GENETIC STUDY OF THE RELATIONSHIPS BETWEEN GROWTH AND WALKING ABILITY IN TURKEYS

by

SAMET SOYALP

(Under the Direction of Romdhane Rekaya)

ABSTRACT

Rapid growth resulted in heavy turkey birds at a young age. The extreme imbalance between skeleton development and body weigh has led to several fitness and animal wellbeing anomalies. Of particular interest is the decay in leg soundness and the bird walking abilities. In the current study, different statistical models and traits were used to investigate the genetic relationships between growth and walking ability in a commercial turkey population. Estimates of the heritability of growth traits were moderate and ranged between 0.44 and 0.51. The heritability of walking ability was 0.25 using a linear-threshold model. The genetic correlations between walking ability and growth traits ranged between -0.45 to -0.35 depending on the statistical model used. Genetic correlations between walking ability across different growth rate classes seem to indicate a non-linear relationship between growth and leg problems. These results indicate that walking ability should be included in the selection index.

INDEX WORDS: Walking ability, growth, heritability, genetic correlations

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DEDICATION

I would like to dedicate this study to the poultry industry and help farmers.

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TABLE OF CONTENTS

LIST OF TABLES

Page

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Birds should be able to walk to access feed and water, compete for free space, and to avoid aggressive behavior of other birds. Thus, walking ability is crucial for the bird's productivity and wellbeing. Unfortunately, a disproportional increase in body weight compared to skeletal system maturity resulted in birds with leg and mobility problems. Balancing these two traits has productivity and welfare implications. Modern poultry species have been subjected to intensive directional selection for growth rate and feed efficiency. Although undeniable successes have been realized in increasing productivity, several non-intended negative consequences due to correlative response were observed. Skeletal integrity, leg soundness, and walking ability are some of the traits that have decayed over the years due to intensive selection for fast growth. More recently, this situation has become a societal issue that raises the concerns of stakeholders including consumers, retail and food industries, and producers. In fact, several countries, including the US, and food chains (e.g., McDonalds and KFC) are requiring flock welfare audits to ensure that birds are raised humanly. Leg soundness and bird mobility are crucial elements of the welfare audit.

SELECTION FOR BODY WEIGHT GAIN

High demand for turkey meat from both consumers and industries had led to the rapid increase in the world-wide turkey population from around 100 million in 1970 to over 580 million birds in 2021. Responding to this market need required major intensification of the production system. One of the pillars of this intensification effort was the production of fast-growing birds with a high market body weight and a desirable body composition. Preferred prime cuts (e.g., breast meat yield) were optimized due to their lucrative economic value. Current commercial turkey birds weigh nearly 17 kg at 16 weeks of age compared to 5 to7 kg 50 years ago. Similar gains in body weight were observed at 8, and 20 weeks of age in males and female turkey birds. Clark et al. (2019) reported that after 50 generations of selection for increased body weight, selected turkeys are currently 2.5 times heavier than the non-selected counterparts. Furthermore, the magnitude of the difference in body weight increased with the age of the bird. At 5 weeks of age the selected turkeys (2.02 $\pm$ 0.03 kg) were over twice as heavy as the non-selected turkeys (0.98 $\pm$ 0.03 kg). By 16 weeks of age, the selected line turkeys (16.4 $\pm$ 0.4 kg) were approximately 2.5 times heavier than the non-selected turkeys (6.7 $\pm$ 0.4 kg). In fact, Nestor et al. (2008) reported that the body weight between 8 to 20 weeks ranged from 5.82 kg to 19.57 kg and 4.86 kg to 17.47 for male and females, respectively. Rafat et al. (2011) reported that body weight of turkeys measured at 8, 10 and 12 weeks of age ranged from 560 to 1228 g.

Havenstein et al. (1988) using long-term growth turkey lines selected for carcass composition were significantly heavier than in the non-selected line. Similarly, Bayyari et al. (1997) reported that turkey lines selected for increased 16-week body weight and egg production were significantly heavier than a non-selected line. Bacon et al. (1986) reported that body weight of selected male turkeys was significantly heavier than non-selected line at 16 weeks of age. Similarly, Nestor et al. (2001) noted that by 16 weeks of age, males of selected turkeys for body weight were heavier than non-selected male turkeys and the absolute difference continued to increase at 20 weeks of age.

