



Genetics of gait score in broilers: Genetic parameters of gait score in purebred broiler lines[☆]

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ABSTRACT

Leg health assessment is a vital component of poultry breeding goals; it includes a range of skeletal disorders and contact dermatitis traits as well as a general assessment of a bird's walking ability in the form of gait score (GS). If trained scorers are used, GS correlates well with more objective walking assessment methods and allows for high throughput data collection from large numbers of individuals. The paper describes for the first time GS heritabilities for broilers. The Aviagen GS system (AGS) consists of an 8-class scale of 10–45 in increments of 5, whereby 10 is the best score and 45 the worst. It has sufficient variation between categories to enable a clear distinction of GS classes for selection purposes. The results of GS at 4–5 weeks of age show GS heritabilities between 0.14 and 0.24 which is higher than turkey (0.08–0.13) or duck (0.06–0.12) heritabilities. Genetic correlations with body weight and breast percentage were unfavorable but moderate. Correlations among leg health traits (AGS, long bone deformities, crooked toes, hockburn and footpad dermatitis) were generally low (–0.16–0.10) for most traits and lines. While genetic correlations between AGS and production traits were unfavorable, both AGS and other leg health and production traits can be improved simultaneously in a multi-trait selection strategy combining production and welfare characteristics. AGS has been included in the Aviagen breeding goal since 2011.

Introduction

Leg health is an important aspect of broiler production, and a vital component of meat poultry breeding goals (Kapell et al., 2012a, 2012b; Kapell et al., 2017). Assessment includes a range of skeletal disorders and contact dermatitis traits as well as a general evaluation of a bird's walking ability, in the form of gait score (GS) (Le Bihan-Duval et al., 1996, 1997; Neeteson et al., 2023). Skeletal disorders include valgus/varus long bone deformities (LD), tibial dyschondroplasia or crooked toes (CT) while contact dermatitis traits include foot pad dermatitis (FPD) and hockburn (HB). Leg disorders have been described extensively (e.g., Wise, 1975; Greene et al., 1985; Bradshaw et al., 2002; Knowles et al., 2008; Kierończy et al., 2017; Liu et al., 2023). Leg health characteristics have been included in broiler and turkey breeding goals for several decades (e.g., Mercer and Hill, 1984; Kapell et al., 2012b; Neeteson et al., 2023). Methodologies for assessing the overall walking ability aspect of leg health have been described in turkeys (e.g., Kapell et al., 2017), ducks (e.g., Duggan et al., 2016, 2017) and broilers (e.g., Wurtz and Riber, 2024). Gait scoring systems described for broilers are

based on a 3-class (Dawkins et al., 2004; Grandin, 2020; Webster et al., 2008; Opengart et al., 2018; National Chicken Council, 2022), a 4-class (Konca et al., 2008) or a 6-class scale (Kestin et al., 1992; Garner et al., 2002; Assurewell, 2016) scale, with higher scores indicating poorer gait. An antagonistic relationship between GS and a production trait like BW thus would mean that gait will be less favorable with increasing BW. One of the earliest, and most widely used, methodologies is the Bristol gait scoring system (Bristol gait score, BGS) developed by Kestin et al. (1992). It distinguishes 6 classes, from 0 for a bird showing no detectable abnormality to 5 for a bird that is incapable of sustained walking. The distinction between the categories is subjective, and modified versions of this system have been developed which use more objective criteria, such as the modified BGS (Garner et al., 2002). More recently, 3-class systems have been developed as a practical means to distinguish birds walking excellently, birds not able to walk, and an in-between category.

While all the aforementioned methodologies are subjective, others have focused on objective methodologies to assess walking ability. This includes for example the latency to lie test, a relatively low-tech methodology which measures the length of time until a bird lies down in

