	12.61 (9.66-16.14)	11.78 (9.00-15.12)	11.03 (8.84-14.98)
172-183 cm	329	10.87 (7.86-14.63)	10.98 (7.95-14.76)	10.44 (7.57-14.02)	10.29 (7.43-13.87)

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Estimation of genetic parameters for the prevalence of osseous fragments in limb joints of Hanoverian Warmblood horses

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Summary

Genetic parameters were estimated on osseous fragments in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ) of Hanoverian Warmblood horses using restricted maximum likelihood (REML) approach under both, linear animal and sire models. The analyses were based on the results of a standardized radiographic examination of 3725 young riding horses selected for sale at auction. Binary coded data of the radiographic findings were investigated jointly with height at withers. A simulation study was performed to verify the transformation procedures employed. The transformation factors were found to match the data quite well. In most cases, animal and sire model heritability and correlation estimates were in good agreement. The heritability estimates of osseous fragments in the investigated joints were in the range of $h^2 = 0.19$-0.47. Further analyses of osseous fragments in FJ and HJ were performed separately in males and females. The heritability of osseous fragments in FJ and HJ was estimated to be higher in males ($h^2 = 0.18$-0.24 for FJ, $h^2 = 0.34$-0.38 for HJ) than in females ($h^2 = 0.11$-0.13 for FJ, $h^2 = 0.12$-0.14 for HJ). Osseous fragments in the phalangeal joints (DIJ, PIJ, FJ) largely appeared to be correlated moderately positive among each other ($r_g = 0.14$-0.37). But the additive genetic correlations between osseous fragments in the phalangeal joints and in HJ were found to be negative ($r_g = -0.26$ to -0.66). Particularly, this applied to osseous fragments in FJ in general and in both sexes, to osseous fragments in front FJ in males and to osseous fragments in front and hind FJ of females (up to $r_g = -1$). The heritability of height at withers was estimated at $h^2 = 0.21$-0.27. Additive genetic correlations between height at withers and osseous fragments in equine limb joints were mostly moderately positive (up to $r_g = 0.75$).

Keywords: Horse; radiological findings; osseous fragments; genetic parameters; heritability.

Schätzung genetischer Parameter für die Prävalenz isolierter röntgenologischer Verschattungen in Gliedmaßengelenken Hannoverscher Warmblutpferde

Zusammenfassung

Mit der Restricted Maximum Likelihood (REML) Methode wurden im Tier- und Vatermodell genetische Parameter für die Prävalenz isolierter röntgenologischer Verschattungen in Huf-, Kron-, Fessel- und Sprunggelenken Hannoverscher Warmblutpferde geschätzt. Hierfür wurden die Ergebnisse einer standardisierten Röntgenuntersuchung von 3725 jungen, für Reitpferdeauktionen ausgewählten Pferden verwendet. Die Auswertung der binär kodierten Röntgenbefunde erfolgte gemeinsam mit der Analyse der Widerristhöhe der Pferde. In einer Simulationsstudie konnte die Eignung der verwendeten Transformationsfaktoren für die eigenen Daten bestätigt werden. Die in Tier- und Vatermodellen ermittelten Schätzwerte stimmten weitgehend überein. Die Heritabilitätsschätzwerte für isolierte röntgenologische Verschattungen in den untersuchten Gliedmaßengelenken lagen bei h^2 = 0,19-0,47. Isolierte röntgenologische Verschattungen in Fessel- und Sprunggelenken wurden ferner getrennt für männliche und weibliche Pferde untersucht. Die Heritabilität isolierter röntgenologischer Verschattungen in Fessel- und Sprunggelenken wurde für männliche Pferde jeweils höher geschätzt (h^2 = 0,18-0,24 für Fessel-, h^2 = 0,34-0,38 für Sprunggelenke) als für weibliche Pferde (h^2 = 0,11-0,13 für Fessel-, h^2 = 0,12-0,14 für Sprunggelenke). Während isolierte röntgenologische Verschattungen in den Zehengelenken untereinander positiv korreliert erschienen (r_g = 0,14-0,37), ergaben sich negative additiv-genetische Korrelationen zwischen isolierten röntgenologischen Verschattungen in Zehen- und Sprunggelenken (r_g = -0,26 bis -0,66). Dies traf insbesondere für Fesselgelenksbefunde zu, und zwar sowohl für Fesselgelenke insgesamt und bei beiden Geschlechtern als auch für Fesselgelenke der Vorhand bei männlichen und Fesselgelenke der Vor- und Hinterhand bei männlichen und weiblichen Pferden (bis zu r_g = -1). Die für die Widerristhöhe ermittelten Heritabilitätsschätzwerte lagen zwischen h^2 = 0,21 und h^2 = 0,27. Größtenteils ergaben sich positive additiv-genetische Korrelationen zwischen der Widerristhöhe der Pferde und isolierten röntgenologischen Verschattungen in den Gliedmaßengelenken (bis zu r_g = 0,75).

Schlüsselwörter: Pferde; Röntgenbefunde; isolierte röntgenologische Verschattungen; genetische Parameter; Heritabilität.

Introduction

The prevalence of musculoskeletal conditions is considerably high in today's horse population (WINTER et al. 1996). Lameness problems significantly interfere with the performance and longevity of riding, racing and working horses (Grøndahl and Engeland 1995, Storgaard Jørgensen et al. 1997, Wallin et al. 2000). For that reason horse breeders attach more importance to the soundness of the locomotory system when selecting animals for breeding. However, little is known about the genetic background of equine orthopedic diseases.

Many equine locomotory diseases are considered to result from the horses' regular use, i.e., from chronic physical stress. However, some common orthopedic problems become clinically or at least radiographically manifest at a very young age. Among these, alterations ranked among the osteochondrosis syndrome, different types of juvenile degenerative joint disease, and navicular disease appear to be of utmost importance in the Warmblood horse.

Osteochondrosis is a developmental disease that occurs in many different species (Samy 1977). In the horse, it might become visible radiographically already in foals (Hoppe 1984, Carlsten et al. 1993). However, dependent on the affected joint, diagnosis is considered to be definite at an age of between 8 and 12 months (point of no return; Dik et al. 1999, Kroll et al. 2001). In the course of some abnormal cartilage maturation, cartilaginous flaps may (partly) detach and become calcified or ossified secondarily, specifying the condition as osteochondrosis dissecans. Consequently, joint-specifically varying percentages of intra-articular osseous fragments will be referable to the osteochondrosis complex. Though etiology is not completely understood so far there is no doubt that genetic components play some role in this syndrome (Jeffcott 1991). In order to make use of this finding, detailed understanding of genetic influences and correlations between the different forms of manifestation is needed. Till now, investigations that differentiate between the limb joints affected as well as between the sexes are missing in respect of osteochondrosis in the horse.

In the course of an extensive study on radiographic findings in Warmblood riding horses, the prevalence of osseous fragments in different limb joints was analyzed with regard to potential risk factors. Statistical models have been determined that describe the observed distribution of joint affections best (Stock et al. 2004a, b). The objectives of the present study were to estimate genetic parameters for the prevalences of osseous fragments in the limb joints of young riding horses. For the fetlock and hock joints which were the sites mainly affected by osseous fragments, a distinction was also made between findings in the forehand and the hindquarters and between findings in male and female horses

Material und methods

The analysis was based on the results of a standardized radiographic examination of 3,725 young Hanoverian Warmblood horses, for which pedigree information was available. The examination included ten standard projections of the limbs, allowing the inspection of the distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ; metacarpo- and metatarsophalangeal) and hock joints (HJ). All the horses were selected for sale at riding horse auctions in 1991-1998 by the Association of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. However, 245 of the horses had been pulled out of auction for different reasons and were therefore not listed in the official auction catalogues. Twice as many male than female horses were selected for auction sale (2,490 stallions and geldings, 1,235 mares). The horses had a mean age of 3.92 ± 0.77 years and a mean height at withers of 166.96 ± 3.74 cm.

This paper deals with the genetic analysis of osseous fragments in particular joints of the equine limbs. At least one osseous fragment in DIJ, PIJ, FJ or HJ was found in 1,177 horses (31.6%). Among the horses with intra-articular osseous fragments, 87.3% (n = 1,028) had only one type of joint, 12.3% (n = 145) had two, and 0.3% (n = 4) had three different types of joints affected. In no horse, osseous fragments were found in DIJ, PIJ, FJ and HJ simultaneously. Osseous fragments were most often diagnosed in FJ (20.8% of the horses) and HJ (9.6% of the horses). DIJ (168 or 4.5% of the horses) or PIJ (34 or 0.9% of the horses) were less often affected. The prevalences of osseous fragments in DIJ, PIJ, FJ and HJ did not differ significantly between male and female horses ($P > 0.15$).

Statistical analyses

The prevalences of osseous fragments were analyzed as binary traits: 0 = no indication of an osseous fragment, 1 = presence of at least one osseous fragment on all available X-rays. Generally, the radiographical findings in DIJ, PIJ, FJ and HJ were analyzed separately. Generally, no distinction was drawn between the specific locations of osseous fragments in the particular joints (e.g., dorsal vs. palmar/plantar osseous fragments in FJ). For more detailed analyses, following subdivisions were made: - prevalence of osseous fragments in joints of the forehand and the hindquarters (e.g., FJ front), - prevalence of osseous fragments in FJ and HJ of males and females (e.g., FJ male), and - prevalence of osseous fragments in front and hind FJ of males and females (e.g., FJ front male). Height at withers was analyzed as continuous trait.

The procedure GENMOD of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2002) was used for the preliminary analysis of systematic effects providing the basis for the genetic analyses.

The estimation of genetic parameters was performed using restricted maximum likelihood (REML) with VCE4 Version 4.2.5 (Variance Component Estimation, GROENEVELD 1998). Linear animal (LAM) and sire models (LSM) were applied for the estimation of variances and covariances. Given the significance of height at withers for the prevalence of osseous fragments in FJ and HJ, height at withers was regarded as a separate trait in the analyses of the radiographic findings. Following univariate analyses of the individual traits, three different sets of multivariate analyses were performed: (I) osseous fragments in DIJ, PIJ, FJ and HJ, and height at withers, (II) osseous fragments in FJ of males, in FJ of females, in HJ of males, in HJ of females, and height at withers, (III) osseous fragments in FJ of the front limbs of males, in FJ of the front limbs of females, in FJ of the hind limbs of males, in FJ of the hind limbs of females, in HJ of males, in HJ of females, and height at withers. Each set of multivariate analyses was assembled by multiple bi- and tri-variate analyses, including all possible combinations of two or three traits.

Because the estimates obtained from the multivariate analyses were very similar among each other and to the univariate estimates only the mean heritabilities (h^2), mean additive genetic (r_g) and residual correlations (r_e) and the mean standard errors (s_{h^2}, s_{rg}, s_{re}), calculated from all the respective uni- and multivariate estimates, are reported.

The models which entered the genetic analyses included trait-specific fixed effects (F_i) and the random additive genetic effect of the animal (a_j) or the sire (s_j).

$$y_{ijk} = \mu + F_i + a_j + e_{ijk}$$

$$y_{ijk} = \mu + F_i + s_j + e_{ijk}$$

with y_{ijk} = radiographic finding of the examined horse, μ = model constant, and e_{ijk} = residual error.

The results of the preliminary study were used to determine the fixed effects which influenced the prevalence of the osseous fragments in the different joints and should therefore be included in the model. For the different traits investigated the fixed effects were specified as follows:

distal interphalangeal joint (DIJ): $F_i = Auct_m + Sex_n + Age_o$

proximal interphalangeal joint (PIJ): $F_i = Auct_m + Sex_n + RegE_r$

fetlock joint (FJ): $F_i = Auct_m + Sex_n + Age_o$

hock joint (HJ): $F_i = Auct_m + Sex_n + Age_o + Suit_p + RegB_q + RegE_r$

height at withers: $F_i = Sex_n + Age_o$

with $Auct_m$ = fixed effect of the date of auction (m = 1-50),

Sex_n = fixed effect of the sex (n = 1-2),

Age_o = fixed effect of the age group (o = 1-3; three, four, five or more years old),

$Suit_p$ = fixed effect of the anticipated suitability (p = 1-4; dressage, show-jumping, dressage and show-jumping, no specification),

$RegB_q$ = fixed effect of the region of breeder (q = 1-4), and

$RegE_r$ = fixed effect of the region of exhibitor (r = 1-4).

In the sex-stratified analyses, the sex effect had to be removed from the model since radiographic findings in males and females were analyzed separately (e.g., FJ male).

The heritability estimates of the LAM and LSM analyses were transformed according to DEMPSTER and LERNER (1950). Let p_i be the frequency of outcome 1 for trait i, z_i be the ordinate of a standard normal distribution at the threshold point corresponding to a fraction p_i of the population having the character, h^2_{obs} be the heritability of trait i on the observed (binary) scale, and h^2_{liab} be the heritability of trait i on the underlying continuous scale. Then

$$h^2_{liab} = h^2_{obs} [p_i (1 - p_i)] / z_i^2 .$$

The estimates of the residual correlations (r_e) were analogously transformed according to VINSON et al. (1976).

$$r_{e\,liab} = r_{e\,obs} \{[p_{i\,1} (1 - p_{i\,1})] / z_{i\,1}{}^2\}^{1/2} \{[p_{i\,2} (1 - p_{i\,2})] / z_{i\,2}{}^2\}^{1/2}$$

Simulation study

In order to ensure reliability of the estimates obtained in the linear models, equivalent data sets were simulated resembling different prevalences and heritabilities of binary traits. As in the analyses of the observed data, for each horse with a simulated observation a pedigree of four ancestral generations was used. For the Monte Carlo simulation, the additive genetic effect "a" of the animal was assumed to be distributed normally in the base animals with $N(0, \sigma_a^2)$. For non-base animals this resulted in distributions of $N(0.5(a_{sire} + a_{dam}), 0.5\sigma_a^2)$ with a_{sire} and a_{dam} denoting the additive genetic effects of sire and dam, respectively, and $0.5\sigma_a^2$ denoting the Mendelian sampling variance. Subsequently, a residual effect "e" with $N(0, \sigma_e^2)$ was generated for the probands. Moreover, the fixed effect of the sex was included in the simulation model with males assumed to be more likely to be affected.

Simulation model: $l_{ijk} = a_i + sex_j + e_{ijk}$

with l_{ijk} = liability of the i-th animal, a_i = additive genetic effect of the i-th animal, sex_j = fixed effect of sex, and e_{ijk} = residual effect.

The variance of the liability σ_l^2 was set to one, and the threshold on the underlying liability scale defined according to the trait's prevalence.

Different levels of heritabilities (h^2_{s1} = 0.00, h^2_{s2} = 0.10, …, h^2_{s11} = 1.00) were used for the simulation assuming low (p_{sI} = 0.04), moderate (p_{sII} = 0.25) and high (p_{sIII} = 0.50) prevalences of the trait. For each of the 33 combinations ($p_{sI} - h^2_{s1}$, $p_{sI} - h^2_{s2}$, …, $p_{sIII} - h^2_{s11}$) 20 repeats of univariate REML analyses were run. In each case the mean of all the heritability estimates obtained was compared to the true heritability.

In order to evaluate the additive genetic and residual correlations between the most relevant traits (i.e., osseous fragments in fetlock and hock joints), additional multivariate analyses were performed. Starting from our results of the observed data analyses and given the observed prevalences (0.25 and 0.10, respectively), different levels of r_g and r_e were simulated. In each case, the means of the r_g and r_e estimates derived from at least 50 repeats of bivariate REML analyses were compared with the r_g and r_e estimates obtained in the analyses of the observed data.

Results

Analysis of collected data

Genetic parameters estimated for the prevalences of osseous fragments in DIJ, PIJ, FJ and HJ, and for height at withers are shown in Table 1. The heritability estimates for the prevalences of osseous fragments were in the range of h^2 = 0.03-0.14 before and of h^2 = 0.19-0.47 after transformation to the underlying liability scale. The lowest heritability was estimated for osseous fragments in FJ (h^2 = 0.19-0.25), the highest for osseous fragments in PIJ (h^2 = 0.43-0.47). The heritability of height at withers was estimated at h^2 = 0.21-0.27. Osseous fragments in DIJ were significantly positively correlated additive genetically with osseous fragments in FJ (r_g = 0.23-0.37). Significant negative additive genetic correlations were estimated between osseous fragments in the distal limb joints (DIJ, PIJ, FJ) and in HJ (r_g = -0.26 to -0.66). The genetic correlation between height at withers and osseous fragments was positive for DIJ and FJ (r_g = 0.19-0.38), but negative for PIJ (r_g = -0.59 to -0.64). In most cases, the standard errors for the genetic correlations (s_{rg} = 0.08-0.36) were higher than the standard errors for the heritabilities (s_{h^2} = 0.03-0.25). The residual correlations between all the traits were originally small (r_e = -0.04 to 0.09), but the transformation of estimates resulted in considerably higher values (r_e = -0.27 to 0.20).

The results of the analyses of the prevalences of osseous fragments in FJ and HJ of females and males, and for height at withers are shown in Table 2. For both sexes, the heritability

estimates for osseous fragments in FJ and HJ were in the range of h^2 = 0.02-0.13 before and h^2 = 0.11-0.38 after transformation. The heritability of osseous fragments in both, FJ and HJ, was estimated to be higher in males (h^2 = 0.18-0.24 for FJ, h^2 = 0.34-0.38 for HJ) than in females (h^2 = 0.11-0.13 for FJ, h^2 = 0.12-0.14 for HJ). The heritability estimates for height at withers were h^2 = 0.26 under LAM, and h^2 = 0.21 under LSM. Referring to one type of joint affected (FJ and HJ, respectively), additive genetic correlations between radiographic findings in the two sexes were close to r_g = 1. However, highly negative additive genetic correlations were determined between osseous fragments in HJ of females and in FJ of both, males and females (r_g = -0.63 to -1.00). Only under LAM a significant negative additive genetic correlation was estimated between osseous fragments in FJ of females and in HJ of males (r_g = -0.45). Osseous fragments in FJ were found to be significantly positively correlated additive genetically with height at withers in males as well as in females (r_g = 0.20-0.53). The standard errors amounted to s_{h^2} = 0.03-0.10 and s_{rg} = 0.00-0.74. The transformed estimates of the residual correlations between all the traits were in the range of r_e = -0.03 to 0.16.
Genetic parameters estimated for the prevalences of osseous fragments in front and hind FJ and in HJ of females and males, and for height at withers are shown in Table 3. The heritability estimates for osseous fragments in front FJ of females were considerably lower (h^2 = 0.01-0.05 before and h^2 = 0.05-0.08 after transformation) than that for osseous fragments in front FJ of males and in hind FJ of both, males and females (h^2 = 0.07-0.18 before and h^2 = 0.20-0.37 after transformation). Moderately to highly positive additive genetic correlations were estimated between osseous fragments in front and hind FJ of both sexes (r_g = 0.27-1.00). Under LAM and/or LSM significant negative additive genetic correlations were determined between osseous fragments in front and hind FJ and osseous fragments in HJ of both sexes (r_g = -0.10 to -1.00). Radiographic findings in males meant some exception with inconsistent, i.e., moderately negative to moderately positive additive genetic correlation estimates between osseous fragments in front and hind FJ and in HJ (r_g = -0.21 to 0.35). Height at withers was found to be significantly positively correlated additive genetically with osseous fragments in front FJ of females and in hind FJ of both sexes (r_g = 0.14-0.74). The standard errors were s_{h^2} = 0.03-0.13 and s_{rg} = 0.01-0.74. After transformation the residual correlations were in the range of r_e = -0.07 to 0.37.

Simulation study

The results of the univariate part of the simulation study are shown in Figure 2. For low, moderate and high prevalences of the binary trait, the REML heritability estimates were distributed almost linearly and were consistently below the true heritability. The factors to compensate for this underestimation were 4.386, 1.912 and 1.716 for prevalences of 0.04, 0.25 and 0.50, respectively. Hence, they were quite similar to those derived by DEMPSTER and LERNER (1950) (Table 4).

Assuming heritabilities on the underlying scale of $h^2_I = 0.17$ and $h^2_{II} = 0.35$, prevalences of $p_I = 0.25$ and $p_{II} = 0.10$, an additive genetic correlation of $r_g = -0.30$ and residual correlation of $r_e = 0.10$, i.e. approximately resembling the conditions determined for osseous fragments in FJ and HJ under LAM, the correlations were estimated at $r_g = -0.25$ and $r_e = 0.03$. The corresponding transformed estimate was $r_e = 0.07$.

Discussion

The objective of this study was to determine the amount of additive genetic contribution to the pathogenesis of osseous fragments in different limb joints of Hanoverian Warmblood horses. Furthermore, we wanted to show whether the development of osseous fragments visible radiographically is, from a genetic point of view, a matter of a single disease with various, arbitrary sites of manifestation, or whether genetically different conditions might cause joint-specific or even joint- and sex-specific affections. For this reason, the specific joint locations of the radiographic findings (distal interphalangeal, proximal interphalangeal, fetlock or hock joint; forehand or hindquarters) as well as the sex of the horse were taken into account.

Osseous fragments as analyzed in the present study can not generally be attributed to the osteochondrosis syndrome. Traumatic geneses in particular can not always be precluded on the basis of the radiological appearance. This should be particularly true for those detected in distal and proximal interphalangeal joints. However, it seems to be reasonable to assume that a large part of osseous fragments found in fetlock and hock joints represents osteochondrosis dissecans. Given the lack of literature on genetic analyses of the prevalence of intra-articular osseous fragments in general, we will entirely refer to reports on equine osteochondrosis.

Heritability estimations mostly confine to tarsal osteochondrosis (KWPN 1994, SCHOUGAARD et al. 1990) or to osteochondral fragments in hock and fetlock joints (GRØNDAHL and DOLVIK 1993, PHILIPSSON et al. 1993); partly, no specification is made which joints are taken in consideration when statements are taken about osteochondrosis (WILLMS et al. 1999a, WINTER et al. 1996). The reported heritability estimates were in the range of h^2 =0.02-0.64 (Table 5). Estimates from animal models were partly lower, partly higher than estimates from sire models, as it was the case in the present investigation (h^2_{LSM} / h^2_{LAM} = 0.6 to 1.4).

Furthermore, in the view of the different methods used for the estimation of genetic parameters no clear methodical trends could be derived from literature.

Considering the affected joints, GRØNDAHL and DOLVIK (1993) found a noticeably higher heritability for OCD in metacarpo-/metatarsophalangeal joints ($h^2 = 0.52$) than for OCD in tarsocrural joints ($h^2 = 0.21$). However, with $h^2 = 0.19$-0.24 for fetlock OCD and $h^2 = 0.17$-0.27 for hock OCD the results of PHILIPSSON et al. (1993) are in accordance with our results. The heritability of osseous fragments in hock joints was about 0.30 on the underlying liability scale and therefore 1.1- to 1.8-fold higher than that of osseous fragments in fetlock joints ($h^2 \approx 0.20$). However, more detailed analyses, i.e., separate analyses for males and females and for front and hind limb joints revealed some characteristics not known yet. In males, the heritability estimates for osseous fragments in hock joints were again considerably (i.e., 1.4- to 2.1-fold) higher than that for osseous fragments in fetlock joints. However, in females the heritability estimates for osseous fragments in hock and fetlock joints were very similar ($h^2_{hock} / h^2_{fetlock} = 0.9$-$1.3$). Further differentiation between the location of the radiographic findings in front or hind limbs revealed additional sex differences in respect of osseous fragments in front fetlock joints. In females, the heritability of this radiographic finding was found to be very low. But the heritability of osseous fragments in front fetlock joints of males was even higher than that of osseous fragments in hind fetlock joints of both, males and females. However, considering the high additive genetic correlations between corresponding radiographic findings in front and hind fetlock joints and in hock joints of male and female horses, one might conclude that they represent genetically uniform traits with variances differing between the sexes.

With heritability estimates in the range of $h^2 = 0.21$-0.27 for height at withers our results are in good agreement with previous investigations in German Warmblood horses ($h^2 = 0.25$; VON BUTLER and KROLLIKOWSKY 1986).

Referring to literature, no significant genetic correlation (GRØNDAHL and DOLVIK 1993) or a positive genetic correlation with a high standard error was found between hock joint osteochondrosis and osteochondral fragments in fetlock joints of trotters (PHILIPSSON et al. 1993: $r_g = 0.58 \pm 0.49$). According to our results, the prevalences of osseous fragments in the distal limb joints are correlated genetically positively among each other, but negatively with the prevalence of osseous fragments in hock joints. In the more detailed analyses, the negative additive genetic correlation between osseous fragments in fetlock and hock joints was substantiated primarily for females. Highly positive genetic correlations between osseous fragments in front and hind fetlock joints of females opposed to non-significant genetic correlations between corresponding findings in males that only tended to be positive. Consequently, at least in female horses there seems to be no genetic distinction between osseous fragments in metacarpo- and metatarsophalangeal joints. In both sexes osseous fragments in fetlock and hock joints have to be regarded as genetically somewhat opposing traits that should therefore be considered separately. It will probably be difficult to develop breeding strategies that aim to improve the health status of the distal limb joints, and fetlock joints in particular, and of hock joints in respect of osseous fragments simultaneously.

As opposed to WILLMS et al. (1999b) who analyzed the prevalence of OCD in German riding horses, we found relevant genetic correlations between height at withers and osseous fragments in equine limb joints. Height at withers was determined to significantly influence the prevalence of osseous fragments in fetlock and hock joints of our probands. Given the largely positive additive genetic correlations between height at withers and osseous fragments in these joints, intense selection for larger horses appears not to be advisable if one wants to lower the prevalence of osseous fragments in the predominantly affected limb joints.

In general, the estimates of the additive genetic correlations had considerably higher standard errors than the heritability estimates (range s_{rg} = 0.01 to 0.74 vs. s_{h^2} = 0.03 to 0.25), and there were larger discrepancies between LAM and LSM estimates (Δ ($r_{g\,LSM}$ - $r_{g\,LAM}$) = 0 to 0.52 vs. Δ ($h^2{}_{LSM} - h^2{}_{LAM}$) = 0 to 0.10). These discrepancies are probably due to the specific data structures concerning the distribution of probands and affected animals among the progeny of the represented sires. The low precision of the correlation estimates we encountered is in agreement with the results of previous authors who also found very high standard errors (s_{rg}), irrespective of the method used (MEYER 1991, SIMIANER and SCHAEFFER 1989, LUO et al. 1999). Moreover, GATES et al. (1999) concluded from their simulation study that REML tends to underestimate genetic correlations between one continuous and one binary trait as well as between two binary traits under both AM and SM. This finding was confirmed in our bivariate simulation study (underestimation of about 16%).

Whilst additive genetic correlations are directly estimable in mixed linear models irrespective of binary coding, the respective residual correlations need to be transformed (VINSON et al. 1976, MÄNTYSAARI et al. 1991). On the present data, this resulted in estimates of residual correlations in the range of r_e = -0.27 to 0.33, but with most estimates remaining smaller than r_e = ± 0.05. Although our bivariate data simulation suggested residual correlations being somewhat underestimated even after transformation, more extensive simulations would be necessary to verify this finding.

For this investigation we used the restricted maximum likelihood (REML) approach, a widespread application of mixed linear model methodology, for the estimation of genetic parameters. Likelihood-based methods are favored by several investigators and regarded as the method of choice for the estimation of variance components (PATTERSON and THOMPSON 1971, MEYER 1991) though some investigators stressed the limitations and potential deficiencies of the REML approach (GIANOLA and FOULLEY 1983, LUO et al. 2001). Applying linear models to genetic analyses of categorical traits, and of binary traits in particular, is controversial since the discontinuous character of such data clearly violates the assumption of normality (THOMPSON 1979, GIANOLA 1982). Nevertheless, many studies used mixed linear model methodology for the genetic analyses of categorical traits (see LUO et al. 1999).
To overcome the problem of analyzing categorical traits linearly, we made use of the transformation according to DEMPSTER and LERNER (1950) which is based on the threshold liability concept (WRIGHT 1934). It takes into account the trend of linear model analyses to underestimate the heritability of traits with extreme prevalences and provides some adjustment. The transformation of estimates based on observed discrete categories to estimates referring to the underlying liability scale should allow for parameter estimation unbiased by categorical problems (DEMPSTER and LERNER 1950). Furthermore, transformation might improve the identification and selection of genetically superior animals and hence allow for a more rapid genetic improvement (GIANOLA 1982, HOESCHELE 1986, MEIJERING and GIANOLA 1985, MATOS et al. 1997). However, some authors have questioned general reliability of the traditionally used transformation factors (VAN VLECK and GREGORY 1992), whilst others found close agreement between transformed heritability estimates and simulated heritabilities (MÄNTYSAARI et al. 1991). With simulated data and for the prevalences chosen exemplarily, we could derive transformation factors differing little from the DEMPSTER-LERNER factors (f_S - f_{DL} = 0.06-0.79). Consequently, we can justify the use of the later for the analyses of our collected data. However, heritabilities will be somewhat overestimated for traits with low prevalences (such as osseous fragments in proximal and distal interphalangeal joints), but slightly underestimated for more prevalent traits (such as osseous fragments in fetlock joints).
An alternative strategy to alleviate the bias problem in linear model analyses would be the use of more than two categories when coding the data. However, in our case this was not applicable: from the medical records we could only derive if an osseous fragment was visible on one of the radiographs in a particular limb joint or not; but there was no general documentation of the number and the location of fragments in an affected joint, and if or to

what extent additional alterations of the joints existed, which would have enabled us to grade the radiographic findings.

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Table 1. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of osseous fragments in different limb joints and for height at withers using a linear animal model (LAM) and a linear sire model (LSM)**

Limb joint	DIJ	PIJ	FJ	HJ	Height at withers
DIJ	$0.221^{0.080}$ $0.286^{0.105}$	$0.302^{0.242}$ $-0.220^{0.358}$	$0.372^{0.210}$ $0.233^{0.153}$	$-0.314^{0.163}$ $-0.294^{0.130}$	$0.220^{0.125}$ $0.201^{0.162}$
PIJ	$-0.267^{0.122}$ $-0.145^{0.092}$	$0.474^{0.228}$ $0.429^{0.249}$	$0.138^{0.279}$ $0.260^{0.255}$	$-0.656^{0.173}$ $-0.462^{0.268}$	$-0.589^{0.170}$ $-0.641^{0.202}$
FJ	$-0.070^{0.027}$ $-0.006^{0.033}$	$0.126^{0.091}$ $0.137^{0.066}$	$0.191^{0.042}$ $0.253^{0.059}$	$-0.257^{0.135}$ $-0.308^{0.171}$	$0.375^{0.081}$ $0.185^{0.129}$
HJ	$0.199^{0.059}$ $0.122^{0.035}$	$0.190^{0.127}$ $-0.082^{0.076}$	$0.076^{0.044}$ $0.025^{0.021}$	$0.334^{0.063}$ $0.273^{0.070}$	$0.159^{0.114}$ $-0.008^{0.129}$
Height at withers	$0.054^{0.041}$ $0.088^{0.027}$	$0.188^{0.085}$ $0.006^{0.048}$	$0.032^{0.027}$ $0.101^{0.016}$	$0.128^{0.040}$ $0.152^{0.020}$	$0.267^{0.033}$ $0.208^{0.033}$

DIJ – distal interphalangeal joint; PIJ – proximal interphalangeal joint; FJ – fetlock joint; HJ – hock joint

Table 2. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of osseous fragments in fetlock (FJ) and hock joints (HJ) by sex, and for height at withers using a linear animal model (LAM) and a linear sire model (LSM)**

Limb joint and sex	FJ_m	FJ_f	HJ_m	HJ_f	Height at withers (m, f)
FJ_m	$0.182^{0.055}$ $0.237^{0.072}$	$0.986^{0.034}$ $1.000^{0.001}$	$-0.006^{0.080}$ $-0.036^{0.136}$	$-0.839^{0.231}$ $-0.995^{0.032}$	$0.299^{0.131}$ $0.198^{0.119}$
FJ_f	$-0.011^{0.022}$ $0.002^{0.013}$	$0.134^{0.075}$ $0.106^{0.084}$	$-0.448^{0.148}$ $-0.386^{0.735}$	$-0.632^{0.296}$ $-0.976^{0.146}$	$0.534^{0.235}$ $0.226^{0.365}$
HJ_m	$0.009^{0.041}$ $0.009^{0.034}$	$-0.030^{0.025}$ $-0.005^{0.016}$	$0.377^{0.086}$ $0.337^{0.091}$	$0.982^{0.038}$ $1.000^{0.001}$	$0.095^{0.128}$ $0.015^{0.151}$
HJ_f	$-0.017^{0.028}$ $-0.002^{0.019}$	$0.090^{0.066}$ $0.038^{0.050}$	$-0.009^{0.035}$ $0.009^{0.021}$	$0.139^{0.082}$ $0.116^{0.096}$	$0.294^{0.280}$ $-0.046^{0.338}$
Height at withers (m, f)	$0.069^{0.039}$ $0.113^{0.021}$	$0.001^{0.049}$ $0.087^{0.031}$	$0.132^{0.045}$ $0.138^{0.023}$	$0.151^{0.056}$ $0.160^{0.035}$	$0.264^{0.034}$ $0.207^{0.034}$

FJ – fetlock joint; HJ – hock joint; m – male; f - female

Table 3. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of osseous fragments in fetlock joints of forehand and hindquarters and in hock joints by sex and for height at withers using a linear animal model (LAM) and a linear sire model (LSM)**

Limb joint and sex	FJ_m front	FJ_f front	FJ_m back	FJ_f back	HJ_m	HJ_f	Height at withers (m, f)
FJ_m front	$0.265^{0.078}$ $0.369^{0.101}$	$0.588^{\text{n.e.}}$ $0.645^{\text{n.e.}}$	$0.483^{0.222}$ $0.572^{0.209}$	$0.265^{0.178}$ $0.307^{0.259}$	$0.073^{0.090}$ $-0.207^{0.197}$	$-0.630^{0.733}$ $-0.900^{0.624}$	$0.044^{0.091}$ $0.007^{0.145}$
FJ_f front	$-0.006^{\text{n.e.}}$ $0.003^{\text{n.e.}}$	$0.082^{0.065}$ $0.052^{0.059}$	$0.997^{0.021}$ $0.999^{0.014}$	$0.952^{0.101}$ $0.756^{0.351}$	$-0.557^{0.252}$ $-0.262^{0.577}$	$-1.000^{0.053}$ $-0.668^{0.470}$	$0.753^{0.210}$ $0.695^{0.293}$
FJ_m back	$0.242^{0.059}$ $0.298^{0.038}$	$0.029^{0.032}$ $0.005^{0.018}$	$0.199^{0.076}$ $0.199^{0.079}$	$0.987^{0.031}$ $0.963^{0.057}$	$0.190^{0.219}$ $0.348^{0.237}$	$-0.791^{0.740}$ $-0.510^{0.530}$	$0.583^{0.127}$ $0.535^{0.152}$
FJ_f back	$-0.005^{0.027}$ $0.003^{0.018}$	$0.292^{0.079}$ $0.373^{0.052}$	$-0.011^{0.026}$ $-0.002^{0.017}$	$0.317^{0.117}$ $0.267^{0.130}$	$-0.347^{0.210}$ $-0.091^{0.269}$	$-0.999^{0.101}$ $-0.673^{0.562}$	$0.425^{0.167}$ $0.139^{0.226}$
HJ_m	$0.031^{0.045}$ $0.065^{0.028}$	$0.000^{0.045}$ $0.003^{0.021}$	$-0.066^{0.066}$ $-0.030^{0.038}$	$0.000^{0.037}$ $-0.012^{0.020}$	$0.377^{0.086}$ $0.337^{0.091}$	$0.982^{0.038}$ $1.000^{0.001}$	$0.095^{0.128}$ $0.015^{0.151}$
HJ_f	$0.000^{0.041}$ $0.000^{0.020}$	$0.046^{0.067}$ $-0.006^{0.058}$	$0.000^{0.036}$ $-0.005^{0.018}$	$0.172^{0.091}$ $0.053^{0.035}$	$-0.009^{0.035}$ $0.009^{0.021}$	$0.139^{0.082}$ $0.116^{0.096}$	$0.294^{0.280}$ $-0.046^{0.338}$
Height at withers (m, f)	$0.053^{0.035}$ $0.056^{0.022}$	$-0.107^{0.056}$ $0.002^{0.036}$	$0.002^{0.045}$ $0.115^{0.022}$	$-0.003^{0.059}$ $0.104^{0.033}$	$0.132^{0.045}$ $0.138^{0.023}$	$0.151^{0.034}$ $0.160^{0.035}$	$0.266^{0.033}$ $0.207^{0.034}$

FJ – fetlock joint; HJ – hock joint; m – male; f – female; n.e. – not estimable

Table 4. **Comparison of the Dempster-Lerner transformation factor (f_{DL}; DEMPSTER and LERNER 1950) and the transformation factor derived from simulated data (f_S)**

Prevalence	f_{DL}	f_S
0.04	5.171	4.386
0.25	1.857	1.912
0.50	1.571	1.716

Table 5. **Heritability estimates for osseous fragments in different limb joints**

Population and number of investigated horses	Radiographic finding	Heritability estimate	Method of analysis	Author
Danish trotters (n = 325)	OCD (hock)	0.26 ± 0.14	STM (χ^2-heterogeneity test)	SCHOUGAARD et al. 1987
Norwegian trotters (n = 644)	OCD (fetlock) OCD (hock)	0.52 0.21	STM (REML)	GRØNDAHL and DOLVIK 1993
Swedish Standardbred trotters (n = 793)	OCD (fetlock) OCD (hock)	0.09 -> 0.19 0.09 -> 0.24	LSM (χ^2-heterogeneity test -> DL transformation)	PHILIPSSON et al. 1993
		0.08 -> 0.17 0.09 -> 0.27	LSM (Henderson III -> DL transformation)	
Maremmano horses (n = 350)	OCD	0.13-0.14 ± 0.22-0.23	LAM (REML, DL transformation)	PIERAMATI et al. 2003
		0.08-0.09 ± 0.23-0.24	ATM (Average Information REML)	
Dutch Warmblood horses (mares; n = 590)	OCD (hock)	0.14 ± 0.17	LAM (REML, transformation)	KWPN 1994
		0.01 ± 0.06 -> 0.02 ± 0.14	LSM (REML -> transformation)	
		0.02 ± 0.06	STM (REML)	
German Riding Horses (n = 2407 resp. 3566)	OCD	0.07 ± 0.03	LAM (REML)	WINTER et al. 1996
		0.06 ± 0.04	LSM (Henderson III)	
German Riding Horses (mares; n = 401 resp. 456)	OCD	0.45 ± 0.23	LSM (GS)	WILLMS et al. 1999a
		0.64	STM (REML-type algorithm)	
		0.34 ± 0.06	ATM (GS)	
German Riding Horses (foals; n = 144)		0.58 ± 0.15	LSM (GS)	
		0.19 ± 0.02	ATM (GS)	

ATM – animal threshold model; STM – sire threshold model; LAM – linear animal model; LSM – linear sire model; REML – restricted maximum likelihood; GS – Gibbs Sampling; DL – Dempster-Lerner; OCD – osteochondrosis dissecans

Fig. 1. Distribution of osseous fragments in different limb joints by sex

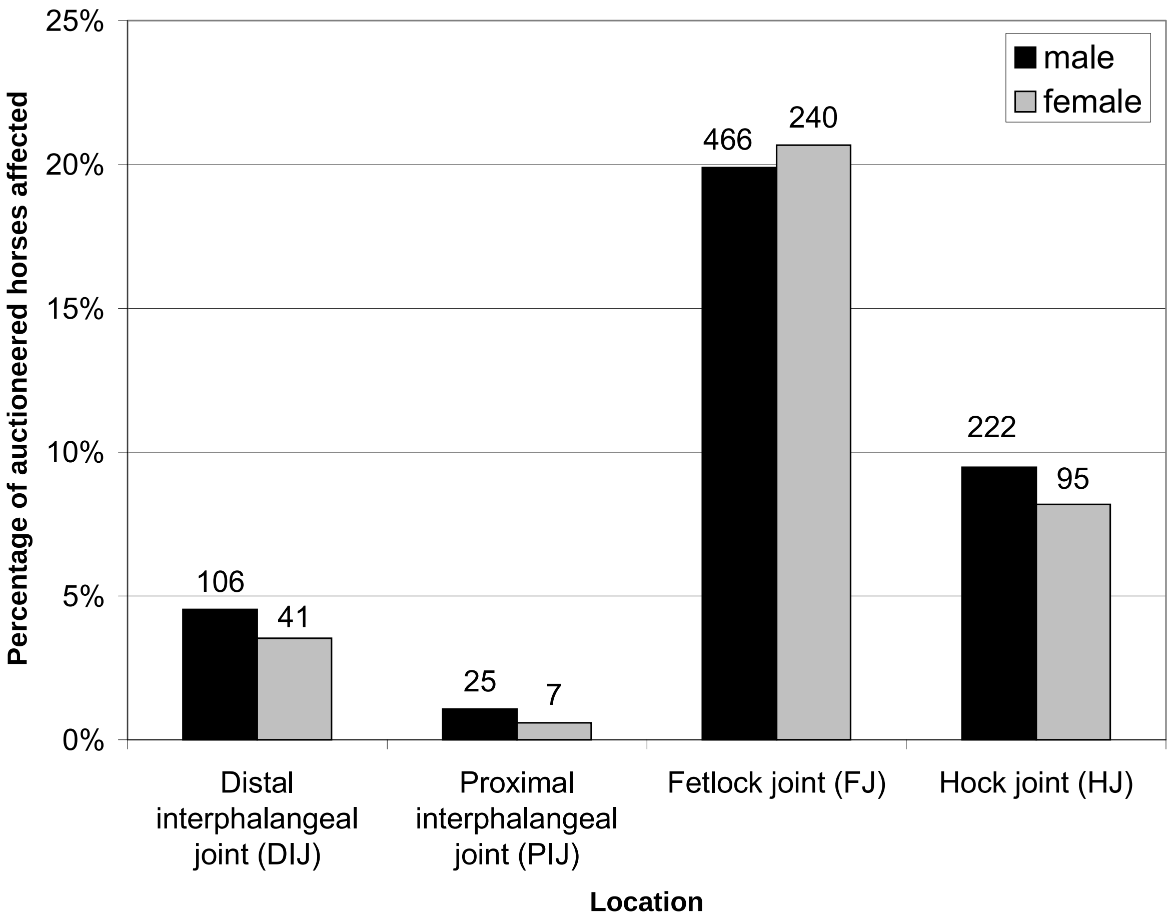
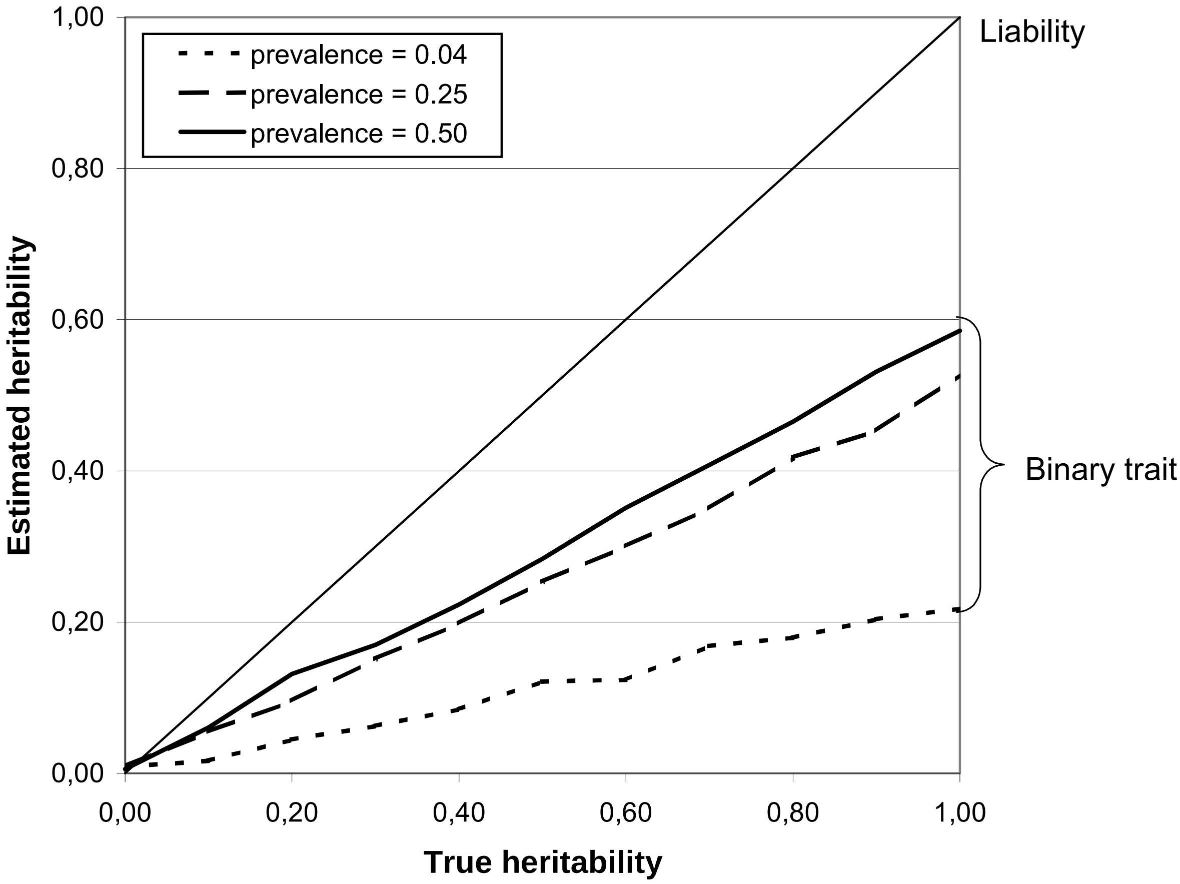


Fig. 2. Comparison of the true and the estimated heritability based on simulated data with prevalences of 0.04, 0.25 and 0.50



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Variance component estimation on the frequency of deforming arthropathies in limb joints of Hanoverian Warmblood horses

BY K. F. STOCK, H. HAMANN, O. DISTL

Summary

Following the analysis of systematic effects, the restricted maximum likelihood (REML) approach was used to estimate genetic parameters on deforming arthropathies in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ) under both linear animal and linear sire models. The data comprised of the results of a standardized radiological examination of 3,748 young Hanoverian Warmblood horses selected for sale at auction as riding horses. 17.7 % of the horses showed radiographic findings indicative of degenerative joint disease in at least one of the examined joints. HJ were found to be most often affected. The examiner as well as the date of the auction had a significant influence on the prevalence of documented radiological findings. Only deformations in DIJ appeared to be significantly dependent on the age of horse, with older horses being more often affected. With increasing height at withers the probability to show deformations of DIJ or PIJ tended to increase. Having genes of the Holstein Warmblood resulted in a higher probability to show deforming arthropathies in DIJ. The higher the proportion of Thoroughbred genes, the more likely was the horse to present slight HJ deformations (HJ I). Neither male and female founder animals nor sex, suitability or region of origin of the horse significantly influenced the prevalences of deforming arthropathies in the investigated joints. Sire effect had a significant influence on moderate alterations of HJ (HJ II). The estimation of genetic parameters was performed multivariately, including height at withers as a separate trait. When analyzing deforming arthropathies in males and females together, the heritability estimates were in the range of $h^2 = 0.10\text{-}0.36$. Separate analyses for HJ deformations in males and females revealed noticeably sex differences. Additive genetic correlations between radiological findings in HJ and in phalangeal joints (DIJ, PIJ, FJ) were estimated to be moderately positive. However, conflicting results were obtained for the additive genetic correlation between deforming arthropathies and height at withers.

Keywords: Horse; radiological findings; deforming arthropathy; genetic parameters; heritability.

Zusammenfassung

Im Anschluss an die Analyse systematischer Effekte wurden mit der Restricted Maximum Likelihood (REML) Methode im Tier- und im Vatermodell genetische Parameter für das Auftreten deformierender Arthropathien in Huf-, Kron-, Fessel- und Sprunggelenken Hannoverscher Warmblutpferde geschätzt. Das Datenmaterial bestand aus den Ergebnissen einer standardisierten röntgenologischen Untersuchung von 3748 jungen, für Reitpferdeauktionen ausgewählten Pferden. 17,7 % der Pferde zeigten röntgenologisch in mindestens einem der untersuchten Gelenke Anzeichen für eine degenerative Gelenkerkrankung. Sprunggelenke waren dabei am häufigsten betroffen. Der Untersucher und der Effekt der einzelnen Auktion erwiesen sich durchgängig als signifikant im Hinblick auf die Prävalenz dokumentierter Röntgenbefunde. Eine signifikante Altersabhängigkeit mit steigendem Anteil betroffener Pferde mit zunehmendem Alter wurde nur für deformierende Arthropathien im Hufgelenk festgestellt. Eine größere Widerristhöhe ging mit einer erhöhten Wahrscheinlichkeit einher, Gelenkdeformationen in Huf- oder Krongelenk zu zeigen. Hufgelenkbefunde traten häufiger bei Pferden mit Genanteilen des Holsteiner Warmblutes auf. Ein steigender Vollblutanteil machte das Auftreten geringgradiger Sprunggelenkveränderungen wahrscheinlicher. Weder das männliche oder weibliche Gründertier, noch Geschlecht, Nutzungseignung oder Herkunftsregion der Pferde hatten einen signifikanten Einfluss auf die Prävalenz deformierender Arthropathien in den untersuchten Gliedmaßengelenken. Ein signifikanter Vatereffekt ließ sich nur für mittelgradige Sprunggelenkbefunde ermitteln. Die Schätzung genetischer Parameter erfolgte multivariat unter Einbeziehung der Widerristhöhe als eigenständigem Merkmal. Bei der Analyse der Röntgenbefunde ohne Geschlechtsdifferenzierung ergaben sich Heritabilitätsschätzwerte im Bereich von h^2 = 0,10-0,36. Bei der nach Geschlechtern getrennten Auswertung der Sprunggelenkbefunde wurden deutliche Geschlechtsunterschiede erkennbar. Es wurden positive additiv genetische Korrelationen zwischen deformierenden Arthropathien in Zehen- und Sprunggelenken geschätzt. Widersprüchlich Ergebnisse ergaben sich hingegen für die additiv genetischen Korrelationen zwischen der Widerristhöhe und den untersuchten Röntgenbefunden.

Schlüsselwörter: Pferde; Röntgenbefunde; deformierende Arthropathie; genetische Parameter; Heritabilität.

Introduction

Epidemiological studies as well as statistical analyses of insurance companies substantiated the predominant role of locomotory diseases in respect of premature retirement and culling of horses (CLAUSEN et al. 1990, PHILIPSSON et al. 1998, SEIDENSTICKER1999, WALLIN et al. 2000). This applies to horses used for racing, riding and working mainly irrespective of their age.

Deforming arthropathies are not only found in older horses, but also in young, almost unstressed horses (BÖHM and NAGEL 1980, HARTUNG 1976, HARTUNG et al. 1978, MÜNZER et al. 1984, SCHUBE et al. 1991). Besides rearing conditions and feeding practices, limb deformations (e.g. axial deviation) are most decisive for time and amount of primary joint diseases (EDWARDS 1984, HAAKENSTAD 1968, RAKER 1968, ROONEY 1973, SCHUBE et al. 1991, WINTER et al. 1996,). Secondary arthropathies might be remnants of traumatic or infectious joint affection. Both primary and secondary arthropathies are important causes for reduced performance and might question the horses' further use.

Prevalences of equine orthopaedic diseases determined among patients of veterinary clinics or among very young horses may not reflect their relevance in the whole population. Few epidemiological studies in Dutch (KWPN 1994) and German (WILLMS et al. 1999, WINTER et al. 1996) Warmblood horses comprised large numbers of adult horses, but confined to fetlock joint arthrosis and bone spavin.

For this reason, the prevalence of deforming arthropathies in different limb joints was investigated in young riding horses selected for sale by auction. It was the objective of the present study to determine the influence of systematic environmental effects, founder animals and breed composition, and to estimate genetic parameters for these radiographic findings. In this, the extent of radiologically visible alterations was considered when analyzing deforming arthropathies in hock joints in general, and separately in males and females.

Material and methods

The data used consisted of informations on 3,748 Hanoverian Warmblood horses selected for sale by auction as riding horses in the years 1991-1998 by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. Therefore, they all underwent a standardized radiological examination the results of which were brought in relation to the basic data drawn from the official auction catalogues. A detailed description of the data and the methods of recording as well as a specification of the analytical approaches employed is given by STOCK et al. (2004a, b).