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shallow water (Weeks et al., 2002; Berg and Sanotra, 2003; Caplen et al., 2014; Aydin et al., 2015). More high-tech methodologies include kinetic methodologies, which measure forces involved in walking using tools like the pedobarograph (Corr et al., 1998; Aydin, 2018), the force plate (Corr et al., 2007a, 2007b; Sandilands et al., 2011; Paxton et al., 2013) or the piezoelectric pressure-sensing mat (de Alencar Nääs et al., 2010). Recently, kinematic methodologies, which look at body motion via video images, have been used to record laying behavior (Aydin 2017a, 2017b) or activity (e.g., Corr et al., 1998; Abourachid, 2001; Corr et al., 2003; Kristensen and Cornou, 2011; Dawkins et al., 2009; Aydin et al., 2010, 2013; Caplen et al., 2012; Paxton et al., 2013; Silvera et al., 2017; Tahamtani et al., 2021; Pearce et al., 2022; Fodor et al., 2023). Sensors on the body, such as backpacks (van der Sluis et al., 2019, 2021) or accelerometers (Abdoli et al., 2018), have been trialed to monitor bird movement and/or behavior. The walking quality monitoring may include analysis of changes in position or orientation of body segments. This can, amongst others, be achieved via a decision tree system (de Alencar Nääs et al., 2021) or through body key-point tracking (Nasiri et al., 2022). The transect walk, a method assessing walking ability of birds during standardized walks in a barn environment, was developed as a method to assess walking ability in a barn environment (Marchewka et al., 2013; BenSassi et al., 2018, 2019; Marchewka et al., 2015).

Gait scoring may be a subjective methodology in nature, but if trained scorers are used it correlates well with more objective walking assessment methods (e.g., optimal flow test (Dawkins et al., 2009), or latency to lie test (Dawkins, 2024)) and allows for high throughput data collection from large numbers of individuals.

The gait outcome of a bird can be influenced by a range of environmental or management factors. Photoperiod, feed composition, feeding pattern and feed form have all been linked to variation in the walking ability of birds, although body weight (BW) may play a role in this as well (Sorensen et al., 1999; Su et al., 1999; Brickett et al., 2007). Increased BW was generally found to be antagonistically correlated with higher GS, meaning a poorer gait (Kestin et al., 1999, 2001; Kristensen et al., 2006). Sanotra et al. (2001, 2003) reported significant interactions between BW and sex for walking ability, with males showing a rapid increase in probability of impaired walking ability with increase in BW compared to females.

Reports of phenotypic correlations of GS with other leg health traits are inconsistent. Some studies found positive phenotypic correlations of GS with HB, CT, FPD and LD in a range of commercial broiler crosses (Kestin et al., 1999; Sanotra et al., 2001; Kristensen et al., 2006). Others however reported no significant correlations of GS with FPD, tibial dyschondroplasia or asymmetry of the tarsometatarsus (e.g., Kestin et al., 1999, 2001; Garner et al., 2002; Kristensen et al., 2006). Several studies found differences in GS between broilers from different genetic strains (e.g., Kestin et al., 1992, 1999; Knowles et al., 2008).

Currently, more objective walking assessment methodologies are not suitable yet for the routine assessment of large numbers of individuals for the purpose of genetic selection. GS is an appealing approach to score large numbers of birds individually. To be suitable for selection purposes it should be highly repeatable and it must have a heritable basis. While there are estimates of heritability and genetic correlations for GS in turkeys (Kapell et al., 2017) and ducks (Duggan et al., 2016, 2017), there are currently no available estimates for broiler chickens. GS heritabilities in turkeys ranged from 0.08 to 0.13 (Kapell et al., 2017) while in ducks it ranged from 0.06 to 0.12 (Duggan et al., 2016, 2017). The same study found a higher heritability estimate for ducks for step width, a component of gait, ranging from 0.17 to 0.24.

The GS score used should allow sufficient distinction between categories to enable a clear distinction of GS classes for selection. To evaluate the walking ability of birds within Aviagen, the previously discussed BGS was trialed, but two issues arose: the higher categories were never (category 5) or seldom (category 4) seen due to a stringent policy regarding culling for welfare reasons, and the lower categories did not show enough variation for the purpose of genetic selection. For

this reason, Aviagen developed the Aviagen gait score (AGS) system, adding intermediate categories. The aim of this study is to describe the AGS system and to estimate genetic parameters in purebred commercial broiler lines from the Aviagen UK breeding program. The genetic correlations were estimated between AGS and the two production traits (BW) and breast meat percentage (BR), as well as the leg health traits (FPD, HB, CT and LD). This research provides the first estimates of the genetic basis of walking ability measured as GS in broilers and its correlation with production and other leg health characteristics.

Materials and methods

Trait description and scoring

The data for this study originate from the ongoing recording of leg health and performance traits on four purebred commercial broiler lines within the Aviagen UK (Newbridge, UK) breeding program. It spans three to four generations, hatched between September 2020 and January 2023 (line A) or February 2020 and January 2023 (lines B to D). For the estimation of genetic parameters, additional depth of pedigree was added starting in February 2019. The analysis combined AGS with the routinely measured production traits BW and BR and the leg health traits FPD, HB, CT and LD.

AGS was assessed at 4 weeks (lines A and B) or 5 weeks (lines C and D) by evaluating the movement and posture of a bird as seen from behind (Fig. 1). Part of a pen was converted into a walkway of ca. 4 meters by 1 meter, which was open at both ends. Birds were placed at one end of the walkway and encouraged to walk towards their cohorts located at the other end (Fig. 1).

AGS was measured on an 8-class scale of 10–45 in increments of 5, whereby 10 was the best score and 45 the worst. Birds with score 10 or 15 showed a regular, balanced leg movement in a forward direction, with no lateral movement. Birds with a score 10 showed an upright posture, while birds with score 15 were downwards oriented. Birds with a score 20 showed a regular gait and upright posture, but some lateral movement of the legs or body. Birds that showed lateral movement of the legs or body combined with either a downward posture or a slight rocking motion were scored as 25. If a bird displayed an asymmetry combined with a downward posture in the gait, it was scored as 30. Scores 35 and 40 were assigned to birds that preferred to sit when not encouraged to walk. They showed no balance in their gait, with often twisted or bowed legs that moved in a clear, outwards circling motion. The severity of the leg defect determined the distinction between 35 and 40; a distinction in posture was not considered for these scores. All birds up to and including score 40 were able to stand, walk and reach water and food. Any bird unable to walk was scored as 45 and culled immediately for welfare reasons. Because of the continuous monitoring of the flocks, this was seen in only 228 out of 346,536 birds (0.066 %). Aviagen practices a strict welfare policy, in which birds are observed several times a day; any birds whose welfare is compromised (e.g., birds ill or injured and not likely to recover) must be humanely culled as soon as possible. In total 556 birds displaying a run instead of a walk were recorded as a separate value and excluded from the genetic analysis. Males were routinely scored in all lines, females only in line A.

Birds were individually weighed and visually assessed for skeletal leg health (LD and CT) and dermatitis (FPD and HB) by a trained team at 5 weeks (lines A and B) or 6 weeks of age (lines C and D). BR was measured on part of the birds rejected as selection candidates. It was defined as the weight of the breast muscle (pectoralis major and pectoralis minor) without skin as a proportion of the live BW. The breast was weighed at around 24 h post-slaughter following air chill. The team of scorers was regularly benchmarked for consistency using correlations between and within scorers and was the same across the whole data set.

A description of the traits is provided in Table 1. LD and CT are key defects and under a 'zero tolerance' policy, no bird showing any of these is kept for breeding. For a more in-depth description of LD, CT and HB

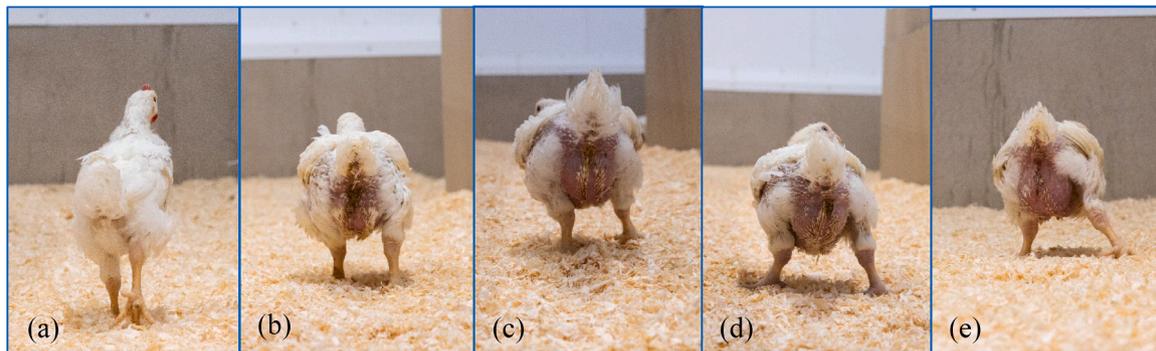


Fig. 1. Illustrations of gait scores. Various examples of the gait scores ranging from (a) score 10 over (b) score 25, (c) score 30 and (d) score 35 up to (e) score 40.

Table 1

Trait abbreviations, description and scale of measurement.