In the following, only deforming arthropathies will be considered, the prevalences of which were analyzed as binary traits. We distinguished between deforming arthropathies in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ). Concerning radiographic findings in hock joints, slight, moderate and severe alterations (HJ I - III) were analyzed separately. Furthermore, separate analyses were performed for the respective findings in males and females (e.g., HJ I male).

Statistical analysis

The following factors were tested for their influence on the occurrence of deforming arthropathies: Sex (male, female), age group (3 years old, 4 years old, 5 years old and older), height at withers (up to 163 cm, 164-165 cm, 166-167 cm, 168-169 cm, 170-171 cm, 172 cm and larger), anticipated suitability of the horse (dressage [and driving], show-jumping, dressage and show-jumping), region of origin (place of the breeder resp. exhibitor of the horse; representing varying rearing conditions), date of auction (42 auctions of young riding horses), type of auction (winter auction, elite auction in spring, Equitop auction in May, summer auction, elite auction in autumn, Equitop auction in November), quality of auction (elite auction, subsidiary auction, Equitop auction), year of auction (8 years from 1991 to 1998), examiner (one examiner 1991 - 1997, additional second veterinarian for commenting on the radiographs in 1998), percentage of genes of the different horse breeds (Hanoverian Warmblood, Thoroughbred, Trakehner, Holstein Warmblood, Arabs, other breeds), male and female founder.

Possible interrelationships between deforming arthropathies in different joint locations were studied using Fisher's exact test. For all investigated joints, we differentiated by location at the respective limb (e.g., FJ front left) and location in forehand or hindquarters. For the joints found to be most often affected, i.e., DIJ and HJ, the findings were further subdivided by sex (e.g., DIJ front male). Regarding hock joints, the extent of radiologically detectable alterations was considered concurrently (e.g., HJ I left; HJ II right male)

Generalized linear models were used for the analysis of variance with the function of distribution considered binomial and the probit function used as the link function. The inverse of the link function was employed to transform the estimates obtained into relative frequencies. The analyses were performed with the procedure GENMOD of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2002).

Models including only fixed effects and no random effects or genetically correlated traits were developed for each trait under analysis. The reference models comprised the date of auction as the primary fixed effect. Sub-models included year, type and quality of auction, and mode of examination, respectively, instead.

reference model:

$$y_{inopqrs} = \mu + Auction_i + Sex_n + Age_o + Suit_p + RegB_q + RegE_r + e_{inopqrs}$$

sub-models:

$$y_{jnopqrst} = \mu + Year_j + Sex_n + Age_o + Suit_p + RegB_q + RegE_r + e_{jnopqrs}$$

$$y_{knopqrst} = \mu + Type_k + Sex_n + Age_o + Suit_p + RegB_q + RegE_r + e_{knopqrs}$$

$$y_{lnopqrst} = \mu + Quality_l + Sex_n + Age_o + Suit_p + RegB_q + RegE_r + e_{lnopqrs}$$

$$y_{mnopqrst} = \mu + Examiner_m + Sex_n + Age_o + Suit_p + RegB_q + RegE_r + e_{mnopqrs}$$

with $y_{i...s}$ = radiographic finding of deforming arthropathy in the *i…s*-th horse,
μ = model constant,
$Auction_i$ = fixed effect of the date of auction (i = 1 - 42),
$Year_j$ = fixed effect of the year of auction (j = 1 - 8),
$Type_k$ = fixed effect of the type of auction (k = 1 - 6),
$Quality_l$ = fixed effect of the quality of auction (l = 1 - 3),
$Examiner_m$ = fixed effect of the mode of examination (m = 1 - 2),
Sex_n = fixed effect of the sex (n = 1 - 2),
Age_o = fixed effect of the age group (o = 1 - 3),
$Suit_p$ = fixed effect of the suitability (p = 1 - 3),
$RegB_q$ = fixed effect of the region of breeder (q = 1 - 3),
$RegE_r$ = fixed effect of the region of exhibitor (r = 1 - 3), and
$e_{i...s}$ = residual error.

The different reduced models were compared by likelihood ratio tests in order to determine the most parsimonious model not differing significantly from the respective reference model.

Genetic parameters were estimated with Restricted maximum likelihood (REML). Both, linear animal models (LAM) and linear sire models (LSM) were applied for the estimation of variances and covariances using VCE4 Version 4.2.5 (GROENEVELD 1998).

After univariate LAM and LSM analyses of all the investigated traits, deforming arthropathies were analyzed multivariately in different combinations to obtain covariance estimates. Since a significant influence of height at withers was found for the prevalence of deforming arthropathies (see below), it was analyzed as a separate trait.

Firstly, the distinction was drawn by joint location and severity of the radiological findings. For more detailed analyses, findings in the hock joints were subdivided by sex and severity of the alterations detected. Hence, two types of multivariate analyses for six and five traits were performed: (1) deforming arthropathies in DIJ, PIJ, FJ and HJ (HJ I and HJ II), and height at withers, and (2) slight and moderate deforming arthropathies in HJ (HJ I and HJ II) of males and females, and height at withers.
The estimates obtained from the different multivariate analyses were very similar among each other and to the univariate estimates. Therefore, only the mean heritabilities (h^2), mean additive genetic (r_g) and residual correlations (r_e), and the mean standard errors (s_{h^2} , s_{ca}, s_{ce}), calculated from all the respective uni- and multivariate estimates, will be reported.
The estimates for heritabilities and residual correlations were then transformed from the observed scale to the underlying liability scale (Dempster and Lerner 1950, Vinson et al. 1976). The transformation factors derived by Dempster and Lerner (1950) were used as their reliability for the present data set was already substantiated (Stock et al. 2004c).

Results

Distribution of the radiographic findings

Deformations of joint shape occurred in 662 (17.7%) of the horses in at least one DIJ, PIJ, FJ or HJ. Changes in hock joints were the predominant findings that were met in 15.6% of all probands and 12.6% of the auctioned horses. Most hock alterations were classified as HJ II (moderate deformations in 9.6% of all probands and 8.7% of the auctioned horses). Indications of deforming arthropathy in DIJ were seen in 4.4% of all probands and 4.0% of the auctioned horses. 93.6% of those findings referred to front DIJ. The incidence of corresponding findings in PIJ and FJ was considerably smaller (2.0% and 1.2% of all probands, 1.7% and 0.9% of the auctioned horses, respectively; Table 1).
The majority of radiographic findings confined to one type of joints (e.g. DIJ). Only 9.4% of the horses showed analogous changes in two types and 0.9% in three different types of joints. No horse had DIJ, PIJ, FJ and HJ affected simultaneously. Nevertheless more than one single joint showed alterations in more than half of the horses (52.7%). 54.6% to 82.4% of the diseased horses were affected bilaterally in one type of joint (e.g. DIJ front left and front right). In contrast to this, changes in analogous joints in front and hind limbs occurred only in 3.2% to 45.5% of the diseased horses. Among the horses with degenerative changes in HJ , the severity of the documented alterations differed between left and right side to 13.0 - 76.3%.

The prevalences of radiographic findings differed little between the sexes (Fig. 1). However, slight hock deformations (HJ I) appeared to be slightly more prevalent in females than in males (Fig. 2).

In 1991-1997 there was some irregular fluctuation of the prevalences of deforming arthropathies in different limb joints (Fig. 3). However, for all the investigated joints there was a marked rise of the percentages of horses with documented alterations between 1997 and 1998 (by up to 10.4%). This leap between the two consecutive years also emerged for slight and moderate changes in HJ: In 1998 11.6% more horses were classified as HJ I and 5.2% less horses were classified as HJ II when compared to 1997. In contrast to this, the percentage of horses classified HJ III remained almost constant (Fig. 4).

Analysis of variance

The results of the simple analyses of variance are summarized in Tables 2 and 3. For all the investigated limb joints the mode of examination had a significant influence on the prevalence of documented deforming arthropathies. The estimated values for the effect of the single examiner in 1991-1997 and the two scrutinising veterinarians in 1998 differed by 4.6% (PIJ) to 11.3% (HJ I). The portion of horses with affected DIJ was significantly increasing with age. Height at withers was found to be significant for the prevalence of deforming arthropathies in DIJ and PIJ. In general, larger horses were more likely to show these alterations. The prevalence of suspicious radiographic findings in DIJ and FJ was significantly influenced by type and/or quality of auction: Findings were most probable in Equitop auctions, particularly in Equitop auctions in May. The effect of the proband's sire was estimable only for radiographic findings classified as HJ II. For these, it was found to be significant.

No significance could be determined for the other tested effects in respect of deforming arthropathies in the investigated limb joints.

Of the different horse breeds taken into account only the varying proportion of genes of Holstein Warmblood and Thoroughbred played a relevant role in one joint location each: A higher percentage of genes of these breeds correlated with a greater risk of showing deformations in DIJ and slight alterations in hock joints (HJ I), respectively (Table 4). The male founder did not significantly influence the prevalence of deforming arthropathies in any joint. However, a significant influence of the female descent line was determined for deformations in PIJ.

Some interrelationships were detected between radiographic findings indicative of degenerative joint disease in different limb joints (Tables 5 and 6). Deforming arthropathies in DIJ and PIJ, in DIJ and HJ (HJ I), in PIJ and FJ as well as in FJ and HJ (HJ I) appeared to be significantly interrelated. When analyzing the radiographic findings in DIJ and HJ separately for the two sexes, the significant interrelation was verified only for females (Table 5). The corresponding regressions were low and positive (0.03 - 0.21) throughout.

Bilateral joint alterations in corresponding pairs of joints as well as alterations in analogous limb joints in front and hind limbs were significantly positively correlated with each other, independently of the extent of diagnosed alterations (HJ I, HJ II). Deformations in front and hind DIJ of females meant the only exception ($P > 0.05$; Table 6). In most cases, the left-right-comparison resulted in markedly higher regressions than the comparison between corresponding joints in front and hind limbs (44.2-70.7% vs. 7.4-17.0%). However, the regression coefficients for radiographic findings in left and right HJ were somewhat lower (14.8% for HJ I and 24.0% for HJ II).

Model assessment

Table 7 shows a subset of results of the likelihood ratio tests in which the different reduced models were compared with the corresponding reference model separately for each trait. For each trait, the test results for three reduced models not differing significantly from the corresponding reference model are given.

For deforming arthropathies in DIJ and HJ (HJ I and HJ II), the date of auction made up the main effect in the models. For deforming arthropathies in PIJ and FJ, the mode of examination appeared to be of major importance so that the effect of the examiner was included in the final models. The models chosen for the further analyses comprised only three fixed effects each, but fitted the data as good as the corresponding reference models.

DIJ: $y_{inpst} = \mu + Auction_i + Sex_n + Suit_p + a_t\ (s_t) + e_{inpst}$

PIJ: $y_{mnpst} = \mu + Examiner_m + Sex_n + Suit_p + a_t\ (s_t) + e_{mnpst}$

FJ: $y_{mnost} = \mu + Examiner_m + Sex_n + Age_o + a_t\ (s_t) + e_{mnost}$

HJ I: $y_{inqst} = \mu + Auction_i + Sex_n + RegB_q + a_t\ (s_t) + e_{inqst}$

HJ II: $y_{inpst} = \mu + Auction_i + Sex_n + Suit_p + a_t\ (s_t) + e_{inpst}$

with $a_t\ (s_t)$ = random additive genetic effect of the t-th animal (sire).

When analyzing slight and moderate deforming arthropathies in hock joints (HJ I and HJ II) separately for males and females (2), the sex effect had to be removed from the models accordingly.

Analyses of the prevalences of deforming arthropathies in DIJ, PIJ, FJ and HJ, and of height at withers

Genetic parameters estimated under LAM and LSM for the prevalences of deforming arthropathies in DIJ, PIJ, FJ and HJ (HJ I and HJ II), and for height at withers are shown in Table 8. Both methods revealed low heritability estimates between 0.02 and 0.06 for the radiographic findings. However, transformation resulted in estimates in the range of 0.14-0.36 and 0.10-0.31 under LAM and LSM, respectively. In each case the highest heritability was obtained for deforming arthropathies in PIJ (h^2 = 0.31-0.36). Deforming arthropathies in DIJ and moderate changes in HJ (HJ II) showed lower heritabilities with h^2 = 0.10-0.16 and h^2 = 0.14-0.17, respectively. The corresponding standard errors were in the range of s_{h^2} = 0.05-0.21. The heritability estimate for height at withers was $h^2 = 0.29 \pm 0.03$ and $h^2 = 0.22 \pm 0.04$ under LAM and LSM, respectively.

The additive genetic correlations were estimated slightly to highly positive (r_g = 0.07-0.82) between deforming arthropathies in DIJ and PIJ, PIJ and HJ (HJ I and HJ II), and FJ and HJ (HJ I and HJ II). Deformations in DIJ and moderate changes in HJ (HJ II) as well as slight and moderate alterations in HJ (HJ I and HJ II) were found to be correlated to a high degree (r_g = 0.82-1.). However, negative additive genetic correlations (r_g = -0.64 to -0.15) were estimated between deforming arthropathies in FJ and DIJ, FJ and PIJ, and between deformations in DIJ and slight alterations in HJ (HJ I). PIJ, FJ and slight HJ (HJ I) deformations were moderately positively correlated with height at withers (r_g = 0.15-0.21). However, conflicting results were obtained under LAM and LSM for the additive genetic correlations of height at withers with deforming arthropathies in DIJ (r_g = -0.08 to 0.12) and with moderate alterations in HJ (HJ II; r_g = -0.01 to 0.10). The corresponding standard errors amounted to s_{rg} = 0.12-0.53.

The estimates of the residual correlations were between -0.05 and 0.20, corresponding to transformed estimates of r_e = -0.13 to 0.76 with standard errors in the range of s_{re} = 0.02-0.14.

Analyses of the prevalences of slight and moderate deforming arthropathies in HJ of males and females, and of height at withers

Genetic parameters estimated in LAM and LSM for the prevalences of deforming arthropathies of different severity in the HJ (HJ I and HJ II) of males and females are shown in Table 9.

Under both LAM and LSM lower heritabilities of HJ alterations were estimated for males ($h^2 = 0.04$-0.05 for HJ I, $h^2 = 0.002$-0.020 for HJ II) than for females ($h^2 = 0.08$-0.13 for HJ I, $h^2 = 0.13$-0.15 for HJ II). This remained to be true after transformation, with $h^2 = 0.01$-0.33 and $h^2 = 0.40$-0.66 for deforming arthropathies in HJ of males and females, respectively. The corresponding standard errors were in the range of $s_{h^2} = 0.02$-0.32. The heritability estimates for height at withers were $h^2 = 0.28 \pm 0.03$ under LAM and $h^2 = 0.22 \pm 0.04$ under LSM.

Under both, LAM and LSM, the additive genetic correlations between deforming HJ arthropathies of different severity in the two sexes were estimated moderately to highly positive ($r_g = 0.16$-0.97). The corresponding standard errors mostly amounted to $s_{rg} = 0.06$-0.71. However, under LAM the correlation of HJ II in males with HJ I in males and females was estimated with noticeably low accuracy ($s_{rg} = 2.94$ and $s_{rg} = 3.80$, respectively). Slight HJ deformations (HJ I) in females appeared to be moderately positively correlated to height at withers ($r_g = 0.27$-0.39). As opposed to this, lowly to moderately negative additive genetic correlations to height at withers were estimated for HJ I in males and HJ II in females ($r_g = -0.06$ to -0.20). However, conflicting results were obtained for the additive genetic correlation between HJ II in males and height at withers ($r_g = 0.47$ under LAM vs. $r_g = -0.06$ under LSM). The estimates of the residual correlations were between -0.05 and 0.13, corresponding to transformed estimates of $r_e = -0.19$ to 0.72 with standard errors of $s_{re} = 0.02$-0.19.

Discussion

The objective of this study was to determine factors that influence the occurrence of deforming arthropathies in the limbs of physically fit young Warmblood riding horses. Genetic parameters were estimated with a special view to possible differences between different joints as well as between males and females.

As discussed elsewhere (Stock et al. 2004a, b) the choice of young riding horses intended for sale at auction allows to presume approximate homogeneity of the data. The radiological findings which entered our analyses were recorded uniformly and in a standardized manner in a selected Warmblood horse population.

Considering the complex etiology of alterations of joint shape, influencing factors do not confine to age and riding resp. racing stress. The constitution of the horse is of great importance (Edwards 1984, Haakenstad 1968, Raker 1968, Rooney 1973, Schube et al. 1991, Winter et al. 1996). Every kind of limb deformation results in irregular traction and pressure forces in the bone that cause local remodeling of existing bone structures. In joint areas, sclerotic zones and so-called spurs up to bony bridging of the whole joint space might occur.

In other sides lytic processes might predominate so that reduced radiographic density of joint forming bones is recognizable. Narrowing of the joint space and an impaired sharpness of the bone contours might indicate thinning of joint cartilage (DIK 1983, EDWARDS 1984, HARTUNG 1976, MCILWRAITH 1982, MÜNZER and HARTUNG 1977, SHELLEY and DYSON 1984, VAN SUNTUM 1983, UELTSCHI 2002, WINTZER 1976). The supply of this bradytrophic tissue is reduced by unphysiological load and wear of the respective joint.
The clinical consequences of degenerative joint disease depend on the extent of the alterations as well as on the type of the affected joint (radius of motion) and the strain put on the horse. Even extensive new bone growth might exist without any lameness in tight joints contributing little to the movement of the limbs (BJØRNSDOTTIR et al. 2000b, EDWARDS 1984, MCILWRAITH 1982, MÜNZER et al. 1984, MÜNZER and HARTUNG 1977, ROONEY 1973, SHELLEY and DYSON 1984). Nevertheless, there is always the potential risk that the performance of the respective horse will be impaired later on (reactivation, fractures; MCILWRAITH 1982, SHELLEY and DYSON 1984, VAN SUNTUM 1983, UELTSCHI 2002). Accordingly, in only some of the affected horses degenerative changes in the intertarsal joints and the tarsometatarsal joint cause permanent pain and a marked impairment of performance. Frequently, the period of active remodelling that is usually attended with an intermitting lameness is followed by a stationary period without any clinical symptoms (BARNEVELD 1983, DIK 1983, RAKER 1968, ROONEY 1979). However, marked structural (and particularly osteolytic) changes and more extensive ossification processes (which were not found among our probands and might have been classified as HJ IV) commonly cause persistent lameness and a more or less restricted joint flexion (BARNEVELD 1983, DIK 1983, RAKER 1968).
Even though the probands of this study presumably had no major exterior faults, were clinically free from pathological findings (e.g., joint distension, lameness), and for the most part stood the strain of an auction training of several weeks' duration, 18% of them showed radiographic findings indicative of degenerative joint disease in DIJ, PIJ, FJ or HJ. This supports the impression that deforming arthropathies do not inevitably reduce the performance of affected horses, at least at the beginning of their use as riding horses.
In the horse arthrotic findings are most often found in HJ (bone spavin). In literature prevalences of up to 61% are reported, depending on the population investigated and the strictness of scrutinising the taken radiographs (BARNEVELD 1983, BJØRNSDOTTIR et al. 2000, BÖHM and NAGEL 1980, DIK 1983, EKSELL et al. 1998, HARTUNG et al. 1978, HOFMANN 1984, KWPN 1994, RICARD et al. 2002, UELTSCHI 1979, WINTER et al. 1996). The medical records presently used did not contain a detailed description of the radiologically detectable changes

throughout. In order to guarantee the uniform interpretation of the data, the different osteoarthrotic findings were not split up for the analyses but investigated summarily per joint. In respect of HJ deformations, in most cases only the severity of visible alterations was documented (HJ I - III). This qualitative differentiation was adopted for the present analyses. WINTER et al. (1996) found a total of more than 90% of young German riding horses of different breeds affected of HJ deformations when slight changes were included as well. In that investigation there was a trend of a decreasing incidence of degenerative findings in HJ in 1982-1990. Even if we assume that this trend continued, the prevalence cited clearly contrasts with the results of the present study (92.8% vs. 15.6%) though both investigators used comparable data. Hence, differing documentation practices may have been the main causes for this discrepancy, i.e., horses showing more discreet alterations in the HJ might have been classified as "unaffected" in the present study.

Radiographs of high quality are particularly necessary for the reliable evaluation of the width of the joint space. Every deviation from the orthograd projection results in distortions which limit the diagnostical interpretation. This is especially true in complex joints like HJ. In general, two different radiographic projections of the HJ are accepted as the absolute minimum standard for to have an adequate diagnostical certainty (UELTSCHI 2002). According to a basic principle in radiology, every structure of interest must be projected from (at least) two different angles. For this study, 90° and 45° radiographs of the tarsus and 90° universal radiographs of the phalanges were available for all probands. This means that the distal limb joints (DIJ, PIJ, FJ) could be judged from only one projection. Hence, discreet osteoarthrotic changes might have been undetectable in these joints.

Even if there is no doubt about the existence of particular radiological findings, their valuation is an subject of controversial discussion. Since visible joint deformations need not be of clinical relevance (at least at the time of examination), the extent of documentation is mainly on the discretion of the individual examiner. In the present study, this effect was evident: For all the investigated limb joints there was a pronounced leap in the prevalence of signs indicative of degenerative joint disease documented in the medical records. Only the additional consultation of another veterinarian for scrutinising the radiographs might explain this fact. However, the two examiners agreed in respect of severe findings (classified as HJ III) where the prognostic value for the respective horse was out of question. Previous repeatability analyses also documented the problem of the valuation of radiographic findings indicative of degenerative joint disease. In the study of WINTER et al. (1996) the repeated interpretation of radiographs by even the same examiner resulted in an agreement of only 63-

76%. Radiographic findings in HJ, indicative of bone spavin, were classified differently to 23%. Inter-individually differing opinions about the documentation demand of certain radiographic findings might lead to even greater discrepancies. Hence, the more extensive documentation practice in 1998 seems to be responsible for the 1.4- to 5.5-fold increase of prevalences when compared to the previous years (1991-1997).

In young horses arthropathia deformans occurs less often in the distal limb joints. In horses with orthopedic problems as well as in clinically healthy horses, FJ seem to be affected more frequently (11-34%) than DIJ (1-12%; low ringbone disease) and PIJ (1-3%; high ringbone disease) (BÖHM and NAGEL 1980, HOFMANN 1984, KWPN 1994, RICARD et al. 2002, VAN SUNTUM 1983, WINTER et al. 1996). However, the opposite relation of prevalences emerged from the present study: The percentages of horses with degenerative changes in DIJ and PIJ were of the same order as described in literature (4% resp. 2%), but osteoarthrotic findings in FJ occurred very rarely (1%). Even in the last year of investigation (1998) with a presumably more extensive documentation practice, characteristic radiographic findings in DIJ (13%) outweighed over such in PIJ (6%) and in FJ (5%). A possible explanation is that degenerative changes in FJ earlier lead to clinical symptoms so that affected horses do not meet the selection requirements for sale at auction.

The phalangeal joints in the frontlimbs seem to be predisposed to develop osteoarthroses compared to the respective joints in the hindquarters (HAAKENSTAD 1968). This correlates with the fact that the equine forehand bears a larger part of the body weight while standing and, even more marked, while moving. Correspondingly, we found 71% of deforming arthropathies in the phalangeal joints (DIJ, PIJ, FJ) to be located in the frontlimbs.

In many cases deforming arthropathies are encountered bilaterally in corresponding joints (ROONEY 1979), but the severity of radiographic alterations might differ between left and right (BÖHM and NAGEL 1980). Corresponding joints of front and hind limbs seem to be less often affected simultaneously (BÖHM and NAGEL 1980, HAAKENSTAD 1968). The pattern of distribution as the interrelations we found entirely agree with these clinical findings. A possible explanation is the fact that most internal and external factors considered to predispose horses to develop degenerative joint disease are unlikely to affect just one single limb. Limb deformations such as axial deviation will also impair the contralateral limb. Rapid growth and poor rearing conditions (imbalances in mineral supply, overnutrition, lack of exercise etc.) represent effects with systemic implications (BÖHM and NAGEL 1980, CLAUSEN et al. 1990, HAAKENSTAD 1968, WINTER et al. 1996).

Contrary to the widespread assumption that degenerative joint disease is mainly a problem of older, especially highly strained horses, radiographic findings of deforming arthropathies are not infrequently detected already in young horses (BÖHM and NAGEL 1980, EKSELL et al. 1998, HARTUNG 1976, HARTUNG et al. 1978, MCILWRAITH 1982, MÜNZER et al. 1984, SCHUBE et al. 1991, WINTER et al. 1996). The present investigation again substantiates the important role of this disease complex even in a group of well-performing young riding horses: Almost every fifth horse had findings of deforming arthropathy in at least one of the investigated limb joints though the probands' mean age was as low as 3.9 years. Furthermore, age was found to have a significant effect only on the prevalence of deformations in DIJ. This appears to conflict with the findings of a group of Icelandic investigators (EKSELL et al. 1998, BJØRNSDÓTTIR et al. 2000b, AXELSSON et al. 2001) who considered age to be one of the most important effects on the occurrence of radiographic signs of bone spavin in Icelandic horses, regarding bone spavin as a universal feature of the Icelandic horse with varying age of onset. But apart from the inequality of horse breeds, the populations of horses investigated by these authors was still quite different from ours: The unselected horses, ranging from 0 to 19 years of age (mean age 8 years), were mostly used as riding horses over years, and many of them were lame after flexion test of the tarsus.

Some authors described the particular predisposition of show jumping horses (besides Western horses and racing trotters) and of horses used for competition because of the extreme strain put on the HJ (RAKER 1968, ROONEY 1979, AXELSSON et al. 2001, EKSELL et al. 1998). The present data did not allow for this conclusion. The young age of the probands might have been the reason. The horses investigated were mainly trained under saddle less than a year. Harder work had presumably not (or at least not regularly) been demanded from them prior to their medical examination.

Considering eventual sex differences, the results of the present study agree with previous investigations in Warmblood horses. On the one hand, female horses seemed to be affected more often than males (WINTER et al. 1996). On the other hand, severe alterations were found to be more prevalent in stallions than in mares in an extensive epidemiological study (KWPN 1994). However, the data structure of the later study did not permit to separate sex and age effects (young mares vs. considerably older demanded sires). In the own data set, the age of male and female auction horses did not differ significantly. Therefore, interdependencies between sex and age could be largely precluded. Nevertheless, we observed some virtually significant differing prevalences of radiographic findings in males and females ($P = 0.09$).

Consequently, it seemed to be advisable to perform genetic analyses of the most prevalent findings (i.e., HJ I and HJ II) separately for males and females.

Some inherited proneness to the development of osteoarthrotic alterations has been surmised to exist in the horse as in other species (BARNEVELD 1983). Accordingly, heritability estimates of up to $h^2 = 0.65$, for the most part in the range of $h^2 = 0.10$-0.30, have been reported for equine deforming arthropathies. However, some studies revealed only negligible heritabilities of deforming arthropathies in distal limb joints as in HJ (BJØRNSDÓTTIR et al. 2000a, WINTER et al. 1996) (Tab.10). The present study wanted to overcome some shortcomings of previous investigations by analysing the radiographic findings as specific as possible (separate analyses for different limb joints, for alterations of different severity in HJ, and for findings in males and females). In doing so, low heritabilities only emerged for more distinct HJ deformations in stallions and geldings (HJ II; $h^2 = 0.01$-0.06). All other kinds of deforming arthropathies appeared to be at least moderately heritable ($h^2 \geq 0.10$). Further investigations seem to be advisable to re-examine the inconsistently low heritability estimate for moderate hock deformations (HJ II) in male horses. However, considering the high genetic correlations we found in our analyses focused on HJ, deforming arthropathies in HJ can be regarded as a genetically uniform trait, irrespective of the animal's sex and of the severity of alterations. In connection with the mostly positive genetic correlations between deforming arthropathies in the phalangeal joints (DIJ, PIJ, FJ) and in HJ, the medium-level heritabilities provide a good basis for the development of breeding strategies to lower their prevalences simultaneously.

Height at withers was included in the multivariate analyses because of its partly significant (DIJ, PIJ) or virtually significant (HJ I) influence on the prevalence of deforming arthropathies. However, literature provides conflicting statements in this respect. WINTER et al. (1996) detected significantly increasing prevalences of deforming arthropathies in phalangeal joints and of bone spavin with increasing height at withers. On the contrary, WILLMS et al. (1999) did not find any significant correlation between phalangeal joint arthroses or bone spavin and height at withers.

The moderate heritability of height at withers estimated in our probands agrees with estimates previously reported for German Warmblood horses (VON BUTLER and KROLLIKOWSKY 1986, KAISER et al. 1991). However, there was no consistent pattern of additive genetic correlations between deforming arthropathies and this exterior parameter. Therefore, height at withers appears not to be a useful criterion to select on if one wants to lower the prevalence of radiographic findings indicative of degenerative joint disease. At the moment, no alternative to a thorough radiographic examination of the equine limbs and selection on the radiological appearance of the joints seems to exists.

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Table 1. **Distribution of deforming arthropathies by joints referred to all horses selected for sale by auction and to the auctioned horses**

Location of the radiographic finding	Horses selected for one of the 42 auctions (n = 3748)		Horses auctioned in one of the 42 auctions (n = 3503)	
	Prevalence		Prevalence	
	absolute	relative (%)	absolute	relative (%)
Distal interphalangeal joint (DIJ)	165	4.40	140	4.00
Proximal interphalangeal joint (PIJ)	76	2.03	61	1.74
Fetlock joint (FJ)	45	1.20	31	0.88
Hock joint (HJ I)	159	4.24	113	3.23
(HJ II)	361	9.63	304	8.68
(HJ III)	63	1.68	25	0.71

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations; HJ III: severe hock joint deformations

Table 2. **Analyses of variance for the prevalence of deforming arthropathies in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ)**

Source of variation (degrees of freedom)	Deforming arthropathy in DIJ	Deforming arthropathy in PIJ	Deforming arthropathy in FJ	Slight deforming arthropathy in HJ (HJ I)	Moderate deforming arthropathy in HJ (HJ II)
	χ^2 P	χ^2 P	χ^2 P	χ^2 P	χ^2 P
Auction (41)	191.28 < 0.001	89.52 < 0.001	108.60 < 0.001	187.56 < 0.001	92.18 < 0.001
Year of auction (7)	121.01 < 0.001	56.72 < 0.001	92.33 < 0.001	134.35 < 0.001	33.00 < 0.001
Examiner (1)	84.49 < 0.001	39.82 < 0.001	80.48 < 0.001	125.54 < 0.001	24.23 < 0.001
Type of auction (5)	12.38 0.030	4.19 0.523	10.98 0.052	9.29 0.098	10.49 0.063
Quality of auction (2)	6.53 0.038	3.71 0.156	8.47 0.015	3.65 0.161	2.48 0.289
Sex (1)	0.01 0.797	0.00 0.952	2.94 0.086	2.92 0.087	0.23 0.631
Age (2)	7.08 0.029	0.60 0.741	1.90 0.386	2.09 0.351	0.31 0.857
Height at withers (5)	11.27 0.046	15.95 0.007	6.57 0.255	9.44 0.093	4.89 0.430
Suitability (2)	3.63 0.163	4.07 0.131	1.07 0.585	0.73 0.695	1.23 0.540
Region of breeder (2)	2.20 0.333	0.46 0.794	1.37 0.516	3.60 0.165	0.64 0.725
Region of exhibitor (2)	1.73 0.421	1.71 0.425	0.07 0.966	2.63 0.268	1.06 0.590
Sire (113)	n.e. n.e.	n.e. n.e.	n.e. n.e.	n.e. n.e.	173.41 < 0.001

Table 3. **Means and 95 % confidence intervals (CI) of the relative frequencies of deforming arthropathies in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ; slight – HJ I; moderate – HJ II) for significant systematic effects**

Joint location	Fixed effect	Fixed effect levels	No. of probands	Relative frequency	
				$\bar{x}$	95 % CI
DIJ	Examiner	1 examiner (1991-1997)	2972	2.49 %	1.98 - 3.11 %
		2 examiners (1998)	531	12.43 %	9.84 - 15.46 %
	Type of auction	winter-auction	839	2.98 %	2.00 - 4.33 %
		elite-auction in spring	569	3.51 %	2.25 - 5.32 %
		Equitop-auction in May	290	7.93 %	5.26 - 11.52 %
		summer-auction	854	3.75 %	2.64 - 5.21 %
		elite-auction in autumn	642	4.36 %	3.00 - 6.19 %
		Equitop-auction in Nov.	309	3.88 %	2.17 - 6.57 %
	Quality of auction	elite-auction	1211	3.96 %	2.98 - 5.19 %
		subsidiary auction	1693	3.37 %	2.59 - 4.32 %
		Equitop-auction	599	5.84 %	4.19 - 7.97 %
	Age group	3 years old	1081	3.24 %	2.32 - 4.44 %
		4 years old	1772	3.78 %	2.97 - 4.76 %
		≥ 5 years old	650	5.86 %	4.26 - 7.89 %
	Height at withers	≤ 163 cm	652	1.99 %	1.14 - 3.34 %
		164 - 165 cm	627	3.83 %	2.55 - 5.59 %
		166 - 167 cm	732	4.78 %	3.34 - 6.54 %
		168 - 169 cm	601	4.66 %	3.20 - 6.60 %
		170 - 171 cm	498	4.02 %	2.57 - 6.06 %
		≥ 172 cm	392	5.10 %	3.27 - 7.68 %
	Holstein Warmblood horse	I (0.0 %)	3154	3.05 %	2.09 - 4.36 %
		II (0.1 - 15.6 %)	400	5.61 %	3.39 - 8.85 %
		III (15.7 - 46.9 %)	195	7.17 %	3.65 - 12.86 %
PIJ	Examiner	1 examiner (1991-1997)	2972	1.04 %	0.73 - 1.47 %
		2 examiners (1998)	531	5.65 %	3.94 - 7.90 %
	Height at withers	≤ 163 cm	652	1.23 %	0.60 - 2.37 %
		164 - 165 cm	627	1.28 %	0.62 - 2.46 %
		166 - 167 cm	732	2.32 %	1.43 - 3.65 %
		168 - 169 cm	601	2.16 %	1.24 - 3.62 %
		170 - 171 cm	498	0.40 %	0.09 - 1.45 %
		≥ 172 cm	392	3.32 %	1.89 - 5.52 %
FJ	Examiner	1 examiner (1991-1997)	2972	0.13 %	0.05 - 0.34 %
		2 examiners (1998)	531	5.08 %	3.47 - 7.24 %
	Quality of auction	elite-auction	1211	0.74 %	0.38 - 1.39 %
		subsidiary auction	1693	0.59 %	0.31 - 1.07 %
		Equitop-auction	599	2.00 %	1.12 - 3.43 %
HJ I	Examiner	1 examiner (1991-1997)	2972	1.51 %	1.13 - 2.01 %
		2 examiners (1998)	531	12.81 %	10.18 - 15.87 %
	Thoroughbred horse	I (0.0 – 18.0 %)	1371	2.92 %	1.82 - 4.54 %
		II (18.1 – 27.0 %)	1063	3.84 %	2.36 - 5.99 %
		III (≥ 27.1 %)	1315	5.90 %	3.51 - 9.41 %
HJ II	Examiner	1 examiner (1991-1997)	2972	9.59 %	8.57 - 10.69 %
		2 examiners (1998)	531	3.58 %	2.26 - 5.47 %

Table 4. **Influence of the proportion of genes of different horse breeds, and of male and female founders on the prevalence of deforming arthropathies in distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ; slight – HJ I; moderate – HJ II) using multiple analyses of variance**

Joint location	Source of variation	χ^2	P
DIJ	Hanoverian Warmblood	1.46	0.483
	Thoroughbred	0.64	0.728
	Trakehner	2.21	0.331
	Holstein Warmblood	9.36	0.009
	Arabs	0.96	0.620
	other breeds	0.24	0.888
	male founder	0.01	0.932
	female founder	0.00	0.993
PIJ	Hanoverian Warmblood	0.64	0.726
	Thoroughbred	0.43	0.805
	Trakehner	0.31	0.857
	Holstein Warmblood	0.95	0.623
	Arabs	0.30	0.859
	other breeds	0.73	0.693
	male founder	1.77	0.184
	female founder	6.09	0.014
FJ	Hanoverian Warmblood	1.90	0.387
	Thoroughbred	5.07	0.079
	Trakehner	0.47	0.791
	Holstein Warmblood	2.14	0.343
	Arabs	2.88	0.237
	other breeds	4.84	0.089
	male founder	2.53	0.112
	female founder	0.12	0.731
HJ I	Hanoverian Warmblood	2.73	0.255
	Thoroughbred	7.26	0.027
	Trakehner	1.50	0.473
	Holstein Warmblood	1.63	0.442
	Arabs	2.49	0.287
	other breeds	2.92	0.233
	male founder	1.79	0.181
	female founder	0.31	0.576
HJ II	Hanoverian Warmblood	0.03	0.983
	Thoroughbred	1.59	0.451
	Trakehner	1.95	0.377
	Holstein Warmblood	0.85	0.652
	Arabs	2.02	0.364
	other breeds	0.02	0.991
	male founder	2.91	0.088
	female founder	1.59	0.207

Table 5. **Interrelationships between deforming arthropathies in different types of joints (distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ)) and in dependence on sex for distal interphalangeal (DIJ) and hock joints (HJ)**

Joint location 1	Joint location 2	P
DIJ	PIJ	< 0.001
	FJ	0.482
	HJ I	0.002
	HJ II	0.587
DIJ male	HJ I male	0.122
	HJ II male	0.705
DIJ female	HJ I female	< 0.001
	HJ II female	0.790
PIJ	FJ	0.015
	HJ I	0.083
	HJ II	0.065
FJ	HJ I	< 0.001
	HJ II	0.611

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations

Table 6. **Interrelationships between deforming arthropathies in different limbs (distal (DIJ) and proximal interphalangeal (PIJ), fetlock (FJ) and hock joints (HJ)) by the type of the affected joint and in dependence on sex within one type of joint**

Joint location	Trait 1	Trait 2	P
Distal interphalangeal joint (DIJ)	front	back	< 0.001
	front male	back male	0.007
	front female	back female	0.167
	front left	front right	< 0.001
	back left	back right	< 0.001
Proximal interphalangeal joint (PIJ)	front	back	< 0.001
	front left	front right	< 0.001
	back left	back right	< 0.001
Fetlock joint (FJ)	front	back	< 0.001
	front left	front right	< 0.001
	back left	back right	< 0.001
Hock joint (HJ)	I left	I right	< 0.001
	I left	II right	< 0.001
	II left	II right	< 0.001
	II left	I right	< 0.001

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations

Table 7. **Comparison of models for deforming arthropathies in different limb joints (distal interphalangeal joint (DIJ), proximal interphalangeal joint (PIJ), fetlock joint (FJ), hock joint (HJ)) using likelihood ratio tests**

Joint location	Fixed effects	DF	ΔDF	-2 log L	χ^2	P
DIJ	Auction Sex Age Suit RegB RegE	50	/	972.17	/	/
	Auction Sex Age	44	6	978.44	6.27	0.3938
	Auction Sex Suit	44	6	978.27	6.09	0.4129
	Auction Suit RegB	45	5	976.63	4.45	0.4861
PIJ	Auction Sex Age Suit RegB RegE	50	/	518.46	/	/
	Examiner Suit	3	47	571.77	53.32	0.2443
	Examiner Sex Suit	4	46	571.23	52.78	0.2287
	Examiner Sex RegE	4	46	573.77	55.32	0.1633
FJ	Auction Sex Age Suit RegB RegE	50	/	232.41	/	/
	Examiner Sex	2	48	266.65	34.24	0.9328
	Examiner Sex Age	4	46	262.18	29.77	0.9695
	Examiner Age RegB	5	45	269.89	37.49	0.7792
HJ I	Auction Sex Age Suit RegB RegE	50	/	803.10	/	/
	Auction RegB	43	7	806.28	3.19	0.8673
	Auction Sex RegB	44	6	805.92	2.83	0.8303
	Auction Age RegB	45	5	805.04	1.94	0.8568
HJ II	Auction Sex Age Suit RegB RegE	50	/	1957.40	/	/
	Auction Suit	43	7	1961.88	4.49	0.7224
	Auction Sex Suit	44	6	1961.83	4.44	0.6180
	Auction Suit RegB	45	5	1960.34	2.94	0.7094

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations;
Auction: date of auction; Examiner: mode of examination; Age: age group; Suit: suitability; RegB: region of breeder; RegE: region of exhibitor;
DF: degrees of freedom of all fixed effects in the model; ΔDF: difference in degrees of freedom between reduced and reference model; -2 log L: logarithm of the maximum likelihood multiplied by minus two.

Table 8. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of deforming arthropathies in different limb joints (distal interphalangeal joint (DIJ), proximal interphalangeal joint (PIJ), fetlock joint (FJ), hock joint (HJ)), and for height at withers using a linear animal model (LAM; first line) and a linear sire model (LSM; second line)**

Trait	DIJ	PIJ	FJ	HJ I	HJ II	Height at withers
DIJ	0.163 $^{0.071}$ 0.100 $^{0.067}$	0.111 $^{0.289}$ 0.069 $^{0.417}$	-0.511 $^{0.305}$ -0.644 $^{0.521}$	-0.148 $^{0.260}$ -0.279 $^{0.346}$	0.956 $^{0.203}$ 0.986 $^{0.039}$	-0.078 $^{0.186}$ 0.122 $^{0.251}$
PIJ	0.342 $^{0.092}$ 0.353 $^{0.065}$	0.360 $^{0.127}$ 0.311 $^{0.141}$	-0.346 $^{0.337}$ -0.539 $^{0.526}$	0.073 $^{0.218}$ 0.224 $^{0.254}$	0.368 $^{0.247}$ 0.820 $^{0.237}$	0.183 $^{0.116}$ 0.119 $^{0.185}$
FJ	-0.033 $^{0.119}$ -0.126 $^{0.093}$	0.438 $^{0.137}$ 0.352 $^{0.112}$	0.261 $^{0.199}$ 0.167 $^{0.209}$	0.245 $^{0.143}$ 0.713 $^{0.486}$	0.659 $^{0.198}$ 0.382 $^{0.443}$	0.202 $^{0.223}$ 0.210 $^{0.318}$
HJ I	0.117 $^{0.072}$ 0.094 $^{0.045}$	0.017 $^{0.093}$ 0.023 $^{0.058}$	0.191 $^{0.085}$ 0.206 $^{0.085}$	0.269 $^{0.154}$ 0.288 $^{0.115}$	0.999 $^{0.068}$ 0.820 $^{0.153}$	0.146 $^{0.148}$ 0.175 $^{0.158}$
HJ II	-0.098 $^{0.052}$ 0.003 $^{0.038}$	0.095 $^{0.077}$ 0.127 $^{0.041}$	-0.116 $^{0.088}$ 0.006 $^{0.050}$	0.654 $^{0.052}$ 0.762 $^{0.037}$	0.137 $^{0.052}$ 0.174 $^{0.070}$	0.104 $^{0.131}$ -0.005 $^{0.179}$
Height at withers	0.123 $^{0.049}$ 0.086 $^{0.027}$	0.061 $^{0.058}$ 0.096 $^{0.035}$	-0.146 $^{0.084}$ -0.078 $^{0.049}$	0.024 $^{0.053}$ 0.050 $^{0.024}$	0.060 $^{0.034}$ 0.072 $^{0.020}$	0.286 $^{0.034}$ 0.224 $^{0.036}$

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations

Table 9. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of slight (HJ I) and moderate (HJ II) deforming arthropathies in hock joints by sex and for height at withers using a linear animal model (LAM; first line) and a linear sire model (LSM; second line)**

Trait	HJ I, male	HJ I, female	HJ II, male	HJ II, female	Height at withers
HJ I, male	$0.258^{0.164}$ $0.328^{0.202}$	$0.906^{0.111}$ $0.558^{0.285}$	$0.420^{2.938}$ $0.351^{0.711}$	$0.442^{0.361}$ $0.544^{0.269}$	$-0.055^{0.173}$ $-0.195^{0.204}$
HJ I, female	$-0.006^{0.062}$ $0.000^{0.039}$	$0.400^{0.215}$ $0.660^{0.320}$	$0.556^{3.804}$ $0.156^{0.536}$	$0.965^{0.062}$ $0.716^{0.420}$	$0.267^{0.211}$ $0.393^{0.174}$
HJ II, male	$0.718^{0.107}$ $0.554^{0.066}$	$0.012^{0.043}$ $0.004^{0.027}$	$0.006^{0.018}$ $0.061^{0.086}$	$0.807^{0.302}$ $0.412^{0.509}$	$0.473^{0.780}$ $-0.056^{0.326}$
HJ II, female	$-0.004^{0.053}$ $0.000^{0.031}$	$-0.194^{0.170}$ $0.178^{0.083}$	$0.000^{0.037}$ $0.000^{0.022}$	$0.457^{0.188}$ $0.413^{0.226}$	$-0.070^{0.167}$ $-0.106^{0.178}$
Height at withers	$0.123^{0.060}$ $0.105^{0.035}$	$-0.094^{0.083}$ $-0.034^{0.042}$	$0.082^{0.040}$ $0.089^{0.026}$	$0.076^{0.073}$ $0.046^{0.037}$	$0.284^{0.034}$ $0.224^{0.036}$

HJ I: slight hock joint deformations; HJ II: moderate hock joint deformations

Table 10. **Heritability estimates for deforming arthropathies in different limb joints**

Population and number of investigated horses	Radiographic finding	Heritability estimate	Method of analysis	Author
Dutch Warmblood horses (mares; n = 590)	Fetlock joint arthrosis	0.26 ± 0.15	LAM (REML, transformation[1])	KWPN 1994
		0.16 ± 0.09 -> 0.24 ± 0.14	LSM (REML -> transformation[1])	
		0.24 ± 0.11	STM (REML[2])	
	Bone spavin	0.31 ± 0.14	LAM (REML, transformation[1])	
		0.20 ± 0.10 -> 0.26 ± 0.15	LSM (REML -> transformation[1])	
		0.31 ± 0.12	STM (REML[2])	
German Riding Horses (n = 2407 resp. 3566)	Arthropathia deformans (phalangeal joints)	0.05 ± 0.03	LAM (REML)	WINTER et al. 1996
		0.07 ± 0.04	LSM (Henderson III[3])	
	Bone spavin	0.04 ± 0.03	LAM (REML)	
		0.02 ± 0.04	LSM (Henderson III [3])	
German Riding Horses (mares; n = 401 resp. 456)	Arthrosis (phalangeal joints)	0.36 ± 0.22	LSM (GS)	WILLMS et al. 1999
		0.21	STM (REML-type algorithm[4])	
		0.29 ± 0.04	ATM (GS)	
	Bone spavin	0.53 ± 0.20	LSM (GS)	
		0.65	STM (REML-type algorithm[4])	
		0.35 ± 0.06	ATM (GS)	
German Riding Horses (foals; n = 144)	Arthrosis (phalangeal joints)	0.19 ± 0.14	LSM (GS)	
		0.18 ± 0.03	ATM (GS)	
	Bone spavin	0.16 ± 0.15	LSM (GS)	
		0.19 ± 0.03	ATM (GS)	
Icelandic Horses (n = 614)	Bone spavin	0.06 -> 0.10 ± 0.06	LAM (REML -> transformation[6])	BJØRNSDÓTTIR et al. 2000
		0.09 ± 0.11	STM (REML[2])	
	Bone spavin and lameness	0.10 -> 0.22 ± 0.08	LAM (REML -> transformation[6])	
		0.28 ± 0.19	STM (REML[2])	ÁRNASON et al. 2003
Icelandic Horses (n = 439)	Age at onset of bone spavin	0.26	STM (Weibull regression model[7])	
		0.33	STM[8]	

ATM – animal threshold model; STM – sire threshold model; LAM – linear animal model; LSM – linear sire model; REML – restricted maximum likelihood; GS – Gibbs Sampling

[1] GIANOLA 1982, [2] MISZTAL et al. 1989, [3] HARVEY 1985, [4] MISZTAL 1989, [5] MEYER 1993, [6] DEMPSTER and LERNER 1950, [7] DUCROCQ and SÖLKNER 1999, [8] PRENTICE and GLOECKLER 1978

Fig. 1. Distribution of deforming arthropathies in different limb joints by sex

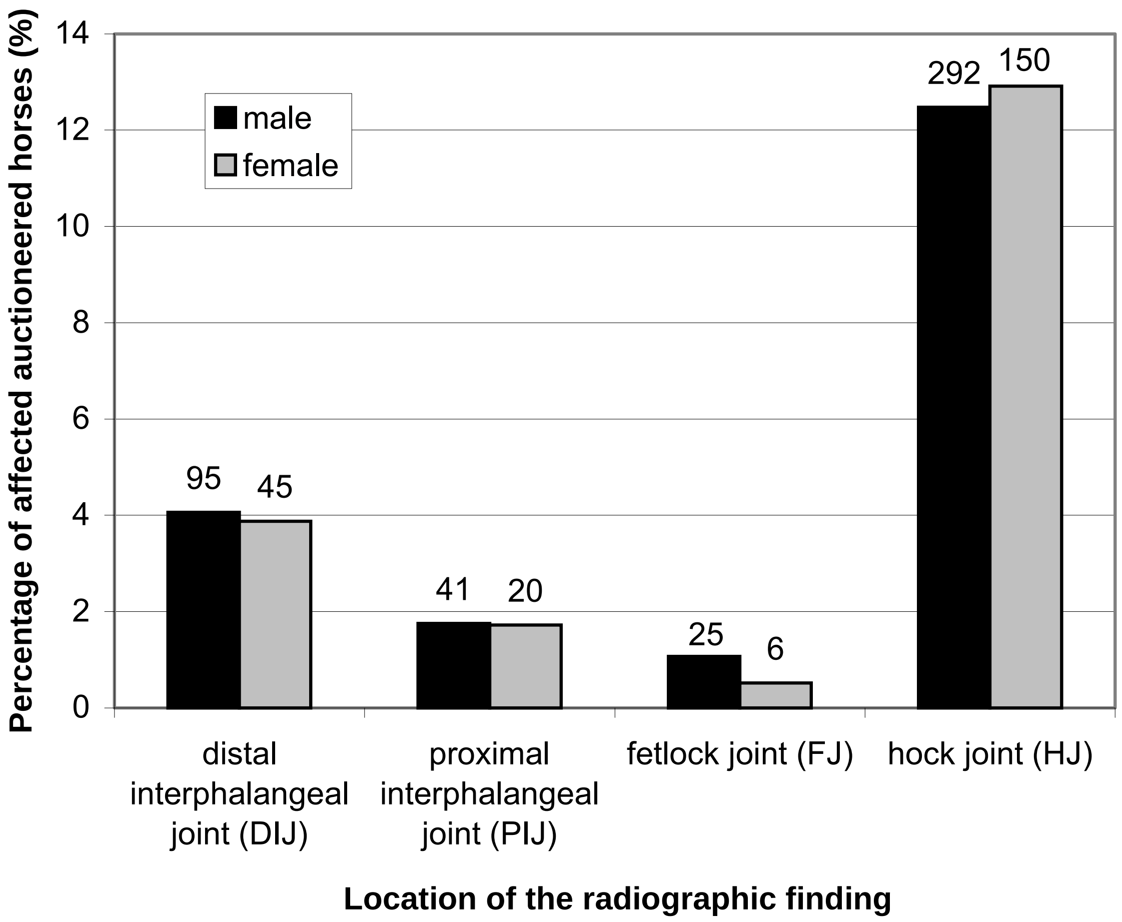


Fig. 2 Distribution of deforming arthropathies in hock joint (HJ) by sex and severity