Abbreviation	Description	Variable type
BW	Body weight (g)	continuous
BR	Breast percentage: weight of the breast muscle as proportion of the live BW	continuous
FPD	Food pad dermatitis: the extent to which the plantar surface of the foot is affected	ordinal, 4 scores
HB	Hock burn: the extent to which the plantar surface of the hock is affected	ordinal, 4 scores
LD	Long bone deformity: a valgus or a varus deformity of the tarsometatarsi/tibiotarsi or a bending of the tarsometatarsi, occasionally continued in the middle forward digit	binary
CT	Crooked toes: curling of one or more of the toes due to a deviation of the phalanges	ordinal, 3 scores
AGS	Aviagen gait score: visual assessment of walking ability	ordinal, 8 scores

we refer to our publication on 25 years of selection for leg health (Kapell et al., 2012a), while for more detail on the trait FPD we refer to our publication on selection against FPD in two different environments (Kapell et al., 2012b). Aviagen uses a stringent approach for all traits, whereby both legs are evaluated and the higher scoring leg determines the final score.

Birds, housing and management

The birds were hatched in the same hatchery, tagged with a barcoded wing band and then distributed over pens on the growing farms, all according to line. These farms were located in southern Scotland with a high bio-secure pedigree environment where breeding program selection candidates are recorded and selected. See Kapell et al. (2012a, 2012b) for a more detailed description of the management and housing. Table 2 provides an overview of the environmental parameters relevant

Table 2

Description of the environmental parameters.

Parameter	Feed 1 (lines A and C)
Feed d 0-10	Starter (247 g of CP/kg; 12.2 MJ of ME/kg)
Feed d 11-25	Grower (228 g of CP/kg; 12.7 MJ of ME/kg)
Feed d 25-final weighing	Finisher (207 g of CP/kg; 12.8 MJ of ME/kg)
Parameter	Feed 2 (lines B and D)
Feed d 0-10	Starter (234 g of CP/kg; 11.3 MJ of ME/kg)
Feed d 11-25	Grower (214 g of CP/kg; 11.6 MJ of ME/kg)
Feed d 25-final weighing	Finisher (191 g of CP/kg; 12.0 MJ of ME/kg)
Stocking density	33 kg bird weight per m ²
Temperature	Gradually reduced from 35 to 21 °C
Photoperiod d 0-7	23L:1D
Photoperiod d 8-final weighing	18L:6D
Light intensity d 0-7	40 lx
Light intensity d 8-final weighing	Gradually reduced to 20 lx

to the birds in this study.

Statistical analyses

The genetic analysis followed the approach and structure as detailed in our previous papers (Kapell et al., 2012a,b) using a multiple trait model including 7 traits – BW, BR, FPD, HB, CT, LD and AGS – to estimate genetic parameters in the software VCE (Groeneveld et al., 2008). The model included a fixed effect accounting for the interaction between the hatch week, pen, contributing mating group and sex of the individual (“batch”), additive genetic effects, maternal permanent environmental effects (PEm) and residuals. Numbers of levels for the bird, PEm and batch effect are provided in Table 3.

Results

Descriptive statistics

The mean BW, FPD, HB, CT and LD scores are given in Table 4, while Table 5 shows the respective information for BR and AGS. The lines ranged from 2.6 to 2.0 kg average BW across both sexes with females 7–17 % lighter than males. BR was higher in females than males in all lines, and ranged (averaged across sexes) from 24.6 % in line D to 32.7 % in line C. For all leg health traits females had a lower (better) average score than males, with the exception of CT in line D, although the difference at 0.09 in males and 0.10 in females was low. Line A showed the most extreme differences between sexes, with the average scores for FPD, HB, CT and LD being 2, 4, 10 and 2 times as high respectively in males. Line B showed a similarly strong pattern, at 2, 4, 8 and 2 times as high average scores in males for these four traits. Lines C and D were more similar between the sexes, with the difference being at most twice as high for males (FPD, HB and CT in line C, HB and CT in line D). Line A had the highest average score for FPD, HB and LD but the lowest for CT. At the other end of the spectrum, line D had the lowest average scores for FPD, HB and LD, but the second highest for CT. In absolute values, the difference between sexes was generally least in line D, with the highest difference being 0.03 in HB and LD. This is in strong contrast to the other three strains, where differences in average score between sexes ran as

Table 3

Number of birds with phenotypic information (Phenotypes), number of birds in the pedigree file (Pedigree), number of levels for the maternal permanent environmental effect (PEm) and number of levels for the fixed effect (Batch).

Line	Numbers of levels of			
	Phenotypes	Pedigree	PEm	Batch
A	205,971	226,013	7,703	3,444
B	171,103	183,289	7,944	3,484
C	158,405	163,148	4,204	3,274
D	125,892	132,043	2,594	2,931

Table 4

Descriptive statistics for traits measured on every individual per sex (♂ = male, ♀ = female) and combined (tot.), (n = number of records, mean and s.d. in grams for BW, mean score for FPD, HB, LD and CT with classifications rescaled to range 0–1). For key to traits, see Table 2.

Line	Sex	N	BW Mean (s.d.)	FPD Mean	HB Mean	LD Mean	CT Mean
A	♂	98,941	2,839 (226)	0.57	0.53	0.41	0.09
	♀	102,238	2,362 (218)	0.28	0.13	0.04	0.05
	tot.	201,179	2,597 (326)	0.42	0.33	0.23	0.07
B	♂	87,663	2,388 (253)	0.47	0.36	0.24	0.12
	♀	81,169	2,209 (224)	0.25	0.10	0.03	0.07
	tot.	168,832	2,302 (256)	0.37	0.23	0.14	0.09
C	♂	75,026	2,455 (247)	0.28	0.17	0.04	0.15
	♀	83,218	2,179 (211)	0.13	0.09	0.02	0.12
	tot.	158,244	2,310 (267)	0.20	0.13	0.03	0.14
D	♂	62,974	2,162 (216)	0.19	0.06	0.06	0.09
	♀	62,834	1,843 (196)	0.18	0.03	0.03	0.10
	tot.	125,808	2,003 (261)	0.18	0.04	0.04	0.10

Table 5

Descriptive statistics for traits measured on a subset of individuals per sex (♂ = male, ♀ = female) and combined (tot.) where applicable, (n = number of records, mean and s.d. in % for BR, mean score for AGS (range 10–45)). For key to traits, see Table 2.

Line	Sex	BR		AGS	
		n	Mean (s.d.)	n	Mean
A	♂	19,146	27.4 (2.0)	91,798	24.5
	♀	15,427	27.6 (1.7)	48,080	24.1
	tot.	34,573	27.5 (1.9)	139,878	24.4
B	♂	14,764	25.7 (2.0)	75,030	24.5
	♀	16,705	26.1 (1.7)		
	tot.	31,469	25.9 (1.8)		
C	♂	7,660	32.1 (2.1)	71,890	25.7
	♀	7,445	33.3 (2.0)		
	tot.	15,105	32.7 (2.1)		
D	♂	5,271	24.5 (2.1)	59,738	24.1
	♀	4,416	24.7 (2.1)		
	tot.	9,687	24.6 (2.1)		

high as 0.40 for HB in line A. Across all lines, CT tended to show the least difference.

Line A was the only line where females were routinely scored for AGS. They had a lower (better) average score than males. However, both males and females averaged between the 20 and 25 classification. Fig. 2 shows the distribution of the birds across the different classes by line/sex. In all cases score 25 was the most common one, with more than 50 % of birds falling into this category. The scores at either end (10, 40 and 45) were always below 1 %. A score of 25 or lower was observed in around 85 % of all birds in lines A, B and D, and around 75 % of birds in line C. Lines A and B were scored a week earlier than lines C and D to achieve optimal distributions of scores at similar weights. While age may have an impact on the gait score, this effect is not estimable as the effect of age was wholly confounded with the line effect.

Heritabilities

Heritability estimates for BW were moderate to high in all four lines, ranging from 0.36 (line A) to 0.47 (line D). Similarly, BR showed a moderate to high heritability across all lines, at 0.38 (line A) to 0.54 (line D) (Table 6). The five leg health traits all showed lower heritabilities. FPD, the trait with the highest average score, was the most heritable at 0.25 (line C) to 0.28 (lines A and D). HB, with a much lower average score, ranged from 0.10 (line D) to 0.16 (line C). The two skeletal abnormalities CT and LD ranged from 0.04 (line B) to 0.14 (line D) and 0.04 (line A) to 0.10 (line D), respectively. The heritability estimates for AGS were low to moderate ranging from 0.14 in line B to 0.24 in line D. The SE for all heritabilities estimated across the four lines were low, ranging from 0.00–0.02.