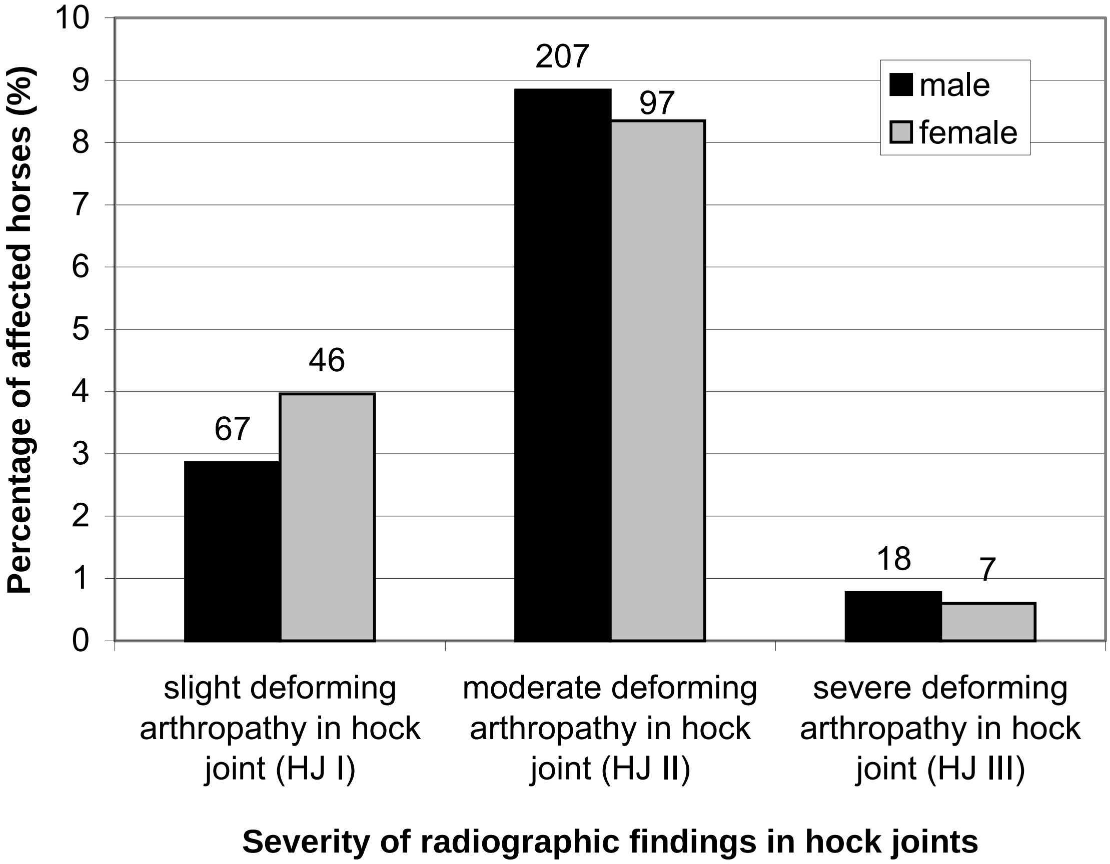


Fig. 3 Distribution of deforming arthropathies in different limb joints by years of auction

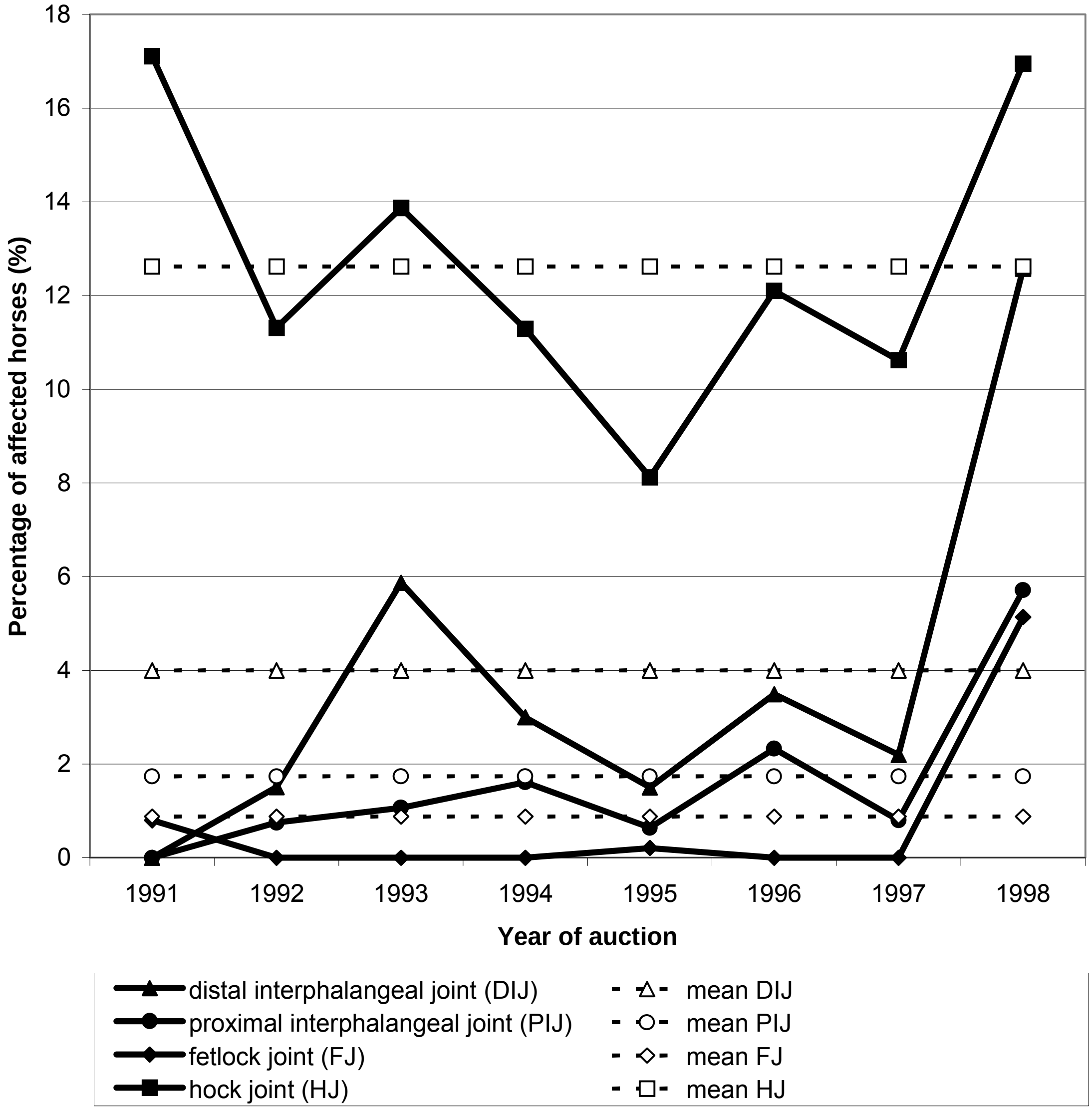
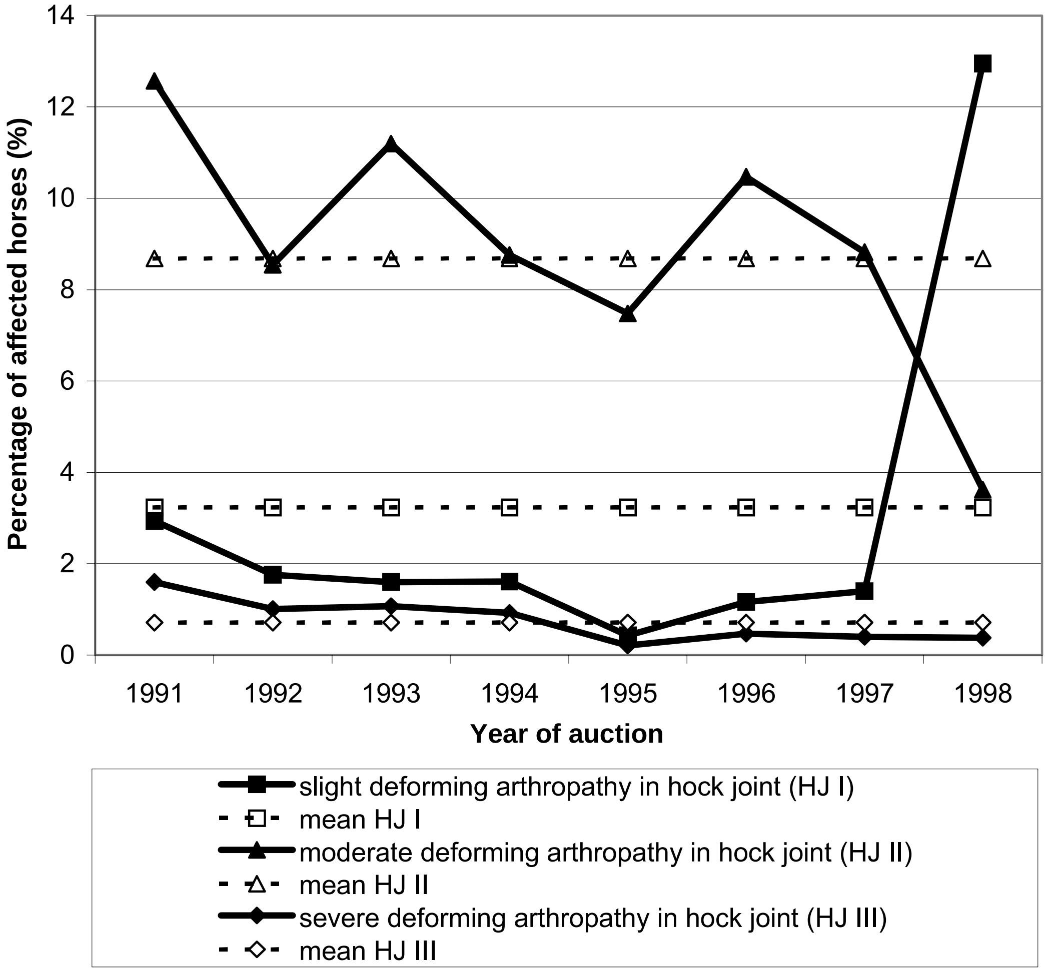


Fig. 4 Distribution of deforming arthropathies in hock joint (HJ) by severity and year of auction



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Variance component estimation on the frequency of pathologic changes in the navicular bones of Hanoverian Warmblood horses

BY K. F. STOCK, H. HAMANN, O. DISTL

Summary

The results of a standardized radiological examination of 3,748 young Hanoverian Warmblood horses selected for sale at auction as riding horses were used to quantify the influence of systematic effects on and to estimate genetic parameters for the prevalence of pathologic changes in the navicular bones. Radiographic findings in the navicular bones of the front limbs were analyzed as all-or-none traits. The pathologic changes were mostly classified as slight (PCN(I); 14.9%), less often as moderate (PCN(II); 5.3%) or severe (PCN(III); 1.8%). Date and year of auction had a significant influence on the prevalence of documented radiographic findings. The prevalence of PCN(I) was further significantly dependent on the examiner, the type and the quality of auction. PCN(II) was significantly more prevalent in male than in female horses. The age, the anticipated suitability and the region of origin of the horses did not have any significant influence on the prevalence of pathologic changes in navicular bones. A higher percentage of genes of the Hanoverian and the Holstein Warmblood horse increased the probability of PCN(I) classification. A significant influence of the sire was found for PCN(I) and (II), and of the male founder for PCN(II) and (III). The female founder was significant only for PCN(II). In general, radiographic findings of any severity in front left and right navicular bones were significantly correlated with each other. Restricted maximum likelihood (REML) was used for the estimation of genetic parameters. The analyses were performed multivariately in linear animal and sire models including height at withers as a separate trait. Heritability estimates for the prevalence of PCN(I), (II) and (III) of horses of both sexes ranged between $h^2 = 0.09$ and $h^2 = 0.21$. When distinguishing between findings in males and females, somewhat implausible estimates were obtained for PCN(II) in females, which might have been caused by their low prevalence. The additive genetic correlations between the investigated traits indicated that radiographic findings consistent with navicular syndrome have a uniform genetic pattern in males and in females, and irrespective of their severity. However, their genetic correlation to height at withers was found to be inconsistent and, therefore, not to be utilizable for selection.

Keywords: Horse; radiographic findings; pathologic findings in navicular bones; genetic parameters; heritability.

Zusammenfassung

Anhand der Ergebnisse einer standardisierten röntgenologischen Untersuchung von 3748 jungen Reitpferden wurde der Einfluss systematischer Effekte auf die Prävalenz pathologischer Strahlbeinveränderungen bestimmt. Für diese wurden zudem genetische Parameter geschätzt. Für die Auswertung standen die Daten von für Reitpferdeauktionen ausgewählten Hannoverschen Warmblutpferden zur Verfügung. Röntgenologische Strahlbeinbefunde an den Vordergliedmaßen wurden als 0-1-Merkmale ausgewertet. Hiervon waren insgesamt 21,6% der Pferde betroffen, wobei die Veränderungen überwiegend als geringgradig (PCN(I); 14,9%), seltener als mittel- (PCN(II); 5,3%) oder hochgradig (PCN(III); 1,8%) eingestuft wurden. Sowohl die einzelne Auktion als auch das Auktionsjahr hatten einen signifikanten Einfluss auf die Prävalenz der dokumentierten Befunde. Ein signifikanter Zusammenhang ließ sich zudem zwischen Untersucher, Auktionstyp und Auktionsqualität auf der einen und der PCN(I)-Prävalenz auf der anderen Seite feststellen. PCN(II) war bei männlichen Pferden signifikant häufiger als bei weiblichen Pferden. Alter, Nutzungseignung und Herkunftsregion des Pferdes hatten keinen signifikanten Einfluss auf die Häufigkeit pathologischer Strahlbeinveränderungen. Ein steigender Anteil von Genen des Hannoverschen und des Holsteiner Warmblutes erhöhte die Wahrscheinlichkeit der Klassifikation als PCN(I). Ein signifikanter Vatereffekt ergab sich für PCN(I) und (II). Männliche Liniengründer beeinflussten das Auftreten von PCN(II) und (III), weibliche Liniengründer dagegen lediglich das Auftreten von PCN(II) signifikant. Unabhängig von dem Ausmaß der Veränderungen ergab sich eine signifikante Korrelation zwischen den an rechtem und linkem Strahlbein erhobenen Röntgenbefunden. Die multivariate Schätzung genetischer Parameter erfolgte mittels REML in linearen Tier- und Vatermodellen. Die Widerristhöhe wurde hierbei als eigenständiges Merkmal in die Analysen eingeschlossen. Die Heritabilitätsschätzwerte für PCN(I), (II) und (III) lagen in der gemeinsamen Auswertung für beide Geschlechter zwischen $h^2 = 0,09$ und $h^2 = 0,21$. Bei der nach Geschlecht getrennten Analyse ergaben sich unerwartet hohe Schätzwerte für PCN(II) bei weiblichen Pferden, welche möglicherweise aus deren niedriger Prävalenz resultierten. Die ermittelten additiv genetischen Korrelationen deuten darauf hin, dass die verschiedenen Podotrochlose-verdächtigen Röntgenbefunde eine einheitliche genetische Grundlage besitzen, bei der weder das Geschlecht noch der Schweregrad der beobachteten Veränderungen eine Rolle spielt.

Angesichts der uneinheitlichen genetischen Korrelationen der röntgenologischen Strahlbeinbefunde zur Widerristhöhe scheint diese nicht als Selektionsmerkmal geeignet.

Schlüsselwörter: Pferd; Röntgenbefunde; Strahlbeinbefunde; genetische Parameter; Heritabilität.

Introduction

In the horse, lameness problems are the main reasons for premature retirement and for culling (PHILIPSSON et al. 1998, WALLIN et al. 2000). The term navicular disease, navicular syndrome or podotrochlosis denotes chronic, generally progressive, degenerative alterations of the equine podotrochlea. Pathological changes might primarily affect the navicular bone (os sesamoideum distale), the navicular bursa (bursa podotrochlearis) or the distal end of the deep flexor tendon. However, only the bony component of the podotrochlea, i.e., navicular bone, is accessible via diagnostic radiography. Several special projections have been suggested in order to get a meaningful image of this fundamental part of the skeleton. The number, location, form and size of the Canales sesamoidales as well as the structure and the contour of the navicular bone are the main diagnostic criteria that have to be considered (DIK 1992, HERTSCH et al. 1982, HERTSCH and STEFFEN 1986, KASER-HOTZ and UELTSCHI 1992, OXSPRING 1935, WRIGHT 1993b).

Navicular disease associated with lameness appears to be mainly a problem of middle-aged horses (maximal incidence at the age of about 7 to 9 years; ACKERMANN et al. 1977, BODENMÜLLER 1983, BRUNKEN 1986, WRIGHT 1993a). However, radiographically detectable changes of navicular bones also occur in younger lameness patients as well as in clinically healthy horses of all ages (including foals; BRANSCHEID 1977, HORNIG 1993, KASER-HOTZ and UELTSCHI 1992). Because of strongly differing modes of progression, a single radiograph does not admit of a prognosis about the further course of the disease. One can deduce neither if nor to what extent remodeling might proceed or clinical symptoms might occur (BRUNKEN 1986, GRUNDMANN 1993, SEYREK-INTAS 1993). Furthermore, it has to be taken into account that the radiographic findings do not reliably reflect the pathohistological changes (DELIUS 1982, DROMMER et al. 1992). The complex anatomy of the equine foot impedes to diagnose podotrochlosis merely radiographically. Clinical findings have to be taken into account (deteriorating stride length, stepping on toe-tip, shifting forehand lameness after diagnostic anestesia).

Though navicular disease has been known for a very long time (it was first described in 1802 by EDWARD COLEMAN), it is still subject of multiple scientific research. There are still several unsettled questions in respect of the pathogenesis of this widespread disease. Especially mode

and amount of stress, and in particular excessive impact and pressure forces acting on navicular region, are held responsible for the initiation of structural remodeling (BRANSCHEID 1977). Others hypothesized some perfusion disorder being the cause of obvious degenerative changes in navicular bone (COLLES and HICKMAN 1977, SVALASTOGA 1983).
There are innumerable reports on prevalences of diverse radiological findings in the equine navicular bone. Studies have been conducted in different breeds and in horses of varying age. However, literature on specific risk factors which predispose horses to develop navicular bone pathology is rare. Therefore, this study aimed to determine the influence of systematic environmental effects, founder animals and breed composition on the prevalence of pathologic changes in navicular bones of young riding horses. Genetic parameters should be estimated to define its surmised role as a hereditary disease.

Material and methods

Information on 3,748 Hanoverian Warmblood horses selected for sale by auction as riding horses in the years 1991-1998 by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany, were used for this study. They were all examined radiographically in a standardized way. The results of these examinations drawn from the horses' medical records were analyzed in connection with the basic data drawn from the official auction catalogues. A detailed description of the data, the methods of recording and the analytical approaches is given by STOCK et al. (2004a, b).
In the following, only pathologic changes in navicular bones of the front limbs will be considered. Slight, moderate and severe radiological alterations, referred to as PCN(I), PCN(II), and PCN(III), were analyzed as individual traits. The classification of horses was done according to their navicular bone quality. In that, for each horse the worst documented finding was taken into consideration (e.g., slight changes in navicular bone front left and moderate changes in navicular bone front right, resulting in an overall classification as PCN(II)). For more detailed analyses we further distinguished between findings in left and right fore feet. Additional analyses were performed separately for radiological findings in males and females. Binary coding was used throughout.
The following factors were tested for their influence on the prevalence of pathologic changes in navicular bones: Sex (male, female), age group (3 years old, 4 years old, 5 years old and older), height at withers (up to 163 cm, 164-165 cm, 166-167 cm, 168-169 cm, 170-171 cm, 172 cm and larger), anticipated suitability of the horse (dressage [and driving], show-jumping, dressage and show-jumping), region of origin (place of the breeder resp. exhibitor of the

horse; representing varying rearing conditions), date of auction (42 auctions of young riding horses), type of auction (winter-auction, elite-auction in spring, Equitop-auction in May, summer-auction, elite-auction in autumn, Equitop-auction in November), quality of auction (elite-auction, subsidiary auction, Equitop-auction), year of auction (8 years from 1991 to 1998), examiner (one examiner 1991-1997, additional second veterinarian for commenting on the radiographs in 1998), percentage of genes of the different horse breeds (Hanoverian Warmblood, Thoroughbred, Trakehner, Holstein Warmblood, Arabs, other breeds), male and female founder.

The interrelationships between pathologic changes of different severity in left and right navicular bones were studied using Fisher's exact test.

Analyses of variance were performed in generalized linear models with the function of distribution considered binomial and the probit function applied as the link function. For this, the procedure GENMOD of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2002) was used. The obtained estimates were transformed into relative frequencies with the inverse of the link function.

For each of the traits under analysis we developed models including only fixed effects and no random effects or genetically correlated traits. The date of auction entered all reference models, whilst submodels included year, type and quality of auction, and mode of examination, respectively. The different reduced models were compared by likelihood ratio tests in order to determine the most parsimonious model not differing significantly from the respective reference model.

Genetic parameters were estimated using the program VCE4 Version 4.2.5 (Groeneveld 1998) based on the restricted maximum likelihood (REML) approach. In that, linear animal models (LAM) as well as linear sire models (LSM) were applied. All traits were analyzed uni- and multivariately using LAM and LSM. Because height at withers was found to have a significant influence on the prevalence of PCN(II) (see below), it was included in the multivariate analyses of radiographic findings as a separate trait. Analyses of findings in both sexes were followed by analyses stratified by sex. Estimated heritabilities and residual correlations were transformed from the observed scale to the underlying liability scale (Dempster and Lerner 1950, Vinson et al. 1976). Since only minor differences among the results of the different uni- and multivariate analyses emerged, only the mean heritabilities (h^2), mean additive genetic (r_g) and residual correlations (r_e), and the mean standard errors (s_{h^2}, s_{rg} , s_{re}), calculated from all the respective uni- and multivariate estimates, will be reported.

Results

Distribution of radiographic findings

The radiographs of a total of 811 horses (21.6%) showed pathologic changes in at least one navicular bone of the fore feet. 14.9% of the horses were classified as PCN(I), 5.3% classified as PCN(II), and only 1.8% classified as PCN(III). However, in the group of selected, but finally not auctioned horses there were as many horses with severe as with more decent navicular pathologies (13.1% PCN(III) vs. 7.0% PCN(I) and 6.1% PCN(II); Table1).

In most cases (76-89%) left and right front navicular bones were altered to the same extent. In 11.2%, 10.6% and 24.2% of the horses with PCN(I), PCN(II), and PCN(III), respectively, the findings were unilateral. The severity of radiologically detected changes differed between left and right in only 11 horses (coinciding PCN(I) and (II) type alterations).

When comparing the prevalences of pathological findings in navicular bones by sex, males were generally more often affected than females (Table 1). Except for 1991, the prevalences of PCN(II) and PCN(III) remained almost constant throughout the period of investigation. The fluctuation of the prevalence of PCN(I) over the years of auction was more pronounced, with a marked rise of the portion of horses classified as PCN(I) from 1997 to 1998. In 1998, their percentage was 1.8 times greater than in the preceding year (Fig. 1).

Analysis of variance

The results of the simple and multiple analyses of variance are summarized in Tables 2 to 4. Both, date and year of auction were significant for PCN(I), PCN(II) and PCN(III). The ranges of the estimated values for the effect of the individual date of auction were 0.0-37.8% for PCN(I), 0.0-16.7% for PCN(II), and 0.0-5.9% for PCN(III). For the effect of the year of auction values between 9.2% and 26.7% (PCN(I)), 3.3% and 11.6% (PCN(II)), and 0.0% and 7.9% (PCN(III)) were estimated. Corresponding to the marked rise of PCN(I) classification in 1998, the effect of the examiner was significant in respect of this finding. The estimated value for the examination by two veterinarians (1998) was 2.1-fold higher than that for the inspection by only one examiner (1991-1997). Type and quality of auction also significantly influenced the incidence of PCN(I). This finding was most likely to occur in Equitop-auctions, especially in Equitop-auctions in May. On the contrary, it was least probable in elite-auctions and especially in elite-auctions in spring. PCN(II) were twice as prevalent in male than in female horses. Height at withers was found to have a significant influence on the prevalence of PCN(II) with a trend towards higher proportion of larger horses being classified as PCN(II).

The proportion of genes of different horse breeds was significant only for the prevalence of PCN(I). This classification was more likely in probands with a higher amount of Hanoverian genes and in probands with Holstein Warmblood horses in their pedigree. The male and female founder had a significant influence only on the distribution of PCN(II).

Radiographic findings in the navicular bones of left and right front limbs were mainly significantly interrelated ($P < 0.001$). The concurrent occurrence of PCN(II) and PCN(III) type alterations in left and right front limbs meant the only exception ($P > 0.05$). In the case of bilateral classification as PCN(I), (II) or (III), there was a highly positive relation between changes of equal severity ($r = 0.92$, 0.90 and 0.86, respectively). Contrarily, for PCN(I) and PCN(II) as well as for PCN(I) and PCN(III) in left and right front navicular bones interrelations were slightly negative ($r = -0.05$ to -0.08).

Model assessment and estimation of genetic parameters

For each trait, the model comparison via likelihood ratio tests revealed reduced models not differing significantly from the corresponding reference model. For PCN(I) and (II) the individual date of auction made up the main effect in the models, whilst the year of auction had the major impact on the prevalence of PCN(III). For each trait a reduced model including only three fixed effects, was found to fit the data as good as the corresponding reference model. Therefore, the following models were used for the further analyses:

PCN(I): $y_{inos} = \mu + Auction_i + Sex_n + Age_o + a_t\ (s_t) + e_{inos}$

PCN(II): $y_{inos} = \mu + Auction_i + Sex_n + Age_o + a_t\ (s_t) + e_{inos}$

PCN(III): $y_{jnrs} = \mu + Year_j + Sex_n + RegE_r + a_t\ (s_t) + e_{jnrs}$

with $a_t\ (s_t)$ = random additive genetic effect of the t-th animal (sire).

In the analyses performed separately for males and females, the sex effect had to be removed from the models accordingly.

Genetic parameters estimated under LAM and LSM for the prevalences of PCN(I), (II) and (III), and for height at withers are shown in Table 5. The observed linear heritability estimates for PCN(I), (II) and (III) were in the range of $h_{obs}^2 = 0.01$ to $h_{obs}^2 = 0.09$. After transformation the heritabilities ranged between $h_{tr}^2 = 0.09$ and $h_{tr}^2 = 0.21$. The heritability of height at withers was $h^2 = 0.23$-0.29.

Additive genetic correlations between the radiographic findings of different severity in navicular bones were highly positive ($r_g = 0.80$-1.00). PCN(I) appeared to be genetically correlated moderately positive, PCN(III) moderately negative with height at withers. However, conflicting results were obtained for the additive genetic correlation between

PCN(II) and height at withers (r_g = -0.001 to 0.126). The respective standard errors amounted to s_{h^2} = 0.01-0.04, corresponding to s_{h^2} = 0.04-0.11 after transformation, and s_{rg} = 0.001-0.283. Mostly negative residual correlations were found between the investigated traits (r_e = -0.18 to 0.06, corresponding to r_e = -0.57 to 0.21 after transformation).

Genetic parameters estimated under LAM and LSM for the prevalences of PCN(I) and (II) in males and females, and for height at withers are shown in Table 6. The heritability of PCN(I) was estimated to be higher in males (h_{obs}^2 = 0.11; h_{tr}^2 = 0.24-0.25) than in females (h_{obs}^2 = 0.04-0.08; h_{tr}^2 = 0.10-0.18). Contrarily, the heritability estimates for PCN(II) were higher in females (h_{obs}^2 = 0.17-0.26; h_{tr}^2 = 0.96-1.50) than in males (h_{obs}^2 = 0.03-0.06; h_{tr}^2 = 0.11-0.24). However, the transformed LSM estimate for PCN(II) in females fell out of parameter space. The heritability of height at withers was estimated as h^2 = 0.22-0.29. The standard errors amounted to s_{h^2} = 0.02-0.08 before and s_{h^2} = 0.06-0.48 after transformation.

Pathologic changes in navicular bones of males and females mostly appeared to be correlated additive genetically moderately to highly positive (r_g = 0.50-1.00). The additive genetic correlation between PCN(II) of males and females meant the only exception with estimates in the range of r_g = -0.20 to 0.10. Considering height at withers, mostly moderately positive additive genetic correlations to radiographic findings in navicular bones emerged (r_g = 0.06-0.40). But findings classified as PCN(II) in females behaved differently again as the additive genetic correlation to height at withers was slightly negative (r_g = -0.01). The standard errors were in the range of s_{rg} = 0.01-0.39 under LAM and s_{rg} = 0.15-0.40 under LSM.

The residual correlations were estimated at r_e = -0.20 to 0.05, resulting in transformed estimates of r_e = -0.69 to 0.09.

Discussion

The present study aimed to quantify the importance of influences on the prevalence of radiographically detectable pathologic changes in the navicular bones of physically fit young Warmblood riding horses. In this connection the role of genetics and possible sex differences were of particular interest.

Depending on the investigated horse population and on the study designs, prevalences between 6.8% and 87.9% were reported for the different types of pathologic changes of navicular bones detected radiographically (ASTNER 1996, BODENMÜLLER 1983, SEYREK-INTAS 1993, KWPN 1994, PHILIPSSON et al. 1998, WINTER et al. 1996). Even though we analyzed on well-performing young riding horses, some alterations of the normal radiological appearance of navicular bone was documented for about every fifth horse.

Because of the uncertain clinical relevance of particular alterations in navicular bone, any attempt to schematize the radiographic findings has to be faced very carefully (HERTSCH et al. 1982). Nevertheless, the present investigation also had to use a simplified mode of recording (PCN(I)-(III)) to ensure appropriate analyses of the data, as differentiation when documenting the radiographic findings was little and did not allow for more detailed analyses.

Considering the various special radiographic views of the navicular bone, the upright pedal view (dorsopalmar projection according to OXSPRING 1935) is most widely accepted and considered one of the standard radiographs in the equine veterinary practice. Nevertheless, there is some controversy about its exclusive use. Many radiologists plead for taking additional radiographs from different projections (tangential or skyline projection, lateral view; GRUNDMANN 1993, KASER-HOTZ and UELTSCHI 1992, SEYREK-INTAS 1993, UELTSCHI 1983, 2002). However, for the present investigation only dorsopalmar radiographs (OXSPRING) of the navicular bones of the front limbs were available for all the probands (90° universal radiographs of the toes are not suitable to scrutinize the navicular bones). Thus, some discreet alterations might not have been visible on the available radiographs, and the real incidence of (slight) pathologic changes of the navicular bone might exceed the prevalence determined.

Considerable controversy about the valuation of the various findings concerning the equine podotrochlea persists (SEYREK-INTAS 1993). In the present study the different valuation of particular radiographic findings became obvious in respect of slight changes in navicular bones: With the revised mode of examination the proportion of horses classified as PCN(I) rose from 12.7% on the average in 1991-1997 to 26.9% in 1998. WINTER et al. (1996) found similar evidence for existing uncertainty of valuation, particularly in respect of drawing a sharp line between “still physiological” and “already (slightly) pathological”. The only possibility to ensure reliable analyses seems to be the uniform standardized evaluation of high-quality radiographs by one experienced veterinarian, as it took place through the major part of our study period.

The prevalence of more precisely defined, distinct radiographic findings (classified as PCN(II) and (III)) was higher in the horses pulled out of auction than in the auctioned horses. On the basis of the available data it was not possible to determine the definite reason, but one might speculate that the strain of the auction training of several weeks’ duration led to clinical symptoms in the horses showing more distinct radiological alterations. Sluggish gaits or a manifest lameness might have caused the exclusion of the respective horse, then. Considering less appealing gaits because of some subclinical limitation of performance or some “medical selection” of the horses, one might have expected a significant influence of type and quality of auction on the prevalence of PCN(II) and (III). However, this significance was found only in respect of PCN(I) despite the fact that their clinical relevance is quite improbable at least at the time of the veterinary examination. However, the radiological status of the individual horse might have played some role yet, for what auction the respective horse was put forward. A slightly abnormal appearance of the navicular bone on the radiographs was obviously more likely to be accepted in a candidate for a subsidiary or an Equitop-auction than in a horse designated for an elite-auction.

Regarding potential etiological factors for the podotrochlosis syndrome, literature provides quite contradictory statements. In Dutch Warmblood mares a significant effect was determined neither for age or height at withers nor for the rearing conditions of the horses (KWPN 1994). But in young German Warmblood horses of different breeds, a linear increase of navicular bone alterations and a higher proportion of affected mares have been found (WINTER et al. 1996). Other investigators found males more often affected (ACKERMANN et al. 1977) or could not detect any sex differences (BODENMÜLLER 1983). Similarly, the present study revealed no clear sex effect, as male horses only carried a higher risk to be classified as PCN(II).

Generally, the greatest importance in respect of the development of pathologic changes of navicular bones is ascribed to the strain put on the horse (BRANSCHEID 1977). This is compatible with the fact that the alterations almost exclusively occur bilaterally in the front limbs (WRIGHT 1993b) which are bearing the major part of the horses' body weight. Furthermore, the use of the horse for riding, and for show jumping in particular, puts additional stress on the equine forehand (BRANSCHEID 1977, WRIGHT 1993a). However, not all investigators found a correlation between the horses' use and the radiographically detectable alterations of navicular bones (ACKERMANN et al. 1977). The present study also revealed no significant influence of the anticipated suitability and therefore of the predominant mode of training of the investigated horses. However, it must be taken into account that the probands were all still very young (mean age of 3.9 years). Accordingly, their use as riding horses mostly lasted only about one year. Hence, the effect of chronic excessive strain of work might not have taken effect yet.

Limb deformations and inappropriate shoeing can cause detrimental loading of the equine foot (WRIGHT 1993a). However, the selection that took place prior to the veterinarian examination should have precluded horses with serious exterior faults from the present investigation. Since it has not been recorded if hoof corrections became necessary during the training phase in Verden prior to the auction, there is information about if or to what extent hoof grooming and shoeing occurred in the rearing period. Because of the diversity of horse breeders and exhibitors, we could only test the effect of regional provenance which was found to be irrelevant in respect of the radiological appearance of the navicular bone.

Concerning possible breed effects, significant differences have been reported in the radiographic appearance of navicular bones of Freiberger horses and Swiss halfbred horses JORDAN (1996). For Thoroughbreds the results were more contradictory (KWPN 1994). However, when investigating the effects of particular horse breeds, one has to take into account the interdependence between the breed and its typical use. Consequently, it will not always be possible to distinguish between the effect of the breed itself and the stress horses of this breed are usually exposed to. In the present study the prevalence of radiographic findings in navicular bones did not seem to be affected by the proportion of genes of the Thoroughbred. But higher amounts of Hanoverian and Holstein Warmblood genes were found to be significantly correlated with a higher risk to show PCN(I) type alterations.

The heritability estimates we obtained for height at withers are in good agreement with literature (VON BUTLER and KROLLIKOWSKY 1986). However, neither WINTER et al. (1996) nor WILLMS et al. (1999) observed significant correlations between height at withers and radiographic findings indicative of podotrochlosis. Despite the significant influence we found in respect of PCN(II), the corresponding correlation estimates were quite inconclusive.

Early authors already presumed hereditary factors to be involved in the pathogenesis of navicular disease (ACKERMANN et al. 1977). Recently, this idea was taken up again and could be substantiated with prevalences differing significantly between progeny of different sires (ASTNER 1996, BOS et al. 1986, DIK and VAN DER BROEK 1995, HORNIG 1993, PHILIPSSON et al. 1998) and heritability estimates in the range of $h^2 = 0.06\text{-}0.32$ (KWPN 1994, WILLMS et al. 1999, WINTER et al. 1996). Accordingly, we found that the probands' sire had a significant effect on the prevalence of pathologic changes in navicular bones of his progeny, as did the male and female line the probands originated from. Finally, low to moderate heritability estimates emerged from our data.

However, previous studies did not differentiate between varying severity of radiological alterations or between radiographic findings in males and females. Doing so we mainly found slightly higher heritabilities for discreet than for more distinct alterations. The heritability estimates for PCN(II) in females were the only results falling out off this pattern. But the transformed estimates evidenced that considerable overestimation must have taken place in respect of this trait which was the least prevalent in the sex-differentiated analyses. However, it still exceeded that of PCN(III) for which plausible estimates arose. But according to the results of a preliminary simulation study (Stock et al. 2004c), one has to be aware of somewhat inflated transformation factors (Dempster and Lerner 1950) for traits with prevalences of around 5% or below. The results obtained for PCN(III) and for PCN(II) in females should be therefore interpreted carefully.

The additive genetic correlations between radiological alterations of different severity in navicular bones were mostly close to one. Therefore, we conclude that different radiographic findings consistent with the navicular syndrome have a uniform genetic pattern in male and female horses. The mainly moderate heritabilities we determined facilitate to develop breeding strategies that aim to improve the radiological status of the navicular bone. Height at withers does not appear to be a reasonable criterion to select on. Therefore, the radiological appearance of the navicular bones, appraised in the thorough radiographic examination of animals intended for breeding, should provide the basis for selection.

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Table 1. **Distribution of pathologic changes of navicular bones of different severity, referred to as PCN(I), (II) and (III), in all horses selected for sale by auction and in the auctioned horses**

Radiographic finding	Horses selected for one of the 42 auctions (n = 3748)		Horses auctioned in one of the 42 auctions (n = 3503)	
	prevalence		prevalence	
	absolute	relative (%)	absolute	relative (%)
PCN(I)	557	14.86	523	14.93
PCN(I), male			365	15.58
PCN(I), female			158	13.61
PCN(II)	198	5.28	182	5.20
PCN(II), male			143	6.11
PCN(II), female			39	3.36
PCN(III)	66	1.76	34	0.97
PCN(III), male			27	1.15
PCN(III), female			7	0.60

Table 2. **Simple analyses of variance for slight (PCN(I)), moderate (PCN(II)) and severe pathologic changes of navicular bones (PCN(III))**

Source of variation	DF	PCN(I)		PCN(II)		PCN(III)	
		χ^2	P	χ^2	P	χ^2	P
Auction	41	174.36	< 0.001	104.26	< 0.001	76.98	0.001
Year of auction	7	75.44	< 0.001	33.77	< 0.001	30.59	< 0.001
Examiner	1	62.73	< 0.001	2.33	0.127	0.18	0.670
Type of auction	5	19.91	0.001	5.23	0.388	10.38	0.065
Quality of auction	2	13.10	0.001	1.67	0.434	1.57	0.456
Sex	1	2.93	0.087	12.22	0.001	2.65	0.104
Height at withers	5	4.82	0.438	12.23	0.032	5.21	0.391
Age	2	2.45	0.294	3.65	0.162	0.22	0.896
Suitability	2	0.22	0.895	2.61	0.271	1.82	0.403
Region of breeder	2	2.86	0.240	4.83	0.089	0.13	0.939
Region of exhibitor	2	1.45	0.484	4.34	0.114	4.31	0.116
Sire	113	170.24	< 0.001	140.30	0.042	n.e.	n.e.

Table 3. **Mean and 95% confidence interval (CI) of the relative frequencies of pathologic changes in navicular bones (PCN(I) and (II)) for the significant systematic effects**

Trait	Fixed effect	Fixed effect levels	Number of probands	Relative frequency $\bar{x}$	Relative frequency 95% CI
PCN(I)	Type of auction	winter-auction	839	12.87%	10.74-15.28%
		elite-auction in spring	569	11.95%	9.49-14.83%
		Equitop-auction in May	290	20.34%	16.03-25.28%
		summer-auction	854	16.74%	14.36-19.37%
		elite-auction in autumn	642	14.49%	11.93-17.38%
		Equitop-auction in Nov.	309	19.42%	15.32-24.13%
	Quality of auction	elite-auction	1211	13.29%	11.48-15.30%
		subsidiary auction	1693	14.83%	13.20-16.58%
		Equitop-auction	599	19.87%	16.83-23.21%
	Examiner	1 examiner (1991-1997)	2972	12.99%	11.82-14.24%
		2 examiners (1998)	531	27.31%	23.65-31.22%
	Hanoverian Warmblood horse	I (0.0 – 50.5%)	1127	15.88%	13.16-18.94%
		II (50.6 – 70.3%)	1440	19.98%	16.38-24.01%
		III (≥ 70.4%)	1182	22.49%	17.25-28.54%
	Holstein Warmblood horse	I (0.0%)	3154	14.60%	12.42-17.02%
		II (0.1 - 15.6%)	400	19.63%	15.29-24.65%
		III (15.7 - 46.9%)	195	24.54%	17.83-32.41%
PCN(II)	Sex	male	2342	6.15%	5.23-7.18%
		female	1161	3.45%	2.52-4.63%
	Height at withers	≤ 163 cm	652	3.22%	2.08-4.83%
		164 - 165 cm	627	4.63%	3.20-6.52%
		166 - 167 cm	732	6.56%	4.95-8.55%
		168 - 169 cm	601	5.66%	4.04-7.75%
		170 - 171 cm	498	4.62%	3.05-6.78%
		≥ 172 cm	392	7.14%	4.92-10.06%

Table 4. **Influence of the proportion of genes of different horse breeds and of male and female founders on the prevalence of pathologic changes of different severity in navicular bones (PCN(I), (II) and (III)) using multiple analyses of variance**

Source of variation (mean ± SD proportion of genes)		PCN(I)		PCN(II)		PCN(III)	
		χ^2	P	χ^2	P	χ^2	P
Hanoverian Warmblood	(59.4 ± 17.8%)	6.73	0.035	1.21	0.547	0.12	0.940
Thoroughbred	(24.6 ± 14.8%)	0.44	0.803	1.52	0.468	1.26	0.533
Trakehner	(7.9 ± 7.8%)	1.79	0.409	0.17	0.918	0.86	0.650
Holstein Warmblood	(2.1 ± 5.8%)	12.24	0.002	3.80	0.150	0.76	0.684
Arabs	(1.2 ± 3.1%)	2.28	0.319	4.18	0.124	1.08	0.582
other breeds	(4.0 ± 8.7%)	3.42	0.181	5.64	0.060	3.86	0.145
male founder		0.31	0.580	4.38	0.036	3.76	0.053
female founder		0.05	0.825	3.94	0.047	0.04	0.842

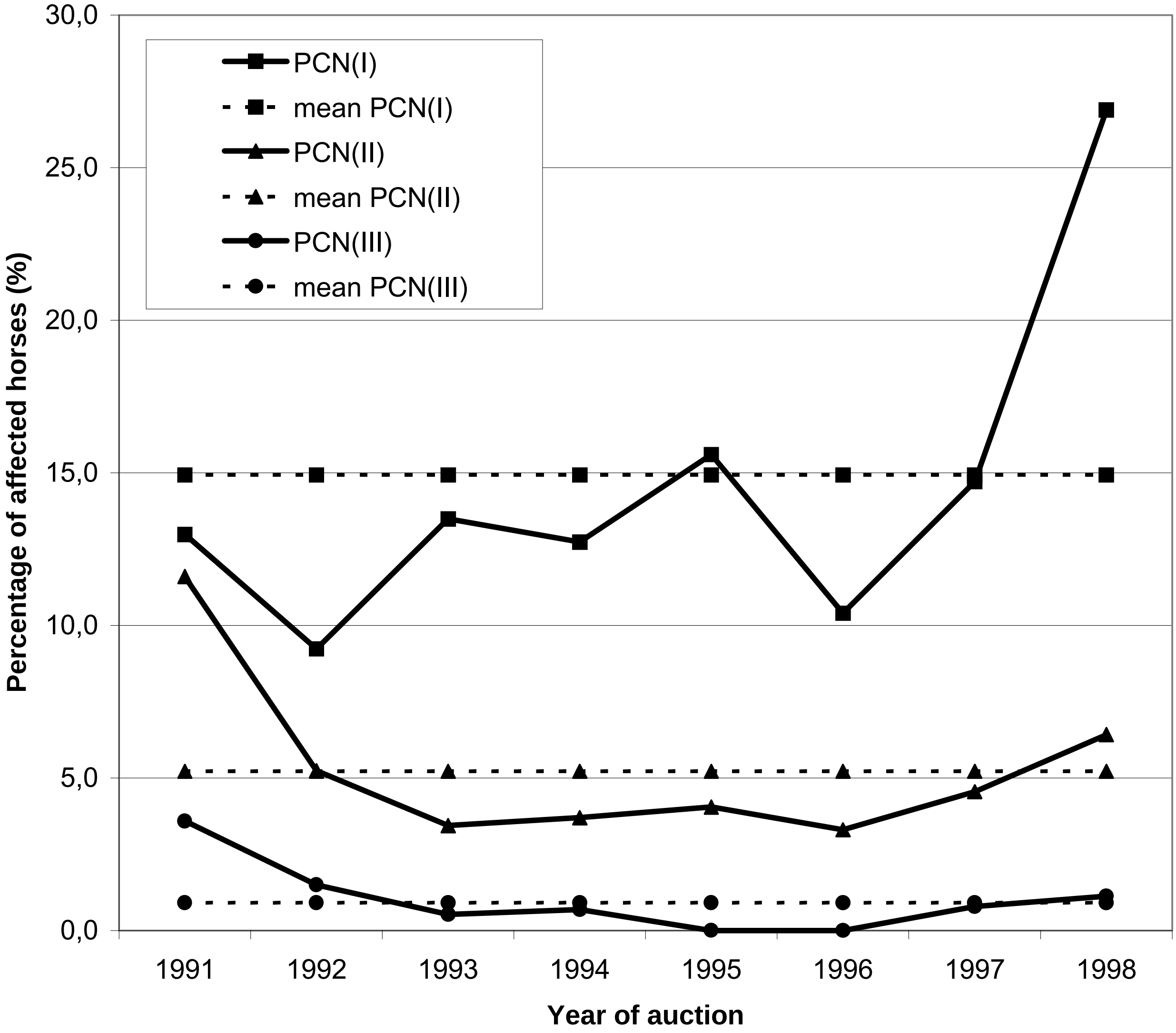
Table 5. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of slight, moderate and severe pathologic changes in navicular bones, and for height at withers using a linear animal model (LAM; first line) and a linear sire model (LSM; second line)**

Trait	Navicular bone (I)	Navicular bone (II)	Navicular bone (III)	Height at withers
Navicular bone (I)	$0.206^{0.044}$ $0.194^{0.046}$	$1.000^{0.001}$ $0.996^{0.017}$	$0.796^{0.125}$ $0.939^{0.083}$	$0.151^{0.086}$ $0.132^{0.135}$
Navicular bone (II)	$-0.568^{0.050}$ $-0.418^{0.035}$	$0.094^{0.051}$ $0.189^{0.086}$	$0.809^{0.164}$ $0.961^{0.088}$	$0.126^{0.166}$ $-0.001^{0.192}$
Navicular bone (III)	$-0.446^{0.068}$ $-0.305^{0.050}$	$-0.471^{0.081}$ $-0.397^{0.068}$	$0.126^{0.063}$ $0.180^{0.108}$	$-0.666^{0.128}$ $-0.273^{0.283}$
Height at withers	$-0.058^{0.029}$ $-0.020^{0.015}$	$0.050^{0.035}$ $0.062^{0.021}$	$0.213^{0.066}$ $0.075^{0.045}$	$0.285^{0.035}$ $0.228^{0.040}$

Table 6. **Heritability estimates (transformed estimate on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (transformed estimate below the diagonal) with their standard errors for the prevalence of slight and moderate changes in navicular bones by sex, and for height at withers using a linear animal model (LAM; first line) and a linear sire model (LSM; second line)**

Trait	Navicular bone (I), male	Navicular bone (I), female	Navicular bone (II), male	Navicular bone (II), female	Height at withers
Navicular bone (I), male	$0.242^{0.060}$ $0.251^{0.072}$	$0.949^{0.127}$ $0.820^{0.324}$	$1.000^{0.010}$ $0.963^{0.239}$	$0.609^{0.188}$ $0.503^{0.193}$	$0.063^{0.085}$ $0.114^{0.150}$
Navicular bone (I), female	$0.002^{0.025}$ $0.000^{0.016}$	$0.100^{0.072}$ $0.181^{0.105}$	$0.913^{0.387}$ $0.644^{0.404}$	$0.929^{0.112}$ $0.549^{0.336}$	$0.399^{0.276}$ $0.167^{0.237}$
Navicular bone (II), male	$-0.597^{0.065}$ $-0.434^{0.039}$	$0.018^{0.039}$ $0.000^{0.021}$	$0.107^{0.063}$ $0.237^{0.110}$	$-0.200^{0.368}$ $0.102^{0.271}$	$0.147^{0.150}$ $0.067^{0.154}$
Navicular bone (II), female	$0.000^{0.042}$ $0.000^{0.025}$	$-0.694^{0.146}$ $-0.405^{0.077}$	$0.014^{0.056}$ $-0.005^{0.033}$	$0.960^{0.296}$ $1.499^{0.477}$	$-0.013^{0.126}$ $-0.013^{0.156}$
Height at withers	$-0.037^{0.031}$ $-0.022^{0.021}$	$-0.088^{0.057}$ $-0.015^{0.032}$	$0.087^{0.040}$ $0.093^{0.026}$	$-0.073^{0.085}$ $-0.062^{0.052}$	$0.285^{0.035}$ $0.224^{0.032}$

Fig. 1. Distribution of pathologic changes of navicular bone of different severity, referred to as PCN(I), (II), and (III), by year of auction and severity



Estimation of genetic parameters for osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in the navicular bones of Warmblood riding horses

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Keywords: Warmblood riding horse; radiographic findings; osseous fragments; deforming arthropathy; navicular bones; heritability

Summary

The results of a standardized radiological examination of 5,928 Hanoverian Warmblood horses selected for sale at auction were analyzed for their genetic background. Osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in navicular bones were found in 20.8%, 9.1%, 11.7% and 24.7% of the probands, respectively. Genetic parameters were estimated using Residual Maximum Likelihood (REML) under both linear animal and linear sire models. Heritability estimates and estimated residual correlations were transformed to the underlying liability scale. Additive genetic variances and covariances were estimated at σ^2_a = 0.03-0.47 and cov_a = -0.02 to 0.01, respectively. The heritability estimates obtained for the radiographic findings were in the range of h^2 = 0.14-0.46. They were correlated additive genetically with r_g = -0.34 to 0.24.

Introduction

The health of a horse is a fundamental prerequisite for its performance and durability in all sectors of horse industry. Diseases of the locomotory system particularly interfere with the horse's usability (Grøndahl and Engeland 1995, Jørgensen *et al.* 1997, Rossdale *et al.* 1985, Wallin *et al.* 2000). Though there was considerable progress in veterinary diagnostics and therapeutics in the last decades, all such measures involve additional expenses. Furthermore, satisfactory results in terms of athletic ability cannot be achieved in all cases. Therefore, more and more importance is attached to prophylactic measures such as rearing conditions, training and competition management. However, there are evidences of genetic components in the

development of certain affections of the equine limbs (e.g., Bjørnsdottir *et al.* 2000; Grøndahl and Dolvik 1993; KWPN 1994; Philipsson *et al.* 1993; Pieramati *et al.* 2003; Stock *et al.* 2004b,c,d,e; Willms *et al.* 1999; Winter *et al.* 1996), and the most efficient way to lower the prevalences of heritable diseases will be the implementation of specific breeding programs.
For this reason, the present study aimed to substantiate the role of genetics in the development of radiographic findings in the limbs of young Warmblood riding horses. The results of this investigation should provide the basis to derive appropriate breeding strategies.

Material and methods

The present study was based on the results of a standardized radiographic examination of a total of 5,928 Hanoverian Warmblood horses (probands) selected for sale at auction as riding horses in 1991-2003 by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. The basic data of the 5,680 horses that were actually offered for sale (auction horses) were drawn from the official auction catalogues. Those included: animal number, sex (male, female), age group (3 years old, 4 years old, 5 years old and older), anticipated suitability of the horse (dressage [and driving], show-jumping, dressage and show-jumping), region of origin (place of the breeder resp. exhibitor of the horse; representing varying rearing conditions), date of auction (67 auctions of young riding horses), year of auction (13 years from 1991 to 2003), examiner (one examiner in 1991-1997, additional second veterinarian for scrutinizing the radiographs in 1998-2003). For the 248 horses which were selected, but pulled out of the auction no background data were available.
Between 38 and 145 horses were offered per auction, adding up to 145 (2003 with only one auction, the winter auction, included in this study) to 549 horses (1999) per year. Amongst the auction horses, the male to female ratio was about 2 to 1 (3,601 stallions and geldings, 2079 mares). 1,471 3-year-olds, 2,953 4-year-olds and 1,256 horses 5 years old or older were offered. Most of them were advertised as suited for dressage (3,401 horses), less as particularly suited for show-jumping (1,367 horses) or for both dressage and show-jumping (912 horses).

Analysis of radiographic findings

Each horse listed as a potential auction candidate had a standardized veterinary examination comparable to a routine pre-purchase examination. Therefore, generally ten radiographs of the limbs were available per horse: laterolateral (90°) projections of all four feet, dorsopalmar

(DP) projections of both front navicular bones (upright pedal route according to Oxspring (1935)), and laterolateral (90°) as well as dorsolateral-plantaromedial-oblique (45°) projections of both hock joints. Radiographic findings detected by the responsible veterinarian were documented in the horses' medical records which were available for our study. Documentation was incomplete for 11.6% of the horses.

The four most prevalent radiographic findings among the probands chosen for further analyses were (1) osseous fragments in fetlock joints (OFF), (2) osseous fragments in hock joints (OFH), (3) deforming arthropathy in hock joints (DAH), and (4) pathologic changes in navicular bones (PCN). They were analyzed as separate all-or-none traits, as described by Stock *et al.* (2004a, b). However, according to the results obtained previously (Stock *et al.* 2004c), no distinction was drawn between alterations of different severity (deforming arthropathy in hock joints, pathologic changes in navicular bones).

Phenotypic correlations between the different radiographic findings were tested using the χ^2-test with the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003).

Pedigree data were taken from a unified animal ownership database (Vereinigte Informationssystems Tierhaltung w.V., VIT) in Verden on the Aller, Germany. The 5,928 probands were sired by 614 different sires which contributed up to 211 horses selected for sale at auction in 1991-2003. However, 167 sires were represented by only one and 79 sires by only two probands, leaving 368 sires with at least three offspring among the probands. For the estimation of genetic parameters pedigree informations on four generations were considered.

Genetic parameters were estimated multivariately using Residual Maximum Likelihood (REML) with VCE4, Version 4.2.5 (Variance Component Estimation; Groeneveld 1998) under both, linear animal models (LAM) and linear sire models (LSM). Multivariate analyses of different combinations of traits were performed. Since their results were very similar among each other, only the mean heritabilities (h^2), mean additive genetic (r_g) and residual correlations (r_e) and the mean standard errors (SE), calculated from all the respective multivariate estimates, will be reported.

The procedure GENMOD of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003) was used for simple and multiple analyses of variance. In that, the function of distribution was considered binomial and the probit function was applied as the link function. The systematic effects derived from the above-mentioned basic data drawn from the auction catalogues were tested for their influence on the occurrence of radiographic findings. For each trait under analysis we developed models comprising only significant fixed effects. Likelihood ratio tests were used in order to determine the most parsimonious model not differing significantly from the respective reference model (see Stock *et al.* 2004c,d,e for details).

Accordingly, the following multivariate linear animal (a_o) or sire (s_o) models were used for the genetic analyses of the four binary traits osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints, and pathologic changes in navicular bones:

osseous fragments in fetlock joints (OFF)

$$y_{ijko} = \mu + Auction_i + Sex_j + Age_k + a_o\ (s_o) + e_{ijko}$$

osseous fragments in hock joints (OFH)

$$y_{ijklmno} = \mu + Auction_i + Sex_j + Age_k + Suit_l + RegB_m + RegE_n + a_o\ (s_o) + e_{ijklmno}$$

deforming arthropathy in hock joints (DAH)

$$y_{ijlo} = \mu + Auction_i + Sex_j + Suit_l + a_o\ (s_o) + e_{ijlo}$$

pathologic changes in navicular bones (PCN)

$$y_{ijko} = \mu + Auction_i + Sex_j + Age_k + a_o\ (s_o) + e_{ijko}$$

with $y_{ijklmno}$ = radiographic finding of the proband,
μ = model constant,
$Auction_i$ = fixed effect of the date of auction (i = 1 - 67),
Sex_j = fixed effect of the sex (j = 1 - 2),
Age_k = fixed effect of the age group (k = 1 - 3),
$Suit_l$ = fixed effect of the suitability (l = 1 - 3),
$RegB_m$ = fixed effect of the region of breeder (m = 1 - 3),
$RegE_n$ = fixed effect of the region of exhibitor (n = 1 - 3),
$a_o\ (s_o)$ = random additive genetic effect of the o-th animal (sire), and
$e_{ijklmno}$ = residual error.

Heritabilities (h^2), additive genetic (r_g) and residual correlations (r_e) were calculated from the estimates of the additive genetic (σ^2_a, cov_a) and residual (co)variances (σ^2_e, cov_e) as

$$h^2 = \sigma^2_a / (\sigma^2_a + \sigma^2_e),$$

$$r_{gij} = cov_{aij} / (\sigma^2_{ai} * \sigma^2_{aj}),\text{ and}$$

$$r_{eij} = cov_{eij} / (\sigma^2_{ei} * \sigma^2_{ej}).$$

The heritability estimates of the LAM and LSM analyses were transformed onto the liability according to Dempster and Lerner (1950).

$$h^2_{liab} = h^2_{obs}\ [p_i\ (1 - p_i)] / z_i^2$$

with h^2_{liab} = heritability of trait i on the underlying continuous scale,
h^2_{obs} = heritability of trait i on the observed (binary) scale,

p_i = frequency of outcome 1 for trait i, and

z_i = ordinate of a standard normal distribution at the threshold point corresponding to a fraction p_i of the population having the character.

This transformation should compensate for the underestimation of heritabilities when applying linear models to binary traits. In a preceding simulation study we tested the applicability of the Dempster-Lerner transformation factors to our data. The data structure of the simulated data set resembled the observed data, and a four generation pedigree was considered. The transformation factors derived from the simulated data set (f_{sim}) were in good agreement with the Dempster-Lerner transformation factors (f_{DL}) (Stock *et al.* 2004c). With very low prevalence of the analyzed trait they might result in a slight overestimation of its heritability ($p_i = 0.04$: $f_{DL} / f_{sim} = 1.18$). With prevalences in the range of $p_i = 0.25$ they fit very well ($f_{DL} / f_{sim} = 0.97$).

The estimates of the residual (r_e) and phenotypic correlations (r_p) were analogously transformed according to Vinson *et al.* (1976).

$$r_{e\,liab} = r_{e\,obs} \{[p_{i\,1} (1 - p_{i\,1})] / z_{i\,1}{}^2\}^{1/2} \{[p_{i\,2} (1 - p_{i\,2})] / z_{i\,2}{}^2\}^{1/2}$$

In the following only the transformed estimates will be reported.

Results

Distribution of radiographic findings

In all, osseous fragments in fetlock and/or hock joints were found in 28.0% of the probands. There were more horses affected with osseous fragments in fetlock joints (20.8%) than with osseous fragments in hock joints (9.1%). Osseous fragments in fetlock joints of the hindquarters were more prevalent than osseous fragments in fetlock joints of the forehand or in hock joints. Pathologic changes in navicular bones were detected in 24.7%, and deforming arthropathy in hock joints in 11.7% of the probands (Table 1).

The prevalences of osseous fragments in fetlock and hock joint, and of deforming arthropathy in hock joints were fluctuating in 1991-2003 without any detectable trend. On the contrary, pathologic changes in navicular bones were documented more often at the end of the study period than at the beginning (Fig 1).

Table 2 shows the distribution of radiographic findings among the probands. 3,047 of the 5,928 examined horses (51.4%) had at least one of the investigated radiographic findings. 2,249 of the horses (37.9%) were affected singularly, whilst in 798 of the horses (13.5%) more than one radiological abnormality was found. However, only 3 horses (0.05%) had simultaneously all four radiographic findings included in our analyses.

Low correlation coefficients in the range of r_p = -0.02 to 0.05 were determined between the radiographic findings. The only significant correlation was found between deforming arthropathy in hock joints and pathologic changes in navicular bones (Table 3).

Estimation of genetic parameters

The additive genetic variances estimated for the radiographic findings were between σ^2_a = 0.08 and σ^2_a = 0.47. The corresponding covariances were in the range of cov_a = -0.02 to 0.03 (Table 4).

Genetic parameters estimated for the prevalences of osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints, and pathologic changes in navicular bones, applying LAM and LSM, are shown in Table 5. In general, LAM and LSM estimates were in close agreement with differences of ≤ 0.06, ≤ 0.15 and ≤ 0.03 for heritabilities, additive genetic correlations and residual correlations, respectively.

The heritability estimates were in the range of h^2 = 0.15-0.46, with the lowest and highest estimates obtained for osseous fragments in fetlock joints (h^2 = 0.15) and pathologic changes in navicular bones (h^2 = 0.41-0.46), respectively. Slightly to moderately negative additive genetic correlations were estimated between osseous fragments in fetlock and hock joints (r_g = -0.19 to -0.34), between osseous fragments in hock joints and deforming arthropathy in hock joints (r_g = -0.12 to -0.14), and between pathologic changes in navicular bones and osseous fragments in both, fetlock and hock joints (r_g = -0.07 to -0.11). On the contrary, osseous fragments in fetlock joints appeared to be genetically correlated moderately positive with deforming arthropathy in hock joints (r_g = 0.23-0.39). Negligible small estimates were obtained for the additive genetic correlation between deforming arthropathy in hock joints and pathologic changes in navicular bones (r_g = -0.01-0.04). The residual correlations between all the traits were in the range of r_e = -0.05 to 0.10 throughout. The standard errors (SE) of the genetic correlations were considerably larger (SE = 0.09-0.15) than the standard errors of the heritabilities (SE = 0.03-0.06) and of the residual correlations (SE = 0.02-0.04).

Discussion

The objective of this study was to quantify the role of genetics in the pathogenesis of prevalent radiographic findings in the limbs of Hanoverian Warmblood horses.

In a preceding study on a smaller data set comprising only horses selected for auctions in 1991-1998 we determined those radiographic findings that appeared to be of major importance in that population of Warmblood riding horses. Accordingly, we chose four different types of radiographic findings for the present study: Osseous fragments in fetlock (OFF) and in hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN). Prevalences of between 9.1% and 24.7% as determined among our probands for the individual findings and of 13.5% of multiply affected horses agree with literature and document the importance of these findings even in a population of performance selected young riding horses.

The potential of radiographically detectable alterations to compromise the horses' performance at least in the long term justifies to look for alternatives to therapeutic measures. Considering breeding measures, the estimation of genetic parameters will provide the required basis.

Likelihood-based methods are favoured by several investigators and regarded as the method of choice for the estimation of variance components (Meyer 1991). Sire models have been commonly used for genetic analyses but imply random mating and unrelated sires. These assumptions do usually not hold with field data (Van Vleck and Hudson 1982). Animal models use all available pedigree informations, but because of sparse informations per animal effect convergence may be critical. Concerning the analysis of categorical traits, some authors consider animal threshold models as improper (Hoeschele and Tier 1995). Therefore, we used animal as well as sire models with REML for the estimation of genetic parameters and accounted for the nonlinearity of the data by transforming the estimates.

Several studies substantiated the heritable character of the above mentioned conditions. Our results indicating a moderate heritability of osseous fragments in fetlock and hock joints as well as of deforming arthropathy in hock joints and of pathologic changes in navicular bones, fall into the wide range of reported heritability estimates (h^2 = 0.02-0.64 for osteochondrosis dissecans in fetlock and/or hock joints; h^2 = 0.02-0.65 for bone spavin; h^2 = 0.06-0.31 for podotrochlosis; Àrnason *et al.* 2003; Bjørnsdottir *et al.* 2000; Grøndahl and Dolvik 1993; KWPN 1994; Philipsson *et al.* 1993; Pieramati *et al.* 2003; Schougaard et al. 1987; Stock *et al.* 2004c,d, e; Willms *et al.* 1999; Winter *et al.* 1996). These somewhat diverging estimates might be caused by differing data structures (age, breed and use of the investigated horse populations) and by varying methods used for the analyses (mode of investigation, definition of traits; linear vs. threshold models, REML vs. Gibbs Sampling).

Few authors commented on the phenotypic and/or genetic correlations between these conditions. The phenotypic correlations between podotrochlosis, bone spavin and tarsal osteochondrosis (dissecans) were found to be negligibly small in Dutch as well as in German Warmblood horses (r_p = -0.03 to 0.17; KWPN 1994; Willms *et al.* 1999; Winter *et al.* 1996).

We determined correlation coefficients in the same order of magnitude (r_p = -0.04 to 0.11) between the corresponding radiographic findings investigated.

On the contrary, the additive genetic correlations we estimated were in the range of r_g = -0.34 to 0.24. In particular, osseous fragments in fetlock joints appeared to be genetically correlated moderately negative with osseous fragments in hock joints and with pathologic changes in navicular bones (r_g = -0.34 to -0.19 and r_g = -0.11 to -0.07, respectively), and moderately positive with deforming arthropathy in hock joints (r_g = 0.12-0.24). The absolute values of the estimates obtained for the additive genetic correlations between the remaining radiographic findings (OFH, DAH, PCN) were considerably smaller (r_g = -0.09 to 0.06). However, literature provides conflicting results in respect of the genetic correlations between the studied conditions. Whilst Willms *et al.* (1999) found moderately positive genetic correlations between podotrochlosis, bone spavin and tarsal osteochondrosis dissecans in the range of rg = 0.10-0.25 ± 0.02-0.16, Winter *et al.* (1996) determined a negative genetic correlation between tarsal osteochondrosis and bone spavin (r_g = -0.42 ± 0.40).

Nevertheless, additive genetic correlations between different traits should be considered when developing breeding plans. Highly positive correlations would allow to combine the corresponding traits, whilst considerably negative correlations would interfere with simultaneous improvement in the respective traits. In our data, no additive genetic correlations were estimated to be larger than 0.39. Consequently, all the four investigated radiographic findings were considered as individual traits throughout the analyses. Furthermore, the negative additive genetic correlation we found between osseous fragments in fetlock and hock joints indicates the necessity to simultaneously consider these two traits when aiming to improve the overall radiological status of the horse.

With a view to the final intention, i.e., the development of a breeding strategy that aims to lower the prevalence of radiographic findings in the limbs of riding horses, we come to the conclusion that it appears to be possible to consider all the four investigated traits simultaneously. Their heritabilities were estimated in a range utilizable for horse breeders, and there were no highly negative genetic correlations that would strongly interfere with their simultaneous improvement.

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TABLE 1: Prevalences of osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints, and pathologic changes in navicular bones of Hanoverian Warmblood horses selected for sale at auction (n = 5,928)

Radiographic finding	Prevalence	
	absolute	relative (%)
Osseous fragments in fetlock joints	1,234	20.82
forehand	539	9.09
hindquarters	818	13.80
Osseous fragments in hock joints	539	9.09
Deforming arthropathy in hock joints	695	11.72
Pathologic changes in navicular bones	1,466	24.73

TABLE 2: Distribution of the investigated radiographic findings (osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN)) among the probands (n = 5,928)

Number of different kinds of affections	Number (proportion) of horses		OFF	OFH	DAH	PCN
IV	3 (0.05%)		(+)	(+)	(+)	(+)
III	83 (1.40%)	9	(+)	(+)	(+)	(–)
		23	(+)	(+)	(–)	(+)
		38	(+)	(–)	(+)	(+)
		9	(–)	(+)	(+)	(+)
		4	( )	(+)	(+)	(+)
II	712 (12.01%)	77	(+)	(+)	(–)	(–)
		100	(+)	(–)	(+)	(–)
		231	(+)	(–)	(–)	(+)
		30	(–)	(+)	(+)	(–)
		4	( )	(+)	(+)	(–)
		1	( )	(+)	(+)	( )
		99	(–)	(+)	(–)	(+)
		12	( )	(+)	(–)	(+)
		146	(–)	(–)	(+)	(+)
		12	( )	(–)	(+)	(+)
I	2,249 (37.94%)	750	(+)	(–)	(–)	(–)
		1	(+)	(–)	(–)	( )
		2	(+)	( )	( )	( )
		231	(–)	(+)	(–)	(–)
		37	( )	(+)	(–)	(–)
		294	(–)	(–)	(+)	(–)
		45	( )	(–)	(+)	(–)
		801	(–)	(–)	(–)	(+)
		86	( )	(–)	(–)	(+)
		2	( )	( )	( )	(+)
0	2,881 (48.60%)	2397	(–)	(–)	(–)	(–)
		275	( )	(–)	(–)	(–)
		1	(–)	( )	( )	(–)
		3	( )	( )	( )	(–)
		205	( )	( )	( )	( )
0 - IV	5,928 (100%)		1,234 affected horses (20.82%)	539 affected horses (9.09%)	695 affected horses (11.72%)	1,466 affected horses (24.73%)

(+) : affected;   (–) : not affected;   (   ) : not investigated

TABLE 3: Correlation coefficients between osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

Radiographic finding	OFF	OFH	DAH	PCN
OFF	1.00	-0.002	0.003	-0.023 +
OFH		1.00	-0.014	0.015
DAH			1.00	0.046 **
PCN				1.00

Levels of significance:
*** : $P < 0.001$; ** : $P < 0.01$; * : $P < 0.05$; + : $P < 0.10$

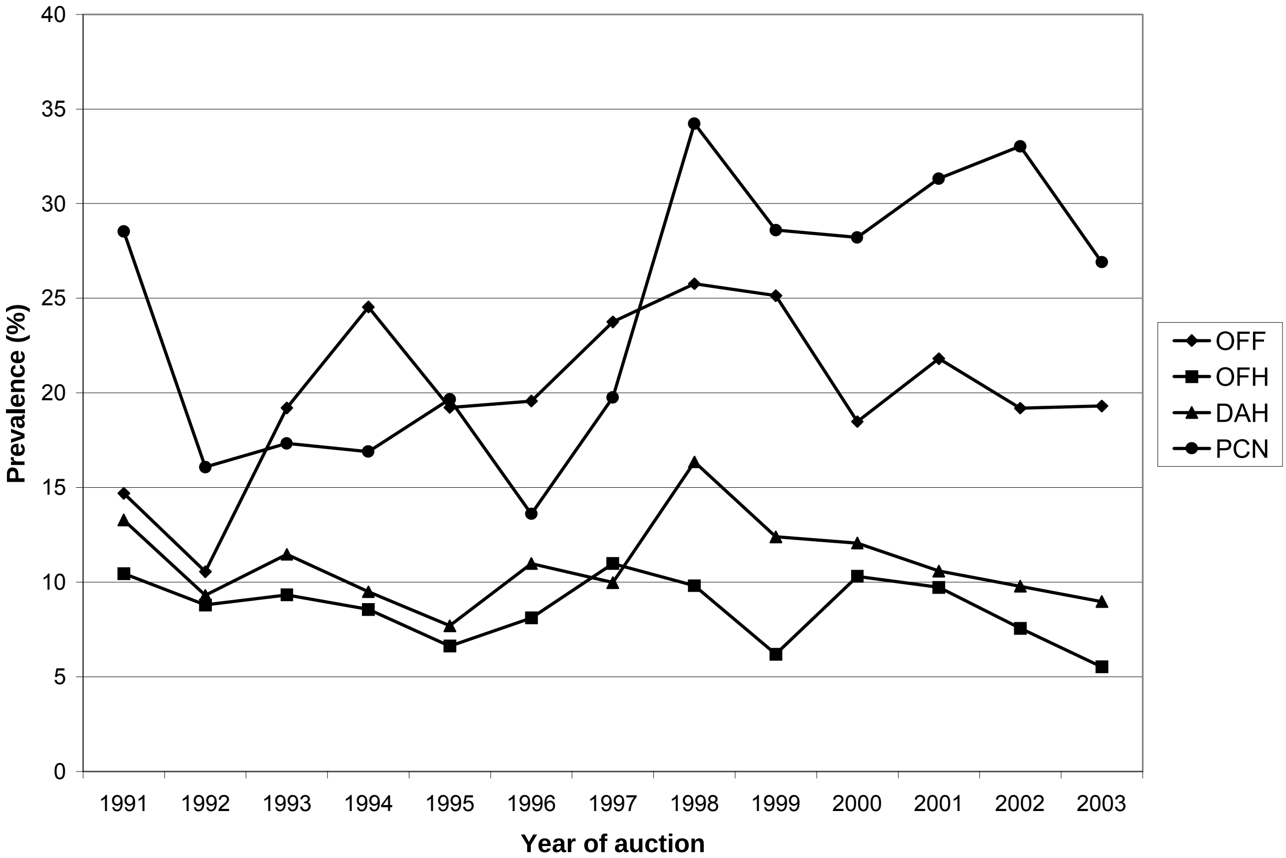
TABLE 4: Additive genetic variances (on the diagonal) and covariances (above the diagonal) for the prevalences of osseous fragments in fetlock (OFF) and hock joints (OFH), of deforming arthropathy in hock joints (DAH), and of pathologic changes in navicular bones (PCN), obtained under LAM (above) and LSM (below)

Radiographic finding	OFF	OFH	DAH	PCN
OFF	0.135 0.128	-0.021 -0.009	0.025 0.010	-0.016 -0.006
OFH		0.090 0.088	-0.012 -0.002	-0.016 -0.004
DAH			0.087 0.080	-0.002 0.002
PCN				0.407 0.468

TABLE 5: Heritability estimates (on the diagonal), additive genetic correlations (above the diagonal), and residual correlations (below the diagonal) with their standard errors for the prevalences of osseous fragments in fetlock (OFF) and hock joints (OFH), of deforming arthropathy in hock joints (DAH), and of pathologic changes in navicular bones (PCN), obtained under LAM (above) and LSM (below)

Radiographic finding	OFF	OFH	DAH	PCN
OFF	**$0.150^{0.027}$** **$0.145^{0.030}$**	$-0.191^{0.123}$ $-0.338^{0.140}$	$0.226^{0.132}$ $0.390^{0.146}$	$-0.069^{0.102}$ $-0.109^{0.120}$
OFH	$0.022^{0.034}$ $-0.007^{0.024}$	**$0.323^{0.051}$** **$0.314^{0.060}$**	$-0.137^{0.125}$ $-0.116^{0.152}$	$-0.086^{0.089}$ $-0.086^{0.105}$
DAH	$-0.051^{0.031}$ $-0.020^{0.022}$	$-0.020^{0.039}$ $-0.051^{0.028}$	**$0.215^{0.042}$** **$0.199^{0.052}$**	$-0.011^{0.097}$ $0.036^{0.116}$
PCN	$-0.017^{0.030}$ $-0.026^{0.019}$	$0.073^{0.038}$ $0.042^{0.024}$	$0.097^{0.033}$ $0.079^{0.022}$	**$0.406^{0.039}$** **$0.463^{0.051}$**

Fig 1: Prevalences of osseous fragments in fetlock (OFF) and in hock joints (OFH), of deforming arthropathy in hock joints (DAH), and of pathologic changes in navicular bones (PCN) in 1991-2003



Prediction of breeding values for osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in the navicular bones of Hanoverian Warmblood horses

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Abstract

The results of a standardized radiological examination of 5,928 Hanoverian Warmblood horses selected for sale at auction were used to predict relative breeding values (RBV) in the 23,662 horses included in the last four generations of the probands' pedigree. The distribution of the RBV was investigated in the whole four generation pedigree, in the probands and in those stallions that contributed at least three offspring to the probands. The RBV of the probands' sires were further compared with the officially published performance based relative breeding values, i.e., total indices dressage (TID) and jumping (TIJ). The sires had a considerably higher level of dressage (mean TID = 110) than of jumping indices (mean TIJ = 98). Total indices radiographic findings (TIR) were calculated for the sires giving varying weight to the individual RBV. In each case this resulted in a mean TIR of 99. Finally, total indices were derived from TIR and TID and/or TIJ in order to develop different selection schemes for all-purpose breeding, and for breeding focused on dressage and show-jumping, respectively. When weighting radiographic findings with 30-60% as opposed to the respective performance parameters, and selecting only sires with above-average total indices, all the considered breeding values increased by 1-19%. The prevalences of the investigated radiographic findings were concurrently lowered by up to 10% each. Considering only one radiographic finding at a time, the maximum attainable response to selection was an increase of relative breeding values by 16-23% and a relative decrease of prevalences of radiographic findings by 31-52%. The results of this study indicate that it is possible to simultaneously allow for health and performance traits in horse breeding. Medical data should be considered in the prediction of breeding values in order to improve the radiological status of today's riding horses.

Keywords: Hanoverian Warmblood horse; Radiological status; Breeding values; Response to selection

1. Introduction

Diseases of the equine locomotory system interfere with the horses' use and affect all sections of the horse industry (Rossdale et al., 1985; Grøndahl and Engeland, 1995; Storgaard Jørgensen et al., 1997; Wallin et al., 2000). Failure of performance reduces the value of the individual horse. Since radiographic findings are often considered to be useful predictors for the future soundness of the individual horse, the radiological examination of the equine limbs has become an integral part of pre-purchase examinations. Its results have a considerable impact on the outcome of sale and on the sale value of a horse (Van Hoogmoed, 2003). Furthermore, therapeutic measures cause economic losses and sometimes give only unsatisfactory results in terms of athletic ability. Therefore, more and more importance is attached to prophylactic measures. Besides reconsiderations of how to keep and to use a horse, attempts are made to improve the general health status of the horse population by systematic selection of breeding animals. In many modern horse breeds the approval of breeding animals is dependent not only on type traits and performance criteria such as quality of gaits and jumping ability, but also on their clinical and radiological health status (Koenen, 2000). However, the prediction of breeding values in the horse is still exclusively based on type and performance data derived from competition results and from stallion and mare performance tests. Data concerning the horses' health status are not allowed for so far when predicting breeding values for the whole population. But in the view of the hereditary nature of particular diseases of the equine skeleton that has been documented in several studies (e.g., Grøndahl and Dolvik, 1993; Philipsson et al., 1993; KWPN, 1994; Winter et al., 1996; Willms et al., 1999a; Bjørnsdottir et al., 2000; Pieramati et al., 2003; Stock et al., 2004a,b,c), they appear to be worth considering.

For this reason, the results of an extensive study on radiographic findings in the limbs of young Warmblood riding horses were used for the prediction of breeding values for those orthopedic diseases that were found to be of major importance. Furthermore, interrelationships between the relative breeding values predicted for osseous fragments in fetlock and hock joints, for deforming arthropathy in hock joints and for pathologic changes in the navicular bones were investigated. The main objective of the present paper is to develop selection schemes which concurrently account for radiographic findings and for performance traits.

2. Material and methods

The results of a standardized radiographic examination of 5,928 Hanoverian Warmblood horses (probands) were used for this study. All these horses were selected for sale at auction as riding horses in 1991-2003 by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. 5,680 horses were actually offered for sale (auction horses), 248 horses were selected, but pulled out of the auction. The probands had a mean age of 4.0 ± 0.8 years. The four most prevalent radiographic findings, i.e., osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN), were further analyzed as binary traits.

3,047 (51.4%) of the 5,928 horses had at least one of the investigated radiographic findings. 37.9% of the probands were affected singularly. Multiple radiological alterations were detected in 13.5% of the probands. In particular, the prevalences of osseous fragments in fetlock and hock joints, of deforming arthropathy in hock joints, and of pathologic changes in navicular bones were 20.8%, 9.1%, 11.7%, and 24.7%, respectively. For details see Stock and Distl (2004).

Pedigree data were taken from a unified animal ownership database (Vereinigte Informationssysteme Tierhaltung w.V., VIT) in Verden on the Aller, Germany. The 5,928 probands were sired by 614 different stallions contributing up to 211 horses selected for sale at auction in 1991-2003. 246 sires (40.0%) were represented by only one or two probands, 368 sires had three or more offspring among the probands.

In a preceding study, genetic parameters for the prevalences of OFF, OFH, DAH and PCN were estimated multivariately using Residual Maximum Likelihood (REML) with VCE4 Version 4.2.5 (Variance Component Estimation; Groeneveld, 1998). The estimates of the additive genetic and residual (co)variances (Tables 1 and 2) were used to derive the heritabilities, and the additive genetic and residual correlations. The additive genetic and residual variances of the investigated radiographic findings were estimated at between σ_a^2 = 0.09 and σ_a^2 = 0.41, and between σ_e^2 = 0.75 and σ_e^2 = 1.58, respectively. The corresponding additive genetic and residual covariances were in the range of cov_a = -0.02 to 0.03, and cov_e = -0.03 to 0.05, respectively. After transformation onto the liability scale (Dempster and Lerner 1950), the heritability estimates for OFF, OFH, DAH and PCN were h^2 = 0.15, h^2 = 0.32, h^2 = 0.22, and h^2 = 0.41, respectively (SE = 0.03-0.05).

The (co)variance matrices were further utilized to predict breeding values for the investigated radiographic findings for all the 23,662 horses appearing in the last four generations of the probands' pedigree. The calculations were done using PEST (Groeneveld, 1990) and applying the same multivariate linear animal models (LAM) as for the estimation of genetic parameters, i.e.:

osseous fragments in fetlock joints (OFF)

$y_{ijko} \quad = \mu + Auction_i + Sex_j + Age_k + a_o\ (s_o) + e_{ijko}$

osseous fragments in hock joints (OFH)

$y_{ijklmno} \quad = \mu + Auction_i + Sex_j + Age_k + Suit_l + RegB_m + RegE_n + a_o\ (s_o) + e_{ijklmno}$

deforming arthropathy in hock joints (DAH)

$y_{ijlo} \quad = \mu + Auction_i + Sex_j + Suit_l + a_o\ (s_o) + e_{ijlo}$

pathologic changes in navicular bones (PCN)

$y_{ijko} \quad = \mu + Auction_i + Sex_j + Age_k + a_o\ (s_o) + e_{ijko}$

with $y_{ijklmno}$ = radiographic finding of the proband,

μ = model constant,

$Auction_i$ = fixed effect of the date of auction (i = 1 - 68),

Sex_j = fixed effect of the sex (j = 1 - 3),

Age_k = fixed effect of the age group (k = 1 - 4),

$Suit_l$ = fixed effect of the suitability (l = 1 - 4),

$RegB_m$ = fixed effect of the region of breeder (m = 1 - 4),

$RegE_n$ = fixed effect of the region of exhibitor (n = 1 - 4),

$a_o\ (s_o)$ = random additive genetic effect of the o-th animal (sire), and

$e_{ijklmno}$ = residual error.

The breeding values were then standardized on a relative scale with a mean of 100 and a standard deviation of 20. The 1,981 probands born in 1987-1991 were used as the reference population for the standardization. Transformation was done that way that larger relative breeding values (RBV) will mean that the horses are less likely to transmit a predisposition for a particular radiological finding. Accordingly, horses with lower RBV are considered to transmit a higher disposition for particular radiological findings. The distributions of the RBV in the whole four generation pedigree (n = 23,662), in the probands (n = 5928) and in the probands' sires with three or more offspring included in our analyses (n = 368) were tested for normality using the Kolmogorov-Smirnov test with the procedure UNIVARIATE of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003).

The officially published relative breeding values for dressage and show-jumping (total indices dressage and jumping), the accuracy of the estimates as well the number of progeny in sports were drawn from the Annual for Breeding and Sports 2002 (Jahrbuch Zucht und Sport, JZS, 2002), published by the Fédération Equestre Nationale (FN, Deutsche Reiterliche Vereinigung e.V.) in Warendorf, Germany. In that, partial as well as total relative breeding values for stallions are displayed if their evaluation is based on a minimum of 5 offspring being active in sports and reliability of the respective total index is at least 75%. The applied multitrait repeatability animal model considers own performance test results and sport data as well as corresponding performance data of related horses (results of performance tests of stallions and mares, sport event results attained as of 1995 in dressage and show-jumping competitions; Integrated Estimation of Breeding Values according to Von Velsen-Zerweck (1998)).

358 of the 368 sires with at least three offspring among our probands (Ø 15.23 ± 19.93 offspring; range 3-211) were listed with total indices for dressage (TID) and/or jumping (TIJ). The estimation of the later took into account data of 4-1488 (Ø 128.36 ± 158.22) offspring active in dressage sport events and of 4-1156 (Ø 131.82 ± 172.53) offspring having started in show-jumping competitions. For these 358 stallions the RBV for radiographic findings (OFF, OFH, DAH and PCN) were compared with the official performance based relative breeding values (TID, TIJ) using the Pearson correlation coefficients of the procedure CORR of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003). The distributions of the RBV and TI were tested for normality using Kolmogorov-Smirnov test with the procedure UNIVARIATE of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003). Stallions with relative breeding values outside the range of three standard deviations (outliers; n = 37) were tested for differences to the remaining stallions (n = 321) with all available relative breeding values ranging between 41 and 159.

In order to take into account the total performance and health status of the horse, we developed total indices on the basis of the RBV for radiographic findings and the TID and/or TIJ. At first, the RBV predicted for OFF, OFH, DAH and PCN were combined to a total index radiographic findings (TIR). In that, each of the investigated radiographic findings was given equal (TIR_A) or differential weight (TIR_B). In the later, the weighting factors were chosen according to their presumed clinical relevance and curability (e.g., Ackermann et al., 1977; Brehm and Staecker, 2000; McIlwraith and Vachon, 1988; Hertsch, 1990; Möller, 1993; Grøndahl and Engeland, 1995; Jaugstetter et al., 2003; Peremans and Verschooten, 1997; Storgaard Jørgensen et al., 1997).

$TIR_A = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$

$TIR_B = (RBV_{OFF} + 2*RBV_{OFH} + 2*RBV_{DAH} + 3*RBV_{PCN}) / 8$

Subsequently, dressage and jumping ability and the radiological status should be considered simultaneously. According to the different breeding strategies that can be adopted we used three different ways to do so. In general, the breeding aim of the Hanoverian Warmblood horse requests a horse talented for dressage as well as for show-jumping, eventing and driving. Bruns (2000) proposed that weighting dressage and show-jumping with 60% and 40%, respectively, would result in maximum breeding progress in both disciplines. However, many breeders depart from this all-purpose breeding and aim at dressage or jumping specialists. Therefore, we calculated total indices dressage-jumping-radiographic findings (DJR) as well as total indices dressage-radiographic findings (DR) and total indices jumping-radiographic findings (JR). In DJR dressage (TID) and show-jumping (TIJ) were weighted 6 to 4, whilst in DR only dressage (TID) and in JR only show-jumping ability (TIJ) were considered. In the respective total indices, radiographic findings (TIR) were given weights of between 0% and 100% in steps of 10%.

$DJR_w \quad = \quad w/10 * TIR + (1 – w/10) * (0.6 * TID + 0.4 * TIJ)$

$DR_w \quad = \quad w/10 * TIR + (1 – w/10) * TID$

$JR_w \quad = \quad w/10 * TIR + (1 – w/10) * TIJ$

with $w = 0 - 10$

For example, DJR_3 denotes the total index dressage-jumping-radiographic findings in which radiographic findings were weighted with 30%. The remaining 70% were made up by dressage and show-jumping at 60 and 40%, respectively.

The total indices (DJR_w, DR_w, JR_w with w = 0-10 and using TIR_A and TIR_B, respectively) we determined for the probands' sires were used to simulate different selection schemes. In each case, only those stallions with above-average total indices (i.e., $DJR_w > 100$, $DR_w > 100$ and $JR_w > 100$, respectively) were selected that had no individual relative breeding value (TID, TIJ; RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN}) smaller than 40. The selection procedure is illustrated in Figure 1. In order to assess the expected response to selection, the lots of the selected sires were then compared with the whole group of the probands' sires (n = 358) by their mean relative breeding values (TID, TIJ, TIR; RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN}) and by the prevalences of the investigated radiographic findings in their offspring.

The maximum attainable response to selection was determined for each of the investigated radiographic findings. For this purpose selection was based on the relative breeding value for the respective radiographic finding only, i.e., all stallions with $RBV_{OFF} > 100$, $RBV_{OFH} > 100$,

RBV_{DAH} > 100 or RBV_{PCN} > 100 that had no individual relative breeding value (TID, TIJ; RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN}) smaller than 40 were selected, respectively.

3. Results

As shown in Table 3, the ranges of the relative breeding values were the same in the four generation pedigree and in the probands' sires. As a whole, the estimates ranged between -13 and 185. However, the relative breeding values of the probands spread somewhat less (range -2 to 162). Considering the mean relative breeding values in the four generation pedigree, in the probands and in the probands' sires differences of up to 4.6 relative points were found. The corresponding standard deviations increased from SD = 13.5-15.3 in the four generation pedigree through SD = 19.1-21.5 in the probands to SD = 23.7-26.7 in the probands' sires.

Figures 2 to 5 show the distribution of RBV for radiographic findings among all horses in the four generation pedigree, among the probands and among the probands' sires. For all the investigated radiographic findings the curves for the four generation pedigree was highly peaked, and flatness of the curves increased over the probands to the probands' sires. Accordingly, horses with RBV in the range of one standard deviation made up 82.2-87.6%, 63.5-75.3% and 52.7-62.5%, respectively. The distribution of RBV for osseous fragments in fetlock joints appeared to be approximately normal (Figure 2). However, this finding could be substantiated statistically only for the distribution of RBV for OFF in the probands' sires (skewness -0.09; $p > 0.10$), but not in the probands themselves (skewness -0.38; $p < 0.01$) and in the four generation pedigree (skewness -0.40; $p < 0.01$). As opposed to this, the curves of RBV for osseous fragments in hock joints, for deforming arthropathy in hock joints and for pathologic changes in navicular bones all clearly deviated from normal distributions, in the four generation pedigree and in the probands as well as in the probands' sires. This appearance of mostly being more or less skewed to the right (Figures 3 to 5) was documented by skewness parameters in the range of -1.43 to 0.16 and the results of the tests for normality ($p < 0.01$).

In the 358 sires of probands that were listed in the JZS 2002 the total indices dressage and jumping ranged between 64 and 161, and between 32 and 154, respectively. The corresponding TI means and standard deviations were 110.27 ± 19.15 and 98.11 ± 22.65. Only 6.4% of the sires had a TID of less than 80, whilst 26.3% of the sires had a TI jumping of less than 80. On the other hand, TI greater than 120 were given for 29.1% and 19.3% of the sires for dressage and jumping, respectively. Accordingly, 64.5% of the sires had TI dressage and 54.5% of the sires had TI jumping in the range of 81-119.

Comparing the stallions with relative breeding values smaller than 40 (n = 28) or greater than 160 (n = 9) with the stallions with all relative breeding values in the range of three standard deviations, we found no relevant differences. Their years of birth were very similar, and the outliers contributed on the average even more probands (n = 29) than the stallions with all relative breeding values between 41 and 159 (n = 15).

The correlations between the performance based official relative breeding values (TID, TIJ) and the RBV predicted for radiographic findings (OFF, OFH, DAH, PCN) are given in Table 4. Significant negative correlations existed between RBV_{OFF} and RBV_{OFH} ($r = -0.23$), between RBV_{OFH} and RBV_{DAH} ($r = -0.24$), and between RBV_{PCN} and TIJ ($r = -0.16$). RBV_{PCN} and TID tended to be correlated negatively with $r = -0.10$. On the contrary, RBV_{OFF} and RBV_{DAH} were found to be significantly correlated positively with $r = 0.18$.

We investigated the distribution of RBV and TI in the probands' sires more closely in view of the performance traits. For "dressage stallions" only TID (not TIJ), for "jumping stallions" only TIJ (not TID) were taken into account besides the RBV for radiographic findings. For "all-purpose stallions" both TID and TIJ were considered. None of the 358 sires had all RBV and TID and / or TIJ equal or greater than 120 simultaneously. However, 120 dressage stallions, 94 jumping stallions and 84 all-purpose stallions, representing 33.5%, 26.3% and 23.5% of the sires with at least three offspring among our probands, had all considered relative breeding values greater than 80.

Analyzing the distribution of the total indices (TID, TIJ, TIR_A, TIR_B) we found that none of the sires (n = 358) had all total indices ≥ 120. Giving equal weight to the investigated radiographic findings (TIR_A), 226 sires (63.1%) had no total index of 80 or smaller. When weighting OFF, OFH, DAH and PCN with one, two, two and three, respectively (TIR_B), 218 sires (60.9%) had no total index of 80 or smaller.

The tests for normality revealed that only the total indices jumping were distributed normally in the probands' sires (skewness 0.07; $p > 0.05$). For the total indices dressage (skewness 0.28) as well as the total indices radiographic findings (TIR_A skewness -0.28, and TIR_B skewness -0.42) the null hypotheses of normal distributions were rejected ($p < 0.05$).

The maximum response attainable in respect of OFF, OFH, DAH and PCN was an increase in the respective relative breeding values by 22.7%, 15.8%, 18.4% and 20.4% and a decrease in the prevalences of these radiographic findings of 31.1% (from 20.8% to 14.4%), 51.6% (from 9.1% to 4.4%), 41.6% (from 11.7% to 6.8%) and 42.7% (from 24.7% to 14.4%), respectively.

The expected response to selection when applying different selection schemes is depicted in Tables 5 to 10, separately for all-purpose breeding (Tables 5 and 6), and for breeding focused on dressage (Tables 7 and 8) and on show-jumping (Tables 9 and 10), respectively. In each case, the expected means of the relative breeding values in the selected sires and the expected prevalences of radiographic findings in their offspring are shown. Improved values (i.e., increased relative breeding values and lowered prevalences) are pointed out (in bold print).

The exclusion of those sires with single relative breeding values of 40 or smaller increases the mean relative breeding values for radiographic findings (RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}; TIR_A, TIR_B), but not the total indices dressage and jumping. Of the considered 358 sires, 330 (92%) pass this step of selection. If performance parameters are additionally allowed for by calculating total indices (DJR, DR, JR), and sires with total indices smaller than 100 are excluded, all relative breeding values are increased by up to 19%. However, the prevalences of radiographic findings in the offspring of these sires that are selected this way are not lowered concomitantly. The selection of all sires with all single relative breeding values larger than 40 lowers the prevalences of osseous fragments in fetlock and hock joints, of deforming arthropathy in hock joints and of pathologic changes in navicular bones by 0.5-6.9%. But the prevalence of osseous fragments in fetlock joints is not lowered consistently until TIR is weighted with 30-60% when calculating the total index used for the selection of sires. Applying the selection schemes DJR_{A3} or DJR_{B6} for all-purpose breeding, DR_{A4} or DR_{B5} for breeding focused on dressage, and JR_{A5} or JR_{B5} for breeding focused on show-jumping, both, relative breeding values in the stallions and the prevalences of radiographic findings are improved simultaneously. If additional weight is given to the total index radiographic findings, this total index (TIR_A and TIR_B, respectively) as well as the individual relative breeding values for radiographic findings (RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) were further increased in the probands' sires and the prevalences of radiographic findings (OFF, OFH, DAH, PCN) were further decreased in the probands. The simultaneous consideration of OFF, OFH, DAH and PCN permitted a maximum increase of relative breeding values of between 6 and 14% and a maximum decrease of prevalences of between 13.5 and 27.4%.

When comparing the selection schemes A and B, the former appears to be favorable. The decrease of the prevalences of radiographic findings will be more distinct when giving equal weight to the investigated radiographic findings (OFF, OFH, DAH, PCN), i.e., choosing selection scheme A. At the same time, more sires pass this mode of selection, namely 55% of all-purpose stallions, 66% of dressage stallions and 46% of jumping stallions, corresponding to 59%, 65% and 44% of our probands.

4. Discussion

The objective of this study was to investigate the feasibility of selection schemes that simultaneously account for the health of the equine skeleton and for performance traits. For this purpose we predicted breeding values for different radiographic findings in the limbs of Hanoverian Warmblood horses and accounted for the officially published relative breeding values predicted on the basis of performance data.

We chose four different types of radiographic findings for this study: Osseous fragments in fetlock (OFF) and in hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN). These were found to be the most prevalent radiographic findings in the population of performance selected young Warmblood riding horses we based our study on (Stock and Distl, 2004). The high proportion of affected horses (individual radiographic findings in 9.1-24.7% of the probands; 13.5% of the probands multiply affected) and the potential of radiographically detectable alterations to compromise the horses' performance at least in the long term justifies to look for alternatives to therapeutic measures.

In spite of binary coding, we used mixed linear animal models for the estimation of genetic parameters and the prediction of breeding values. Animal models should be preferred to sire models since the later imply random mating and unrelated sires, i.e., assumptions that do usually not hold in horse breeding. However, some authors considered animal threshold models to be improper for the analyses of categorical data (Hoeschele and Tier, 1995; Moreno et al., 1997). Alternatively, estimates based on observed discrete categories can be transformed to estimates referring to the underlying liability scale according to Dempster and Lerner (1950). This was found to reliably account for nonlinearity of the data in many cases (Mäntysaari et al., 1991). In a preliminary simulation study we could verify the applicability of the Dempster-Lerner transformation factors to our data (Stock et al., 2004a).

Concerning the prediction of breeding values, there is no clear advantage of the use of threshold models over the use of linear models; the ranking of the sires remains largely the same (Meijering and Gianola, 1985; Jensen, 1986; Djemali et al., 1987; Weller et a., 1988). Accordingly, in this study breeding values were predicted on the basis of multivariate mixed linear model (co)variance estimates.

Several studies have been performed in different horse populations about the prediction of breeding values for performance parameters (e.g., Bruns, 1981; Meinardus and Bruns, 1989; Kühl, 1991; Kühl et al., 1994; Christmann, 1996; Schade, 1996; Von Velsen-Zerweck, 1998). In these studies as in preceding investigations, very different estimates were obtained for the additive genetic correlations between dressage ability (or related parameters such as gaits and rideability) and jumping ability, ranging from moderately negative to moderately positive (r_g = -0.58 to 0.54; Bruns and Bade, 1984; Meinardus and Bruns, 1989; Kühl, 1991; Uphaus, 1993; Kühl et al., 1994; Ohlsson et al., 1994; Willms et al., 1999b; Bösch et al., 2000; Olsson et al., 2000). In the stallions having sired at least three of our probands we found no significant correlation between the total indices dressage and jumping.

There are few reports on the prediction of breeding values for orthopedic health traits in the horse (Grøndahl and Dolvik, 1993). Nevertheless, given the moderately heritable character of the investigated radiographic findings (h^2 = 0.15-0.41; Stock and Distl, 2004), they could be reasonably considered in equine breeding programs.

The ranges of the RBV we predicted for the investigated radiographic findings were the same in the whole four generation pedigree and in the probands' sires. Furthermore, there were only minor differences between their respective mean RBV (Δ (RBV_{ped} - RBV_{sires}) $\leq$ 3.68). Accordingly, the 368 sires with three or more offspring among our probands might represent a representative sample of the current population of Hanoverian Warmblood horses. On the contrary, the RBV showed somewhat less variation in our probands (e.g., $RBV_{OFF\ ped/sires}$ min. -10, max. 185 vs. $RBV_{OFF\ prob}$ min. 5, max. 162). The respective mean RBV differed by maximally only less than one fourth of a standard deviation from the mean RBV of the four generation pedigree (Δ (RBV_{ped} – $RBV_{probands}$) $\leq$ 4.62). Nevertheless, except for osseous fragments in fetlock joints, the mode of the RBV in the probands was markedly different from that in the four generation pedigree. This distribution of RBV being somewhat skewed to the right, might be the result of the selection of the probands that took place on the basis of their performance as riding horses prior to auction. Though there is some controversy about the effect of radiographic abnormalities on the performance of (young) horses (Brehm and Staecker, 2000; Grøndahl and Engeland, 1995; Storgaard Jørgensen et al., 1997), horses without osseous fragments and deforming arthropathy in hock joints, and without pathologic changes in navicular bones might have been more likely to perform well than those with the respective radiographic findings.

The correlations between the relative breeding values for radiographic findings were in accordance with the estimated additive genetic correlations between the respective radiographic findings (Stock and Distl, 2004). The positive correlation between osseous fragments in fetlock joints and deforming arthropathy in hock joints (r_a = 0.23 ± 0.13) facilitates the concurrent improvement of these traits. On the contrary, the negative correlations between osseous fragments in fetlock and in hock joints (r_a = -0.19 ± 0.12) and between osseous fragments in hock joints and deforming arthropathy in hock joints (r_a = -0.14 ± 0.13) interfere with the simultaneous consideration of these traits. Pathologic changes in navicular bones appeared to be genetically independent of osseous fragments in fetlock and hock joints and of deforming arthropathy in hock joints (r_a = -0.09 to -0.11 with SE = 0.09-0.10). Grøndahl and Dolvik (1993) found no significant correlation between the breeding values predicted for bony fragments in the palmar/plantar portion of the metacarpo- and metatarsophalangeal joints and for osteochondrosis in the tibiotarsal joints, and concluded a varying genetic background of these conditions. However, the later used the results of a radiographic examination of a considerably smaller number of Norwegian trotters (n = 644) what might have caused a detrimental low accuracy of the heritability estimates as well as of the predicted breeding values.

There are no reports on the correlations between relative breeding values predicted for orthopaedic health traits and for performance parameters. We observed a significantly negative correlation between RBV_{PCN} and the total index jumping, and a trend towards a negative correlation between RBV_{PCN} and the total index dressage. Accordingly, desirable breeding values for jumping and to a lesser extent for dressage seem to coincide with undesirable breeding values for pathologic changes in navicular bones, and vice versa. However, the low correlation coefficients we found (r = -0.16 and r = -0.10, respectively) will not relevantly interfere with the simultaneous selection on and the concurrent improvement of these traits.

With a view to the overall genetic value of a sire, health traits as well as performance parameters should be considered. Accordingly, we concurrently took into account the RBV predicted for different radiographic findings and the official total indices dressage and/or jumping. Assuming breeding values in the range of one standard deviation to be acceptable and larger breeding values to be eligible for stallions selected for breeding, 34% of the dressage stallions, 26% of the jumping stallions, and still 23% of the all-purpose stallions were found to be selectable.

The calculation of total indices that take into account the radiological status of the horse as well as its performance in dressage and/or show-jumping should permit the comparison of different selection schemes. When deriving total indices radiographic findings, equal or differential weight can be given to the individual radiographic findings. Weighting factors should relate to the importance of the respective traits. However, the only studies on long-term effects of radiological alterations in equine limbs refer to racehorses (e.g., Brehm and Staecker, 2000; Grøndahl and Engeland, 1995; Storgaard Jørgensen et al., 1997). Similar investigations in Warmblood riding horses seem to be entirely missing. Therefore, we chose equal weighting of the individual radiographic findings for one selection scheme (A), and adopted weighting factors of one (OFF), two (OFH, DAH) and three (PCN) for an alternative selection scheme (B). This was based on their presumed clinical relevance and curability (e.g., Ackermann et al., 1977; McIlwraith and Vachon, 1988; Hertsch, 1990; Möller, 1993; Grøndahl and Engeland, 1995; Storgaard Jørgensen et al., 1997; Jaugstetter et al., 2003). However, further studies should be performed to establish the ranking of the clinical relevance of the investigated radiographic findings. The derived economic weights could then be introduced in the prediction of breeding values.

Based on the assumption that the breeder aims to improve and not just to stabilize the relevant traits, only stallions with above-average total indices were considered further. The exclusion of stallions with considerably small relative breeding values (≤ 40) in combination with the selection on above-average performance based total indices (DJR_0, DR_0, JR_0) increased both, health and performance related breeding values. However, with a view to the noticeably phenotypic improvement we found that radiographic findings had to be weighted with at least 30-60% in the calculation of total indices when compared with the performance parameters presently considered. As expected from a population genetic point of view, the applied mode of differential weighting turned out to be less suitable to achieve a positive response to selection than equal weighting. The later accounts for the data structure and the different level of heritability and therefore maximizes the response of selection. Consequently, selection scheme A, giving equal weight to the investigated radiographic findings, should be preferred until their relative weights are ascertained scientifically for the Warmblood riding horse. After all, the weight given to radiographic findings depends on the breeding progress in relevant performance and orthopedic health traits that is aspired for the particular horse breed.

The prediction of relative breeding values for individual orthopedic health traits makes it possible to place emphasis on particular radiographic findings, considered to be of primary importance in the respective horse population. For example, with a view to tarsocrural osteochondrosis one might focus on the selection against osseous fragments in hock joints. However, genetic correlations to other relevant radiographic findings and to performance traits have to be considered. The status of deforming arthropathy in hock joints is expected to be improved, the status of osseous fragments in fetlock joints and of pathologic changes in navicular bones is expected to be impaired when selecting solely on the basis of osseous fragments of hock joints.

The selection on the basis of a total index radiographic findings gave maximally 38-71% of the maximum response to selection that could be attained when selecting against only one particular radiographic finding. According to the existing negative genetic correlations (between OFH and OFF, and between OFH and DAH), TIR-based selection was least effective in respect of osseous fragments in hock joints.

Between 46% (show-jumping) and 66% (dressage) of the sires included in our analyses passed selection aiming at an improvement of both, relative breeding values of stallions and prevalences of radiographic findings in their offspring. Applied to breeding practice this intensification of selection means increasing the mares-to-stallions ratio from about 40:1 to 80:1 (currently about 19,000 registered breeding mares and 420-500 approved stallions in the VHW). The extensive and mature use of artificial insemination should provide for breeding progress without detrimental side effects. Therefore, it is obviously not impracticable to concurrently allow for health traits and for performance parameters. Even the all-purpose breeding which is traditionally fixed in the breeding aim of the Hanoverian Warmblood horse appears to be feasible when allowing concomitantly for radiographic findings (55% selected sires).

When applying a higher standard and selecting only sires with total indices of 120 or greater, a proportion of about 6-15% of the stallions could be further used for breeding. However, this strict selection might be applicable only to sires of future sires when aiming to raise the genetic level of the new generation of sires.

It has to be taken into account that the probands of this study and the corresponding sires represent only a part of the population of Hanoverian Warmblood horses pre-selected on the basis of performance parameters. Therefore, it can not be precluded that there is some bias in the distribution of the relative breeding values, and of the total indices dressage and jumping in particular. Furthermore, a multitude of non-genetic parameters influencing the prevalences of radiographic findings have been identified or at least suspected (e.g., McIlwraith and Vachon, 1988; Jeffcott, 1991; Van Weeren and Barneveld, 1999; Van Weeren et al., 1999). Consequently, the maximum improvement of the radiological state will only be attained if some optimization of keeping and management factors (e.g., exercise, nutrition) takes places.