Correlations among leg health traits

The genetic correlations among the leg health traits were generally very low (between –0.16 and 0.10, with the SE ranging from 0.01–0.02 for all but two genetic correlations in line C) for most traits and lines. The notable exception to this, across all lines, was the genetic correlation between LD and CT, consistently moderately high at 0.28 (line D) to 0.44 (line B). The genetic correlation between AGS and LD was also moderately high (0.27–0.50) in three out of four lines, but low in line D (0.09). Furthermore, line D showed moderate correlations of HB with AGS (0.33) and with LD (0.25). However, all these specifically mentioned

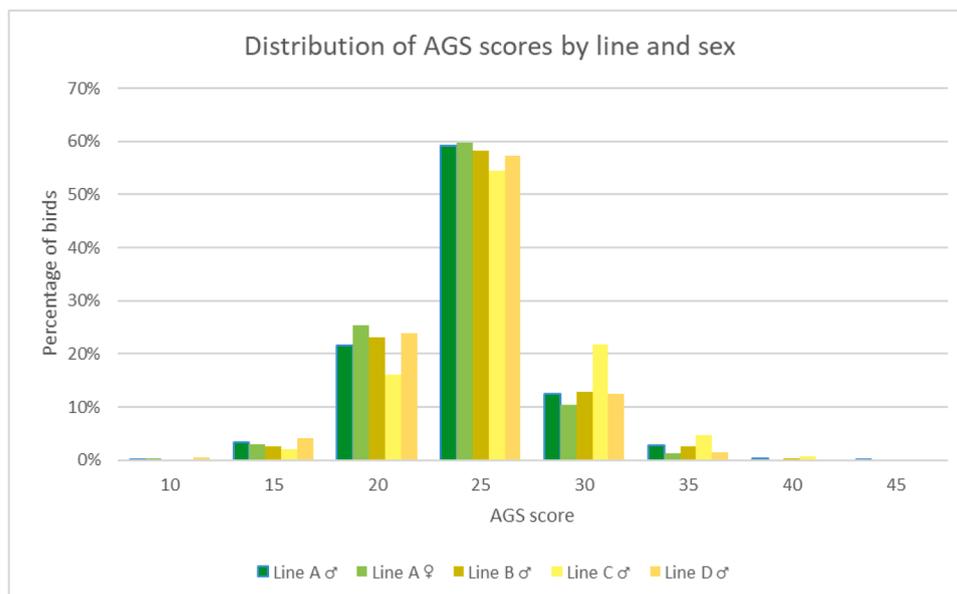


Fig. 2. Distribution of Aviagen gait scores over categories by line and sex.

Table 6

Estimates of heritabilities (bold, diagonal), genetic correlations (above diagonal) and phenotypic correlations (below diagonal). For key to traits, see Table 2. SE as subscript.

Trait	Line A						
	BW	BR	FPD	HB	CT	LD	AGS
BW	0.36	0.13	-0.08	0.32	0.15	0.29	0.48
BR	0.01	0.38	0.01	0.01	0.01	0.02	0.01
	0.25	0.03	0.15	0.01	-0.01	0.07	0.32
FPD	0.01	0.01	0.28	0.02	0.01	0.01	0.01
	-0.08	0.04	0.02	-0.07	0.01	-0.14	0.00
HB	0.01	0.01	0.01	0.15	0.01	0.02	0.02
	0.16	0.02	0.00	0.00	-0.09	0.00	0.11
CT	0.01	0.01	0.01	0.00	0.07	0.01	0.01
	0.02	0.02	0.00	-0.02	0.03	0.31	-0.05
LD	0.01	0.01	0.01	0.00	0.00	0.04	0.01
	-0.01	-0.01	-0.03	-0.01	0.03	0.00	0.50
AGS	0.01	0.01	0.01	0.00	0.00	0.00	0.16
	0.26	0.16	0.02	0.04	0.00	0.11	0.00
Trait	Line B						
	BW	BR	FPD	HB	CT	LD	AGS
BW	0.37	-0.05	-0.15	0.30	0.23	0.20	0.40
BR	0.01	0.45	0.01	0.02	0.02	0.01	0.01
	0.19	0.03	0.07	-0.13	0.00	0.13	0.19
FPD	0.01	0.01	0.27	0.02	0.02	0.02	0.02
	-0.10	0.01	0.02	-0.07	0.04	-0.11	-0.06
HB	0.01	0.01	0.00	0.12	0.02	0.01	0.01
	0.12	-0.03	0.00	0.00	-0.03	0.03	0.03
CT	0.01	0.01	0.01	0.00	0.04	0.01	0.01
	0.03	0.01	0.00	-0.01	0.00	0.44	0.00
LD	0.01	0.01	0.01	0.00	0.02	0.06	0.02
	-0.01	0.02	-0.05	-0.01	0.02	0.00	0.44
AGS	0.01	0.01	0.01	0.00	0.01	0.00	0.14
	0.20	0.14	-0.02	0.00	0.01	0.11	0.00
Trait	Line C						
	BW	BR	FPD	HB	CT	LD	AGS
BW	0.40	0.22	0.13	0.22	0.18	0.31	0.36
BR	0.01	0.47	0.02	0.03	0.03	0.02	0.01
	0.33	0.01	0.21	-0.09	0.01	0.05	0.28
FPD	0.01	0.01	0.25	0.02	0.03	0.03	0.01
	0.03	0.08	0.01	-0.04	0.04	-0.16	-0.01
HB	0.01	0.01	0.01	0.16	0.02	0.02	0.01
	0.14	-0.01	-0.04	0.01	-0.01	0.10	-0.04
CT	0.01	0.01	0.01	0.01	0.08	0.02	0.02
	0.02	0.03	0.00	-0.01	0.01	0.37	-0.09
LD	0.01	0.01	0.01	0.00	0.01	0.04	0.03
	-0.03	0.00	-0.06	0.00	0.08	0.08	0.27
AGS	0.01	0.01	0.01	0.00	0.00	0.00	0.17
	0.18	0.17	-0.01	0.02	0.00	0.14	0.00
Trait	Line D						
	BW	BR	FPD	HB	CT	LD	AGS
BW	0.47	0.15	0.05	0.47	0.11	0.25	0.43
BR	0.01	0.54	0.00	0.02	0.01	0.02	0.02
	0.32	0.03	0.08	0.01	0.08	0.16	0.45
FPD	0.01	0.01	0.28	0.02	0.01	0.01	0.02
	0.00	0.03	0.01	-0.05	-0.04	-0.14	0.15
HB	0.01	0.01	0.00	0.10	0.02	0.02	0.01
	0.18	0.03	-0.01	0.02	-0.08	0.25	0.33
CT	0.01	0.01	0.01	0.00	0.14	0.02	0.02
	0.03	0.02	0.00	-0.01	0.01	0.28	0.12
LD	0.01	0.01	0.01	0.01	0.01	0.10	0.01
	0.02	0.03	-0.05	0.05	0.06	0.01	0.09
AGS	0.01	0.01	0.01	0.00	0.02	0.01	0.24
	0.25	0.27	0.05	0.06	0.02	0.04	0.01

correlations were in a favorable direction. Among the five leg health traits, the majority of correlations were favorable, with the strongest unfavorable correlation found between FPD and LD in line C (-0.16). At the phenotypic level, all correlations among leg health traits were negligible.

Correlations with production traits

The majority of genetic correlations of leg health traits with the two production traits BW and BR were low, between -0.15 and 0.20 (SE ranging from 0.00 to 0.03), with a few exceptions. Across all four lines, BW was moderately highly correlated with HB (0.22–0.47) and slightly stronger with AGS (0.36–0.48). Furthermore, it was in some lines moderately correlated with CT (0.23 in line B) and with LD (0.25–0.31 in lines A, C and D), but 0.20 or lower in all other instances. In three lines, BR was moderately positively correlated with AGS (0.28–0.45 in lines A, C and D), and in line C with FPD (0.21). While genetic correlations between production traits and leg health traits had a tendency to be unfavorable, there were some exceptions to this. Most notably, FPD was favorably (albeit low) correlated with BW in lines A and B at -0.08 and -0.15, respectively. Phenotypically, AGS was always the strongest correlated leg health trait with either BW (0.18–0.26) or BR (0.14–0.27), with no other correlations exceeding 0.14.

Discussion

Leg health is an important welfare indicator in broilers, and selection for leg health contributes to a reduced incidence of leg health issues. This is done through a reduced genetic propensity to develop leg health issues while simultaneously accounting for the antagonistic relationship with production traits like BW or breast meat yield. Selection for specific aspects of leg health (e.g., contact dermatitis or leg deformities) has been part of broiler breeding goals for many decades, as reported in previous studies (Kapell et al., 2012a, 2012b; Neeteson et al., 2023) and policy reports (Farm Animal Welfare Committee, 2012; Hiemstra and Ten Napel, 2013). However, these traits are not necessarily indicative of the functional walking ability of a bird, as shown by the inconsistent phenotypic correlations estimated between leg health traits and gait score in other studies (e.g., Kestin et al., 1999; Garner et al., 2002; Kristensen et al., 2006). Therefore, it is important that walking ability is scored as part of a broader leg health assessment. This approach allows long-term improvements of all components of leg health, accounting for developmental and functional aspects.