5. Conclusions

The results of the present study indicate that it is possible to simultaneously account for performance parameters and for the radiological status of a horse in the selection of breeding animals. This applies for all-purpose breeding as well as for breeding focused on dressage or show-jumping.

The integrated estimation of breeding values (Von Velsen-Zerweck, 1998) facilitates the inclusion of additional parameters in the multitrait animal model currently used. Accordingly, health data obtained for considerable numbers of horses under standardized conditions should be utilized for the genetic evaluation of sires. The radiographic examination of the equine limbs has become a common feature at riding horse auctions and at stallion performance tests, but could be further implemented in mares performance tests (at least at station). This way sufficient amounts of data would be obtained to predict breeding values for the radiological status of the horses' limbs with satisfactory reliability. Presuming the availability of sufficient data on related horses, breeding values can already be predicted for young horses presented for stud-book inspection or stallion licensing. Therefore, parameters of the health of the equine skeleton could be considered at this early stage of selection of breeding animals, allowing to economize performance testing of stallions and mares.

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Table 1
Additive genetic variances (σ_a^2; on the diagonal) and covariances (cov_a; above the diagonal) for the prevalences of osseous fragments in fetlock (OFF) and hock joints (OFH), of deforming arthropathy in hock joints (DAH), and of pathologic changes in navicular bones (PCN)

Radiographic finding	OFF	OFH	DAH	PCN
OFF	0.135	-0.021	0.025	-0.016
OFH		0.090	-0.012	-0.016
DAH			0.087	-0.002
PCN				0.407

Table 2
Residual variances (σ_e^2; on the diagonal) and covariances (cov_e; above the diagonal) for the prevalences of osseous fragments in fetlock (OFF) and hock joints (OFH), of deforming arthropathy in hock joints (DAH), and of pathologic changes in navicular bones (PCN)

Radiographic finding	OFF	OFH	DAH	PCN
OFF	1.581	0.010	-0.028	-0.014
OFH		0.752	-0.006	0.032
DAH			0.967	0.051
PCN				1.432

Table 3

Ranges of relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), in all horses included in the last four generations of the probands' pedigree, in the probands and in the probands' sires

		Four generation pedigree (n = 23,662)	Probands (n = 5,928)	Probands' sires (n = 368)
RBV_{OFF}	min.	-10	5	-10
	max.	185	162	185
	mean ± SD	99.17 ± 14.43	99.63 ± 20.91	98.39 ± 26.50
RBV_{OFH}	min.	-13	-2	-13
	max.	157	141	157
	mean ± SD	101.24 ± 13.48	100.62 ± 19.11	100.07 ± 23.69
RBV_{DAH}	min.	8	18	8
	max.	185	161	185
	mean ± SD	97.13 ± 15.31	101.75 ± 20.11	100.81 ± 25.77
RBV_{PCN}	min.	14	30	14
	max.	157	146	157
	mean ± SD	100.74 ± 14.85	98.76 ± 21.48	97.44 ± 26.66

Table 4

Correlations between the official relative breeding values for dressage (total index dressage, TID) and show-jumping (total index jumping, TIJ) and the relative breeding values predicted for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

	TID	TIJ	RBV_{OFF}	RBV_{OFH}	RBV_{DAH}	RBV_{PCN}
TID	1.000	-0.063	0.079	-0.006	0.048	-0.095 $^{+}$
TIJ		1.000	-0.026	0.030	-0.025	-0.160 **
RBV_{OFF}			1.000	-0.228 ***	0.175 ***	-0.060
RBV_{OFH}				1.000	-0.242 ***	-0.019
RBV_{DAH}					1.000	-0.052
RBV_{PCN}						1.000

Levels of significance:

*** : $P < 0.001$; ** : $P < 0.01$; * : $P < 0.05$; + : $P < 0.10$

Table 5

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_A) in conjunction with the total indices dressage (TID) and jumping (TIJ), and giving equal weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	DJR_{A0}	DJR_{A1}	DJR_{A2}	DJR_{A3}	DJR_{A4}	DJR_{A5}	DJR_{A6}	DJR_{A7}	DJR_{A8}	DJR_{A9}	DJR_{A10}
Number of sires (%)		**358 (100)**	330 (92.2)	202 (56.4)	201 (56.2)	201 (56.2)	196 (54.8)	195 (54.5)	198 (55.3)	199 (55.6)	187 (52.2)	185 (51.7)	178 (49.7)	174 (48.6)
Relative breeding values (mean)	TID	**110**	110	**118**	118	118	118	118	117	115	114	113	112	110
	TIJ	**98**	97	**105**	105	105	105	105	104	103	100	99	96	94
	TIR_A	**99**	**100**	100	101	101	102	103	104	105	106	107	108	108
	RBV_{OFF}	**98**	**99**	99	99	100	101	102	103	105	107	108	108	108
	RBV_{OFH}	**100**	**101**	101	101	102	102	102	103	103	103	103	104	104
	RBV_{DAH}	**101**	**102**	103	103	104	104	105	105	107	109	110	110	112
	RBV_{PCN}	**97**	**100**	98	98	99	100	101	102	104	107	107	108	108
Number of probands (%)		**5565 (100)**	4748 (85.3)	3510 (63.1)	3505 (63.0)	3500 (62.9)	3453 (62.0)	3471 (62.4)	3494 (62.8)	3419 (61.4)	3145 (56.5)	3070 (55.2)	3002 (53.9)	2806 (50.4)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.6	21.5	21.2	**20.7**	20.1	19.8	19.3	19.0	18.5	18.3	18.0
	OFH	**9.1**	**8.9**	8.6	8.5	8.5	8.3	8.2	8.2	8.0	7.5	7.3	7.2	7.1
	DAH	**11.9**	**11.5**	11.3	11.3	11.1	11.0	10.7	10.5	10.0	9.6	9.4	9.2	8.5
	PCN	**24.7**	**23.0**	23.9	23.7	23.6	23.3	23.2	22.9	22.2	20.7	20.5	19.9	19.8

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$DJR_{Aw} = w/10 * TIR_A + (1 - w/10) * (0.6 * TID + 0.4 * TIJ)$

with w = 0-10 and $TIR_A = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$

Table 6

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_B) in conjunction with the total indices dressage (TID) and jumping (TIJ), and giving differential weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	DJR_{B0}	DJR_{B1}	DJR_{B2}	DJR_{B3}	DJR_{B4}	DJR_{B5}	DJR_{B6}	DJR_{B7}	DJR_{B8}	DJR_{B9}	DJR_{B10}
Number of sires (%)		**358 (100)**	330 (92.2)	191 (53.4)	188 (52.5)	190 (53.1)	193 (53.9)	192 (53.6)	195 (54.5)	188 (52.5)	196 (54.8)	191 (53.4)	191 (53.4)	194 (54.2)
Relative breeding values (mean)	TID	**110**	110	**118**	118	118	118	117	116	115	113	112	110	109
	TIJ	**98**	97	**105**	105	105	104	104	103	101	99	97	96	95
	TIR_B	**99**	**100**	101	102	102	104	104	106	107	108	108	109	109
	RBV_{OFF}	**98**	**99**	98	98	98	99	100	100	101	101	101	100	100
	RBV_{OFH}	**100**	**101**	107	108	108	109	110	111	112	111	112	112	106
	RBV_{DAH}	**101**	**102**	107	108	108	109	110	111	112	111	112	112	112
	RBV_{PCN}	**97**	**100**	97	99	99	101	103	105	108	109	110	111	111
Number of probands (%)		**5565 (100)**	4748 (85.3)	3353 (60.3)	3296 (59.2)	3311 (59.5)	3376 (60.7)	3349 (60.2)	3332 (59.9)	3172 (57.0)	3193 (57.4)	3089 (55.5)	3049 (54.8)	3044 (54.7)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.7	21.7	21.6	21.2	21.1	20.9	**20.7**	20.7	20.6	20.5	20.4
	OFH	**9.1**	**8.9**	9.0	8.9	8.8	8.7	8.3	8.2	8.0	7.4	7.4	7.2	7.2
	DAH	**11.9**	**11.5**	10.9	10.9	10.8	10.8	10.4	10.3	10.2	9.9	9.8	9.8	9.8
	PCN	**24.7**	**23.0**	23.7	23.5	23.4	23.2	22.2	21.4	20.9	19.6	19.0	18.6	18.2

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$DJR_{Bw} = w/10 * TIR_B + (1 - w/10) * (0.6 * TID + 0.4 * TIJ)$

with w = 0-10 and $TIR_B = (RBV_{OFF} + 2*RBV_{OFH} + 2*RBV_{DAH} + 3*RBV_{PCN}) / 8$

Table 7

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_A) in conjunction with the total index dressage (TID), and giving equal weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	DR_{A0}	DR_{A1}	DR_{A2}	DR_{A3}	DR_{A4}	DR_{A5}	DR_{A6}	DR_{A7}	DR_{A8}	DR_{A9}	DR_{A10}
Number of sires (%)		**358 (100)**	330 (92.2)	231 (64.5)	231 (64.5)	232 (64.8)	232 (64.8)	237 (66.2)	229 (64.0)	216 (60.3)	218 (60.9)	204 (57.0)	192 (53.6)	174 (48.6)
Relative breeding values (mean)	TID	**110**	110	**120**	120	119	119	119	119	118	116	115	113	110
	TIJ	**98**	97	98	98	98	97	97	97	96	96	96	95	94
	TIR_A	**99**	**100**	100	100	101	101	102	103	104	105	106	107	108
	RBV_{OFF}	**98**	**99**	99	100	100	101	102	103	105	105	107	108	108
	RBV_{OFH}	**100**	**101**	100	100	101	101	101	101	102	103	103	104	104
	RBV_{DAH}	**101**	**102**	101	102	103	103	103	104	106	107	109	109	112
	RBV_{PCN}	**97**	**100**	99	99	99	99	100	102	103	105	106	107	108
Number of probands (%)		**5565 (100)**	4748 (85.3)	3775 (67.8)	3780 (67.9)	3788 (68.1)	3778 (67.9)	3831 (68.8)	3709 (66.6)	3497 (62.8)	3488 (62.7)	3289 (59.1)	3107 (55.8)	2806 (50.4)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.4	21.2	21.1	20.8	**20.4**	20.3	19.7	19.6	18.9	18.4	18.0
	OFH	**9.1**	**8.9**	9.0	8.9	8.8	8.7	8.7	8.5	8.0	7.8	7.6	7.3	7.1
	DAH	**11.9**	**11.5**	11.7	11.6	11.5	11.5	11.3	11.1	10.6	10.3	9.6	9.2	8.5
	PCN	**24.7**	**23.0**	23.6	23.4	23.4	23.4	23.0	22.4	22.1	21.4	20.7	20.1	19.8

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$DR_{Aw} = w/10 * TIR_A + (1 - w/10) * TID$

with w = 0-10 and $TIR_A = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$

Table 8

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_B) in conjunction with the total index dressage (TID), and giving differential weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	DR_{B0}	DR_{B1}	DR_{B2}	DR_{B3}	DR_{B4}	DR_{B5}	DR_{B6}	DR_{B7}	DR_{B8}	DR_{B9}	DR_{B10}
Number of sires (%)		**358 (100)**	330 (92.2)	218 (60.9)	219 (61.2)	220 (61.5)	219 (61.2)	217 (60.6)	214 (59.8)	213 (59.5)	211 (58.9)	208 (58.1)	202 (56.4)	194 (54.2)
Relative breeding values (mean)	TID	**110**	110	**120**	119	119	119	119	118	117	115	114	111	109
	TIJ	**98**	97	98	97	97	98	97	96	96	95	95	95	95
	TIR_B	**99**	**100**	101	101	102	102	104	105	105	107	107	108	109
	RBV_{OFF}	**98**	**99**	99	100	100	100	100	101	101	101	101	100	100
	RBV_{OFH}	**100**	**101**	101	101	101	102	103	103	104	104	105	106	106
	RBV_{DAH}	**101**	**102**	105	106	106	107	108	108	109	110	110	111	112
	RBV_{PCN}	**97**	**100**	98	99	99	100	102	104	106	108	109	110	111
Number of probands (%)		**5565 (100)**	4748 (85.3)	3611 (64.9)	3625 (65.1)	3641 (65.4)	3626 (65.2)	3552 (63.8)	3505 (63.0)	3447 (61.9)	3314 (59.6)	3292 (59.2)	3169 (56.9)	3044 (54.7)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.4	21.2	21.1	21.1	20.8	**20.6**	20.6	20.5	20.6	20.4	20.4
	OFH	**9.1**	**8.9**	9.0	8.9	8.8	8.7	8.3	8.2	8.0	7.4	7.4	7.2	7.2
	DAH	**11.9**	**11.5**	10.9	10.9	10.8	10.8	10.4	10.3	10.2	9.9	9.8	9.8	9.8
	PCN	**24.7**	**23.0**	23.7	23.5	23.4	23.2	22.2	21.4	20.9	19.6	19.0	18.6	18.2

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$DR_{Bw} = w/10 * TIR_B + (1 - w/10) * TID$

with w = 0-10 and $TIR_B = (RBV_{OFF} + 2*RBV_{OFH} + 2*RBV_{DAH} + 3*RBV_{PCN}) / 8$

Table 9

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_A) in conjunction with the total index jumping (TIJ), and giving equal weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	JR_{A0}	JR_{A1}	JR_{A2}	JR_{A3}	JR_{A4}	JR_{A5}	JR_{A6}	JR_{A7}	JR_{A8}	JR_{A9}	JR_{A10}
Number of sires (%)		**358 (100)**	330 (92.2)	142 (39.7)	143 (39.9)	145 (40.5)	147 (41.1)	151 (42.2)	163 (45.5)	157 (43.9)	164 (45.8)	162 (45.3)	162 (45.3)	174 (48.6)
Relative breeding values (mean)	TID	**110**	110	109	109	109	109	109	109	109	109	109	110	110
	TIJ	**98**	97	**117**	117	117	116	115	113	112	109	105	99	94
	TIR_A	**99**	**100**	100	100	100	101	102	103	105	106	107	108	108
	RBV_{OFF}	**98**	**99**	97	98	98	98	100	102	104	106	108	108	108
	RBV_{OFH}	**100**	**101**	102	102	102	103	104	104	105	105	104	104	104
	RBV_{DAH}	**101**	**102**	103	103	104	104	105	106	107	107	109	111	112
	RBV_{PCN}	**97**	**100**	97	97	97	98	100	101	104	105	108	109	108
Number of probands (%)		**5565 (100)**	4748 (85.3)	2214 (39.8)	2214 (39.8)	2253 (40.5)	2286 (41.1)	2312 (41.5)	2621 (47.1)	2515 (45.2)	2586 (46.5)	2494 (44.8)	2691 (48.4)	2806 (50.4)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.3	21.0	21.0	20.9	20.9	**19.8**	18.9	18.3	17.8	18.4	18.0
	OFH	**9.1**	**8.9**	9.0	9.0	9.0	8.8	8.4	8.2	8.1	7.8	7.5	7.1	7.1
	DAH	**11.9**	**11.5**	11.7	11.6	11.5	11.0	10.9	10.5	10.3	9.9	9.5	8.8	8.5
	PCN	**24.7**	**23.0**	24.4	24.2	24.2	23.9	23.4	22.5	21.5	21.2	19.8	19.7	19.8

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$JR_{Aw} = w/10 * TIR_A + (1 - w/10) * TIJ$

with w = 0-10 and $TIR_A = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$

Table 10

Response to selection in dependence of relative weights (w) for the total index radiographic findings (TIR_B) in conjunction with the total index jumping (TIJ), and giving differential weight to the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	**Sel. > 40**	JR_{B0}	JR_{B1}	JR_{B2}	JR_{B3}	JR_{B4}	JR_{B5}	JR_{B6}	JR_{B7}	JR_{B8}	JR_{B9}	JR_{B10}
Number of sires (%)		**358 (100)**	330 (92.2)	134 (37.4)	135 (37.7)	136 (38.0)	140 (39.1)	143 (39.9)	152 (42.5)	161 (45.0)	166 (46.4)	170 (47.5)	177 (49.4)	194 (54.2)
Relative breeding values (mean)	TID	**110**	110	108	108	108	108	109	108	108	108	109	109	109
	TIJ	**98**	97	**117**	117	117	116	115	113	110	107	103	98	95
	TIR_B	**99**	**100**	101	101	102	103	103	105	106	107	109	109	109
	RBV_{OFF}	**98**	**99**	96	97	97	97	97	99	100	99	101	101	100
	RBV_{OFH}	**100**	**101**	102	102	103	105	105	105	105	106	106	107	106
	RBV_{DAH}	**101**	**102**	108	108	108	108	108	110	110	111	112	112	112
	RBV_{PCN}	**97**	**100**	96	97	98	100	100	103	106	108	110	111	111
Number of probands (%)		**5565 (100)**	4748 (85.3)	2097 (37.7)	2083 (37.4)	2074 (37.3)	2142 (38.5)	2170 (39.0)	2372 (42.6)	2489 (44.7)	2786 (50.1)	2834 (50.9)	2828 (50.8)	3044 (54.7)
Pre-valences (%)	OFF	**20.9**	**20.8**	21.6	21.5	21.5	21.6	21.5	**20.7**	20.0	21.1	20.2	20.1	20.4
	OFH	**9.1**	**8.9**	9.2	9.3	8.9	8.5	8.5	8.2	8.1	7.4	7.2	6.9	7.2
	DAH	**11.9**	**11.5**	10.9	10.8	10.5	10.3	10.2	10.2	10.0	9.8	9.7	9.7	9.8
	PCN	**24.7**	**23.0**	24.6	24.4	23.6	23.4	23.2	22.1	20.4	19.9	18.6	18.4	18.2

No sel. : no selection.

Sel. > 40 : all single relative breeding values (i.e., TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) larger than 40.

$JR_{Bw} = w/10 * TIR_B + (1 - w/10) * TIJ$

with w = 0-10 and $TIR_B = (RBV_{OFF} + 2*RBV_{OFH} + 2*RBV_{DAH} + 3*RBV_{PCN}) / 8$

Figures

Figure 1
Schematic selection diagram

Figure 2
Distribution of relative breeding values for osseous fragments in fetlock joints in all horses included in the last four generations of the probands' pedigree, in the probands and in the probands' sires

Figure 3
Distribution of relative breeding values for osseous fragments in hock joints in all horses included in the last four generations of the probands' pedigree, in the probands and in the probands' sires

Figure 4
Distribution of relative breeding values for deforming arthropathy in hock joints in all horses included in the last four generations of the probands' pedigree, in the probands and in the probands' sires

Figure 5
Distribution of relative breeding values for pathologic changes in navicular bones in all horses included in the last four generations of the probands' pedigree, in the probands and in the probands' sires

Sires of probands (n_s = 358; 100%)

⇒ Relative breeding values (TID, TIJ, $TIR_{A/B}$, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

I.
Pre-selection

⇒ Preclusion of sires of probands with TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, or RBV_{PCN} smaller than 40 (n_{SI})

Pre-selected sires of probands (n_s – n_{SI}; 100(n_s – n_{SI}) / 358 %)

⇒ Relative breeding values (TID, TIJ, $TIR_{A/B}$, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

II.
Selection

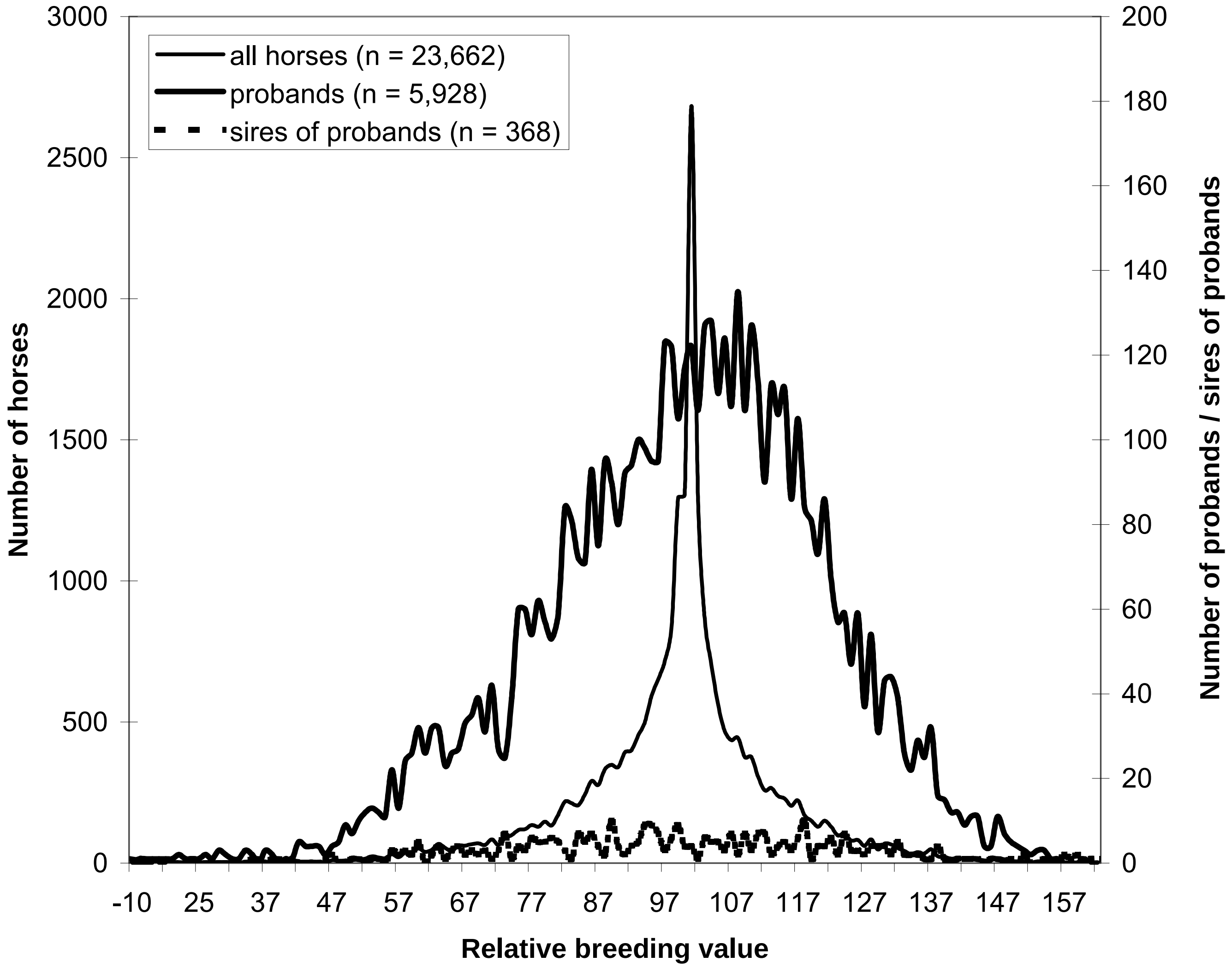
⇒ Preclusion of sires of probands total indices $DJR_{Aw/Bw}$, $DR_{Aw/Bw}$ or $JR_{Aw/Bw}$, respectively, smaller than 100 (n_{SII})

Selected sires of probands (n_s – n_{SII}; 100(n_s – n_{SII}) / 358 %)

⇒ Relative breeding values (TID, TIJ, $TIR_{A/B}$, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

Probands (n_p; 100n_p / 5,565 %), descended from the selected sires of probands

⇒ Prevalences of radiographic findings (OFF, OFH, DAH, PCN)



all horses (n = 23,662)
probands (n = 5,928)
sires of probands (n = 368)
Number of horses
Number of probands / sires of probands
Relative breeding value
3000
2500
2000
1500
1000
500
0
200
180
160
140
120
100
80
60
40
20
0
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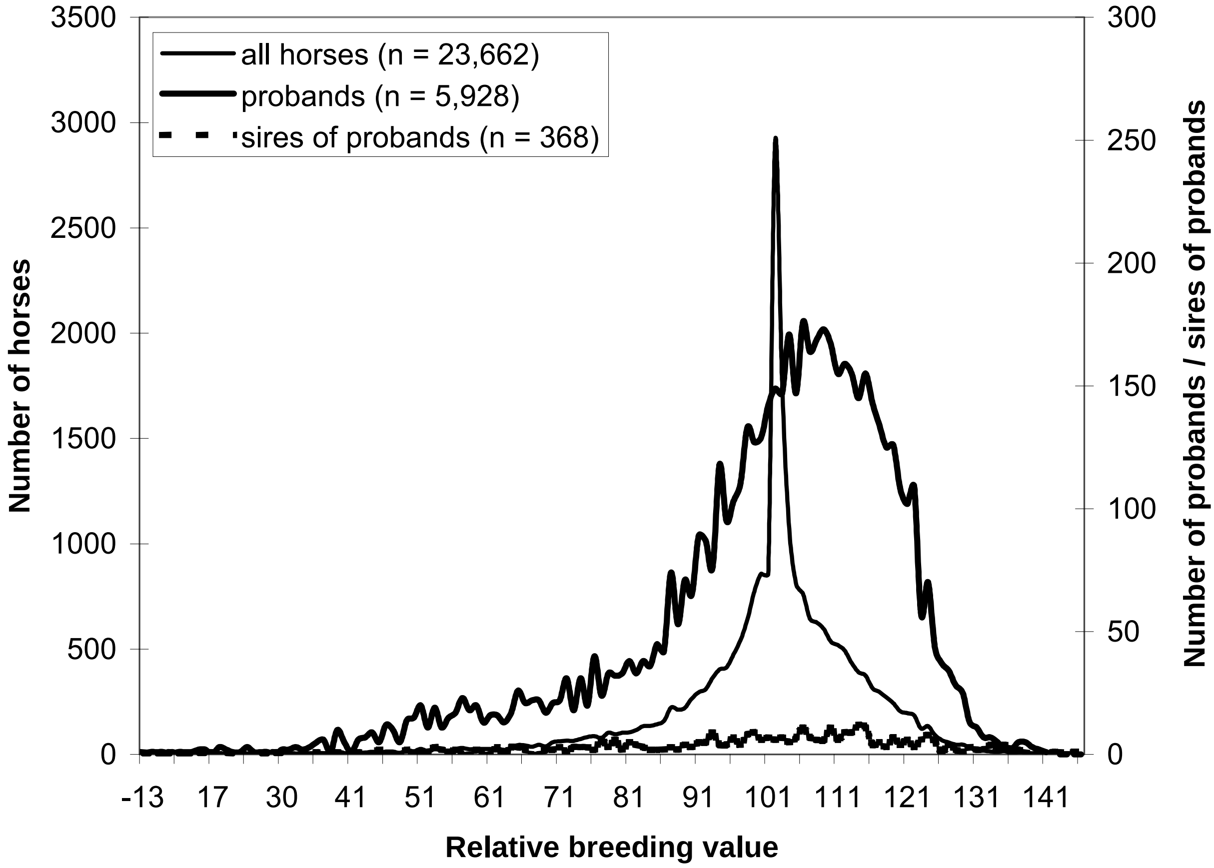

all horses (n = 23,662)
probands (n = 5,928)
sires of probands (n = 368)
Number of horses
Number of probands / sires of probands
Relative breeding value
3500
3000
2500
2000
1500
1000
500
0
300
250
200
150
100
50
0
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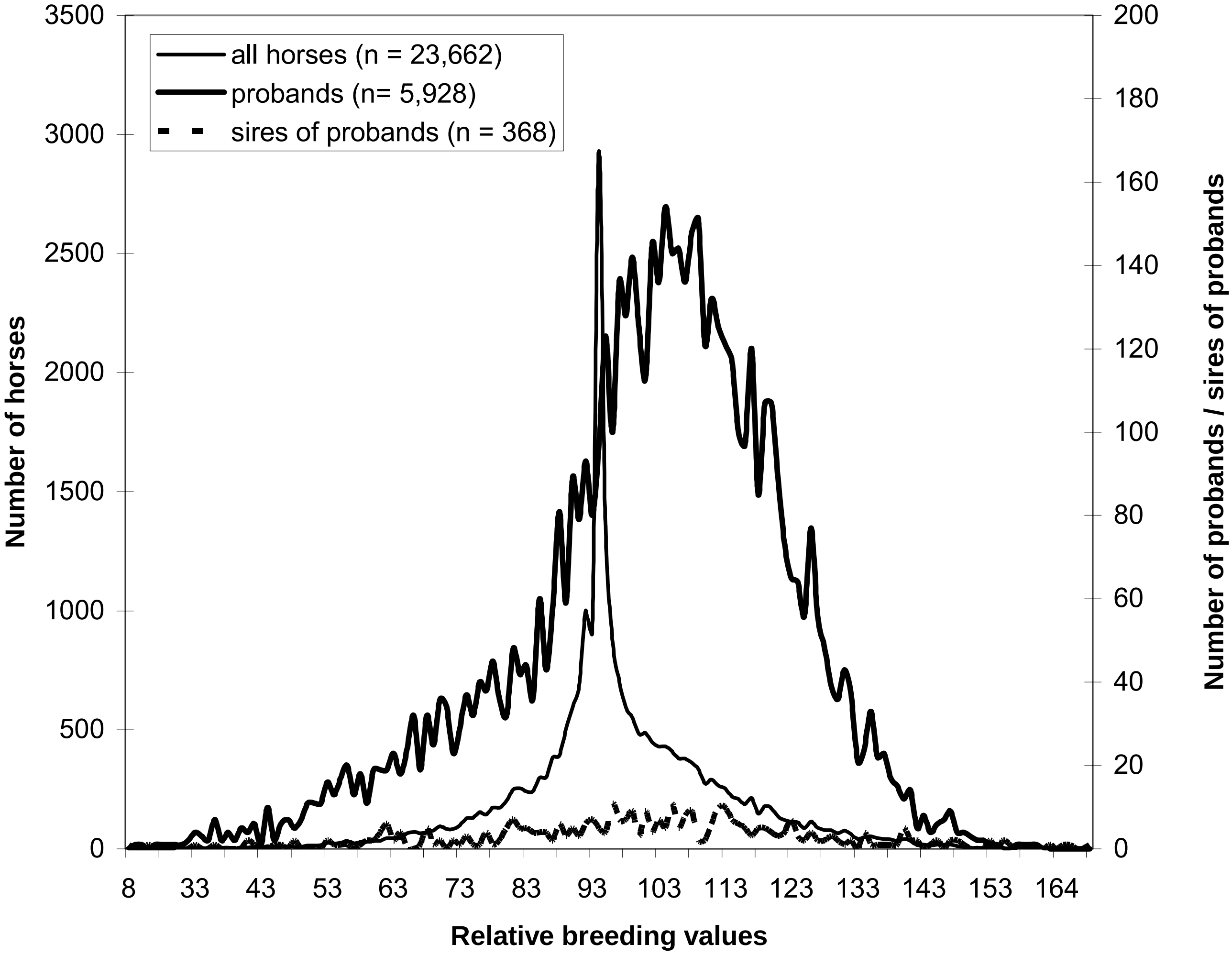

all horses (n = 23,662)
probands (n= 5,928)
sires of probands (n = 368)
Number of horses
Number of probands / sires of probands
Relative breeding values
3500
3000
2500
2000
1500
1000
500
0
200
180
160
140
120
100
80
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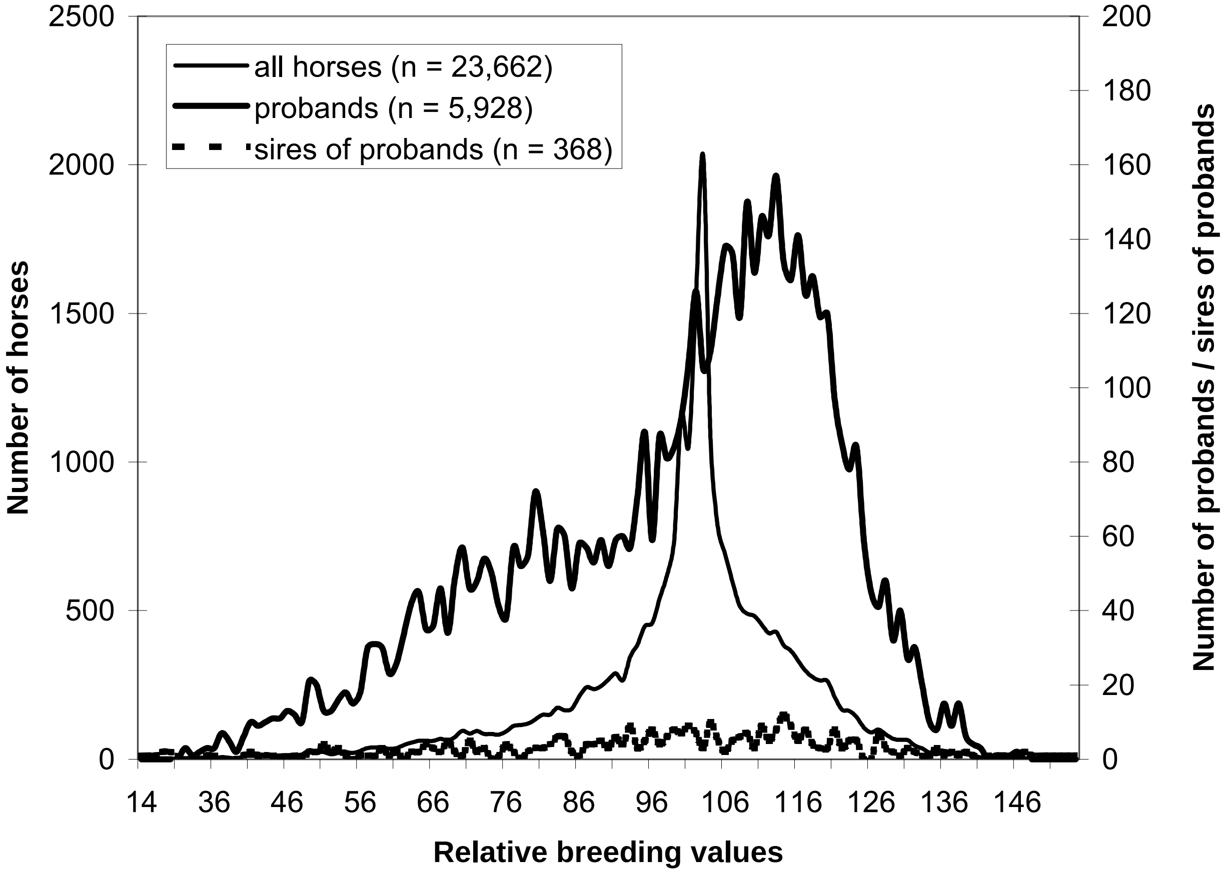
164



all horses (n = 23,662)
probands (n = 5,928)
sires of probands (n = 368)
Number of horses
Number of probands / sires of probands
Relative breeding values
2500
2000
1500
1000
500
0
200
180
160
140
120
100
80
60
40
20
0
14
36
46
56
66
76
86
96
106
116
126
136
146

Expected response to selection when accounting for orthopedic health traits in a population of Warmblood riding horses

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Objective – Verification of the compatibility of selection schemes that account for radiographic findings with breeding progress in performance parameters.

Sample Population – 5,928 radiographically examined Hanoverian Warmblood horses selected for sale at auction (probands)

Procedure – Breeding values were predicted for osseous fragments in fetlock (OFF) and in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN). Relative breeding values (RBV) for radiographic findings were used to derive a total index radiographic findings (TIR). Selection schemes were developed on the basis of the TIR and the published performance-related total indices for dressage (TID) and jumping (TIJ). Response to selection was traced on two generations of horses, separately for dressage, jumping and all-purpose breeding. The development of the mean RBV and the mean total indices in the sires, and of the prevalences of radiographic findings in the probands were used to assess the response to selection.

Results – Giving equal weight to the TIR and the performance-related total index (i.e., TID, TIS or the combined index of 60%TID and 40%TIJ) 43-53% of the paternal grandsires and 70-82% of the descending probands' sires passed selection. In each case, the RBV and the total indices increased by up to 9% in the selected sires when compared to all sires. At the same time, the prevalences of radiographic findings in the probands that descended from the selected sires were relatively lowered by up to 16%. If selection was exclusively based on TID and/or TIJ, the percentages of selected sires were 44-66% in the first and 73-84% in the second generation, and the performance indices increased by 9-10% (TID) and 19-23% (TIJ).

Conclusions – Selection that simultaneously accounts for performance parameters and for radiographic findings appears to be feasible. When compared to exclusively performance-based selection, there were only minor changes in the percentage of selected sires, and the breeding progress in respect of TID and/or TIJ was only slightly diminished. However, the

prevalences of radiographic findings were relevantly lowered in the offspring of TIR-selected sires.

Introduction

The usability and durability of a horse is vitally determined by its health status. In particular, the health of the equine locomotory system is of paramount importance,[7, 12, 18, 20] and the radiological status of the horse is often regarded as an indicator of its performance capacity.[8] Reduced performance and an abated sales value cause economic losses in all sections of the horse industry, as do necessary therapeutic measures, partly combined with unsatisfactory recovery rates. In the long term, effective prophylaxis appears to be the most sustainable approach to this problem. Furthermore, the heritable nature of particular orthopedic diseases has been documented in several studies.[1, 6, 9, 10, 11, 15, 16, 17, 21, 22] Therefore, parameters that reflect the health of the equine skeleton should be considered in the selection of breeding animals. The currently used integrated estimation of breeding values[19] only allows for performance parameters, i.e., primarily for dressage and jumping ability of the horse. In a preceding study, the concurrent consideration of orthopedic health traits turned out to be feasible.[14] However, this investigation was restricted to the direct response to selection, i.e., the development of the prevalences of radiographic findings in the offspring of one generation of selected sires. Until now nothing is known about the expected response to selection over more than one generation of horses.

For this reason, we investigated the expected development of performance-related and health-related breeding values as well as the changes in the prevalences of particular radiographic findings in a population of young Warmblood riding horses. Osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints, and pathologic changes in navicular bones were chosen for this study because of their quantitative importance. The main objective of the present paper was to verify if selection schemes that account for radiographic findings are compatible with breeding progress in performance parameters.

Material and Methods

Probands – 5,928 young Hanoverian Warmblood horses were selected for sale at riding horse auctions in 1991-2003 by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. In the course of this, they all underwent a standardized radiological examination, the results of which were used for this study. Of the 5,928 selected horses, 248 were pulled out of the auction for various reasons, whilst 5,680 horses were actually offered for sale. The probands had a mean age of 4.0 ± 0.8 years. The male (stallions and geldings) to female ratio was about 1.7 : 1. Among the probands, osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN) were the most prevalent radiographic findings, occurring in 20.8%, 9.1%, 11.7%, and 24.7% of the probands, respectively.

Pedigree – A unified animal ownership database (Vereinigte Informationssysteme Tierhaltung w.T., VIT) provided the pedigree data. Pedigree informations spanning four generations were considered for our analyses. The resulting pedigree matrix included a total of 23,662 horses. The 5,928 probands were sired by 614 different stallions, each contributing between 1 and 211 horses selected for sale at auction in 1991-2003. The 298 different paternal grandsires were represented by 1-383 probands and by 1-20 sires of probands. 368 sires, descended from 196 different stallions, had three or more offspring among our probands.

Prediction of breeding values – Based on the multivariate estimation of genetic parameters for the prevalences of the above-mentioned radiographic findings, using Residual Maximum Likelihood (REML) with VCE4 Version 4.2.5 (Variance Component Estimation)[5], we predicted breeding values for OFF, OFH, DAH and PCN. The breeding values were standardized on a relative scale with a mean of 100 and a standard deviation of 20, using the 1,981 probands born in 1987-1991 as the reference population. As a result of the transformation, larger relative breeding values (RBV) will mean that horses are less likely to transmit a predisposition for a particular radiographic finding, and horses with lower RBV are considered to transmit a higher disposition for particular radiographic findings.

Data adjustment – Relative breeding values for dressage and show-jumping (total indices dressage, TID, and jumping, TIJ) are annually published in the Annual for Breeding and Sports (Jahrbuch Zucht und Sport, JZS) by the Fédération Equestre Nationale (FN, Deutsche Reiterliche Vereinigung e.V.) in Warendorf, Germany.[3] Stallions are listed in the JZS with TID and/or TIJ if they have at least five offspring active in sports, and the reliability of the respective total index is ≥ 75%. In the JZS 2002, 144 of the 196 paternal grandsires and 358 of the 368 sires of probands with three or more offspring among our probands were listed with TID and/or TIJ. 308 sires of probands and 4,782 probands descended from the JZS-listed paternal grandsires. 301 of these 308 stallions, having sired 4759 of our probands, were themselves listed in the JZS 2002. Therefore, the two generation data set used for the further analyses included 144 paternal grandsires of probands, 301 sires of probands, and 4759 probands.

The 301 probands' sires were represented by 3-211 (mean 15.5) investigated horses. The 144 paternal grandsires were assigned to 3-383 (mean 33.2) probands. 58 of the 144 paternal grandsires with complete breeding value data also appeared as sires of 3-211 (mean 28.6) probands. These 58 stallions were born between 1965 and 1989 (mean 1978), whilst the birth years of all the 144 paternal grandsires ranged between 1954 to 1989 (mean 1974). The birth year range of the 301 sires of probands was 1965 to 1994 (mean 1984).

A total index radiographic findings (TIR) was derived from the RBV predicted for radiographic findings, giving equal weight to RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN}.

$$TIR = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$$

The distributions of the total indices (TID, TIJ, TIR) and of the relative breeding values for radiographic findings in the paternal grandsires (n = 144) and the probands' sires (n = 301) were tested for normality using the Kolmogorov-Smirnov test with the procedure UNIVARIATE of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2003).

The distributions of total indices and of relative breeding values were further investigated separately in the stallions with TID and TIJ, respectively, in the range of one standard deviation (80-120) and outside (below, i.e., < 80, and above, i.e., > 120) the range of one standard deviation.

In order to get an impression of eventual temporal trends in the total indices and the relative breeding values, we classified the paternal grandsires and the sires of probands by their year of birth. Mean values of TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN} were then calculated separately for the different birth year periods.

Since both, the performance and the orthopedic health status of the horse should be considered simultaneously, we combined TIR with TID and/or TIJ to total indices dressage-jumping-radiographic findings (DJR), dressage-radiographic findings (DR) and jumping-radiographic findings (JR). Varying weights of between 0% and 100% were given to TIR as opposed to TID, TIJ, and TID and TIJ, respectively. The calculation of three different total indices should reflect the varying breeding strategies currently pursued. According to Bruns (2000), maximum breeding progress in dressage and jumping ability may be expected weighting dressage and jumping 6 to 4. However, besides the all-purpose breeding which is traditionally fixed in the breeding aim of the Hanoverian Warmblood horse, many breeders focus on only one discipline, i.e., aim at breeding dressage or jumping specialists.

Selection – In a preceding study we tested the feasibility and effectiveness of different selection strategies applied to the probands' sires. For all-purpose, dressage and jumping accentuated breeding, TIR weights of up to 50% were found to be most effective in improving the respective overall status of the population. Accordingly, we chose the selection schemes DJR_{50}, DR_{50} and JR_{50} to investigate the selection response over two generations, and to compare them with the response to selection based on radiographic findings alone (R_{100}).

DJR_{50} = 0.5 * TIR + 0.5 * (0.6 * TID + 0.4 * TIJ)

DR_{50} = 0.5 * TIR + 0.5 * TID

JR_{50} = 0.5 * TIR + 0.5 * TIJ

R_{100} = 1.0 * TIR

The selection schemes were applied to both paternal grandsires and sires of probands. In each case, only those sires with above-average total indices (i.e., $DJR_{50} > 100$, $DR_{50} > 100$, $JR_{50} > 100$, and $R_{100} > 100$, respectively) that had no individual relative breeding values (TID, TIJ; RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN}) smaller than 40 were selected. The expected response to selection was each assessed via the comparison of the lots of the selected sires with the whole group of sires (n = 144 and n = 301, respectively) by their mean relative breeding values. Concerning the probands' sires, further comparison was drawn by the prevalences of the investigated radiographic findings in the offspring of the selected and of all sires (relative changes).

For each of the investigated radiographic findings (OFF, OFH, DAH and PCN), the maximum attainable response to selection was determined by selecting on the basis of the respective radiographic finding only (OFF_{100}, OFH_{100}, DAH_{100}, PCN_{100}). In the first step of selection, all paternal grandsires were selected that had $RBV_{OFF} > 100$, $RBV_{OFH} > 100$, $RBV_{DAH} > 100$ or $RBV_{PCN} > 100$, respectively. In the second step, analogous selection of above-average stallions was put on the remaining sires of probands (descendants from the selected paternal grandsires). The response to selection was assessed by means of the development of relative breeding values in the paternal grandsires as well as in the probands' sires and of the prevalences of radiographic findings in the probands.

For comparison purposes, we evaluated the development of the relative breeding values and of the prevalences of radiographic findings when selecting for performance without accounting for radiographic findings. With regard to dressage, jumping and all-purpose breeding, selection was based on TID and/or TIJ, irrespective of TIR and the relative breeding values for radiographic findings.

D = 1.0 * TID

J = 1.0 * TIJ

DJ = 0.6 * TID + 0.4 * TIJ

Paternal grandsires and probands' sires were selected that had above-average TID, above-average TIJ, and above-average combined TID-TIJ indices, respectively. In order to simulate common and advanced selection, we chose two different selection limits, namely 100 and 120, respectively. In each case, response to selection was studied via the mean relative breeding values and the prevalences of radiographic findings.

A schematic selection diagram compatible with all the applied selection schemes (DJR_{50}, DR_{50}, JR_{50}, R_{100}; OFF_{100}, OFH_{100}, DAH_{100}, PCN_{100}; DJ, D, J with selection limits 100 and 120) is given in Figure 1.

Results

Table 1 shows the distribution of total indices and of relative breeding values in the 144 paternal grandsires and in the 301 sires with complete breeding value data that had at least three offspring among our probands. As a whole, the relative breeding values ranged between 17 and 185 in the paternal grandsires, and between -13 and 185 in the probands' sires. For the most part, there were only minor differences of 0.2-1.9 between the means calculated in the paternal grandsires and in the sires. Concerning TIJ and TIR as well as RBV_{OFH}, RBV_{DAH} and RBV_{PCN}, the mean values in the probands' sires were slightly larger than those in the paternal grandsires. However, despite the higher maximum RBV_{OFF} in the probands' sires, their mean RBV_{OFF} was below that in the paternal grandsires. The largest difference existed regarding TID. Both minimum and maximum of TID were higher in the probands' sires than in the paternal grandsires (TID_s = 71-161 vs. TID_{pgs} = 61-157), and the sires' mean TID exceeded that calculated in the paternal grandsires by 6.1. On the other hand, the lowest relative breeding values for OFH, DAH and PCN were predicted for sires of probands (RBV_{OFHmin} = -13, RBV_{DAHmin} = 8, RBV_{PCNmin} = 14). For TID, TIJ, RBV_{OFF} and RBV_{OFH} the standard deviations were in the range of 20 ± 5.3. For TIR, RBV_{DAH} and RBV_{PCN} the standard deviations differed from 20 by 6.1-8.6.

In the paternal grandsires, the total indices (TID, TIJ, TIR) as well as the RBV_{DAH} were distributed normally (skewness -0.62 to 0.24; $p > 0.05$). In the probands' sires, normal distributions were asserted statistically for TIJ and RBV_{OFF} (skewness 0.004 and 0.038; $p > 0.15$). For the remaining parameters (i.e., $RBV_{OFF,}$ RBV_{OFH} and RBV_{PCN} in the paternal grandsires, and TID, TIR, RBV_{OFH}, RBV_{DAH} and RBV_{PCN} in the probands' sires) the null hypotheses of normal distributions were rejected (skewness -1.06 to 0.32; $p < 0.05$).

The increase of the mean TID in the stallions with TID below, inside and above the range of one standard deviation was accompanied by a lower decrease in mean TIJ (Table 2). At the same time, there was no clear trend in mean TIR, RBV_{OFF}, RBV_{OFH} and RBV_{DAH}. But with increasing TID mean RBV_{PCN} considerably decreased in the paternal grandsires as well as in the probands' sires. Paternal grandsires with TIJ below, inside and above the range of one standard deviation did not differ in their mean TID, as opposed to the probands' sires. In the later, the considerable increase in mean TIJ paralleled with a minor decrease in mean TID. In both, paternal grandsires and sires of probands, there was a clear trend towards a decreasing RBV_{PCN} with increasing mean TIJ. Furthermore, stallions with higher TIJ tended to have slightly lower mean TIR. No consistent trend could be derived for RBV_{OFF}, RBV_{OFH} and RBV_{DAH} in dependence on TIJ.

Table 3 shows the mean total indices and relative breeding values, calculated for the paternal grandsires and the sires of probands classified by their years of birth. Over the years, there was an almost continuous increase in both performance-related total indices, i.e., in mean TID (+ 24.5-25.2%) and in mean TIJ (+ 15.0-24.2%). Contrarily, there were only minor undirected fluctuations in TIR, RBV_{OFF}, RBV_{OFH} and RBV_{DAH}. However, RBV_{PCN} tended to decrease by-and-by (- 4.1-14.4%)

Selecting on the basis of only one radiographic finding each, the relative breeding values for OFF, OFH, DAH and PCN were increased in the paternal grandsires by 16.0%, 15.2%, 21.0% and 24.5%, respectively (Table 4). Between 46.5% and 57.6% of the paternal grandsires had above-average RBV for the particular radiographic findings, having sired 43.9-61.8% of the probands' sires. Further analogous selection in the probands' sires descending from the selected paternal grandsires raised their RBV by 18.2-27.4%. In this second step of selection, more than 70% of the sires were kept. In the descending probands, the prevalences of OFF, OFH, DAH and PCN were lowered relatively by 32.9%, 54.7%, 42.9% and 47.1%, respectively. This was considered to be the maximum attainable response to selection in respect of the investigated radiographic findings.

The expected response to selection when applying different selection schemes is depicted in Table 5. If all those paternal grandsires and sires of probands were kept that had no single relative breeding value of 40 or less, only 9.0% and 5.3% of the stallions were excluded, respectively. Consequently, there were mostly only minor changes of up to ± 2% in the mean relative breeding values calculated in the selected paternal grandsires and the selected sires of probands. At the same time, the relative changes in the prevalences of radiographic findings were negligibly small (± 3%). The most obvious change was seen in respect of PCN, with an increase of RBV_{PCN} of about 4% and a relative decrease of the prevalence of PCN in the probands of almost 8%.

45.8% of the paternal grandsires and 69.2% of the remaining sires of probands passed selection on the basis of the total index radiographic findings (R_{100}). The relative breeding values predicted for radiographic findings (TIR; RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN}) were raised by 4.0-14.7%. Concomitantly, TID and TIJ were only marginally impaired (- 0.9 to - 4.1%) or even slightly increased (TID in the probands' sires; + 2.6%). The prevalences of radiographic findings in the probands declined relatively by 17.9-31.1%, corresponding to 28.6-72.5% of the maximally attainable response to selection.

The application of selection scheme DJR_{50} resulted in an increase of the relative breeding values in the selected paternal grandsires and the selected sires of probands by 3.0-9.2% and 4.0-9.1%, respectively. Concurrently, the prevalences of OFH, DAH and PCN in the probands were lowered relatively by 2.7-15.8%, and the prevalence of OFF remained constant. Whilst only 45.8% of the paternal grandsires passed this mode of selection, 72.8% of the descending sires of probands could be selected.

When focusing on dressage or show-jumping, i.e., applying selection schemes DR_{50} and JR_{50}, respectively, the increase of mean relative breeding values for radiographic findings was in the range of 1.0-7.4% in the selected paternal grandsires and 0.0-6.3% in the selected probands' sires. The considered performance related total indices increased by 8.0-8.5% (TID in DR_{50}) and 16.3-18.2% (TIJ in JR_{50}), respectively. The unconsidered total indices, i.e., TIJ in DR_{50} and TID in JR_{50}, remained unchanged in the paternal grandsires and declined only slightly in the probands' sires. The prevalences of radiographic findings in the probands were lowered relatively by 0.5-9.2% under DR_{50} and by 0.4-10.5% under JR_{50}. In the paternal grandsires as in the probands' sires, the percentage of selected dressage stallions was higher than that of selected jumping stallions (52.8% vs. 43.1% and 82.4% vs. 70.0%, respectively).

As measured by the prevalences of radiographic findings, 0.0-29.4%, 1.5-21.4% and 0.8-19.2% of the maximum attainable response to selection was achieved with the selection schemes DJR_{50}, DR_{50} and JR_{50}.

Table 6 shows the response to selection on the basis of performance parameters irrespective of the horses' radiological status with a selection limit of 100. Concerning all-purpose breeding, 54.9% of the paternal grandsires and 81.1% of the descending sires of probands had combined TID-TIJ indices of 100 or larger. In the selected sires, TID and TIJ were increased by 8.0-10.1%. When focusing on dressage, the percentages of selected paternal grandsires and of selected sires of probands were 66.0% and 83.7%. Considerable lower percentages of stallions were selected when focusing on show-jumping (44.4% of the paternal grandsires, and 73.4% of the probands' sires). With a selection limit of 100, the maximum attainable increase in the total indices was 8.5% and 9.8% for TID (selection scheme D), and 19.4% and 23.2% for TIJ (selection scheme J) in the paternal grandsires and the sires of probands, respectively. At the same time, TIR as well as RBV_{OFH} and RBV_{DAH} remained almost constant (± 2.0%, except for RBV_{OFH} in the probands' sires which increased by 4.0%). But there was a decline of RBV_{OFF} and RBV_{PCN} of up to 7.4%. Similarly, the prevalences of OFH and DAH approximately leveled off (relative changes of ± 0.8-2.5%), whilst the prevalences of OFF and PCN increased relatively by 1.9-14.8%.

Table 7 shows the expected response to advanced performance based selection (selection limit of 120). Only 10.4-20.1% of the paternal grandsires had TID, TIJ or combined TID-TIJ indices of 120 or larger. However, this applied to 51.9-60.7% of the probands' sires that descended from the selected paternal grandsires. Under selection scheme DJ, TID and TIJ were increased in the selected sires by 22.3-22.6% and 14.1-22.4%, respectively. With dressage-accentuated selection (selection scheme D), the maximum attainable increase in TID was found to reach 23.3-23.6% when a selection limit of 120 was used. Among the show-jumping selected stallions (i.e., under selection scheme J), mean TIJ increased by even 35.4-36.7%. Performance-based selection resulted in changes of TIR, RBV_{OFF} and RBV_{DAH} by ≤ 7.1% in the selected paternal grandsires as well as in the selected probands' sires. With only one exception (paternal grandsires under selection scheme DJ: increase by 10.1%), this also applied to RBV_{OFH}. However, at the same time RBV_{PCN} decreased by up to 17.0% in the selected paternal grandsires and remained constant (selection scheme D) or decreased (1.1-13.7%) in the selected probands' sires. When selection accounted for the horse's dressage ability (selection schemes DJ and D), there were only minor relative changes (± 2.1-7.1%) of the prevalences of radiographic findings in the descending probands. Contrarily, selection for show-jumping resulted in considerable prevalence variations. The prevalences of OFH, DAH and PCN increased relatively by 12.8-40.5%, whilst the prevalence of OFF decreased relatively by 23.1%.

Discussion

The aim of this study was to investigate the expected response to selection in a Warmblood riding horse population when accounting for orthopedic health traits in combination with performance traits. Selection was based on the breeding values we predicted for radiographic findings in the equine limbs and on the officially published performance-related relative breeding values. Different selection schemes were applied to consecutive generations of sires in order to assess the development of the response to selection.

Osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in navicular bones were found to be the four most prevalent radiographic findings in the investigated population of young Warmblood riding horses selected for sale at auction. Prevalences of individual radiographic findings of up to 25% were observed, with almost every seventh horse being multiply affected. In a preceding study we could demonstrate the heritable character of these radiographic findings with heritability estimates ranging between $h^2 = 0.15$ and $h^2 = 0.46$.[13] Therefore, the development and application of specific breeding strategies appeared to be the most effective way to lower the prevalences of radiographic findings in the considered horse population.

In the data set we used for our analyses there was a significant number of stallions with total indices of more than one standard deviation below the mean. In 6.3% of the paternal grandsires and in 3.3% of the probands' sires TID was smaller than 80. TIJ was smaller than 80 in 20.0% and 21.2%, and smaller than 60 in 2.2% and 3.1% of the paternal grandsires and the probands' sires, respectively. In this connection, one has to take into account that all stallions born in 1986-1990 were used as reference population for the standardization of the officially published relative breeding values. The paternal grandsires that were considered in this study were born between 1954 and 1989, the probands' sires between 1965 and 1994. Only 11 of the 144 paternal grandsires (7.6%), but 102 of the 301 probands' sires (33.9%) fell in the reference period. The exclusively performance-based selection using selection schemes D, J and DJ with a selection limit of 100 yielded figures of 44-66% of the paternal grandsires (and 73-84% of the descending sires of probands) passing selection. Referring to all sires of probands, 46-72% of them had TID, TIJ or combined TID-TIJ indices of 100 or larger. This means that the percentage of stallions with above-average performance-related total indices was only slightly higher in the probands' sires than in the paternal grandsires despite the noticeably different mean years of birth (1974 vs. 1984) and the positive temporal trend in the performance parameters we found. These results indicate that the breeders of the Hanoverian Warmblood horse did not tap the full potential of selection based on the officially published breeding values (JZS)[3], and did it more recently less than in former times. They continue to use also stallions with presumably low genetic merit in respect of show-jumping or, to a minor degree, of dressage.

The 1,981 probands born in 1987-1991 were used as the reference population for the standardization of breeding values for radiographic findings. Accordingly, the overlap with the years of birth of the paternal grandsires and of the probands' sires was even smaller (7 of the 144 paternal grandsires (4.9%) and 95 of the 301 sires of probands (31.6%) born in 1987-1991). This resulted in standard deviations partly deviating from 20 by up to 8. Nevertheless, given the limited data we desisted from re-standardization that might be advisable for larger data sets.

There were no sires with both, TID and TIJ, smaller than 80 simultaneously, neither among the paternal grandsires nor among the sires of probands. This might reflect the common specialization in horse industry. A good dressage stallion needs not to be a good show-jumper. Similarly, the dressage ability of a high-quality jumping stallion is of secondary importance.

With regard to selection of sires of future sires, we raised the selection limit for performance-related total indices to 120. This way, eventual negative side effects of advanced selection for dressage and/or show-jumping ability should be checked. It became apparent that better performing stallions were more likely to transmit the disposition to show pathologic changes in the navicular bones. This is in agreement with the negative correlation we determined between the performance-based total indices and the relative breeding value for pathologic changes in navicular bones.[14] It further corresponds to the pattern of mean relative breeding values calculated for the stallions of TID- and TIJ-classes. Despite the otherwise only marginally changed relative breeding values for radiographic findings after intensified selection for show-jumping, their prevalences in the probands descended from the jumping-selected sires changed remarkably. Solely osseous fragments in fetlock joints were detected less often in these probands. The prevalences of the remainder of the investigated radiographic findings, and of pathologic changes in the navicular bones in particular, increased considerably. Therefore, increased selection limits for show-jumping ability irrespective of the radiological state of the selected horses appears to bring about the risk of higher prevalences of radiographic findings. This does obviously not or only to a minor degree apply to advanced selection on dressage ability or advanced all-purpose selection.

When applying selecting schemes that simultaneously account for orthopedic health traits and for performance traits to only one generation of stallions, maximally 66% of sires were found to be eligible.[14] However, the inclusion of two generations of sires resulted in an increase of the percentage of selectable sires from 43-53% in the first step of selection (paternal grandsires) to 69-82% in the second step of selection (probands' sires). Furthermore, the progress in dressage and/or jumping (as measured by the respective mean relative breeding values) was only slightly reduced by allowing for radiographic findings. Between 70% and 100% of the maximum gain in TID and TIJ were achieved with selection schemes DJR_{50}, DR_{50} and JR_{50} when compared to selection schemes DJ, D and J, respectively.

On the other hand, only the consideration of orthopedic health traits provides for an appreciable increase in the relative breeding values for radiographic findings. Concerning the realized response to selection, i.e., the prevalences of radiographic findings in the next generation, the advantage of selection schemes that account for the radiological status of the horse becomes even more obvious. The completely performance based selection (i.e., the application of selection schemes DJ, D and J) results in a stabilization or a slight decrease of the prevalences of the investigated hock alterations (OFH, DAH). But simultaneously, osseous fragments in fetlock joints and pathologic changes in navicular bones become considerably more prevalent. On the contrary, giving equal weight to the radiological status of the horse and to its performance in dressage and/or show-jumping (i.e., the applying selection schemes RDJ_{50}, RD_{50} and RJ_{50}), the prevalences of all the investigated radiographic findings are lowered via selection.

The results of the present study support the feasibility of selection schemes that simultaneously account for performance parameters and for the radiological status of the horse. Tracing the response to selection over two generations of sires, the percentage of above-average, i.e., eligible dressage, jumping and all-purpose stallions was found to be almost the same if radiographic findings are accounted for or not. This fact should provide for the acceptance of selection schemes that allow for orthopedic health traits in addition to the currently exclusively considered performance parameters.

The most precautious, and probably (at least in the long term) the most effective way to lower the prevalences of radiographic findings in young Warmblood riding horses is to utilize the knowledge of their heritable character. Therefore, we recommend the prediction of breeding values for relevant radiographic findings and their implementation in the currently used integrated estimation of breeding values.[19]

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Table 1 – Ranges of the total indices dressage (TID), jumping (TIJ) and radiographic findings (TIR), and of the natural (NBV) and relative breeding values (RBV) for radiographic findings (osseous fragments in fetlock joints, OFF; osseous fragments in hock joints, OFH; deforming arthropathy in hock joints, DAH; pathologic changes in navicular bones, PCN), in the paternal grandsires and in the sires of probands

			Paternal grandsires (n = 144)	Probands' sires (n = 301)
TID		range	61 - 157	71 - 161
		mean ± SD	106.13 ± 17.08	112.19 ± 18.63
TIJ		range	32 - 154	32 - 154
		mean ± SD	97.98 ± 22.81	99.15 ± 23.22
TIR		range	54 - 124	54 - 135
		mean ± SD	98.35 ± 11.44	98.60 ± 11.51
OFF	NBV_{OFF}	range	-17 - 18	-19 - 18
		mean ± SD	0.09 ± 5.71	0.58 ± 5.82
	RBV_{OFF}	range	23 - 175	23 - 185
		mean ± SD	99.83 ± 24.82	97.96 ± 25.27
OFH	NBV_{OFH}	range	-12 - 19	-12 - 26
		mean ± SD	0.69 ± 5.18	0.61 ± 5.36
	RBV_{OFH}	range	17 - 157	-13 - 157
		mean ± SD	98.89 ± 23.22	99.07 ± 24.09
DAH	NBV_{DAH}	range	-17 - 13	-15 - 16
		mean ± SD	-1.13 ± 5.31	-1.52 ± 4.98
	RBV_{DAH}	range	24 - 185	8 - 171
		mean ± SD	99.74 ± 28.03	101.61 ± 26.13
PCN	NBV_{PCN}	range	-30 - 43	-30 - 48
		mean ± SD	4.17 ± 14.85	3.66 ± 14.85
	RBV_{PCN}	range	24 - 157	14 - 157
		mean ± SD	94.33 ± 27.28	95.26 ± 27.32

Table 2 – Distribution of the total indices dressage (TID), jumping (TIJ) and radiographic findings (TIR), and of the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), in the paternal grandsires and in the sires of probands by their TID and TIJ categories

			TID	TIJ	TIR	RBV_{OFF}	RBV_{OFH}	RBV_{DAH}	RBV_{PCN}
Paternal grandsires (n = 144)	TID	< 80 (n = 9)	74	103	101	105	99	103	97
		80-120 (n = 108)	102	100	98	99	97	99	96
		> 120 (n = 27)	132	90	99	100	105	102	87
	TIJ	< 80 (n = 36)	107	68	99	104	102	93	98
		80-120 (n = 87)	106	99	99	98	97	102	97
		> 120 (n = 21)	107	134	96	102	101	101	77
Sires of probands (n = 301)	TID	< 80 (n = 10)	75	104	100	97	102	103	97
		80-120 (n = 203)	104	100	98	97	98	100	96
		> 120 (n = 88)	135	95	99	99	101	105	92
	TIJ	< 80 (n = 72)	116	68	100	98	105	102	96
		80-120 (n = 168)	112	99	99	97	95	103	99
		> 120 (n = 61)	109	132	96	99	104	98	85

Table 3 – Distribution of the total indices dressage (TID), jumping (TIJ) and radiographic findings (TIR), and of the relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), in the paternal grandsires and in the sires of probands by their years of birth

	Years of birth	TID	TIJ	TIR	RBV_{OFF}	RBV_{OFH}	RBV_{DAH}	RBV_{PCN}
Paternal grandsires (n = 144)	1954-1965 (n = 20)	98	91	97	104	97	96	90
	1966-1970 (n = 29)	98	96	101	101	99	100	105
	1971-1975 (n = 42)	101	96	98	99	96	98	97
	1976-1980 (n = 23)	113	96	98	96	97	106	94
	1981-1985 (n = 19)	121	104	99	97	110	102	87
	1986-1989 (n = 11)	122	113	94	105	99	94	77
Sires of probands (n = 301)	1965-1975 (n = 34)	103	100	98	103	98	95	98
	1976-1980 (n = 49)	102	89	99	98	97	103	98
	1981-1985 (n = 80)	107	89	99	93	100	103	97
	1986-1990 (n = 101)	118	107	98	101	97	102	92
	1991-1994 (n = 37)	129	115	99	96	104	101	94

Table 4 – Response to selection on the basis of relative breeding values for one particular radiographic finding each, i.e., osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

		No sel.	OFF_{100}	OFH_{100}	DAH_{100}	PCN_{100}
Number of selected paternal grandsires (%)		**144** **(100)**	83 (57.6)	83 (57.6)	72 (50.0)	67 (46.5)
Relative breeding values (mean)	TID	**106**	106	107	106	103
	TIJ	**98**	99	98	99	95
	TIR	**98**	103	99	102	103
	RBV_{OFF}	**100**	**116**	96	103	102
	RBV_{OFH}	**99**	97	**114**	95	99
	RBV_{DAH}	**100**	102	92	**121**	96
	RBV_{PCN}	**94**	95	95	90	**117**
Number of sires, descended from the selected paternal grandsires (%)		301 (100)	173 (57.5)	171 (56.8)	186 (61.8)	132 (43.9)
Relative breeding values (mean)	TID	112	112	114	113	110
	TIJ	99	103	98	99	100
	TIR	99	102	99	101	103
	RBV_{OFF}	98	112	93	99	100
	RBV_{OFH}	99	97	111	97	98
	RBV_{DAH}	102	103	95	114	100
	RBV_{PCN}	95	94	96	93	112
Number of selected sires (%)		**301** **(100)**	123 (71.1)	132 (77.2)	137 (73.7)	98 (74.2)
Relative breeding values (mean)	TID	**112**	113	114	113	109
	TIJ	**99**	103	98	100	100
	TIR	**99**	103	100	103	104
	RBV_{OFF}	**98**	**122**	92	100	99
	RBV_{OFH}	**99**	96	**117**	94	99
	RBV_{DAH}	**102**	103	94	**123**	99
	RBV_{PCN}	**95**	92	95	93	**121**
Number of probands, descended from the selected sires (%)		**4759** **(100)**	2107 (44.3)	1873 (39.4)	2378 (50.0)	1365 (28.7)
Prevalences of radiographic findings (%)	OFF	**21.2**	**14.3**	23.0	20.7	21.6
	OFH	**9.4**	10.1	**4.3**	9.8	9.8
	DAH	**12.0**	11.8	13.5	**6.8**	12.8
	PCN	**25.7**	28.3	26.1	26.5	**13.6**

No sel. : no selection.

Table 5 – Response to selection on the basis of relative breeding values for osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), combined to a total index radiographic findings (TIR), and of the total indices dressage (TID) and jumping (TIJ)

		No sel.	**Sel. > 40**	R_{100}	DJR_{50}	DR_{50}	JR_{50}
Number of selected paternal grandsires (%)		**144 (100)**	131 (91.0)	66 (45.8)	66 (45.8)	76 (52.8)	62 (43.1)
Relative breeding values (mean)	TID	**106**	105	105	**113**	**115**	106
	TIJ	**98**	98	94	**107**	98	**114**
	TIR	**98**	**100**	**107**	**104**	**103**	**103**
	RBV_{OFF}	**100**	100	**109**	**107**	**105**	**104**
	RBV_{OFH}	**99**	99	**103**	**102**	**100**	**102**
	RBV_{DAH}	**100**	**101**	**111**	**107**	**104**	**105**
	RBV_{PCN}	**94**	**98**	**107**	**99**	**101**	**101**
Number of sires, descended from the selected paternal grandsires (%)		301 (100)	266 (88.4)	146 (48.5)	158 (52.5)	170 (56.5)	140 (46.5)
Relative breeding values (mean)	TID	112	112	115	116	117	112
	TIJ	99	98	95	104	98	109
	TIR	99	100	104	102	102	101
	RBV_{OFF}	98	98	104	100	101	99
	RBV_{OFH}	99	99	99	101	98	101
	RBV_{DAH}	102	103	110	106	107	104
	RBV_{PCN}	95	98	102	99	99	101
Number of selected sires (%)		**301 (100)**	252 (94.7)	101 (69.2)	115 (72.8)	140 (82.4)	98 (70.0)
Relative breeding values (mean)	TID	**112**	112	**115**	**120**	**121**	111
	TIJ	**99**	98	95	**108**	97	**117**
	TIR	**99**	**100**	**109**	**104**	**103**	**103**
	RBV_{OFF}	**98**	98	**109**	**103**	**104**	**101**
	RBV_{OFH}	**99**	**100**	**103**	**103**	99	**104**
	RBV_{DAH}	**102**	**103**	**116**	**108**	**108**	**105**
	RBV_{PCN}	**95**	**99**	**109**	**100**	**101**	**100**
Number of probands, descended from the selected sires (%)		**4759 (100)**	3723 (78.2)	1780 (37.4)	2711 (57.0)	2595 (54.5)	1640 (34.5)
Prevalences of radiographic findings (%)	OFF	**21.2**	21.6	**19.3**	21.3	21.2	**20.4**
	OFH	**9.4**	**9.3**	**7.3**	**8.0**	**9.2**	**8.5**
	DAH	**12.0**	**11.5**	**8.2**	**10.4**	**10.8**	**11.0**
	PCN	**25.7**	**23.7**	**21.1**	**25.0**	**24.1**	**25.6**

No sel. : no selection.

Sel. > 40 : TID, TIJ, RBV_{OFF}, RBV_{OFH}, RBV_{DAH} and RBV_{PCN} all larger than 40.

$R_{100} = 1.0 * TIR$ with $TIR = (RBV_{OFF} + RBV_{OFH} + RBV_{DAH} + RBV_{PCN}) / 4$

$DJR_{50} = 0.5 * TIR + 0.5 * (0.6 * TID + 0.4 * TIJ)$

$DR_{50} = 0.5 * TIR + 0.5 * TID$

$JR_{50} = 0.5 * TIR + 0.5 * TIJ$

Table 6 – Response to selection on the basis of the officially published total indices dressage (TID) and jumping (TIJ), with a selection limit of 100

		No sel.	DJ	D	J
Number of selected paternal grandsires (%)		**144 (100)**	79 (54.9)	95 (66.0)	64 (44.4)
Relative breeding values (mean)	TID	**106**	**116**	**115**	**107**
	TIJ	**98**	**107**	**99**	**117**
	TIR	**98**	98	98	97
	RBV_{OFF}	**100**	99	100	98
	RBV_{OFH}	**99**	**101**	99	**101**
	RBV_{DAH}	**100**	**101**	99	**102**
	RBV_{PCN}	**94**	91	92	89
Number of sires, descended from the selected paternal grandsires (%)		301 (100)	185 (61.5)	202 (67.1)	139 (46.2)
Relative breeding values (mean)	TID	112	118	118	110
	TIJ	99	106	98	114
	TIR	99	98	99	98
	RBV_{OFF}	98	97	97	95
	RBV_{OFH}	99	100	98	101
	RBV_{DAH}	102	103	104	102
	RBV_{PCN}	95	94	94	91
Number of selected sires (%)		**301 (100)**	150 (81.1)	169 (83.7)	102 (73.4)
Relative breeding values (mean)	TID	**112**	**121**	**123**	110
	TIJ	**99**	**109**	98	**122**
	TIR	**99**	98	99	97
	RBV_{OFF}	**98**	98	98	94
	RBV_{OFH}	**99**	99	98	**103**
	RBV_{DAH}	**102**	102	**103**	102
	RBV_{PCN}	**95**	93	94	88
Number of probands, descended from the selected sires (%)		**4759 (100)**	2822 (59.3)	3012 (63.3)	1606 (33.7)
Prevalences of radiographic findings (%)	OFF	**21.2**	22.2	22.2	21.7
	OFH	**9.4**	9.4	9.4	9.4
	DAH	**12.0**	12.0	**11.7**	**11.6**
	PCN	**25.7**	27.7	26.9	29.5

No sel. : no selection.

DJ = 0.6 * TID + 0.4 * TIJ

D = 1.0 * TID

J = 1.0 * TIJ

Table 7 – Response to selection on the basis of the officially published total indices dressage (TID) and jumping (TIJ), with a selection limit of 120

		No sel.	DJ	D	J
Number of selected paternal grandsires (%)		**144** (**100**)	15 (10.4)	29 (20.1)	22 (15.3)
Relative breeding values (mean)	TID	**106**	**130**	**131**	105
	TIJ	**98**	**120**	91	**134**
	TIR	**98**	96	**99**	96
	RBV_{OFF}	**100**	**103**	**101**	**105**
	RBV_{OFH}	**99**	**109**	**104**	**101**
	RBV_{DAH}	**100**	93	**103**	**101**
	RBV_{PCN}	**94**	78	87	78
Number of sires, descended from the selected paternal grandsires (%)		301 (100)	52 (17.3)	98 (32.6)	61 (20.3)
Relative breeding values (mean)	TID	112	131	126	111
	TIJ	99	105	92	125
	TIR	99	99	99	97
	RBV_{OFF}	98	98	99	101
	RBV_{OFH}	99	102	100	100
	RBV_{DAH}	102	102	106	100
	RBV_{PCN}	95	92	92	85
Number of selected sires (%)		**301** (**100**)	27 (51.9)	55 (56.1)	37 (60.7)
Relative breeding values (mean)	TID	**112**	**137**	**138**	112
	TIJ	**99**	**113**	91	**134**
	TIR	**99**	**100**	**101**	96
	RBV_{OFF}	**98**	**104**	**101**	**105**
	RBV_{OFH}	**99**	99	99	**103**
	RBV_{DAH}	**102**	**104**	**109**	95
	RBV_{PCN}	**95**	94	95	82
Number of probands, descended from the selected sires (%)		**4759** (**100**)	481 (10.1)	1273 (26.7)	576 (12.1)
Prevalences of radiographic findings (%)	OFF	**21.2**	**20.4**	22.7	**16.3**
	OFH	**9.4**	9.6	**8.8**	10.6
	DAH	**12.0**	12.5	**11.2**	13.9
	PCN	**25.7**	26.6	**25.0**	36.1

No sel. : no selection.

DJ = 0.6 * TID + 0.4 * TIJ

D = 1.0 * TID

J = 1.0 * TIJ

Figure 1 – Schematic selection diagram

Paternal grandsires (n_{pgs} = 144; 100%)
⇒ relative breeding values
(TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

Selection ⇒ Preclusion of paternal grandsires (n_{S1}),
not fulfilling the respective selection conditions

Selected paternal grandsires (n_{pgs} - n_{S1}; 100(n_{pgs} - n_{S1}) / 144 %)
⇒ relative breeding values
(TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

Sires of probands (n_s; 100n_s / 301 %),
descended from the selected paternal grandsires
⇒ relative breeding values
(TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

Selection ⇒ Preclusion of probands' sires (n_{S2}),
not fulfilling the respective selection conditions

Selected sires of probands (n_s - n_{S2}; 100(n_s - n_{S2}) / n_s %)
⇒ relative breeding values
(TID, TIJ, TIR, RBV_{OFF}, RBV_{OFH}, RBV_{DAH}, RBV_{PCN})

Probands (n_p; 100n_p / 4759 %),
descended from the selected sires of probands
⇒ Prevalences of radiographic findings (OFF, OFH, DAH, PCN)

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Survey on the development of Hanoverian Warmblood horses selected for sale at auction in 1991 to 1998

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Summary

The development of 3,725 Warmblood riding horses selected for sale at auction in 1991-1998 was investigated on the basis of competition data and specifications of the horse owners. Information on entries in tournament competitions and registered competition results obtained in tournaments in Germany in 1991-2002 were analyzed. The annual numbers of tournament entries and placings were used to quantify the horses' use in sports. Several factors were identified that had an influence on these performance parameters, including the sex and the age of the horse, and the discipline of use. When relating the presence or absence of different radiographic findings in the limbs of the probands to their later performance, mostly negative effects could be determined. In particular, horses affected with osseous fragments in distal interphalangeal joints, deforming arthropathy in proximal interphalangeal joints, and pathologic changes in navicular bones had on the average significantly lower number of entries and placings per year. Information derived from standardized questionnaires sent to actual owners of the former auction candidates provided some insight into current routines of keeping and management of Hanoverian Warmblood horses in Germany. The results of the study confirmed the fundamental importance of locomotory problems for the continuity of use of riding horses.

Introduction

Failure of performance is the most important reason for premature retirement and wastage of horses, irrespective of their use. [1, 2, 3] Musculoskeletal problems and respiratory disease are considered to be the main conditions impairing the horses usability. [4] However, most data on the relevance of particular health problems in the riding horse refer to insurance data. In these, locomotory diseases accounted for 30-60%, respiratory diseases for 7-22% and gastrointestinal diseases for 5-18% of notified cases. [5, 6] But it has to be taken into account that only about 10% of all horses are insured against death and/or loss, not being representative for the whole horse population. Furthermore, only claims can be considered in insurance statistics. Consequently, they do not provide a reliable basis to rank disease prevalences and to identify risk factors for the soundness of the whole population of living Warmblood horses.

The performance of riding horses is not quantified with sufficient objectivity as easily as the performance of racehorses. Furthermore, the national recording system of competition data in Germany provides only sparse information on the horses active in sports. This impedes performing reliable epidemiological studies on performance-related conditions in the German riding horse.

The objective of the present study was to investigate the development of a population of young Warmblood riding horses in terms of their performance in sports and of their general health. The annual numbers of tournament entries and placings were utilized as performance measures, reflecting the amount of training and competing activity of the individual horse in particular years. The relevance of radiographic findings, detected in the course of a standardized radiological examination of the horses at a young age, should be analyzed. Current practices and actual problems in management and keeping of Warmblood horses should be identified and correlated with the horses' use in sports.

Material and methods

Between 1991 and 1998 3,748 Hanoverian Warmblood horses were selected for auction sale as a riding horse by the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany. The distribution of radiographic findings among these horses, ranging between 3 and 7 years of age, has been investigated retrospectively by the authors. [7, 8, 9, 10, 11]

Competition data

Competition data of the former candidates were analyzed as measures of performance in sports. With a view to the intended genetic analyses, only data on the 3,725 probands with available pedigree information were considered. Competition data from 1991-2002 were taken from the central national database at the VIT in Verden. In that, competitions in the disciplines dressage, show-jumping and cross-country riding as well as driving competitions are allowed for that have been held at tournaments of regional (category B) or supra-regional (category A) importance.

In each discipline, a distinction is drawn between the so-called build-up competitions for young horses (age limits) and the classical tournament competitions for older horses (only minimum age). The basic abilities of the horse are judged in the build-up competitions. In the classical tournament competitions the performances of horse and rider or driver constitute the judging criteria. For riding horses, there are 29 different standard types of competitions. The distinction is drawn between 5 different types of driving competitions. Other types of competitions that do not fit the standard types (e.g., combined dressage/jumping competitions) are considered jointly. In each discipline, increasing demands are made in level A (novice) over levels L (elementary) and M (medium) to level S (advanced) competitions. Table 1 gives an overview of the judging criteria in the different national tournament competitions in Germany.

The distributions of tournament entries and of registered competition results in 1991-2002 have been analyzed quantitatively in the former auction candidates. The stratification was done by those factors that might have influenced the number of the amount of annual tournament activity, i.e.: year of competition (1991-2002), year of birth (1985-1995), age at entry or age when being placed (3 to 16 years old), discipline (13 disciplines, i.e., RHQT, RHAP, DY, DR, DC, JY, JC, CCY, CCC, HY, DrY, DrC, OC), competition level (0, A, L, M, S), competition type (specification of 36 different types of competitions by discipline and competition level), auction state (auction horses, i.e., horses offered for sale at auction; pulled out of auction), date of auction (42 riding horse auctions), type of auction (4-6 different types of riding horse auctions), quality of auction (2-3 different auction qualities), year of auction (1991-1998), sex of the horse (male, female), age at auction (3 to 7 years old), anticipated suitability (dressage, show-jumping, dressage and show-jumping), region of origin (place of the breeder resp. exhibitor of the horse), height at withers (152-183 cm), percentage of genes of different horse breeds (Hanoverian Warmblood horse, Thoroughbred, Holstein Warmblood, Trakehner, Arabs, other Warmblood breeds), and radiological state of the young riding horse (presence or absence of osseous fragments in distal interphalangeal (OFD), proximal interphalangeal (OFP), fetlock (OFF) and hock joints (OFH); presence or absence of deforming arthropathy in distal interphalangeal (DAD), proximal interphalangeal (DAP), fetlock (DAF) and hock joints (DAH); presence or absence of pathologic changes in navicular bones (PCN)).

No information was available on all the horses having actually started in tournament competitions since only successful, i.e., placed participants have been registered in the national database. The German tournament entry system allows the adjustment of a regular entry just prior to the respective competition. Therefore, it is possible that a rider has an entry with one horse and starts with another horse. These horse changes did not enter the official entry data. Accordingly, it was not possible to correlate the number of recorded competition results and the number of entries per horse and year and type of competition (success rate). Statistical analyses were therefore performed separately for the number of tournament entries (TE) and the number of registered competition results (tournament placings; TP) per horse and year. Differing parameter values in particular fixed effect levels were examined using the chi-square test. The significance limit was set to $P < 0.05$.

Questionnaires

In order to obtain information about the development of the horses, questionnaires were sent to their current owners if these were ascertainable. Whereabouts after auction were derived from a unified animal ownership database (Vereinigte Informationsysteme Tierhaltung w.V., VIT) in Verden on the Aller, Germany, for 3,471 (93%) of the former auction candidates. 14% of the horses had been sold abroad, leaving 2,976 animals for follow-up in Germany. The owner of further 143 animals were contacted in adjacent countries (Switzerland, Netherlands, Austria, Belgium, Luxembourg) since German language ability was assumed. However, considerable numbers of probands might have changed owners at least once without a note in the ownership database. Furthermore, because of reasons of data protection up-to-dateness of the available ownership information could not be checked, resulting in about 250 questionnaires returning with address unknown. Consequently, additional requests for participation in the survey were announced over the homepage and the periodical of the VHW as well as over a popular German equestrian magazine.

The questionnaire sent to the horse owners was largely designed as a standardized multiple choice form which allowed for an easy transformation into a numeric code suitable for statistical analyses. Information was derived about the current and the former use of the horse (riding, driving, breeding, others; disciplines of riding; training levels for the different disciplines; quantity and quality of riders; amount and mode of exercise; use in competitions; shoeing; duration of and reason for intermission of intended use), about stabling and feeding of the horse (kind of stable, access to pasture; structured and concentrated feed, feed supplements; feeding frequency), and about behavioral and disease problems (weaving, air swallowing, aggressiveness, others; lameness problems, respiratory, gastrointestinal, cardiovascular, skin and other diseases). Because we were particularly interested in orthopedic problems, the circumstances of possible lameness periods were considered more detailed (frequency of lameness periods, affected area, diagnosis of the consulted veterinarian, therapy; recovery; availability of radiographs of the locomotory system).

In order to check the possibility to connect the horses' background information (questionnaires) to the competition data, the horses with questionnaires were compared with the respective total group of horses (horses with/without entries, horses with/without registered competition results in 1991-2002) by their mean numbers of entries and competition results. Differing values of the performance parameters (mean numbers of annual tournament entries and of registered competition results per year) in dependence on particular questionnaire items were tested for significance using Fisher's exact test (significance limit of $P < 0.05$).

Results

2,956 of the 3,725 probands (79.4%) were registered with a total of 346,719 entries in tournament competitions in 1991-2002. 2,524 of the 3,725 probands (67,8%) had registered competition results in 1991-2002. Per year of competition 131 (1991) to 1,242 (1998) probands had between one and 78 records of successful tournament participation. The total of 67,953 registered competition results was composed of 11,395 first places (up to 20 per horse and year), 10,946 second places (up to 11 per horse and year), 10,861 third places (up to 11 per horse and year), 10,400 fourth places (up to 8 per horse and year), 8,119 fifth places (up to 6 per horse and year) and 16,232 further places (up to 18 per horse and year).

Auction horses made up 93.4% of our probands, but contributed 94.7% of all entries and 94.6% of all placings. 79.6% of the auction horses had entry records, and 68.0% of the auction horses had registered competition results in the study period. The representation of horses that were selected for sale at auction, but then pulled out of auction for varying reasons was lower (75.9% with entries, 64.8% with placings). On the average, they had 23.8 entries and 7.1 placings per year of competition.

In the auction horses the mean numbers of entries and of placings per horse and year differed considerably between the individual dates of auctions (15.9-34.8 TE; 3.7-9.1 TP). The lowest means appeared for horses offered at Equitop auctions, particularly at Equitop auctions in spring. Elite auction horses, and horses offered at elite auctions in autumn in particular, had on the average most entries and placings per year. Concerning the different types of auctions, 70.0-86.7% and 55.5-81.5% of the offered horses had entry records and registered competition results, respectively. The lowest means were calculated for Equitop auctions in spring and the highest for Elite auctions in autumn.

The horses offered in different years of auctions differed little in the mean numbers of annual entries (24.2-26.8) and placings (6.3-7.7). But whilst 77.9-84.5% of the auction horses offered in 1992-1997 had entries in 1991-2002, this applied to only 72.1% and 72.2% of the auction horses offered in 1991 and 1998, respectively. The proportions of auction horses with placings was similar (64.6-74.1% vs. 63.3% and 57.9%).

2,013 of the 2,490 male probands (80.8%) had a total of 246,096 entries, and 943 of the 1,235 female probands (76,4%) had a total of 100,623 entries in 1991-2002. The males' and the females' average entry number per year differed negligibly (25.0 in males, 25.2 in females). Successful tournament participation was recorded for 69.7% of the male horses with an annual average of 6.9 ± 6.9 registered results. 63.8% of the female probands had a mean of 7.0 ± 7.1 registered competition results per year. The continuity of competing activity was investigated in those horses, that had the chance to have tournament records in the whole study period (1991-2002), i.e., in the 539 horses born in 1988 or earlier (Fig. 1). 40.6% of them had entry records in up to 4 years of competitions, and 10.4% had entry records in 10-12 years of the considered 12-year-period. However, there was a considerable sex difference concerning the number of years with entry records. In males the percentages of horses with 1-4 and 10-12 years with entries were 36.9% and 13.1%. In females, the percentage of horses with up to 4 years with tournament entries was higher (49.1%) and the percentage of horses with 10-12 years with entries was lower (4.2%). 53.4% of the males and 56.9% of the females had registered tournament results in up to 4 competition years (average in both sexes: 54.4%). On the contrary, 5.8% of the male horses and only 0.7% of the female horses had competition result records in 10-12 and 10-11 years, respectively (average in both sexes: 4.3%).

Horses advertised as having noticeable jumping ability had considerably higher mean numbers of entries and placings per year (35.9 ± 30.7 TE; 8.5 ± 8.0 TP) than horses anticipated to be suited for dressage (20.0 ± 17.4 TE; 6.0 ± 6.0 TP) or for both, dressage and show-jumping (25.9 ± 24.4 TE; 7.0 ± 7.5 TP). The means of both, the number of annual entries and the number of annual placings, were highest in those horses that had been offered for auction sale with 6 years of age. There were only minor differences in the mean numbers of annual entries in dependence on the origin of the auction horses (region of breeder and exhibitor). However, horses originating from the northern and eastern part of Germany were on the average placed slightly more often (6.8-7.2 TP) than horses originating from the south and south-western part of Germany (6.6 TP). There was a trend towards a higher activity in sports in relatively small (withers height of up to 165 cm) and in relatively large horses (withers height of 170 cm or larger) when compared to average-sized horses.

The average numbers of annual tournament entries and placings were unevenly distributed among the different auction price classes (Fig.2). The most remarkable findings was that horses that had not been sold (pulled out of auction or no award at auction; 24.3 TE; 6.8 TP) had on the average more entries than and almost as much placings as the highest-priced horses (more than 50,000 and up to 510,000 DM; 23.8 TE; 6.9 TP).

Some influence of the breed composition on tournament activity could be derived from the competition data. The higher the percentages of genes of Thoroughbreds, Trakehner horses and Arabians were in the probands, the lower were their average numbers of annual entries and placings. On the other hand, the means increased with higher percentages of genes of the Holstein Warmblood (Table 2).

The distribution of tournament data was age-related inasmuch the better part of the probands had entries at an age of 4 to 7 years and the highest numbers of entries were contributed by 5 to 9 years old horses (Fig. 3). This age dependence was analogously reflected in the entry distributions by year of birth and by year of competition: Most of the probands were born in 1990-1993, accordingly the number of horses with entries and the total number of entries peaked in 1996-1999. The highest total numbers of entries emerged for horses born in 1988-1992 which had the prime of their use in sports included in the study period. The same age-dependency was observed in respect of successful tournament participation.

2,202 probands with entries in competitions of level 0 (basic build-up competitions), contrasted to 1,337 probands with placings on this competition level. The number of horses with competition records decreased from level A (2,677 horses with entries; 2,119 placed horses) over levels L (2,376 horses with entries; 1,687 placed horses) and M (1,685 horses with entries; 989 placed horses) to level S (834 horses with entries; 373 placed horses). Contrarily, most records referred to level L (113,167 entries; 22,150 placings) and level A competitions (107,108 entries; 22,135 placings) followed by competitions of levels M (73,762 entries; 12,719 placings), S (36,278 entries; 5,910 placings) and 0 (16,404 entries; 5,039 placings).

Most entries and placings were recorded in classical dressage (DC; 33.7% of all entries; 35.0% of all placings) and classical jumping competitions (JC; 41.7% of all entries; 34.3% of all placings). The records in dressage and/or jumping build-up competitions RHQT, RHAP, DY and JY combined made up 22.0% of all entries and 28.0% of all placings. Despite comparable total numbers of entries and placings, the numbers of horses with entries and placings in dressage competitions were considerably larger than the numbers of horses with corresponding records in jumping competitions. In general, horses with entries in classical tournament competitions had on the average more entries and placings per year than horses with entries in the respective build-up competitions. The remaining disciplines (DR, CCY, CCC, HY, DrY, DrC, OC) were of minor quantitative importance. However, the few horses with records for driving competitions and other types of competitions had outstanding high mean numbers of entries and placings (Table 3).

The distribution of tournament entries and placings is given in detail in Table 4.

Radiological state

In order to get an impression of the number of horses with radiological findings in sports, we compared the prevalences of osseous fragments and deforming arthropathy in distal interphalangeal (OFD, DAD), proximal interphalangeal (OFP, DAP), fetlock (OFF, DAF) and hock joints (OFH, DAH), and of pathologic changes in navicular bones (PCN) in the probands with and without tournament entries, and in the probands with and without registered competition results (Table 5). In most cases, there were negligibly small prevalence differences between the probands with and without available competition data ($P > 0.10$). However, the chi-square test statistics revealed that OFF tended to be more prevalent in horses with than in horses without tournament entries ($P = 0.07$). In placed and unplaced horses the frequencies of OFF did not differ significantly ($P = 0.19$). Contrarily, DAF were as prevalent in horses with entries as in horses without entries ($P = 0.28$), but tended to be more prevalent in unplaced horses than in placed horses ($P = 0.08$). The only significant different prevalences were determined for DAH. Probands with tournament entries had been significantly less often positive for this radiographic finding at a young age than probands without tournament entries ($P < 0.05$). However, this prevalence difference was not seen between placed and unplaced horses ($P = 0.17$).

In the groups of probands with tournament data, we further compared the mean numbers of annual entries and placings between horses with and without radiological findings (Table 6). Horses affected with OFD, DAP, DAH and PCN had on the average significantly less entries, and horses affected with OFD, OFF, DAP and PCN had on the average significantly less placings per year than unaffected horses. However, significantly higher means of annual tournament entries and placings were calculated in probands in which OFH had been diagnosed at a young age.

Questionnaires

486 out of the 496 replied questionnaires (approximate reply rate of 17% for the horses traced) could be used for further analyzes. The responses had been given by persons having owned the respective horses for up to 11 years (mean of 5.4 ± 2.6 years).

44 of the questionnaires referred to horses that had died or had been put down in the meantime, having reached an age of between 3 and 15 years (8.9 ± 2.6 years). Irreparable musculoskeletal problems had been the reason for culling in 27 cases. Gastrointestinal diseases (5), tumors (2) and infectious diseases (1) have been mentioned as causes of death of further 8 horses. For 10 resold horses questionnaires had been filled out retrospectively by former owners. Because of the uncertainty about their fate they were excluded from mean age calculation. The 432 horses definitely still alive at the time of questionnaires completion were on the average 10.9 ± 2.3 years old (range 6 to 17 years).

459 of the questionnaires referred to horses with registered entries and 385 to horses with registered competition results in 1991-2002. Consequently, owners information were available for 15.5% of horses with entries and for 15.9% of horses with competition results. On the other hand, questionnaires were sent back for only 3.5% of horses without entry records and for 7.1% of horses without registered competition results. The average numbers of entries and of placings per horse and year mostly differed by less than 10% between the horses with and without questionnaire information, justifying to combine competition and questionnaire data.

The results of the comparison of the frequencies of selected questionnaire specifications in probands with and without competition data are shown in Table 7. Among the probands without tournament entries in 1991-2002 there were significantly more horses that had died or had been put down than among the probands with entry records ($P = 0.03$). The median year of death was 1997 in the horses without entries and 1999 in the horses with entries. However, this difference was not seen between the horses with and without registered competition results ($P = 0.13$).

No questionnaires were sent back for breeding stallions, but according to the owners' statements, a total of 57 mares has been used for breeding for up to 12 years. The proportion of broodmares was significantly higher among the horses without tournament entries and without placings than in the horses with respective competition data ($P < 0.01$). Horses with and without competition data were evenly distributed concerning the main riding disciplines, i.e., dressage and show-jumping ($P = 0.25$-0.72). But horses at least partly used for leisure riding were sparsely represented in the competition data ($P < 0.01$).

About two thirds of all probands with available questionnaire information had intermissions of their intended use because of varying reasons (use for breeding; lameness, other kind of disease affecting the horse; indisposed rider). This applied to horses without competition data as well as to horses with competition data ($P = 0.34$-0.91). The only significant difference was determined in respect of tournament entries and use for breeding: Mares that had their intended use interrupted in favor of having a foal were under-represented in the entry data ($P = 0.04$).

The owners of about 60% of the probands remembered at least one relevant lameness of their horses. Multiple lameness periods have been noted for about 35% of the probands. However, this was not dependent on their presence in the competition data ($P = 0.23$-0.90). Problems of the locomotory system had been most often located in fetlock joints (arthritis, arthrosis; 64 horses), hock joints (arthritis, arthrosis; 34 horses), back (unspecified back pain, "kissing spines"; 73 horses) and tendons (tendonitis/tendovaginitis, tendinosis; 89 horses). Unsatisfactory hoof quality with or without lameness was mentioned for 27 horses.

Respiratory problems have been stated for about one third of the probands. They tended to be more prevalent in unplaced than in placed horses ($P = 0.07$).

Behavioral or temperamental disorders have been rarely mentioned in the questionnaires. Swallowing was said to be present in 24 horses, weaving in 16 horses. 13 horses showed aggressive behavior such as kicking, biting and the like towards their owners or other horses. For 12 horses excessive nervousness was reported. There were no significant prevalence differences in respect of undesirable behavior between horses with and without records of tournament entries or placings ($P = 0.14$-1.00).

Neither the general appreciation of the horses by their owner nor the horses' management appeared to be significantly different in horses with and without competition data ($P > 0.05$). Asked about the development of their horse in general, 52.6% of the owners said to be highly pleased and further 34.1% to be moderately pleased. 13.3% of the repliers stated to be rather displeased with the development of their horses. Requested to assess the fundamental characteristics of a riding horse, namely rideability, diligence and willingness to perform, only 6.5%, 3.6% and 4.0% of the owners expressed their definite dissatisfaction in respect of these three features. On the other hand, rideability was classified as very good in 46.8%, diligence in 59.7% and willingness to perform in 63.8% of the probands. A medium classification (satisfying) was chosen for the remaining 46.6%, 36.7% and 32.2% of horses, respectively.

According to the owners' statements, 80.7% of the probands had exercise every day, whilst 12.8% had routinely one day per week and 6.5% two or more days per week no exercise at all. 95.5% of the horses had been at least occasionally used for riding by one (43.4%), two (48.7%) or less often three or more riders (7.9%). Lunging was frequently considered as an alternative to training under saddle (78.2%). The distribution of the riders' abilities (according to the German classification system for riders) corresponded to the horses' states of training with most horses trained up to level L. All riding horses had at least some dressage training, but 50% of the probands were never used for show-jumping. Only 10 questionnaires each were completed for eventing and driving horses. Specifications given in respect of participation in tournaments indicated that 15.3% of the current owners did not compete at all and 8.2% of them participated only in local tournament competitions. Consequently, 76.5% of the responses came from horse owners, participating in regional and supra-regional tournaments, who might have directly contributed competition data that have been considered in this study.

Most of the probands have been kept in closed stables (42.8% in inwards stables, 42.6% in outwards stables). Less horses (14.3%) have been kept in open stables or boxes with affiliated paddocks. According to the owners' statements, only 6.8% of the horses had no access to pasture at all. 38.5% had access to pasture in summer at least occasionally for a few hours per day. More than half of the horses (54.7%) with available questionnaire data were said to have more extensive pasture access (whole day in summer; all-season pasture access for at least a few hours per day). The horses were usually fed two or three times a day with concentrates and roughage. The traditional oats-hay ration in combination with straw bedding has been mentioned most often (for about 85% of the horses). In many cases pellets, other kinds of cereals (corn, barley, grain mix), mash or special feed supplements (e.g., minerals, vitamins) have been additionally fed.

Discussion

The objective of this study was to investigate the development of young Warmblood riding horses in terms of performance and health parameters. The analyses were based on officially recorded competition data and on owners' information to former riding horse auctions candidates obtained via a postal survey. Dependencies of performance parameters on diverse environmental effects have been the object of statistical research.

The probands of the present study had been selected for sale at riding horse auctions in 1991-1998. Therefore, an above-average performance standard of these young Hanoverian

Warmblood horses could be presumed, qualifying them to have a promising sports career. [12] Furthermore, the clientele of riding horse auctions mainly consists of horsemen with the intension to compete at tournaments themselves or to see their horses presented at tournaments by professionals. According to the German tournament rules, 3-year-olds may have their first starts in build-up competitions. [13] In the considered riding horse auctions, the horses had been offered at an age of between 3 and 7 years. Therefore, the probands were likely to have competition data recorded in the investigation period of 1991-2002 if they were really used in tournament sports. However, it is quite probable that considerable numbers of probands have been resold at least once after their auction offer. The new owners might not have the same interest in tournament participation as the auction customers. These conditions might superpose the age-related decrease of the proportion of (successfully) competing horses with increasing time interval after auction. Therefore, the discontinuation of competition result records should not be displayed as the end of the horse's functional length of life, as it has been previously done. [14] The breeding aim of the German Warmblood horse requests a horse, suited for the use in sports as well as for the use for leisure riding. Accordingly, successful tournament participation can not be regarded as the only "function" of Hanoverian Warmblood horses. Furthermore, the physical strain put on a leisure horse, that participates at the most in local low-level tournaments, might even exceed the strain put on a moderately competing sport horse. Information on the time of definite retirement of former sport horses can not be gathered from the officially recorded competition data. According to the owners' declarations, less than 2% of the former auction candidates that had been used for dressage, jumping or cross-country riding had already been retired (pasture access only).

Almost half of the auction horses (42.7%) had their first records in the competition data even in the year prior to or in the year of their auction offer. However, the traditional training principles account for the fact that riding horses usually achieve their maximum training level not earlier than at an age of about 7 or 8 years. [13] But even those horses that had been offered in the last considered auction year (1998) had the chance to reach their surmised main period of use in sports. The probands' years of birth ranged between 1985 and 1995, resulting in 4-12 years with possible competition records. These varying lengths of the periods of data accumulation precluded the comparison of the total numbers of entries and placings or the determination of the durability of (successful) use in sports. Furthermore, it is not uncommon that horses have some break in their sports career, resulting in periods without competition records. The manifold possible reasons are generally ambiguous and inscrutable (e.g., indisposedness of the rider; temporary use of mares for breeding; prolonged convalescence period after injury). Consequently, the annual measures were chosen for the quantitative analyses. This should allow for reliable comparisons of performances in different years of activity and/or successful use in tournament sports.

For the study period 1991-2002, information on the starts of horses in tournament competitions in Germany have not been available universally. Only successful participation in competitions held at regional or supra-regional tournaments have been registered. Therefore, the actual amount of competing could not be quantified. However, if the horse is not performing well in training it is not likely to have a tournament entry. The existence of entry records might therefore be interpreted as an indicator for the individual's current usability and expedient performance. The existence of registered competition results further provides evidence of successful competing ability. But it has to be taken into account that the success of a sport horse only partly depends on its own abilities. A horse of only fair quality, presented by a professional rider, might have more and better competition results than a high quality horse with a less competent rider. Therefore, both parameters, the number of entries and the number of placings per year, were considered jointly.

Concerning the influences of the percentages of genes of different horse breeds we determined, some confounding with the effects of the different riding horse disciplines have to be assumed. Holstein Warmblood horses are known for their considerable jumping abilities. Given the more frequent use of show-jumpers in tournaments, the increasing means of records in the competition data with increasing percentages of genes of Holstein Warmblood horses were conclusive. On the other hand, Thoroughbred, Trakehner and Arabian sires are often used to improve particular type and interior traits of Warmblood horses. [15, 16] This aspect may be more important in dressage than in jumping horses. The expected lower frequencies of records in the competition data in probands with higher percentages of genes of these horse breeds could be verified. Furthermore, the stamina and toughness brought in by Thoroughbreds might be gained at the expense of competing capacity in the classical riding sports disciplines dressage and show-jumping. [16]

Most literature on the interrelation of health and performance refer to racehorses. Whilst different radiographic conditions of the limbs (hock joint osteochondrosis, radiographic alterations of fetlock joints) seemed to impair the racing performance of Standardbred trotters in terms of the number of race starts, affected horses had similar race earnings as radiologically normal contemporaries. [17, 18] In other studies no significant association was found between the presence or the type of different radiological abnormalities (osteochondrotic changes in hock and fetlock joints; osseous fragments in phalangeal joints;

deforming arthropathy of limb joints; combined lesions) and the subsequent racing performance and longevity of Standardbred trotters. Only horses with multiple lesions tended to have lower earnings and poorer survival than singularly affected horses. [19] Furthermore, high percentages of radiographic findings have been determined even in winning Thoroughbred racehorses. [20]

Nevertheless, in general the existence of radiological alterations negatively affects the outcome of horse sale and the sale value of the individual horse. [21] Given the lacking correlation between the radiological state of a horse and its auction price, this does obviously not apply to auction sale conditions. The amount of the closing bid in an auction depends on a multitude of factors, among which the presence or absence of radiographic findings is of minor importance. Furthermore, according to the results of the present study, high auction prices do not necessarily anticipate excellent performance in sports. As measured by the numbers of annual entries and placings in tournaments, horses pulled out of auction or horses without an auction award might perform as well as the highest-priced horses.

Data on the relevance of radiographic findings to the performance of riding horses are rare. Clinical studies that compared the results of different treatment regimes could not find significant differences in the performance capacity of treated and untreated horses affected with hock joint osteochondrosis. Irrespective of treatment, more than 80% of the horses were able to perform well in their intended use. [22] These findings largely agree with the results of the present study. Horses with radiological alterations were almost evenly distributed among the probands with and without available competition data. However, for most of the investigated radiographic findings the mean numbers of annual entries and placings were considerably higher in unaffected than in affected horses. Osseous fragments in hock joints meant the only exception with significantly higher means in affected horses. The slightly higher prevalences of this radiographic finding in the more frequently competing jumping horses (10.9%) than in dressage horses (9.9%) might have been responsible for this result.