The genetics of leg health

The estimated heritability for AGS, as well as the genetic correlations with production traits and leg health traits, allows simultaneous improvements of all aspects of bird performance even though there might be antagonistic correlations. The estimated heritability for AGS for broilers is, to our knowledge, the first publication of its kind. AGS heritability estimates in broiler chickens are higher (0.14–0.24) than the heritabilities found in turkeys (0.08–0.13) and ducks (0.06–0.12) (Kapell et al., 2017; Duggan et al., 2016, 2017). Despite not seeing extreme scores as per BGS scale due to a stringent welfare culling policy, the AGS captures sufficient variation to achieve significant estimates of genetic variance.

The heritability estimate for FPD is in line with the range of the heritabilities found in other studies, which range from 0.08 to 0.32 in different environments (Kjaer et al., 2006; Ask, 2010; Kapell et al., 2012b). The estimated heritability of HB is at the upper end of the range found in other studies (0.06–0.10 - Kjaer et al., 2006; Ask, 2010; Kapell et al., 2012a). This higher heritability for HB may be a result of the increased prevalence of HB in this data set compared to a previous analysis (Kapell et al., 2012a). The heritability estimates for LD and CT are in line with those estimated by Chen et al. (2011) and Kapell et al. (2012a), ranging from 0.04 to 0.11 for LD and 0.01 to 0.10 for CT. Estimates of heritability for leg health traits in this study and previous studies are generally lower than the estimate found for AGS. This – together with the favorable correlations with other leg health traits in the majority of the lines – makes AGS a very suitable complement to the portfolio of traits available for genetic selection to improve leg health.

Correlations among leg health traits

The genetic correlation between AGS and LD was moderate to high in lines A to C, at 0.26–0.52, and lower for line D at 0.09. This highlights that the relationship between the skeletal deformities (LD) and the functional trait (AGS) is line-specific. Selection against LD has been practiced for decades in the breeding program, which may indirectly have had a beneficial effect on AGS. In lines A to C the genetic correlations between AGS and the other leg health traits were low, and in several cases not significantly different from zero. In line D they ranged from 0.12–0.33, showing that there is diversity between the lines and suggesting that the nature of the leg health traits and walking ability is line-specific. While Greene et al. (1985) described birds with severe contact dermatitis as lame, the low genetic correlation in lines A to C is perhaps not unexpected, since few animals in the present study showed severe levels of FPD (on average 4.6 % per line) and HB (on average 0.4 % per line). The difference with Greene et al. (1985) and this study could be due to environmental differences and the fact that current broiler populations would have a lower genetic propensity to develop FPD and LD due to continuous selection (Kapell et al., 2012a, 2012b).

Correlations of AGS with other production traits

In general, the genetic correlations between welfare and production traits were antagonistic. Phenotypically the antagonistic relationship between AGS and BR, and to a lesser extent BW, could be explained by the breast muscle mass affecting posture, balance and locomotion. This is in line with observations by Corr et al. (2003) who compared the walking quality of birds with varying degrees of breast muscle mass.

Implementation in breeding programs

Kestin et al. (1992) and Bradshaw et al. (2002) suggested that walking ability should be included in broiler selection, indicating that gait problems can be alleviated by selective breeding using individual broiler gait scores. As mentioned previously, including gait score in a breeding program allows long-term improvement of the walking ability of broilers, alongside other welfare and production traits. This strategy of combining leg health and production traits in a broad and balanced breeding goal has been practiced for decades as explained in Kapell et al. (2012a). Indeed, gait score has been part of the Aviagen breeding program since 2011. The management of the antagonistic correlation between AGS and production traits is key to ensure that both type of traits progress in the desired direction. Given that the genetic unfavorable correlations between AGS and production traits were generally low or at worst moderate, there is clear scope for finding selection candidates with acceptable favorable breeding values for both AGS and production traits.

The genetic correlations between AGS, production traits and other leg health traits enable a multi-trait strategy combining production and welfare characteristics and is in fact how modern broiler breeding programs have been operating for decades (Hiemstra and Ten Napel, 2013; Neeteson et al., 2023).

Conclusions

To conclude, this study has shown that an original gait scoring system, comprising an 8-point scale, effectively captures the genetic variation of walking ability in modern broilers. Based on the genetic correlation with LD, a bone deformity that has been part of the breeding goal for many decades, AGS complements the portfolio of leg health traits included in the breeding goal. While genetic correlations with production traits are unfavorable, both leg health and production traits are improved simultaneously in broad breeding goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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