Regarding the analyzed performance parameters, i.e., the mean numbers of annual entries and of annual placings, the probands with questionnaire and competition data differed only marginally from all the probands with competition data. Therefore, it appeared to be justifiable to take the questionnaire information on the keeping and management of the horses as rather representative for all the former auction candidates. The authenticity of questionnaire declarations is always dubious. However, cross-check of information was done in all cases of overlapping of competition and questionnaire data (e.g., disciplines of use and of competition results – horses said not to be used for show-jumping should not have placings in jumping competitions in the period covered by the questionnaire; state of training and level of competitions). This examination revealed extensive compatibility of the two data sets. Sufficient reliability of the owners' specifications appeared to be given.

The paramount importance of musculoskeletal problems for losses in training, that has been determined in racehorses (67.6% of all lost training days) [4] as well as in Warmblood horses (32.4%) [23], has been confirmed in the present study. According to the owners' statements, half of the probands had relevant intermissions of their intended use because of lameness. About one third of the probands experienced multiple lameness periods. As in racehorses, fetlock joints and tendons have been mentioned among the main sites of the underlying conditions in our probands. The dynamic load put on the locomotory system of riding horses is considered to predispose them to develop certain orthopedic problems, depending on the type and the extent of their use. The higher the training state in dressage, jumping and eventing horses, the higher the importance of the disciplines specific stress factors acting mainly on their limbs. Besides incidental soft tissue injuries, tendopathies, joint diseases (arthritis, arthrosis, osteochondrosis) and alterations of the navicular bones (podotrochlosis) have been regarded as occupational diseases of the riding horse. [24]

Among the non-orthopedic diseases, respiratory problems were found to be of major importance (20.5% of all lost training days [4]; 26.3% of affected Warmblood horses, depending on the type of stabling [23]). The questionnaire data revealed that about one third of the riding horses has experienced noteworthy respiratory diseases without longer intermission of their intended use. The long-term relevance of these conditions was mostly considered to be marginal. However, horses with a history of respiratory problems were less likely to have competition data than horses without a history of relevant respiratory diseases. Accordingly, the horses' performance might have been subtly impaired by these conditions even in the long-term.

Conclusions

Most Hanoverian Warmblood horses that have been offered at riding horse auctions at a young age had tournament entries and placings in up to 12 years after their offer for auction sale. The number of annual entries and of registered competition results per year was dependent on several factors, such as the sex and the age of the horse, and the discipline of use. Regarding the annual frequencies of tournament entries and placings the auction price of a horse was not predictive for its later sport performance. The prevalences of different radiographic findings in the horses' limbs had a negative effect on the quantity with which they were annually used in tournament sports, but did not preclude their successful participation in competitions.

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Table 1: Judging criteria in the different national tournament competitions in Germany

	Basic build-up competitions		Build-up competitions	Classical tournament competitions
Dressage	natural gaits, constitution, total impression as a riding horse including the temperament (RHQT)	rideability including the temperament and jumping ability allowing the immediate use as a riding horse (RHAP)	rideability, gaits, total impression (DY-A, -L, -M)	adequate state of training (horse); sitting the horse well, handling of the horse (rider) (DC-A, -L, -M, -S)
Show-jumping			rideability, jumping style, jumping ability (JY-A, -L, -M)	penalty points and/or speed (JC-A, -L, -M, -S)
Cross-country riding			rideability, jumping style, gallopade (CCY-A, -L, -M)	penalty points and/or speed (CCC-A, -L, -M, -S)
Hunters			rideability, jumping style, gallopade, total impression as a hunter, behavior in hunting field (HY-A, -L, -M)	
Driving			being driven, total impression as a driving horse (DrY-A, -L, -M)	state of training (horse); penalty points and/or speed; condition of horse(s) and carriage; skill of the driver (DrC-A, -L, -M, -S)

RHQT – riding horse quality test; RHAP – riding horse aptitude test; DY – dressage competitions for young horses; DC – classical dressage competitions; JY – jumping competitions for young horses; JC – classical jumping competitions; CCY – cross-country competitions for young horses; CCC – classical cross-country competitions; HY – competitions for young hunters; DrY – driving competitions for young horses; DrC – classical driving competitions;
A – level A (novice); L – level L (elementary); M – level M (medium); S – level S (advanced)

Table 2: Mean numbers of annual tournament entries and of registered competition results per year (annual placings) with their standard deviations (SD) in all probands with entries (n = 2,956) and all placed probands (n = 2,524), respectively, by the percentages of genes (PG) of different horse breeds

Horse breed	PG	Tournament entries		Tournament placings	
		No. of horses with entries	No. of annual entries ($\bar{x}$ ± SD)	No. of placed horses	No. of annual placings ($\bar{x}$ ± SD)
Hanoverian	0.0 - 50.5%	869	24.57 ± 23.98	738	6.86 ± 7.26
Warmblood	50.6 - 70.3%	1,139	23.42 ± 21.65	974	6.55 ± 6.46
	70.4 - 100.0%	948	27.41 ± 25.45	812	7.32 ± 7.24
Thoroughbred	0.0 - 18.0%	1,072	27.44 ± 25.38	929	7.38 ± 7.30
	18.1 - 27.0%	843	24.21 ± 23.33	717	6.64 ± 6.65
	27.1 - 81.3%	1,041	23.24 ± 21.84	878	6.57 ± 6.81
Trakehner	0.0%	275	27.25 ± 24.87	238	7.55 ± 7.16
	0.1 - 8.6%	1,640	25.25 ± 24.08	1,394	6.85 ± 7.02
	8.7 - 77.7%	1,041	24.20 ± 22.70	892	6.77 ± 6.82
Holstein	0.0%	2,501	24.21 ± 22.26	2,134	6.73 ± 6.75
Warmblood	0.1 - 5.2%	299	29.35 ± 29.84	253	7.75 ± 8.23
	5.3 - 46.9%	156	31.88 ± 31.20	137	8.02 ± 7.70
Arabians	0.0%	1,879	25.38 ± 24.38	1,614	6.97 ± 7.17
	0.1 - 3.6%	850	24.57 ± 22.49	722	6.82 ± 6.72
	3.7 - 32.8%	227	24.47 ± 22.04	188	6.50 ± 6.04
Other	0.0%	2,027	24.67 ± 22.90	1,729	6.81 ± 6.89
Warmblood	0.1 - 11.0%	533	26.60 ± 27.20	457	7.26 ± 7.42
breeds	11.1 - 50.0%	396	25.34 ± 22.89	338	6.89 ± 6.76

Table 3 : Mean numbers of annual tournament entries and of registered competition results per year (annual placings) with their standard deviations (SD) in all probands with entries (n = 2,956) and all placed probands (n = 2,524), respectively, by the disciplines of tournament competitions

Discipline		Tournament entries		Tournament placings	
		No. of horses with entries	No. of annual entries ($\bar{x}$ ± SD)	No. of placed horses	No. of annual placings ($\bar{x}$ ± SD)
Basic build-up competitions	RHAP	1,207	25.55 ± 19.03	457	8.89 ± 7.48
	RHQT	1,784	10.72 ± 10.56	1,086	4.41 ± 4.37
Dressage competitions	DY	1,854	20.88 ± 15.92	1,096	7.40 ± 6.60
	DR	864	27.92 ± 21.23	326	9.47 ± 8.69
	DC	2,071	25.16 ± 19.50	1,319	7.72 ± 8.10
Show-jumping competitions	JY	1,424	30.39 ± 21.60	877	9.37 ± 7.96
	JC	1,539	34.63 ± 23.70	903	9.34 ± 9.36
Cross-country competitions	CCY	104	37.34 ± 26.33	30	9.40 ± 7.99
	CCC	288	37.79 ± 23.66	71	9.17 ± 9.88
	HY	14	31.50 ± 20.15	6	3.57 ± 2.51
Driving competitions	DrY	7	34.75 ± 41.48	3	12.67 ± 18.48
	DrC	38	40.38 ± 36.71	21	22.78 ± 23.68
Other types of competitions	OC	265	44.34 ± 22.59	75	15.96 ± 16.44

RHAP – riding horse aptitude tests; RHQT – riding horse quality tests; DY – dressage competitions for young horses; DR – dressage competitions for riders; DC – classical dressage competitions; JY – jumping competitions for young horses; JC – classical jumping competitions; CCY – cross-country competitions for young horses; CCC – classical cross-country competitions; HY – competitions for young hunters; DrY – driving competitions for young horses; DrC – classical driving competitions; OC – other types of competitions.

Table 4: Distribution of tournament entries and of registered competition results (placings) in 1991-2002 by competition type

Competition type	No. of horses with entries; n = 2,956 (No. of entries; n = 346,719)	No. of placed horses; n = 2,524 (No. of placings; n = 67,953)
RHAP	1,207 (5,603)	457 (1,386)
RHQT	1,784 (10,788)	1,086 (3,648)
DY-A	1,783 (12,073)	989 (3,192)
DY-L	1,117 (8,273)	556 (2,005)
DY-M	515 (2,411)	217 (579)
DR-A	679 (2,370)	237 (445)
DR-L	431 (1,020)	127 (191)
DR-M	120 (204)	31 (38)
DC-A	1,826 (33,480)	1,001 (7,099)
DC-L	1,454 (40,967)	824 (8,262)
DC-M	926 (26,215)	481 (5,032)
DC-S	485 (16,175)	214 (3,365)
JY-A	1,389 (15,645)	833 (3,647)
JY-L	1,052 (15,875)	582 (3,424)
JY-M	572 (5,728)	269 (1,116)
JC-A	1,427 (40,814)	770 (7,127)
JC-L	1,090 (46,335)	626 (8,045)
JC-M	759 (38,549)	410 (5,792)
JC-S	369 (18,908)	150 (2,332)
CCY-A	96 (251)	25 (47)
CCY-L	44 (153)	17 (35)
CCY-M	5 (6)	3 (3)
CCC-A	278 (1,312)	70 (252)
CCC-L	48 (325)	19 (102)
CCC-M	17 (103)	5 (13)
CCC-S	4 (10)	1 (3)
HY-A	9 (16)	4 (5)
HY-L	5 (11)	1 (5)
HY-M	1 (4)	1 (1)
DrY	7 (13)	3 (5)
DrC-A	25 (569)	15 (216)
DrC-L	16 (172)	11 (72)
DrC-M	23 (542)	12 (145)
DrC-S	23 (1,185)	8 (210)
OC-A	254 (578)	70 (105)
OC-L	27 (36)	7 (9)

For abbreviations of the different competition types see annotations to Table 1.

Table 5: Prevalences of radiological findings in all probands (n = 3,725), in probands with entries (n = 2,956) and without entries (n = 769), and in probands with placings (n = 2,524) and without placings (n = 1,201) in 1991-2002

Radiographic finding		All probands (n = 3,725)	Probands with entries	Probands without entries	Probands with placings	Probands without placings
Osseous fragments	OFD	165 (4.43%)	131 (4.43%)	34 (4.42%)	115 (4.56%)	50 (4.16%)
	OFP	33 (0.89%)	27 (0.91%)	6 (0.78%)	23 (0.91%)	10 (0.83%)
	OFF	774 (20.78%)	634 (21.45%)	140 (18.21%)	537 (21.28%)	237 (19.73%)
	OFH	358 (9.61%)	291 (9.84%)	67 (8.71%)	248 (9.83%)	110 (9.16%)
Deforming arthropathy	DAD	165 (4.43%)	127 (4.30%)	38 (4.94%)	107 (4.24%)	58 (4.83%)
	DAP	76 (2.04%)	61 (2.06%)	15 (1.95%)	51 (2.02%)	25 (2.08%)
	DAF	45 (1.21%)	33 (1.12%)	12 (1.56%)	25 (0.99%)	20 (1.67%)
	DAH	451 (12.11%)	340 (11.50%)	111 (14.43%)	290 (11.49%)	161 (13.41%)
Pathologic changes in navicular bones (PCN)		807 (21.66%)	642 (21.72%)	165 (21.46%)	534 (21.16%)	273 (22.73%)

OFD – osseous fragments in distal interphalangeal joints; OFP – osseous fragments in proximal interphalangeal joints; OFF – osseous fragments in fetlock joints; OFH – osseous fragments in hock joints; DAD – deforming arthropathy in distal interphalangeal joints; DAP – deforming arthropathy in proximal interphalangeal joints; DAF – deforming arthropathy in fetlock joints; DAH – deforming arthropathy in hock joints

Table 6: Mean numbers of annual tournament entries and placings with their standard deviations (SD) by the probands' radiological state, in all probands with entries (n = 2,956) and in all probands with registered competition results (n = 2,254)

Radiographic finding			No. of annual tournament entries		No. of annual placings	
			n	$\bar{x}$ ± SD	n	$\bar{x}$ ± SD
Osseous fragments	OFD	present	131	24.39 ± 23.18	115	6.17 ± 6.11
		not present	2,271	25.03 ± 24.31	1,239	6.93 ± 7.08
	OFP	present	27	23.39 ± 23.17	23	6.64 ± 6.64
		not present	2,363	24.98 ± 24.27	2,004	6.88 ± 7.04
	OFF	present	634	24.45 ± 23.12	537	6.53 ± 6.62
		not present	1,804	25.18 ± 24.52	1,528	6.98 ± 7.12
	OFH	present	291	26.09 ± 23.48	248	6.93 ± 6.56
		not present	2,498	25.05 ± 23.87	2,125	6.89 ± 7.06
Deforming arthropathy	DAD	present	127	26.30 ± 26.09	107	7.21 ± 7.02
		not present	2,254	24.90 ± 24.16	1,912	6.86 ± 7.03
	DAP	present	61	20.75 ± 20.04	51	6.13 ± 7.03
		not present	2,325	25.07 ± 24.33	1,973	6.91 ± 7.06
	DAF	present	33	23.36 ± 27.88	25	6.32 ± 6.25
		not present	2,351	24.98 ± 24.21	1,998	6.88 ± 7.04
	DAH	present	340	24.12 ± 22.82	290	7.12 ± 7.36
		not present	2,449	25.30 ± 23.96	2,083	6.86 ± 6.95
Pathologic changes in navicular bones (PCN)		present	642	24.74 ± 24.36	534	6.75 ± 6.94
		not present	2,149	25.31 ± 23.68	1,843	6.96 ± 7.06

Table 7: Frequencies of selected questionnaire specifications given for horses with (n = 459) and without tournament entries (n = 29) and for horses with (n = 401) and without registered competition results (n = 87) in 1991-2002

Questionnaire specification	Horses with entries	Horses without entries	Horses with placings	Horses without placings
Died or put down	47 (10.24%)[a]	7 (24.01%)[d]	40 (9.98%)	14 (16.09%)
Use for breeding	47 (10.24%)[a]	10 (34.48%)[b]	38 (9.48%)[a]	19 (21.84%)[c]
Use for dressage riding	370 (80.61%)	21 (72.41%)	323 (80.55%)	68 (78.16%)
Use for show-jumping	198 (43.14%)	9 (31.03%)	172 (42.89%)	35 (40.23%)
Use for leisure riding	91 (19.83%)[a]	12 (41.38%)[c]	68 (16.96%)[a]	35 (40.23%)[b]
Intermission of intended use	306 (66.67%)	18 (62.07%)	265 (66.08%)	59 (67.82%)
Intermission of intended use in favor of breeding	19 (4.14%)[a]	4 (13.79%)[d]	16 (3.99%)	7 (8.05%)
Intermission of intended use because of lameness	239 (52.07%)	12 (41.38%)	207 (51.62%)	44 (50.57%)
Lameness at least once	279 (60.92%)	16 (55.17%)	243 (60.75%)	52 (59.77%)
Multiple lameness periods	169 (36.90%)	7 (24.14%)	146 (36.50%)	30 (34.48%)
Respiratory diseases	135 (29.41%)	10 (34.48%)	112 (27.93%)[a]	33 (37.93%)[e]

different letters indicating significant or almost significant differences:
[a b] : P < 0.001; [a c] : P < 0.01; [a d] : P < 0.05; [a e] : P < 0.10

Figure 1: Continuity of recorded tournament entries in 1991-2002 in probands born in 1988 or earlier (n = 539)

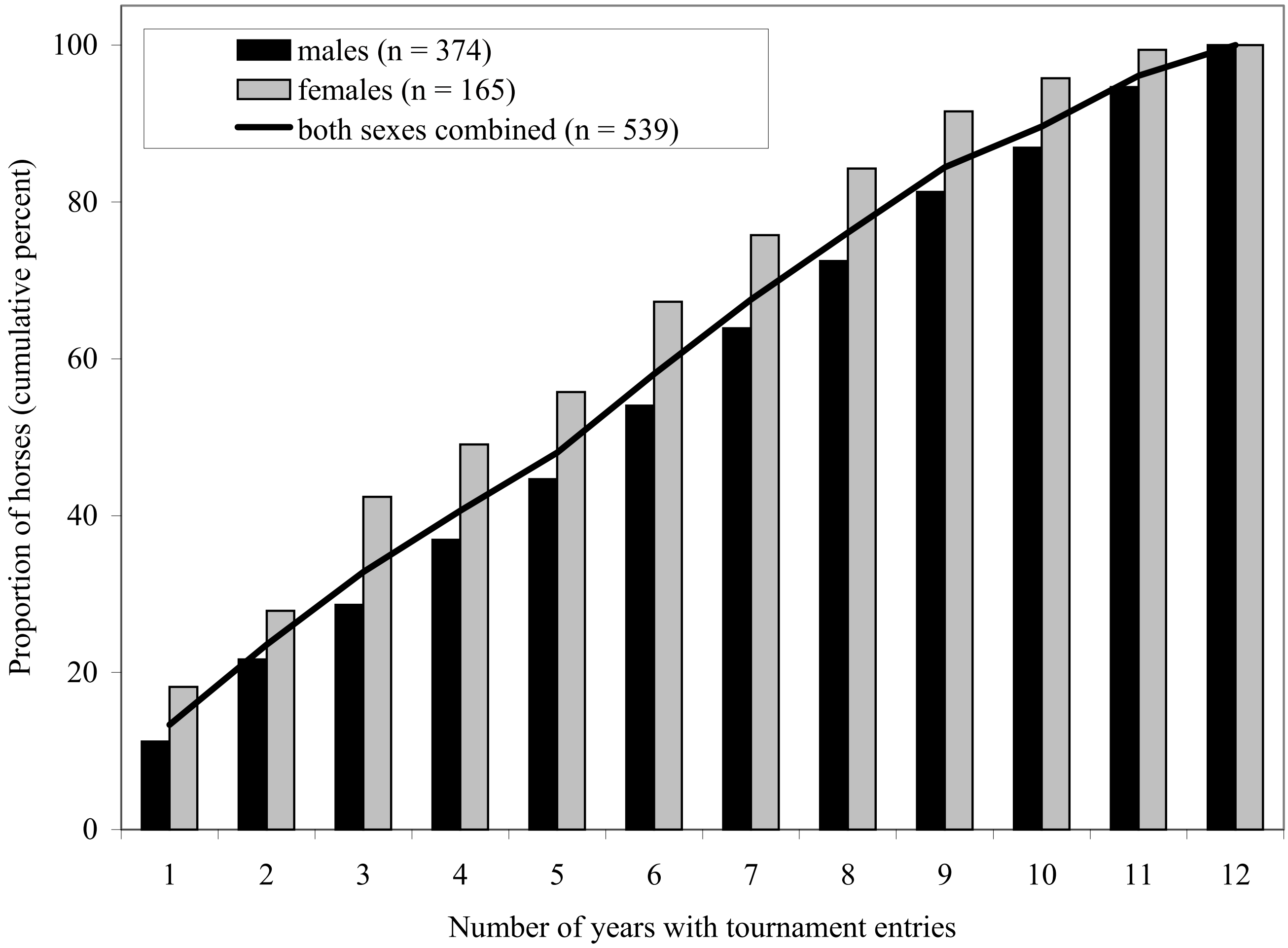


Figure 2: Number of annual tournament entries and of annual tournament placings in the auction horses by their price at auction

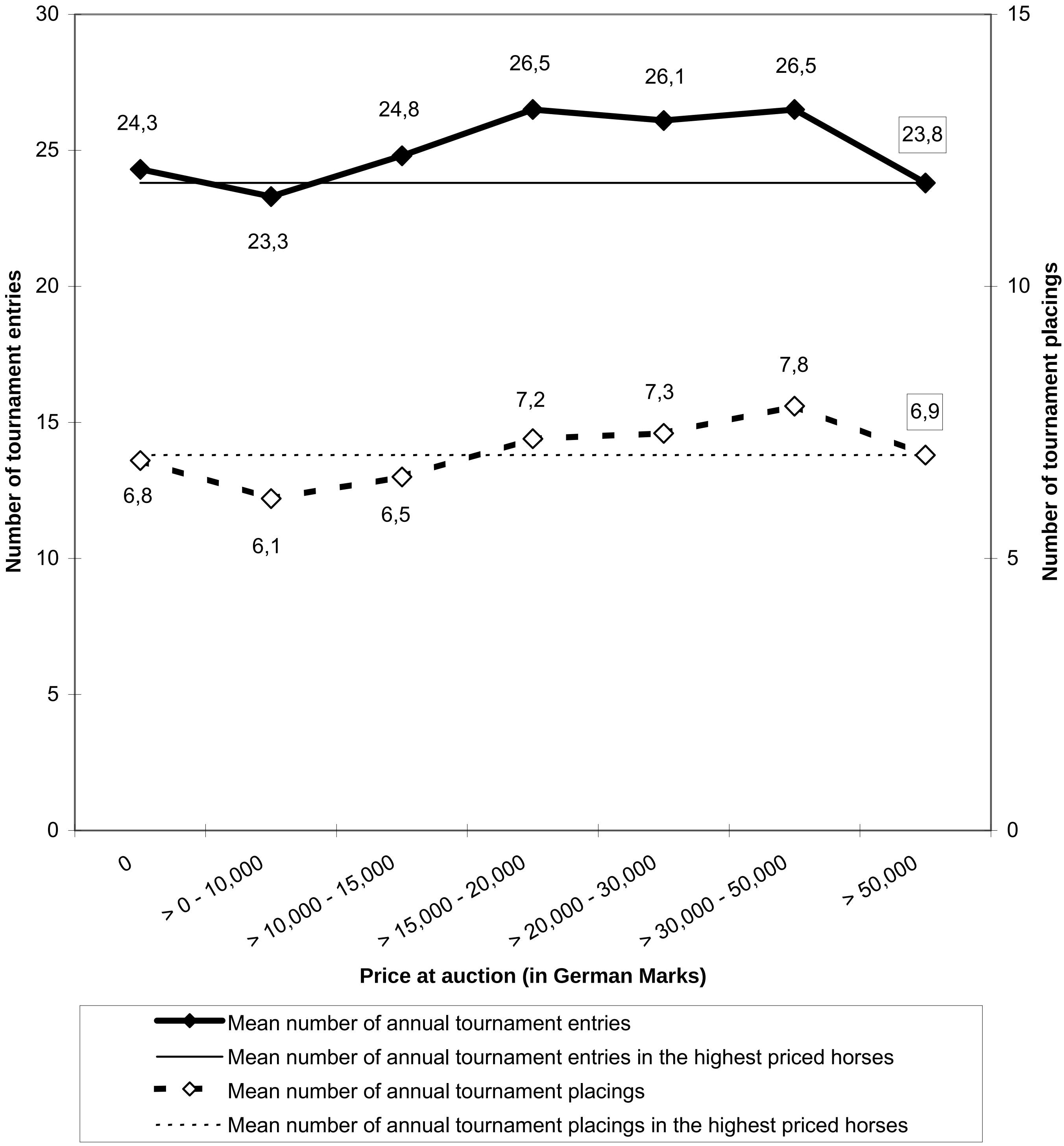


Figure 3: Distribution of tournament entries by the horses' age at entry

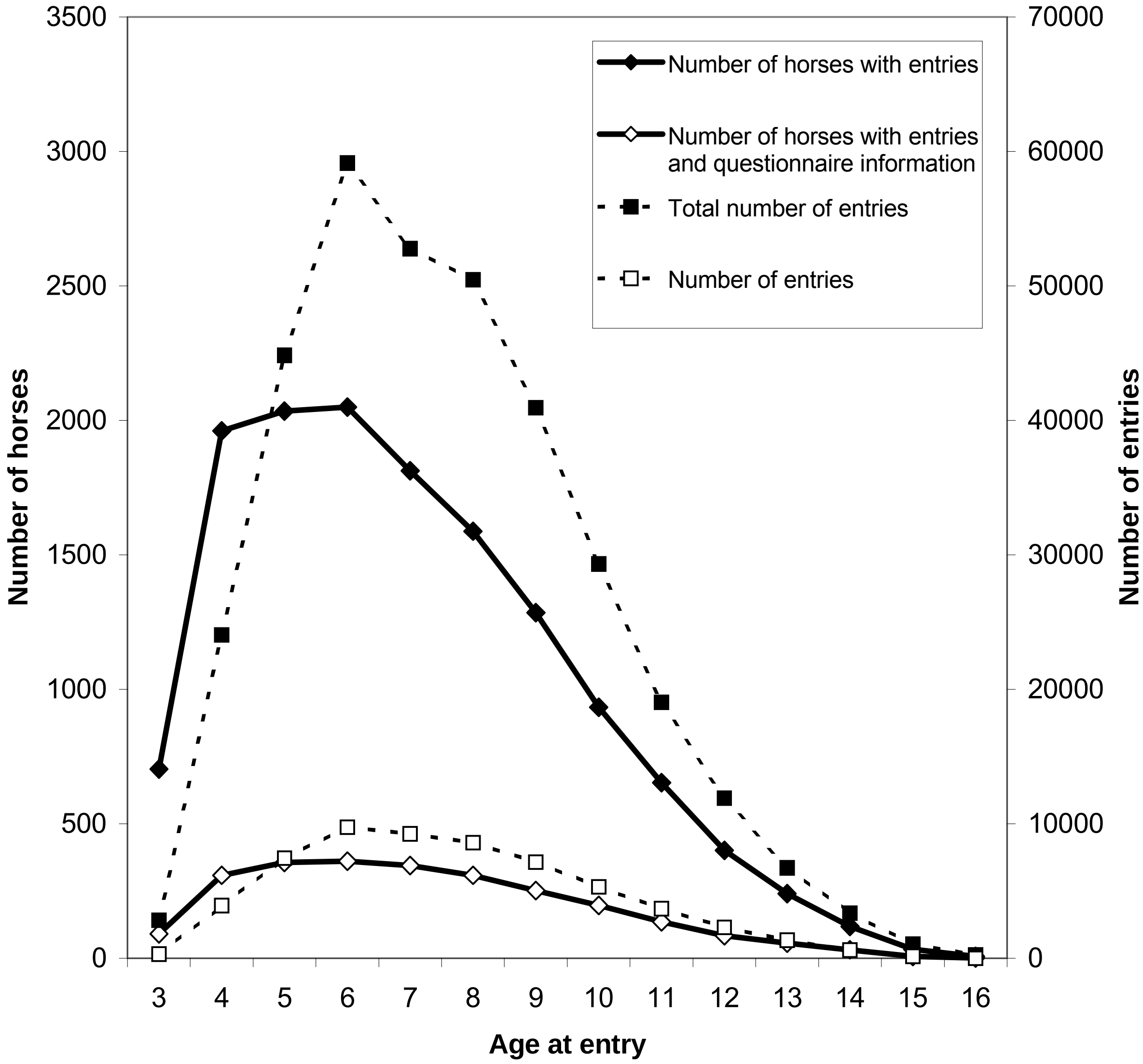
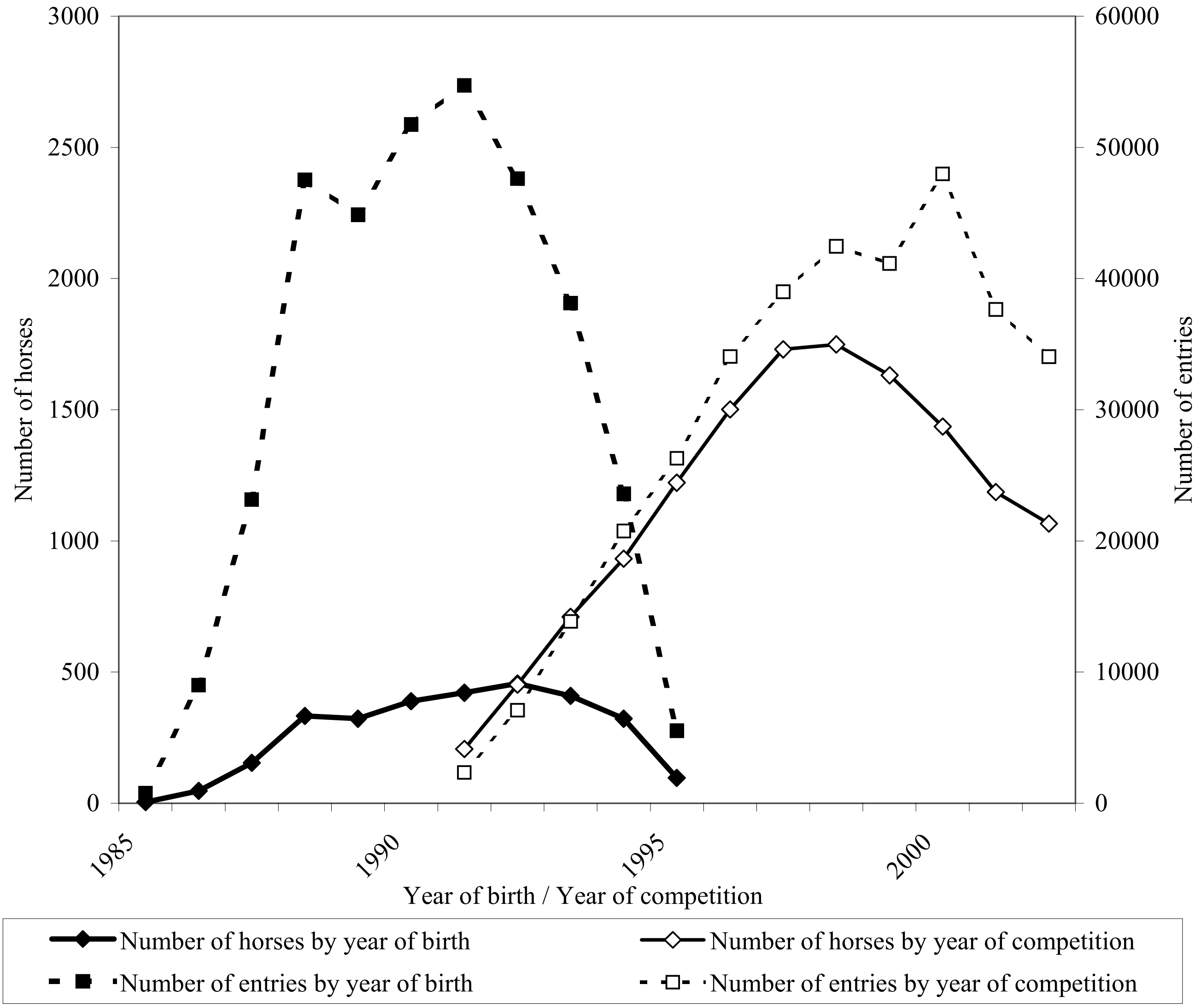


Figure 4: Distribution of tournament entries by the horses' years of birth and by the years of competition



Analysis of the correlations between sport performance and different radiographic findings in the limbs of Hanoverian Warmblood horses

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Keywords: riding horse; radiographic findings; performance; tournament competitions; dressage; show-jumping; heritability; additive genetic correlations

Summary

Reasons for performing study: The relation between particular radiological alterations and the performance of riding horses has not been defined yet.
Objectives: The additive genetic correlations between prevalent radiographic findings in the limbs of Warmblood riding horses and performance parameters were to be quantified.
Methods: Data on 3,725 Hanoverian Warmblood horses selected for sale at auctions in 1991-1998 were used for the present study. The numbers of annual entries (TE) and placings (TP) in tournament competitions in 1991-2002 were utilized as measures of performance in riding sports. Multivariate genetic analyses were performed in linear animal models using REML. The four most prevalent radiographic findings, i.e., osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN) were analyzed jointly with the performance parameters, i.e., TE and TP.
Results: In most cases, moderately negative additive genetic correlations were determined between the radiographic findings and the performance in sports.
Conclusions: Different radiological conditions in the equine limbs antagonize the performance of Warmblood riding horses, irrespective of their discipline of use.
Potential relevance: Breeding measures that allow for orthopaedic health trait should contribute to maximize the breeding progress in terms of sport performance.

Introduction

In the horse, loss of performance has been frequently related to locomotory problems (Rossdale *et al.* 1985; Hertsch 1992). In this connection, radiographic findings are often considered to be useful predictors of future orthopaedic soundness (Van Hoogmoed *et al.* 2003). However, given the high prevalences of radiographic abnormalities in clinically healthy horses, the general relevance of particular radiographic findings has been questioned (Milne 1972; Grøndahl and Engeland 1995; Storgaard Jørgensen *et al.* 1997). Nevertheless, the existence of radiographic alterations reduces the sale value as it poses an incalculable risk on the durability of the horse, irrespective of its intended use (Van Hoogmoed *et al.* 2003).

Horses showing radiological pathology may perform as well as unaffected contemporaries for years (Laws *et al.* 1993; Grøndahl and Engeland 1995). But studies on the long-term effects of different radiologically manifesting bone and joint diseases mostly confined to racehorses in which performance is easier and more objectively measurable than in riding horses. In the later, investigations are complicated by their varying kind and amount of use, resulting in definition problems of performance. In the sport horse, competition data provide some basis for statistical analyses. But suboptimal recording of data and hardly assessable preselection of horses represent common limitations of riding horse data analysis (Reinhardt 1998). The objective of the present study was to quantify the genetic correlations between prevalent radiographic findings in the limbs of Warmblood riding horses and their performance in sports. Implications for breeding strategies that account for orthopaedic health traits should be derived.

Material and Methods

3,748 Hanoverian Warmblood horses have been selected for sale at riding horse auctions of the Society of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V., VHW) in Verden on the Aller, Germany, in 1991-1998. Preliminary to the auctions, they all underwent a standardized radiographic examination of their limbs, the results of which have been analyzed by the authors (Stock *et al.* 2004a, b, c, d, e).

3,725 of these horses for which pedigree information was available from a unified animal ownership database (Vereinigte Informationssysteme Tierhaltung w.V., VIT) in Verden on the Aller, Germany, were included in the present study. 3,480 of the probands were actually offered for sale at one of the 42 riding horse auctions held in 1991-1998 (auction horses). The remaining 245 horses were also selected for auction sale, but then pulled out of auction for different reasons. There were twice as much male horses (mostly geldings, only few stallions) than female horses among the auction candidates. At the time of selection for auction sale, most of the horses were 3 (30.4%) or 4

(50.9%) years old (mean 3.9 years). Concerning the anticipated suitability of the horses, three-fourths of the auction horses were offered as primarily talented for dressage (57.9%) or as talented for both dressage and show-jumping (18.6%). Only 23.5% of the horses had been advertized in the official auction catalogues with remarkable jumping ability.

Osseous fragments in fetlock (OFF) and hock joints (OFH), deforming arthropathy in hock joints (DAH), and pathologic changes in navicular bones (PCN) were found to be the most prevalent radiographic findings in the probands. Therefore, more detailed analyses confined to these four radiographic findings. 1,850 horses (49.7% of the probands) showed at least one of these findings. For most of them (1,367 horses, i.e., 73.9% of the affected horses) only one kind of radiological alterations was documented. However, two, three or all four different kinds of radiological findings were found in 23.1%, 2.9% and 0.1% of affected horses. The prevalences of the individual radiographic findings were 20.8% for OFF, 9.6% for OFH, 12.1% for DAH, and 21.7% for PCN.

The radiographic findings were analyzed as four separate binary traits, with 1 denoting the presence and 0 denoting the absence of OFF, OFH, DAH and PCN, respectively. Simple and multiple analyses of variance were performed using the procedure GENMOD (Generalized Linear Model) of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2002). On this basis, models were developed for the genetic analyses. In order to avoid incalculable bias in the estimation of genetic parameters, the models should contain only significant fixed effects (significance limit of P = 0.05) for which genetic correlations or confounding with genetic groups could be precluded. Therefore, neither height at withers nor sire effects, the anticipated suitability of the horse or its region of origin (breeder, exhibitor) were included in the models. Accordingly, for OFF and OFH only the fixed effect of the auction (for auction horses the date of auction offer – 42 riding horse auctions, for horses pulled out of auction the year of selection for auction sale – 8 years from 1991-1998) and the fixed effect of the horse's sex (male, i.e., stallion or gelding, female) were considered. For DAH and PCN the fixed effect of the auction age (3 years old, 4 years old, 5 years old or older) was additionally included in the model.

Osseous fragments in fetlock joints (OFF) $y_{ijp} = \mu + Auction_i + Sex_j + e_{ijp}$

Osseous fragments in hock joints (OFH) $y_{ijp} = \mu + Auction_i + Sex_j + e_{ijp}$

Deforming arthropathy in hock joints (DAH) $y_{ijkp} = \mu + Auction_i + Sex_j + AuctAge_k + e_{ijkp}$

Pathologic findings in navicular bones (PCN) $y_{ijkp} = \mu + Auction_i + Sex_j + AuctAge_k + e_{ijkp}$

with $y_{i...p}$ = radiographic finding in the $i...p$-th horse,

μ = model constant,

$Auction_i$ = fixed effect of the date of auction (i = 1 - 50),

Sex_j = fixed effect of the sex (j = 1 - 2),

$AuctAge_k$ = fixed effect of the age group at the time of auction (k = 1 - 3), and

$e_{i...p}$ = residual error.

Sports data including tournament entries and records of successful tournament participation in 1991-2002 were taken from the central national database at the VIT in Verden. In that, competitions in riding sports disciplines (dressage, show-jumping, cross-country riding) and driving competitions are allowed for that have been held in Germany at tournaments of regional (category B) and supra-regional (category A) importance.

Because of the current documentation practices in equestrian sports, information on effective starts were largely missing. Until recently, only the competition results of successful tournament participants have been recorded. The development and increasing use of a more extensive recording system (tournament organization and information system, TORIS) that allows for all tournament starters did not yet benefit the data quality in 1991-2002.

In order to ensure sufficient homogeneity of the utilized data, the analyses confined to the following performance parameters that could be universally derived from the documentation. The number of annual tournament entries (TE) and the number of annual tournament placings (i.e., of registered competition results per year; TP), annual earnings (AE), and sum of weighted ranking points per year (WR). For the later, ranking points were assigned to the attained place in competition. Competition winners gained most points, horses placed second, third etc. gained declining numbers of points. The number of ranking points was then multiplied by a factor reflecting the level of the competition the horse has successfully participated in. The weighting factors increased with increasing demands from 1 for build-up competitions to 5 for advanced level competitions. Because of the skewed distributions of the imposed performance parameters, the performance traits were analyzed as categorical traits with 5 to 9 categories. The allocation of categories aimed at the approximate normalization of the data. In this respect, categorization was found to be more beneficial than taking the logarithm of the original values. Nevertheless, for comparison purposes the sum of annual earnings was also analyzed linearly after taking the logarithm (logAE).

2,956 probands (79.4%) had at least one tournament entry, and 2,524 probands (67.8%) had at least one registered competition result in 1991-2002. Because less than 10% of the probands had records for cross-country or driving competitions, these disciplines were excluded from further analyses. Separate analyses were then performed for those disciplines in which sufficient numbers of horses had records, i.e., for basic build-up competitions, for dressage competitions and for show-jumping competitions. Altogether 2,200 horses had entries and 1,336 horses had placings in basic build-up competitions. The corresponding numbers of probands with entries and placings were 2,273 and 1,535 for dressage competitions, and 1,775 and 1,079 for show-jumping competitions. A detailed description of the distribution of competition data is given by Stock and Distl (2004).

For simple and multiple analyses of variance, and the development of models the procedure GLM (General Linear Model) of the Statistical Analysis System (SAS), version 8.2 (SAS Institute, Cary, NC, 2002), was used. The same systematic effects and the same combinations of fixed effects were found to have a significant influence on the different performance parameters. Accordingly, one uniform model was used for the sports data analyses. As in the models for radiographic findings, the individual auction and the sex of the horse were considered as fixed effects. In addition, the fixed effect of the auction price (not sold, up to 10,000 DM, more than 10,000 and up to 15,000 DM, more than 15,000 and up to 20,000 DM, more than 20,000 and up to 30,000 DM, more than 30,000 and up to 50,000 DM, more than 50,000 DM), the year of competition (12 years from 1991 to 2002), the horse's competing age (3-10 years of age considered individually, 11 and 12 years of age, and 13 years of age or older combined) and a combined competition type variable were included in the model. The later accounted for the interaction of the different types of competitions for which tournament entries or placings were recorded. There were only two different competition types in the basic build-up competition data (riding horse aptitude test, riding horse quality test), but nine different competition types in dressage (dressage competitions for young horses of level A, L and M, dressage competitions for riders of level A and L or M, and classical dressage competitions of level A, L, M and S) and seven different competition types in show-jumping (jumping competitions for young horses of level A, L and M, and classical jumping competitions of level A, L, M and S).

$$y_{ijlmnop} = \mu + Auction_i + Sex_j + AuctPrice_l + Year_m + CompAge_n + Comp_o + e_{ijlmnop}$$

with $y_{i \ldots p}$ = competition performance in the $i \ldots o$-th horse,

μ = model constant,

$Auction_i$ = fixed effect of the date of auction (i = 1 - 50),

Sex_j = fixed effect of the sex (j = 1 - 2),

$AuctPrice_l$ = fixed effect of the auction price (l = 1 - 7),

$Year_m$ = year of competition (m = 1 – 12),

$CompAge_n$ = age at entry or at successful tournament participation (n = 1 - 10),

$Comp_o$ = combined variable of recorded competition types (o = 1 - 147), and

$e_{i \ldots p}$ = residual error.

In the first section of genetic analyses, the five different derived performance parameters (TE, TP, AE, logAE, WR) were considered in order to investigate their genetic and residual correlation.

Since TE and TP were considered to represent the best indicators for the amount of the horses' use and performance in sports, the main section of genetic analyses comprised the considered radiographic findings (OFF, OFH, DAH and PCN) and the performance parameters TE and TP.

Genetic parameters were estimated multivariately with Restricted Maximum Likelihood (REML) using VCE4 Version 4.2.5 (Groeneveld 1998). Linear animal repeatability models were applied in order to account for the fact that one horse could have competition records in successive years.

$$y_{qrs} = \mu + F_q + p_r + a_r + e_{qrs}$$

with y_{qrs} = observation in the *qrs*-th animal,
μ = model constant,
F_q = fixed effect component,
p_r = random permanent environmental effect of the *r*-th animal, and
a_r = random additive genetic effect of the *r*-th animal, and
e_{qrs} = residual error.

Different combinations of traits entered the genetic analyses. However, the estimates obtained from the different multivariate analyses were very similar among each other. Therefore, only mean values of heritabilities (h^2), additive genetic (r_g) and residual correlations (r_e) and the corresponding standard errors (s_{h^2}, s_{rg}, s_{re}) will be reported. Concerning the binary data (radiographic findings), the heritability estimates and the estimated residual correlations were transformed from the observed scale to the underlying liability scale (Dempster and Lerner 1950; Vinson *et al.* 1976). The applicability of the transformation factors derived by Dempster and Lerner (1950) to the present data set has been substantiated previously (Stock *et al.* 2004c) so that only the transformed values are given.

Results

Table 1 shows the heritability estimates and the estimated additive-genetic and residual correlations for the different performance parameters in basic build-up, dressage and show-jumping competitions. In general, the success-related performance parameters TP, AE, logAE and WR were highly positively correlated additive genetically (r_g = 0.88-1.00). The correlation between TP and logAE in dressage competitions meant the only exception. However, the estimates of the residual correlations were also considerably high between these traits (r_e = 0.66-0.88). Contrarily, the moderately to highly positive additive genetic correlations between TE and the success-related parameters TP, AE, logAE and WR (r_g = 0.37-1.00) were accompanied by negligibly small residual correlations (r_e = 0.001-0.002). The corresponding standard errors amounted to s_{h^2} = 0.01-0.02, s_{rg} = 0.00-0.21, and s_{re} = 0.004-0.007.

Given the (genetic) equivalence of the four success-related performance parameters, it appeared to be justifiable to consider only one of these traits (TP), additionally to TE, in the further analyses.

The results of the multivariate genetic analyses including the radiographic findings OFF, OFH, DAH and PCN, and the performance parameters TE and TP are given in Tables 2 to 4 for basic build-up, dressage and show-jumping competitions. In all considered disciplines and in all combinations of traits, the heritability and correlation estimates for the radiographic findings were quite consistent. The heritability estimates were h^2 = 0.17 for OFF, h^2 = 0.31-0.33 for OFH, h^2 = 0.12-0.13 for DAH, and h^2 = 0.32-0.33 for PCN. Moderately positive genetic correlations were estimated between OFF and DAH (r_g = 0.36-0.45), and moderately negative genetic correlations between OFF and OFH (r_g = -0.28 to -0.30), OFH and DAH (r_g = -0.30 to -0.39), and DAH and PCN (r_g = -0.41 to –0.43). The estimated residual correlations were mostly close to zero (r_e = -0.08 to 0.13). The order of magnitude of the heritabilities estimated for the performance parameters differed considerably between the sports disciplines. The heritability estimates for TE in the basic build-up competitions (h^2 = 0.03 ± 0.01) and in dressage competitions (h^2 = 0.04 ± 0.01) were by the factor three smaller than the heritability estimates for TE (h^2 = 0.13 ± 0.01) in show-jumping competitions. The heritability estimate for TP was lowest in dressage competitions (h^2 = 0.01 ± 0.01), whilst the heritability of TP was estimated at h^2 = 0.04 in both, basic build-up and show-jumping competitions. As opposed to the basic build-up competitions, the heritability estimate for TP was well below that for TE in dressage and show-jumping competitions. Independent of the discipline, TE and TP were found to be highly positively correlated additive genetically (r_g = 0.56-1.00), in connection with negligible residual correlations (r_e = 0.001-0.003). The additive genetic correlations estimated between the radiographic findings and the performance parameters behaved partly different in the considered sports disciplines. DAH and PCN were found to be moderately negatively correlated additive genetically with both, TE and TP in basic build-up competitions (r_g = -0.15 to -0.77). OFF were negatively correlated with TE (r_g = -0.13), but positively correlated with TP (r_g = 0.26) in this discipline. The opposite was true for OFH (r_g = 0.24 to TE, and r_g = -0.09 to TP). Concerning dressage competitions OFH, DAH and PCN were correlated moderately to highly negatively with both TE and TP (r_g = -0.14 to -0.74). OFF appeared to be genetically independent of TE in dressage competitions (r_g = 0.07 ± 0.16), but showed a highly negative additive genetic correlation to TP in dressage competitions (r_g = -0.53 ± 0.40). Concerning show-jumping competitions only PCN showed a negative additive genetic correlation to both, TE and TP (r_g = -0.19 to -0.68). Moderately positive genetic correlations of OFF and OFH to TE in jumping competitions (r_g = 0.13-0.24) opposed to slightly (OFF; r_g = -0.05 ± 0.13) to moderately (OFH; r_g = -0.42 ± 0.12) negative additive genetic correlations to TP in jumping competitions. Whilst DAH was found to be genetically independent of TE (r_g = 0.00 ± 0.01) and even positively correlated with TP in show-jumping competitions (r_g = 0.46 ± 0.20). The residual correlations between the radiographic findings and the performance parameters were all close to zero (r_e = 0.000-0.002).

Discussion

The objective of this study was to investigate the genetic correlations between prevalent radiographic findings in the limbs of Warmblood riding horses and their performance in sports.

Osseous fragments in fetlock and hock joints, deforming arthropathy in hock joints and pathologic changes in navicular bones have been previously identified as the most important radiographic findings in the limbs of young Hanoverian Warmblood horses selected for sale at auction (Stock *et al.* 2004a). Therefore, the present investigation on the performance correlations of radiological abnormalities confined to these four alterations.

The selection for auction sale predestinated our probands to have a sports career. However, a relevant proportion of horses might have been resold after auction, possibly to horsemen less interested in sport competitions. Therefore, the propensity of the horse owners to participate in tournaments themselves or to see their horses competing was likely to differ considerably. Nevertheless, about 75 percent of the probands had records of tournament entries and/or of successful tournament participation in the study period which should have covered the prime time of use in sports of most horses (Stock and Distl 2004). It is not possible to deduce any reasons for almost 25 percent of former auction candidates not having any competition record in the study period. Health problems of the horses, and lameness problems in particular, are as conceivable as the temporary or even permanent use of mares for breeding, the exclusive use as leisure horses or personal reasons of the riders or owners. Generally, the rider's influence on the amount of use and success of a riding horse in tournaments is substantial (Von Velsen-Zerweck 1995). Despite the fact that information on the riders' quality was not available for the present study, we could at least indirectly account for some management aspects. The individual date of auction and the auction price had a significant influence on the amount of competing activity of the probands and should in some respects reflect the notions and expectations of the purchaser. A tournament entry in a particular year makes it probable that the respective horse was intended to compete in this season. Therefore, quantitative measures of the horses' use in sports should refer to the active years in sports only. The annual number of tournament entries and the number of registered competition results per year appeared to most appropriately reflect the amount of use of sports horses. Having an entry record does not mean that the horse actually starts in the respective competition. But it indicates that the horse is fit and performs well enough for competing, at least in the owners or riders opinion. The registration of successful tournament participation attests the horse's ability to compete at an above-average level.

Literature provides few information on the effect of radiological alterations on the performance of Warmblood riding horses. Most reports refer to racehorses in which the number of starts, the number of winnings or the earnings are taken as measures of the annual or the lifetime performance of the individual horse. In many cases, no clearly negative effect of radiographic findings on the racing performance could be derived (Milne 1972; Laws *et al.* 1993; Beard *et al.* 1994; Grøndahl and Engeland 1995; Storgaard Jørgensen *et al.* 1997; Roneus *et al.* 1998). However, the strain put on the limbs of Thoroughbred racehorses or of Standardbred trotters differs considerably from the strain put on the locomotory systems of a riding horse. Furthermore, the range of use of Warmblood horse is definitely wider than that of a racehorse. But the choice of the probands of this study allowed for a high percentage of horses having a sports career and, therefore, becoming appraisable via competition data. In riding horses, several competition performance traits have been defined, including the sum or the logarithmized sum of the annual earnings, the highest competition level reached, the absolute or relative rank or the square root of the rank in competition or cumulative ranking points (Huizinga and van der Meij 1989; Meinardus and Bruns 1989; Reilly et al. 1998; Hassenstein *et al.* 1999a, b; Aldrigde *et al.* 2000; Ricard and Chanu 2001; Wallin *et al.* 2003). Referring to the individual competition, the advertized earning, the number of penalty points in show-jumping or the score in dressage have been investigated (Meinardus and Bruns 1989; Ricard and Chanu 2001). As in the present investigation, in general highly positive genetic correlations have been found between the different measures of competition performance, independent of the considered sports disciplines (Hassenstein *et al.* 1999b; Ricard and Chanu 2001). However, in the present data the number of annual tournament entries in jumping horses meant some exception. The additive genetic correlation to the success related performance parameters was only moderately positive. This might be caused by differing competition planning and varying competing conditions in young horses and dressage horses on the one hand and jumping horses on the other hand. Horses with records in show-jumping competitions had on the average considerably more entries per year than horses with records in basic build-up and dressage competitions (Stock and Distl 2004). But given the noticeably higher numbers of starters in jumping competitions, show-jumpers have generally a smaller chance to get placed than horses in build-up competitions and dressage horses, resulting in relatively lower numbers of tournament placings.

The choice of the performance measure for detailed analyses has to be made in consideration of the investigated population (breeding aim, main use), the focus of the study and the data structure (age distribution, competition types, available information on entries/starts/placings). The annual numbers of entries and of placings should best reflect the continuity of use in equestrian sports. Therefore, these traits were investigated jointly with the parameters of the orthopaedic state that should be tested for their effect on the usability and performance of sport horses.

The relevantly heritable character of the radiographic findings that have been included in the present study, has been substantiated previously (Stock *et al.* 2004c, d, e). Contrarily, the performance of riding horses to a lesser extent depends on genetic factors. The heritability of different parameters reflecting the performance in riding horse tournament competitions was estimated to be low (h^2 = 0.01-0.19; Huizinga and van der Meij 1989; Meinardus and Bruns 1989; Reilly *et al.* 1998; Hassenstein *et al.* 1999a; Aldrigde *et al.* 2000; Ricard and Chanu 2001). The repeatability of placing-related parameters (R = 0.09-0.18; Meinardus and Bruns 1989; Reilly *et al.* 1998; Aldrigde *et al.* 2000) was found to be lower than the repeatability of earning-related parameters (R = 0.42-0.45; Ricard and Chanu 2001). Nevertheless, given the extensive genetic equivalence of the riding horse performance parameters, they should all be utilizable for genetic correlation analyses.

The few studies that investigated the performance of Warmblood riding horses in relation to their orthopaedic status at a young age, did not supply strong evidence for a negative effect of limb alterations (r_g = -0.04 to 0.20; Holmstrøm and Philipsson 1993; Willms *et al.* 1996; Wallin *et al.* 2003). However, there are no reports on the correlation between individual bone or joint diseases and performance in dressage and show-jumping competitions. Previous investigators only accounted for the overall orthopaedic status of the horse (Holmstrøm and Philipsson 1993; Wallin *et al.* 2003), narrowing the comparability to the results of the present study.

Pathologic changes in navicular bones showed a negative additive genetic correlation to both, the number of annual tournament entries and the number of annual tournament placings, in basic build-up competitions as well as in dressage and show-jumping competitions. Radiological alterations of navicular bones, indicative of navicular disease, are not infrequently detected in young and clinically healthy horses (Kaser-Hotz and Ueltschi 1992). However, podotrochlosis is known as the occupational disease of the riding horse, leading to lameness problems primarily in horses of about 7 to 9 years of age (Wright 1993). The probands of this study had competition records at an age of between 3 and 16 years, with a large part of the competition data referring to the age group of 6 to 9 year old horses. However, there was an age limitation for the basic build-up competitions inasmuch only 3- and 4-year-old horses were allowed to participate. Therefore, the estimated negative effect of an abnormal radiological appearance of navicular bones at a young age might not exclusively ascribed to the common age of manifestation that had been reached. Some sub-clinical impairment might have caused less appealing gaits, deterring the owner or rider already from having an entry in basic competitions in which mainly the gaits and natural abilities of the horse are judged (riding horse aptitude test, riding horse quality test). Pathologic changes in navicular bones antagonize the competing activity and the success in tournament competitions in all riding sports disciplines at least genetically.

Deforming arthropathy in hock joints were clearly negatively correlated additive genetically to performance in basic build-up and dressage competitions. The limited range of motion in the hock, caused by bony remodelling, is likely to interfere with expressive gaits required for promising tournament participation in these disciplines. However, this does not apply to show-jumping competitions. Show-jumping puts considerable strain on the equine joints, and on the hock joints in particular (Hertsch 1992). The more extensive the horse is used for jumping, the more likely it is to develop joint deformations that do not necessarily vitiate their jumping abilities and their use and success in jumping competitions.

Inconsistent results were obtained concerning the genetic correlations between osseous fragments in fetlock and hock joints on the one hand and the number of tournament entries and placings on the other hand. The positive additive genetic correlation estimated between osseous fragments in fetlock joints and the competing success in basic build-up competitions contrasted to the negative correlation between this radiographic findings and the competing success in dressage and show-jumping competitions. This might be due to some long-term effect on the performance of affected horses. However, the high standard errors indicate that there might be considerable inter-individual variation. Osseous fragments in hock joints were negatively correlated additive genetically to the number of tournament placings in all disciplines, and to the number of entries in dressage competitions. This agrees with literature inasmuch tarsocrural osteochondrosis, the underlying condition of most osseous fragments in hock joints, usually earlier leads to clinical signs than osteochondrosis in fetlock joints (Jeffcott 1991). Although the genesis of osseous fragments in fetlock joints is less uniform, and not all osseous fragments in metacarpo- and metatarsophalangeal joints are ascribable to the osteochondrosis complex, the greater importance of osseous fragments in hock than in fetlock joints seems to be of more universal validity.

Conclusions

Mostly negative genetic correlations have been determined between radiographic findings in the limbs and the sports performance of Hanoverian Warmblood horses. Different radiological conditions might therefore antagonize the performance of the riding horse, irrespective of the discipline of use. Given the relevantly heritable character of osseous fragments in fetlock and hock joints, of deforming arthropathy in hock joints and of pathologic changes in navicular bones, selective breeding for radiologically normal horses should be practicable. The addition of orthopaedic health traits to the current selection traits should maximize the breeding progress in terms of dressage and show-jumping performance.

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TABLE 1: Heritability estimates (bold; on the diagonal), additive genetic correlations (above the diagonal) and residual correlations (below the diagonal) with their standard errors for different performance parameters, i.e., the number of annual tournament entries (TE), the number of annual tournament placings (TP), the sum of annual earnings (AE), the logarithmized sum of annual earnings (logAE), and the sum of weighted ranking points per year (WR), concerning basic build-up competitions (first line), dressage competitions (second line), and show-jumping competitions (third line)

	TE	TP	AE	logAE	WR
TE	$\mathbf{0.030^{0.009}}$ $\mathbf{0.037^{0.009}}$ $\mathbf{0.113^{0.018}}$	$1.000^{\text{n.e.}}$ $1.000^{0.001}$ $0.562^{0.161}$	$1.000^{0.000}$ $1.000^{0.000}$ $0.510^{0.171}$	$1.000^{\text{n.e.}}$ $1.000^{\text{n.e.}}$ $0.304^{0.145}$	$1.000^{\text{n.e.}}$ $0.925^{0.219}$ $0.371^{0.214}$
TP	$0.003^{\text{n.e.}}$ $0.002^{0.005}$ $0.001^{0.006}$	$\mathbf{0.036^{0.024}}$ $\mathbf{0.010^{0.010}}$ $\mathbf{0.039^{0.016}}$	$0.988^{0.102}$ $1.000^{\text{n.e.}}$ $1.000^{\text{n.e.}}$	$1.000^{\text{n.e.}}$ $-1.000^{\text{n.e.}}$ $0.988^{\text{n.e.}}$	$1.000^{\text{n.e.}}$ $1.000^{0.000}$ $0.884^{0.070}$
AE	$0.002^{0.009}$ $0.001^{0.005}$ $0.001^{0.007}$	$0.887^{0.006}$ $0.880^{\text{n.e.}}$ $0.864^{\text{n.e.}}$	$\mathbf{0.055^{0.021}}$ $\mathbf{0.019^{0.014}}$ $\mathbf{0.040^{0.018}}$	$0.924^{\text{n.e.}}$ $1.000^{\text{n.e.}}$ $0.875^{0.093}$	$1.000^{0.000}$ $0.811^{0.232}$ $0.961^{0.041}$
logAE	$-0.002^{\text{n.e.}}$ $-0.002^{\text{n.e.}}$ $0.001^{0.026}$	$0.736^{\text{n.e.}}$ $0.784^{\text{n.e.}}$ $0.740^{\text{n.e.}}$	$0.951^{\text{n.e.}}$ $0.885^{\text{n.e.}}$ $0.850^{0.002}$	$\mathbf{0.018^{\text{n.e.}}}$ $\mathbf{0.001^{\text{n.e.}}}$ $\mathbf{0.020^{0.005}}$	$1.000^{\text{n.e.}}$ $1.000^{\text{n.e.}}$ $0.458^{\text{n.e.}}$
WR	$0.001^{\text{n.e.}}$ $0.001^{0.004}$ $0.001^{0.005}$	$0.918^{\text{n.e.}}$ $0.692^{0.005}$ $0.663^{0.006}$	$0.934^{0.003}$ $0.787^{0.004}$ $0.793^{0.004}$	$0.830^{\text{n.e.}}$ $0.642^{\text{n.e.}}$ $0.596^{\text{n.e.}}$	$\mathbf{0.037^{0.017}}$ $\mathbf{0.016^{0.013}}$ $\mathbf{0.038^{0.016}}$

n.e. – not estimable

TABLE 2: Heritability estimates (bold; on the diagonal), additive genetic correlations (above the diagonal) and residual correlations (below the diagonal) with their standard errors for the prevalences of osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), and for the performance parameters number of annual tournament entries (TE) and number of annual tournament placings (TP) in basic build-up competitions

	OFF	OFH	DAH	PCN	TE	TP
OFF	**0.166 $^{0.039}$**	-0.276 $^{0.145}$	0.447 $^{0.166}$	-0.008 $^{0.098}$	-0.134 $^{0.196}$	0.262 $^{0.271}$
OFH	0.077 $^{0.051}$	**0.325 $^{0.057}$**	-0.393 $^{0.186}$	-0.072 $^{0.078}$	0.237 $^{0.185}$	-0.086 $^{0.228}$
DAH	-0.083 $^{0.044}$	0.037 $^{0.034}$	**0.118 $^{0.038}$**	-0.426 $^{0.172}$	-0.546 $^{0.259}$	-0.770 $^{0.241}$
PCN	0.010 $^{0.037}$	0.010 $^{0.045}$	0.124 $^{0.047}$	**0.325 $^{0.043}$**	-0.639 $^{0.141}$	-0.148 $^{0.190}$
TE	0.000 $^{0.008}$	0.000 $^{0.008}$	0.000 $^{0.008}$	0.000 $^{0.008}$	**0.025 $^{0.010}$**	1.000 $^{\text{n.e.}}$
TP	0.000 $^{0.013}$	0.000 $^{0.014}$	0.000 $^{0.014}$	0.000 $^{0.013}$	0.003 $^{\text{n.e.}}$	**0.039 $^{0.019}$**

n.e. – not estimable

TABLE 3: Heritability estimates (bold; on the diagonal), additive genetic correlations (above the diagonal) and residual correlations (below the diagonal) with their standard errors for the prevalences of osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), and for the performance parameters number of annual tournament entries (TE) and number of annual tournament placings (TP) in dressage competitions

	OFF	OFH	DAH	PCN	TE	TP
OFF	**0.169 $^{0.039}$**	-0.293 $^{0.162}$	0.383 $^{0.186}$	-0.024 $^{0.039}$	0.065 $^{0.160}$	-0.529 $^{0.404}$
OFH	0.077 $^{0.046}$	**0.309 $^{0.060}$**	-0.323 $^{0.190}$	-0.058 $^{0.028}$	-0.421 $^{0.118}$	-0.773 $^{0.171}$
DAH	-0.079 $^{0.039}$	0.025 $^{0.046}$	**0.128 $^{0.041}$**	-0.409 $^{0.143}$	-0.206 $^{0.168}$	-0.736 $^{0.593}$
PCN	0.013 $^{0.032}$	0.001 $^{0.026}$	0.122 $^{0.041}$	**0.323 $^{0.045}$**	-0.143 $^{0.121}$	-0.360 $^{0.362}$
TE	0.000 $^{0.005}$	0.000 $^{0.005}$	0.000 $^{0.005}$	0.000 $^{0.005}$	**0.041 $^{0.007}$**	1.000 $^{0.001}$
TP	0.000 $^{0.006}$	0.000 $^{0.006}$	0.000 $^{0.006}$	0.000 $^{0.006}$	0.002 $^{0.005}$	**0.009 $^{0.009}$**

TABLE 4: Heritability estimates (bold; on the diagonal), additive genetic correlations (above the diagonal) and residual correlations (below the diagonal) with their standard errors for the prevalences of osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), and for the performance parameters number of annual tournament entries (TE) and number of annual tournament placings (TP) in show-jumping competitions

	OFF	OFH	DAH	PCN	TE	TP
OFF	**$0.167^{0.042}$**	$-0.296^{0.154}$	$0.362^{0.179}$	$-0.022^{0.130}$	$0.241^{0.109}$	$-0.051^{0.127}$
OFH	$0.077^{0.047}$	**$0.317^{0.065}$**	$-0.304^{0.190}$	$-0.061^{0.120}$	$0.125^{0.083}$	$-0.422^{0.117}$
DAH	$-0.076^{0.038}$	$0.042^{0.048}$	**$0.127^{0.042}$**	$-0.413^{0.162}$	$0.000^{0.149}$	$0.462^{0.201}$
PCN	$0.017^{0.039}$	$0.004^{0.047}$	$0.126^{0.042}$	**$0.321^{0.045}$**	$-0.189^{0.059}$	$-0.683^{0.153}$
TE	$0.000^{0.006}$	$0.000^{0.006}$	$0.000^{0.006}$	$0.000^{0.006}$	**$0.126^{0.012}$**	$0.562^{0.161}$
TP	$0.000^{0.008}$	$0.000^{0.008}$	$0.000^{0.008}$	$0.000^{0.008}$	$0.001^{0.006}$	**$0.042^{0.012}$**

General results and discussion

In the course of an extensive study on radiographic findings in the limbs of young Hanoverian Warmblood horses the prospects and possible limitations of specific breeding measures should be evaluated. First of all, the importance of genetic and non-genetic factors for the development of prevalent radiological alterations had to be defined. Given the relevantly genetic determination of particular radiographic findings, the feasibility of breeding strategies should be tested that simultaneously account for orthopaedic health traits and for performance parameters. Finally, the expedience of selective breeding for radiological soundness had to be investigated on the basis of competition data reflecting the performance of riding horses in sports.

The study was based on the results of standardized radiological examinations of 3- to 7-year-old Hanoverian Warmblood horses selected for sale at auction. The selection of horses was primarily based on type and performance criteria, excluding horses with gross exterior faults, noticeable locomotory problems and unsatisfactory dressage or jumping abilities. Two different data sets were used for this study. The first comprised 3,748 Hanoverian Warmblood horses selected for riding horse auctions in 1991-1998 (dataset 1). In order to verify the results of the analyses obtained on these data, the main items were re-examined in a more comprehensive data set. The later included riding horse auction candidates selected in 1991-2003, i.e., a total of 5,928 horses (dataset 2). Concerning the pedigree structure, the relationship matrix comprised 17,101 horses for the first, and 23,662 horses for the second data set. The probands were sired by 462 and 614 different stallions, respectively. In each case, 40 percent of the sires were represented by only one or two descendants. However, 368 sires had between 3 and 211 offspring selected for auction sale in 1991-2003. The pedigree information should therefore allow for reliable genetic analyses.

In agreement with literature, considerable numbers of the young, clinically healthy and well-performing horses showed radiographic findings considered to be pathological. Osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathological changes in navicular bones (PCN) were found to be the most prevalent radiological alterations. 50% of the probands showed at least one of these radiographic findings. Of the affected horses 73% had only one kind, 23% two kinds, 3% three kinds and less than 1% all four kinds of considered radiological abnormalities. The prevalences of the individual radiographic findings were in the range of 9.1 to 24.7% (Table 1).

Based on the results of simple and multiple analyses of variance, models have been developed for the genetic analyses. The comparison of models was done using the likelihood ratio test. For some of the considered fixed effects confounding with genetic groups could not be precluded. The anticipated suitability of the horses that was mentioned in the official auction catalogues might have been relevantly connected to their pedigree. With the increasing use of artificial insemination the importance of varying availability of sires should have decreased. However, the recognition and demand of particular sires might still vary regionally. Confounding between fixed effects and sires was found to bear the risk of causing some downward bias of genetic correlations (PIERAMATI and VAN VLECK 1993, GATES et al. 1999). In order to avoid some incalculable bias on our estimates, potentially pedigree confounded effects were excluded from the models in the last section of genetic analyses (Paper X). However, the obtained heritability estimates as well as the estimated additive genetic correlations differed negligibly. In all cases (linear animal models and linear sire models; datasets 1 and 2; different models; distinction of different severity of alterations and combined traits) the ranges of heritability estimates were h^2 = 0.15-0.21 for OFF, h^2 = 0.27-0.34 for OFH, h^2 = 0.12-0.27 for DAH, and h^2 = 0.10-0.46 for PCN (Table 2). OFF and DAH were found to be moderately positively correlated additive genetically (r_g = 0.23-0.40). Moderately negative additive genetic correlations were estimated between OFF and OFH (r_g = -1.00 to -0.19), and between OFH and DAH (r_g = -0.34 to -0.12). PCN tended to be correlated negatively additive genetically with OFF (r_g = -0.11 to -0.02), OFH (r_g = -0.09 to -0.06) and DAH (r_g = -0.42 to 0.04) (Table 3).

Given the performance-related definition of probands, selection on correlated traits had to be considered as a further possible source of bias. But in several studies the effect of selection on the estimates of genetic parameters was found to be minor in most cases (MEYER and THOMPSON 1984, SORENSEN and KENNEDY 1984, PIERAMATI and VAN VLECK 1993, VAN TASSELL et al. 1995, GATES et al. 1999). Furthermore, the choice of auction candidates had the advantage of somewhat standardized conditions of examination and documentation of radiographic findings, comparable management and training of the horses, and the prospect of their further use in sports.

For all the considered orthopedic conditions, some genetic background was identified previously (SCHOUGAARD et al. 1987, GRØNDAHL and DOLVIK 1993, PHILIPSSON et al. 1993, KWPN 1994, WINTER et al. 1996, WILLMS et al. 1999, BJØRNSDÓTTIR et al. 2000, ÁRNASON and BJØRNSDÓTTIR 2003, PIERAMATI et al. 2003). However, because of inconsistent methodical approaches the reported heritability estimates were partly well below the estimates of the present study. Using linear models for the analyses of all-or-none traits requires the transformation of the estimated heritabilities and residual correlations to the underlying liability scale (Dempster and Lerner 1950, Vinson et al. 1976). This was not done in all previous investigations, limiting the comparability with the own results.

Heritabilities in the range of $h^2 = 0.10\text{-}0.46$ implies the opportunity to take breeding measures aiming at the fundamental reduction of prevalent radiographic findings in the whole population. Radiological abnormalities bear the incalculable risk that the affected horse might eventually develop locomotory problems interfering with its prolonged use. The undefined duration of unrestricted usability reduces the market value of the individual horse and might question the profitability of horse breeding and sale. The prediction of breeding values for particular radiographic findings gives a ranking of animals according to their prospective genetic disposition to develop these radiological alterations. Therefore, it provides support to horse breeders in the planning of matings. In combination with the performance related breeding values, already regularly published in the Annual for Breeding and Sports (Jahrbuch Zucht und Sport, published by the Fédération Equestre Nationale in Warendorf, Germany), it should be possible to breed for promising horses in terms of performance in dressage and/or show-jumping and of radiological soundness. The feasibility to concurrently select for performance and for orthopedic health traits was tested for the Hanoverian Warmblood horse using the available data (dataset 2). The simulation study on the expected response to selection revealed some unemployed potential of selection for performance. Furthermore, the genetic improvement in dressage and jumping ability was only negligibly retarded by the simultaneous consideration of the horses' radiological state. Given the partly negative genetic correlations between OFF, OFH, DAH and PCN, the four radiological traits had to be considered simultaneously. This way, the prevalences of all the radiological alterations could be lowered considerably.

The relative breeding values predicted for OFF, OFH and DAH were found to be largely unrelated to the officially published, performance related breeding values. However, according to the breeding values the genetic improvement of the radiological appearance of the navicular bones seemed to counteract the progress in dressage and show-jumping ability (Table 4). But the competition data analyses revealed more pronounced dependencies. For horses active in dressage sports, mostly distinct negative additive genetic correlation between radiographic findings and the performance parameters, i.e., the annual number of tournament entries (TE_D) and of tournament placings (TP_D), emerged. The genetic correlations between radiographic findings and performance in show-jumping competitions (TE_J and TP_J), were less consistent. The most demonstrative difference existed in respect of DAH. The additive genetic correlations between DAH and TE_J was zero, and DAH and TP_J were moderately positively correlated additive genetically (Tables 5 and 6). Performance in basic build-up competitions was genetically less closely correlated with OFF and OFH, but similarly negatively correlated with DAH and PCN as the performance in dressage competitions.

The conflicting results obtained for the additive genetic correlations between dressage and show-jumping performance parameters deserved some closer examination, the results of which are given in Table 7. The annual numbers of entries in dressage and basic build-up competitions were highly negatively correlated additive genetically with the annual number of entries in show-jumping competitions, indicating the existence of well-defined dressage and jumping lines of breeding. However, highly positive additive genetic correlations were found between the annual numbers of placings in the respective riding sports disciplines. This might be explained by the elimination of entire pedigree lines that had been numerously represented with tournament entries in dressage competitions from the competition results data. Ultimately, these results argue for the all-round riding horse. The genetic capability to successfully participate in dressage competitions appears to be linked with the potential to have success in show-jumping competitions, and vice versa. In this connection performance parameters referring to basic build-up competitions can be largely regarded as unity with parameters of dressage performance.

In general, the heritability of performance, i.e., of activity and success, in tournament competitions is low (h^2 = 0.01-0.19; HUIZINGA and VAN DER MEIJ 1989, MEINARDUS and BRUNS 1989, BROCKMANN and BRUNS 1998, REILLY et al. 1998, HASSENSTEIN et al. 1999a, ALDRIDGE et al. 2000, RICARD and CHANU 2001). In the present study the heritability estimates for the annual number of tournament entries, considered to be a measure of the horse's training fitness, and for the annual number of tournament placings, i.e., the ability to compete successfully, were in the same range (h^2 = 0.01-0.13). Therefore, tournament performance itself can not be taken as an optimal trait to select on. Furthermore, low heritabilities impair the certainty with which additive genetic correlations can be estimated. But several studies have documented the highly positive genetic correlation between parameters derived from tournament data and the stallions and mares performance test traits. The high heritability of the later was found to provide a good basis for selection decisions (BROCKMANN and BRUNS 1998, CHRISTMANN and BRUNS 1998, VON VELSEN-ZERWECK and BRUNS 1998). Accordingly, the currently applied prediction of breeding values for the German Warmblood horse integrates data from performance tests of young breeding animals (stallions and mares) and of tournament competitions.

Conclusions

According to the results of the present study, it appears to be advisable to utilize available data on the results of standardized radiological examinations of horses (riding horse auctions, stallions licensing, possibly mares performance tests). The increasing amount of data will augment the accuracy of the prediction of breeding values for radiographic findings. Furthermore, the definition of main radiological traits requires continuous adjustment to the present facts. The continuity of data collection will ensure utmost up-to-dateness of the realized radiological state of the horse population and of its additive genetic variance in respect of particular radiographic findings.

The prediction of breeding values for the quantitatively most important radiographic findings could result in the regular publication of relative breeding values for radiographic findings, analogously to the current practice for dressage and show-jumping performance. This will enable the breeding organizations as well as the individual horse breeder to arrange matings systematically. Relative breeding values for radiographic findings will provide the opportunity for selective breeding that aims at the simultaneous improvement of the performance and the radiological state of the German Warmblood horse population.

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Table 1 Prevalences of radiographic findings in the horses selected for sale at auction in 1991-1998 (dataset 1; n = 3,748) and in 1991-2002 (dataset 2; n = 5,928)

Radiographic finding	Horses selected for sale at auction in 1991-1998 (n = 3,748)	Horses selected for sale at auction in 1991-2002 (n = 5,928)
Osseous fragments in fetlock joints (OFF)	778 (20.76%)	1,234 (20.82%)
forehand	357 (9.53%)	539 (9.09%)
hindquarters	516 (13.77%)	818 (13.80%)
Osseous fragments in hock joints (OFH)	360 (9.60%)	539 (9.09%)
Deforming arthropathy in hock joints (DAH)	583 (15.55%)	695 (11.72%)
Pathologic changes in navicular bones (PCN)	825 (22.01%)	1,466 (24.73%)

Table 2 Heritability estimates with their standard errors for different radiographic findings in the horses selected for sale at auction in 1991-1998 (dataset 1) and 1991-2002 (dataset 2) using linear animal models (LAM) and linear sire models (LSM)

Radiographic finding		Horses selected for sale at auction in 1991-1998 (n = 3,748)		Horses selected for sale at auction in 1991-2002 (n = 5,948)
		extensive model	simple model	extensive model
Osseous fragments in fetlock joints (OFF)		$0.177^{0.043}$ (LAM) $0.214^{0.059}$ (LSM)	$0.167^{0.040}$ (LAM)	$0.150^{0.027}$ (LAM) $0.145^{0.030}$ (LSM)
Osseous fragments in hock joints (OFH)		$0.342^{0.064}$ (LAM) $0.267^{0.017}$ (LSM)	$0.317^{0.061}$ (LAM)	$0.323^{0.051}$ (LAM) $0.314^{0.060}$ (LSM)
Deforming arthropathy in hock joints (DAH)	grade I	$0.269^{0.154}$ (LAM) $0.288^{0.115}$ (LSM)	$0.124^{0.040}$ (LAM)	$0.215^{0.042}$ (LAM) $0.199^{0.052}$ (LSM)
	grade II	$0.137^{0.052}$ (LAM) $0.174^{0.070}$ (LSM)		
Pathologic changes in navicular bones (PCN)	grade I	$0.206^{0.044}$ (LAM) $0.194^{0.046}$ (LSM)	$0.323^{0.044}$ (LAM)	$0.406^{0.039}$ (LAM) $0.463^{0.051}$ (LSM)
	grade II	$0.094^{0.051}$ (LAM) $0.189^{0.086}$ (LSM)		
	grade III	$0.126^{0.063}$ (LAM) $0.180^{0.108}$ (LSM)		

Table 3 Additive genetic correlations with their standard errors estimated between osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH); deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN)

Radiographic findings	Horses selected for sale at auction in 1991-1998 (n = 3,748)		Horses selected for sale at auction in 1991-2002 (n = 5,948)
	extensive model	simple model	extensive model
OFF - OFH	$-0.244^{0.118}$ (LAM) $-1.000^{0.008}$ (LSM)	$-0.288^{0.154}$ (LAM)	$-0.191^{0.123}$ (LAM) $-0.338^{0.140}$ (LSM)
OFF - DAH		$0.397^{0.177}$ (LAM)	$0.226^{0.132}$ (LAM) $0.390^{0.146}$ (LSM)
OFF - PCN		$-0.018^{0.089}$ (LAM)	$-0.069^{0.102}$ (LAM) $-0.109^{0.120}$ (LSM)
OFH - DAH		$-0.340^{0.189}$ (LAM)	$-0.137^{0.125}$ (LAM) $-0.116^{0.152}$ (LSM)
OFH - PCN		$-0.064^{0.075}$ (LAM)	$-0.086^{0.089}$ (LAM) $-0.086^{0.105}$ (LSM)
DAH - PCN		$-0.416^{0.159}$ (LAM)	$-0.011^{0.097}$ (LAM) $0.036^{0.116}$ (LSM)

Table 4 Pearson correlation coefficients for the correlations between the relative breeding values predicted for osseous fragments on fetlock joints (RBV_{OFF}), osseous fragments in hock joints (RBV_{OFH}), deforming arthropathy in hock joints (RBV_{DAH}) and pathologic changes in navicular bones (RBV_{PCN}), and the officially published total indices for dressage (TID) and show-jumping (TIJ) in the sires with at least 3 offspring among the horses selected for sale at auction in 1991-2002 (n = 368)

	RBV_{OFF}	RBV_{OFH}	RBV_{DAH}	RBV_{PCN}	TID	TIJ
RBV_{OFF}	1.000	-0.228 ***	0.175 ***	-0.060	0.079	-0.026
RBV_{OFH}		1.000	-0.242 ***	-0.019	-0.006	0.030
RBV_{DAH}			1.000	-0.052	0.048	-0.025
RBV_{PCN}				1.000	-0.095 +	-0.160 **
TID					1.000	-0.063
TIJ						1.000

Levels of significance: *** : $P < 0.001$; ** : $P < 0.01$; * : $P < 0.05$; + : $P < 0.10$

Table 5 Additive genetic correlations between radiographic findings, i.e., osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), and the annual number of tournament entries in dressage (TE_D) and show-jumping competitions (TE_J)

	OFF	OFH	DAH	PCN	TE_D	TE_J
OFF	1.000	-0.295	0.373	-0.023	0.065	0.241
OFH		1.000	-0.314	-0.060	-0.421	0.125
DAH			1.000	-0.411	-0.206	0.000
PCN				1.000	-0.143	-0.189
TE_D					1.000	-1.000
TE_J						1.000

s_{ca} = 0.028-0.190

Table 6 Additive genetic correlations between radiographic findings, i.e., osseous fragments in fetlock joints (OFF), osseous fragments in hock joints (OFH), deforming arthropathy in hock joints (DAH) and pathologic changes in navicular bones (PCN), and the annual number of tournament placings in dressage (TP_D) and show-jumping competitions (TP_J)

	OFF	OFH	DAH	PCN	TP_D	TP_J
OFF	1.000	-0.295	0.373	-0.023	-0.529	-0.051
OFH		1.000	-0.314	-0.060	-0.773	-0.422
DAH			1.000	-0.411	-0.736	0.462
PCN				1.000	-0.360	-0.683
TP_D					1.000	0.889
TP_J						1.000

s_{ca} = 0.028-0.593

Table 7 Heritability estimates (on the diagonal), additive genetic correlations (above the diagonal) and residual correlations (below the diagonal) with their standard errors for the number of annual tournament entries (TE; first line) and the number of annual tournament placings (TP; second line) in different tournament disciplines

	Dressage competitions	Show-jumping competitions	Basic build-up competitions
Dressage competitions	$\mathbf{0.029}^{\mathbf{0.008}}$ $\mathbf{0.004}^{\mathbf{0.003}}$	$-1.000^{0.002}$ $0.889^{0.161}$	$1.000^{0.000}$ $1.000^{0.001}$
Show-jumping competitions	$0.002^{0.005}$ $0.001^{0.006}$	$\mathbf{0.108}^{\mathbf{0.019}}$ $\mathbf{0.043}^{\mathbf{0.015}}$	$-0.773^{0.478}$ $1.000^{0.019}$
Basic build-up competitions	$0.004^{0.004}$ $0.002^{0.006}$	$0.003^{0.005}$ $0.002^{0.007}$	$\mathbf{0.019}^{\mathbf{0.010}}$ $\mathbf{0.043}^{\mathbf{0.023}}$

Kathrin Friederike Stock (2004):

Radiographic findings in the limbs of Hanoverian Warmblood horses:
Genetic analyses and relationships with performance in sports

Summary

The results of a standardized radiological examination of 3,748 young riding horses were analyzed for systematic effects which influenced the frequency of radiographic findings in the equine limbs. The horses were selected for auction sale in 1991-1998 by the Association of Hanoverian Warmblood Breeders (Verband hannoverscher Warmblutzüchter e.V.) in Verden on the Aller, Germany, at between three and seven years of age. Osseous fragments dominated among the documented radiographic findings, with 32 % of the probands being affected in at least on of the considered joint locations. Fetlock joints were most often affected (OFF; 21%), followed by hock (OFH; 10%), distal interphalangeal (OFD; 4%) and proximal interphalangeal joints (OFP; 1%). 18% of the probands showed radiographic findings of deforming arthropathy in at least one of the examined joints. Hock joints were more often affected with deforming arthropathy (DAH; 16%) than distal interphalangeal (DAD; 4%), proximal interphalangeal (DAP; 2%) and fetlock joints (DAF; 1%). Moderate deformations of hock joints were more frequently recorded than slight or severe hock alterations. A significant age effect emerged only for DAD, with older horses being more often affected. Radiographic findings in the navicular bones of the front limbs were found in 22% of the horses. The alterations were mostly classified as slight (PCN I), less often as moderate (PCN II) or severe (PCN III). The date of auction had a significant influence on all the investigated radiographic findings. The prevalences of deforming arthropathies and of PCN I were significantly dependent on the mode of examination. Over the years there was a marked increase of the prevalence of OFF. Higher percentages of genes of the Hanoverian and the Holstein Warmblood horse increased the probability to have an irregular radiological appearance of navicular bones.

Genetic parameters were estimated for the prevalences of radiographic findings uni- and multivariately with REML using linear animal models and linear sire models. Osseous fragments (OFD, OFP, OFF and OFH) and deforming arthropathy (DAD, DAP, DAF and DAH) in different limb joints, and pathologic changes in navicular bones (PCN I, PCN II and PCN III) were analyzed as separate all-or-none traits. Further analyses were performed separately on radiographic findings in males and females. Binary coded data of the

radiographic findings were investigated jointly with height at withers. The heritability estimates and the estimated residual correlations were transformed to the underlying liability scale. The heritability estimates for osseous fragments in the investigated joints were in the range of h^2 = 0.18-0.44. In females, the heritability of OFF was estimated to be higher than that of OFH, whilst the opposite was true in males. Negative additive genetic correlations were found between osseous fragments in the phalangeal joints and in hock joints. The heritability estimates for deforming arthropathies in males and females were in the range of h^2 = 0.10-0.36. Additive genetic correlations between deforming arthropathy in hock joints and in phalangeal joints were estimated to be moderately positive. Heritability estimates for the prevalences of PCN I, PCN II and PCN III ranged between h^2 = 0.09 and h^2 = 0.21. The estimated additive genetic correlations indicated a uniform genetic pattern of the different radiographic findings consistent with navicular syndrome in males and in females. The heritability of height at withers was estimated at h^2 = 0.22-0.29. Conflicting results were obtained for the additive genetic correlations between radiographic findings and height at withers, opposing its use as a trait for indirect selection.

In order to verify the previous results, analogous analyzes on the most prevalent radiographic findings were performed in a larger number of horses. In the 5,928 Hanoverian Warmblood horses selected for sale at auction in 1991-2003 the prevalences of OFH, OFH, DAH and PCN were 21%, 9%, 12% and 25%, respectively. The heritability estimates obtained for these radiographic findings were in the range of h^2 = 0.14-0.46. They were correlated additive genetically with r_g = -0.34 to 0.24. On this basis, relative breeding values (RBV) for radiographic findings were predicted for the 23,662 horses included in the last four generations of the probands' pedigree. Total indices radiographic findings (TIR) were calculated for the sires having contributed at least three of probands, giving varying weight to the individual RBV. Different selection schemes were developed on the basis of the TIR and the officially published performance based relative breeding values, i.e., total indices dressage (TID) and jumping (TIJ). When weighting radiographic findings with 30-60% as opposed to the respective performance parameters, and selecting only sires with above-average total indices, all the considered breeding values increased by 1-19%. The prevalences of the investigated radiographic findings were concurrently lowered by up to 10% each.

The compatibility of the developed selection schemes with breeding progress in performance parameters was subsequently tested in the same population of horses. The expected response to selection was traced on two generations of horses, separately for dressage, jumping and all-purpose breeding. The development of the mean RBV and of the mean total indices (TIR, TID, TIJ) in the sires, and of the prevalences of radiographic findings in the probands were used to assess the response to selection. Giving equal weight to the TIR and the performance-related total index, 43-53% of the paternal grandsires and 70-82% of the descending probands' sires passed selection. In each case, the RBV and the total indices increased by up to 9% in the selected sires when compared to all sires. At the same time, the prevalences of radiographic findings in the probands that descended from the selected sires were relatively lowered by up to 16%. The comparison of the newly developed selection scheme with exclusively performance-based selection revealed only minor changes in the percentages of selected sires and only a slightly diminished breeding progress in respect of TID and/or TIJ.

The development of 3,725 Warmblood riding horses selected for sale at auction in 1991-1998 was investigated on the basis of competition data and specifications of the horse owners. Information on entries and placings in tournament competitions in Germany in 1991-2002 were analyzed. The annual numbers of tournament entries and placings were used to quantify the horses' use in sports. Several factors were identified that had an influence on these performance parameters, including the sex and the age of the horse, and the discipline of use. When relating the presence or absence of different radiographic findings in the limbs of the probands to their later performance, mostly negative effects could be determined. In particular, horses affected with OFD, DAP and PCN had on the average significantly lower number of entries and placings per year. Information derived from standardized questionnaires sent to actual owners of the former auction candidates provided some insight into current routines of keeping and management of Hanoverian Warmblood horses in Germany. The results of the study confirmed the fundamental importance of locomotory problems for the continuity of use of riding horses.

Finally, the additive genetic correlations between prevalent radiographic findings in the limbs of Warmblood riding horses and performance parameters should be quantified. The numbers of annual entries (TE) and placings (TP) in tournament competitions in 1991-2002 were utilized as measures of performance in riding sports. Multivariate genetic analyses were performed in linear animal models using REML. The prevalences of radiographic findings, (OFF, OFH, DAH and PCN) were analyzed jointly with the performance parameters (TE and TP). In most cases, moderately negative additive genetic correlations were determined between the radiographic findings and the performance in sports, irrespective of the horses' discipline of use. Breeding measures that allow for orthopaedic health traits should contribute to maximize the breeding progress in terms of sport performance.

Kathrin Friederike Stock (2004):

Röntgenbefunde an den Gliedmaßen hannoverscher Warmblutpferde: Genetische Analysen und Beziehungen zur Leistung im Sport

Zusammenfassung

Anhand der röntgenologischen Untersuchungsbefunde von 3748 jungen Reitpferden erfolgte die Analyse von Einflussfaktoren auf das Auftreten verschiedener Röntgenbefunde an den Gliedmaßen der Pferde. Bei den Probanden der Studie handelte es sich um hannoversche Warmblutpferde, die in den Jahren 1991-1998 für Reitpferdeauktionen des Verbandes hannoverscher Warmblutzüchter e.V. in Verden an der Aller ausgewählt und einer standardisierten Röntgenuntersuchung unterzogen worden waren. Isolierte röntgenologische Verschattungen stellten den am häufigsten dokumentierten Röntgenbefund dar. 32% der Pferde wiesen diesen Befund in mindestens einer der untersuchten Lokalisationen, d.h. in Huf-, Kron-, Fessel- oder Sprunggelenk, auf. Isolierte röntgenologische Verschattungen im Fesselgelenk stellten mit einem Anteil von 21% betroffenen Pferden den häufigsten Einzelbefund dar. Für isolierte röntgenologische Verschattungen in Sprung-, Huf- und Krongelenken wurden Prävalenzen von 10%, 4% und 1% ermittelt. Hierbei wiesen bis zu 46% der betroffenen Pferde bilaterale Gelenkaffektionen auf. Über die Jahre war ein merklicher Anstieg der Prävalenz isolierter röntgenologischer Verschattungen im Fesselgelenk festzustellen. Von den untersuchten Effekten erwiesen sich das Auktionsdatum sowie Typ und Qualität der Auktion als signifikant für die Prävalenz isolierter röntgenologischer Verschattungen in Fessel- und Sprunggelenken. Ein signifikanter Einfluss ließ sich zudem für die Herkunftsregion der Pferde und ihre im Auktionskatalog vermerkte Nutzungseignung ermitteln. Mit zunehmender Widerristhöhe war eine Zunahme der Prävalenz isolierter röntgenologischer Verschattungen in Fessel- und Sprunggelenken zu verzeichnen. Ein signifikanter Vatereffekt ergab sich für das Auftreten isolierter röntgenologischer Verschattungen in Fessel- und Sprunggelenken, während der mütterliche Großvater lediglich auf die Prävalenz der Sprunggelenkbefunde einen signifikanten Einfluss nahm.

Bei 18% der Probanden wurden röntgenologisch Veränderungen der Gelenkkonturen festgestellt. Sprunggelenke waren am häufigsten betroffen (16%), wobei gering- und hochgradige Veränderungen seltener dokumentiert waren als mittelgradige Veränderungen. Für das Auktionsdatum sowie den Untersuchereffekt ergab sich ein signifikanter Einfluss auf

die Häufigkeit dokumentierter Gelenkdeformationen. Ein Alterseffekt war dagegen nur für deformierende Arthropathien im Hufgelenk festzustellen, welche bei älteren Pferden signifikant häufiger auftraten. Die Häufigkeit von Veränderungen der Huf- und Krongelenkkonturen stieg mit zunehmender Widerristhöhe der Pferde tendenziell an. Bei Pferden mit Genen des Holsteiner Warmblutes traten Hufgelenkveränderungen mit größerer Wahrscheinlichkeit auf, während ein zunehmender Vollblutgenanteil mit einer erhöhten Neigung zu geringgradigen Sprunggelenkveränderungen verbunden war. Ein signifikanter Einfluss des Vaters ergab sich für mittelgradige Veränderungen der Sprunggelenkkontur.

Pathologische Strahlbeinbefunde an den Vordergliedmaßen waren für 22% der Probanden dokumentiert. Überwiegend waren diese als geringgradig (15%), seltener als mittel (5%) oder hochgradig (2%) eingestuft. Das Auktionsdatum und das Auktionsjahr hatten einen signifikanten Einfluss auf die Häufigkeit dokumentierter Strahlbeinbefunde. Für geringgradige Strahlbeinbefunde war ferner eine Signifikanz des Untersuchereffektes sowie des Auktionstyps und der Auktionsqualität zu ermitteln. Mittelgradige Strahlbeinbefunde traten bei männlichen Pferden signifikant häufiger auf als bei weiblichen Pferden. Höhere Genanteile von hannoverschem und Holsteiner Warmblut gingen mit einer erhöhten Wahrscheinlichkeit des Auftretens röntgenologischer Strahlbeinbefunde einher. Ein signifikanter Einfluss des Vaters ergab sich für gering- und mittelgradige, ein signifikanter Einfluss des männlichen Gründertieres für mittel- und hochgradige, ein signifikanter Einfluss des weiblichen Gründertieres für mittelgradige Strahlbeinbefunde. Unabhängig vom Schweregrad der röntgenologisch erkennbaren Strahlbeinveränderungen bestand ein signifikanter Zusammenhang zwischen Befunden in den Strahlbeinen der rechten und linken Vordergliedmaßen.

Die Schätzung genetischer Parameter für die Häufigkeit von Röntgenbefunden erfolgte uni- und multivariat mittels REML in linearen Tier- und Vatermodellen. Isolierte röntgenologische Verschattungen und deformierende Arthropathien in Huf-, Kron-, Fessel- und Sprunggelenken sowie röntgenologische Strahlbeinbefunde unterschiedlichen Schweregrades wurden als einzelne 0-1-Merkmale ausgewertet. Differenzierte Auswertungen wurden ferner getrennt für Röntgenbefunde bei männlichen und weiblichen Pferden durchgeführt. Die Schätzungen genetischer Parameter erfolgten jeweils für die binär codierten Röntgenbefunde und die Widerristhöhe der Pferde. Die Heritabilitätsschätzwerte und die geschätzten Residualkorrelationen wurden in das Schwellenwertmodell transformiert. Die Anwendbarkeit der Transformationsfaktoren auf das vorliegende Datenmaterial hatte sich in einer Simulationsstudie bestätigt. Im allgemeinen bestand eine gute Übereinstimmung zwischen den in Tier- und Vatermodellen ermittelten Schätzwerten. Die Heritabilität isolierter röntgenologischer Verschattungen in Huf-, Kron-, Fessel- und Sprunggelenken wurde auf h^2 = 0,18-0,44 geschätzt. Bei weibliche Pferde ergab sich ein höherer Heritabilitätsschätzwert für isolierte röntgenologische Verschattungen im Fesselgelenk als für solche im Sprunggelenk, während die Verhältnisse bei männlichen Pferden umgekehrt waren. Isolierte röntgenologische Verschattungen in den Zehengelenken waren untereinander mittelgradig positiv korreliert, wiesen aber eine negative additiv-genetische Beziehung zu isolierten röntgenologischen Verschattungen im Sprunggelenk auf. Dies traf insbesondere auch für Fesselgelenke insgesamt sowie für Fesselgelenke der Vor- und Hinterhand bei männlichen und weiblichen Pferden zu. Für die Widerristhöhe, welche eine überwiegend mittlere positive genetische Beziehung zu isolierten röntgenologischen Verschattungen in den verschiedenen Gliedmaßengelenken erkennen ließ, ergab sich eine Heritabilität von h^2 = 0,22-0,29. Für deformierende Arthropathien wurden geschlechtsübergreifend Heritabilitäten von h^2 = 0,10-0,36 geschätzt. Bei den für männliche und weibliche Pferde getrennt durchgeführten Analysen zeichneten sich jedoch gewisse Geschlechtsunterschiede ab. Mittlere positive additiv-genetische Korrelationen wurden zwischen Veränderungen der Gelenkkonturen in den Zehen- und den Sprunggelenken geschätzt. Uneinheitlich stellten sich die genetischen Beziehungen zwischen deformierenden Arthropathien und der Widerristhöhe dar. Die Heritabilitätsschätzwerte für gering-, mittel- und hochgradige Strahlbeinbefunde lagen zwischen h^2 = 0,09 und h^2 = 0,21. Die geringe Prävalenz mittelgradiger Strahlbeinveränderungen bei weiblichen Pferden führte in den geschlechtsdifferenzierten Analysen zu verzerrten Schätzwerten. Die geschätzten additiv-genetischen Korrelationen ließen auf einen einheitlichen genetischen Hintergrund röntgenologischer Strahlbeinbefunde unterschiedlichen Schwergrades und bei männlichen und weiblichen Pferden schließen. Uneinheitliche Schätzwerte ergaben sich jedoch hinsichtlich der genetischen Beziehung zwischen Strahlbeinbefunden und der Größe der Pferde, so dass die Widerristhöhe kein für die Selektion nutzbares Merkmal darstellt.

Zur Absicherung der zuvor erzielten Ergebnisse wurden analoge Analysen an einem umfangreicheren Datenmaterial durchgeführt, welches 5928 hannoversche Warmblutpferde umfasste, die in den Jahren 1991-2003 für Reitpferdeauktionen ausgewählt worden waren. Für isolierte röntgenologische Verschattungen in Fessel- und Sprunggelenken, deformierende Arthropathien im Sprunggelenk und röntgenologische Strahlbeinbefunde waren in diesem Datenmaterial Prävalenzen von 21%, 9%, 12% und 25% zu ermitteln. Die Heritabilitätsschätzwerte für diese Röntgenbefunde lagen im Bereich von h^2 = 0,14-0,46. Die

Schätzwerte der additiv-genetischen Korrelationen lagen zwischen r_g = -0,34 und r_g = 0,24. Auf der dieser Grundlage erfolgte die Zuchtwertschätzung für die ausgewählten Röntgenbefunde. Für alle 23662 Pferde, die in den letzten vier Generationen des Pedigrees der Probanden auftraten, wurden Relativzuchtwerte für die einzelnen Röntgenbefunde bestimmt, deren Verteilung insgesamt, unter der Probanden und unter den Probandenvätern mit mindestens drei Nachkommen im Datenmaterial untersucht wurde. Die Relativzuchtwerte der Probandenväter wurden ferner den im Jahrbuch Zucht und Sport veröffentlichten leistungsbezogenen Relativzuchtwerten, d.h. den Gesamtzuchtwerten für Dressur (TID) und Springen (TIJ), gegenübergestellt. Hierbei war ein deutlich höheres Niveau der Dressurzuchtwerte (mittlerer TID = 110) im Vergleich zu den Springzuchtwerten (mittlerer TIJ = 98) festzustellen. Für die Probandenväter wurden aus den einzelnen Relativzuchtwerten für Röntgenbefunde unter unterschiedlicher Gewichtung Gesamtzuchtwerte für Röntgenbefunde (TIR) abgeleitet, die im Mittel jeweils bei 99 lagen. Schließlich wurden aus den Gesamtzuchtwerten (TIR, TID, TIJ) übergreifende Gesamtindizes abgeleitet, auf deren Grundlage Selektionsschemata getrennt für die Zucht eines vielseitigen Reitpferdes bzw. eines auf Dressur oder Springen spezialisierten Reitpferdes entwickelt wurden. Eine 30- bis 60%-ige Gewichtung des Röntgenbefundgesamtzuchtwertes führte in Verbindung mit einer Beschränkung auf Hengste mit überdurchschnittlichen übergreifenden Gesamtzuchtwerten zu einem Anstieg aller berücksichtigten Zuchtwerte von 1-19%. Gleichzeitig ließ sich die Prävalenz der einzelnen untersuchten Röntgenbefunde um bis zu 10% senken. Wurde die Selektionsentscheidung allein auf der Basis eines einzelnen Röntgenbefundes gefällt, ergab sich ein maximal zu erwartender Anstieg der Relativzuchtwerte um 16-23% und eine maximale Absenkung der Röntgenbefundprävalenzen um 31-52%.

Die Vereinbarkeit der entwickelten Selektionsschemata mit einem Zuchtfortschritt in den Leistungsparametern wurde anschließend in der gleichen Population von Pferden untersucht. Der erwartete Selektionserfolg, gemessen an der Entwicklung der Relativ- und Gesamtzuchtwerte auf Seiten der Probandenväter und der Entwicklung der Röntgenbefundprävalenzen auf Seiten der Probanden, wurde über zwei Generationen verfolgt, und zwar getrennt für die Zucht auf ein vielseitiges Reitpferd bzw. ein auf Dressur oder Springen spezialisiertes Reitpferd. Bei einer Gleichgewichtung des Gesamtzuchtwertes für Röntgenbefunde und des jeweiligen leistungsbezogenen Gesamtzuchtwertes erwiesen sich 43-53% der väterlichen Großväter und 70-82% der von diesen abstammenden Probandenväter als selektionswürdig. Die Relativ- und Gesamtzuchtwerte lagen bei den selektierten Hengsten im Mittel um bis zu 9% höher als bei der Gesamtheit der Hengste. Gleichzeitig verringerte sich die Prävalenz der berücksichtigten Röntgenbefunde bei den von selektierten Hengsten abstammenden Probanden um bis zu 16%. Basierte die Selektionsentscheidung allein auf den leistungsbezogenen Gesamtzuchtwerten, lag der Anteil selektierter Hengste bei 44-66% in der ersten und 73-84% in der zweiten Generation. Der maximal zu erwartende Anstieg der Leistungszuchtwerte betrug hierbei 9-10% (TID) bzw. 19-23% (TIJ). Angesichts der kaum veränderten Anteile selektierter Hengste und des nur geringfügig verlangsamten Zuchtfortschrittes im Hinblick auf die Leistungszuchtwerte erscheint eine gleichzeitig auf Leistung und Röntgenbefunden basierende Selektion praktikabel. Die Häufigkeit verschiedener Röntgenbefunde ließe sich auf diese Weise unter den Nachkommen selektierter Hengste merklich verringern.

Die Entwicklung von 3725 Warmblutpferden, die in den Jahren 1991-1998 für Reitpferdeauktionen ausgewählt worden waren, wurde auf der Basis von Turnierdaten und Besitzerangaben untersucht. Ausgewertet wurde die jährliche Anzahl von Nennungen und Platzierungen bei deutschen Turnieren im Zeitraum 1991-2002. Diverse Einflussfaktoren wurden für den Umfang des sportlichen Einsatzes der Pferde ermittelt, unter anderem das Geschlecht und das Alter der Pferde sowie die Disziplin seiner Nutzung. Das Vorliegen verschiedener Röntgenbefunde zum Zeitpunkt der Auktionsauswahl wurde in Beziehung gesetzt zur späteren Leistung der Pferde im Sport. Hierbei wurde überwiegend eine negative Leistungsbeeinflussung festzustellen. Insbesondere Pferde mit isolierten röntgenologischen Verschattungen im Hufgelenk, mit deformierenden Arthropathien im Krongelenk und mit röntgenologischen Strahlbeinbefunden hatten im Mittel eine signifikant geringere Anzahl von Nennungen und Platzierungen pro Jahr. Angaben zur Entwicklung der ehemaligen Auktionskandidaten standen ferner in Form von den aktuellen Besitzern der Pferde ausgefüllten, standardisierten Fragebögen zur Verfügung. Diese erlaubten einen Einblick in übliche Verfahren der Haltung und des Managements hannoverscher Warmblutpferde in Deutschland. Insgesamt bestätigte sich die grundlegende Bedeutung von Problemen des Bewegungsapparates im Hinblick auf die dauerhafte Einsetzbarkeit eines Reitpferdes.

Abschließend waren die additiv-genetischen Korrelationen zwischen bedeutenden Röntgenbefunden an den Gliedmaßen von Warmblutreitpferden und Leistungsparametern zu quantifizieren. Hierbei dienten die jährliche Anzahl von Nennungen und von Platzierungen im Zeitraum 1991-2002 als Maß für die sportliche Leistung der Pferde. Genetische Parameter wurden mittels REML multivariat in linearen Tiermodellen für die Häufigkeiten der Röntgenbefunde (isolierte röntgenologische Verschattung im Fesselgelenk, isolierte röntgenologische Verschattung im Sprunggelenk, deformierende Arthropathie im

Sprunggelenk, röntgenologische Strahlbeinbefunde) und die Leistungsparameter (jährliche Anzahl von Nennungen, jährliche Anzahl von Platzierungen) geschätzt. Größtenteils ergaben sich mittlere negative additiv-genetische Korrelationen zwischen dem Vorliegen von Röntgenbefunden und der Leistung der Pferde im Sport. Verschiedene röntgenologische Veränderungen an den Gliedmaßen wirken der Leistung von Warmblutpferden in verschiedenen Reitsportdisziplinen entgegen. Züchterische Maßnahmen, die orthopädische Gesundheitsmerkmale berücksichtigen, sollten demnach zu einer Maximierung des Zuchtfortschrittes im Hinblick auf die sportliche Leistung der Pferde beitragen.

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