Updike et al. (2005) reported that random bred control male toms weighed significantly less than both the selected and fast-growing commercial male toms at all ages (P<0.05). Additionally, the total breast meat yield was the lowest in the random bred control male toms. However, the highest breast meat yield was in the fast-growing commercial male toms. Nestor et al. (2005) reported that at 8 weeks of age, selected male turkeys for body weight were larger than non-selected males. Hiscock et al. (2022) concluded that selected turkey males final body weight was higher than their non-selected counterparts. Specifically, selected males grow at a weekly rate of 1.63 kg, which was significantly higher ($P < 0.05$) than the 1.12 kg for non-selected males. Additionally, selected males had heavier whole breast weight (6.08 kg) compared to non-selected males (4.74 kg).

Selection pressure for growth applied to modern turkey populations has resulted in substantial reduction in the age to slaughter. This was motivated by the quest to produce fast growing birds with a high market body weight and a desirable body conformation to increase production efficiency and optimize production of preferred body cuts. Using growth models, Aslam et al. (2011) concluded that turkey populations have been selected for breeding at earlier age, between 60 and 80 days of age, to improve overall production mainly body weight and the production of desirable cuts of meat. Havenstein et al. (2007) reported the performance of modern turkeys produced in 2003 compared to that of 1966 random bred birds, when grown using representative 1966 and 2003 diets. The data showed that growth rate from hatch to market age has approximately doubled throughout the 37-year period, and the body weight of toms and hens have been increasing by approximately 208 and 140 g/yr during the same time period. Correa et al. (2016) reported a positive correlation between age and body weight using Gompertz, Bertalanffy, and Logistic nonlinear models. The positive association between age and body weight ranged from 21 g at 1 day of age to 13 kg at 23 weeks of age for female turkey using these three non-linear models. Similar results were observed for male birds.

Intense selection of commercial turkey population for body weight has led to a significant decrease feed conversion rate (FCR) resulting in a higher feed efficiency. Genetic forces have significantly reduced feed conversion rate. Feed conversion ratio was phenotypically and genetically negatively correlated with body weight gain in commercial turkey populations due to the heavy selection. Willems et al. (2013) reported a negative correlation of -0.68 and -0.64 between feed conversion ratio and body weight gain at the phenotypic and genetic levels, respectively in turkey toms. Havenstein et al. (2007) reported that feed efficiency was approximately 20% better in 2003 selected turkey toms (2.638) than in the 1966 random bred control toms (3.278) at 20 weeks of age. At 11 kg of body weight, feed efficiency in the 2003 toms was 2.132 (at 98 days of age) and that is approximately 50% better than in the random bred control toms observed at 196 days of age (4.208) of age.

On the other hand, few studies reported small positive phenotypic and genetic correlations between body weight and FCR. In fact, Case et al. (2012) reported a correlation of 0.10 and 0.12 between body weight and FCR at the phenotypic and genetic levels, respectively. Additionally, the same authors reported moderate positive phenotypic and genetic correlations between feed intake, body weight, and average daily gain (ADG) ranging between 0.28 and 0.67.

Body weight related traits are reported to be moderate to highly heritable in turkey birds. Aslam et al. (2011) reported that the heritability estimates for body weight traits measured at 40, 60, 80, and 120 days of age ranged between 0.32 to 0.40. Similarly, Uberu et al. (2021) reported estimates of heritability for body weight, body length, and breast girth at 8 weeks of age were 0.47, 0.70, and 0.83, respectively. Begli et al. (2019) reported estimate of heritability for body weight of 0.50 ± 0.05 at 18 weeks of age. However, few studies reported low heritability estimates (0.21) for body weight in turkeys (Kapell et al., 2017). Much lower estimates of body weight heritability were reported at early age of the birds. In fact, Aslam et al. (2011) reported body weight estimates of 0.0 and 0.12 at 1 and 17 days of age, respectively.

Body weight and breast meat yield traits have showed high genetic and phenotypic correlations in turkey birds. In fact, Aslam et al (2011) reported high positive genetic correlation (0.86 to 0.98) between body weights measurements at 17, 40, 60, 80, and 120 days of age. Furthermore, they reported high genetic correlations (0.68 to 0.90) between breast meat yield, breast length, breast width, and asymptotic weight. Similarly, Case et al. (2012) reported that body weight was strongly correlated genetically (0.80 to 0.88) with breast yield in female and male turkey birds. On the other hand, weak and moderate genetic and phenotypic correlations between body weight and breast yield were reported in the literature. Fernandez et al. (2003) reported positive genetic and phenotypic correlations ranging between 0.23 and 0.62 and 0.06 and 0.21, respectively. Abdalla et al. (2019) and Case et al. (2012) reported weak genetic correlation of 0.16 ($\pm$ 0.06) and 0.03 to 0.35 between body weight and breast meat yield, respectively.

Estimates of genetic parameters for growth and meat quality traits in turkeys showed unfavorable relationships between these traits. Molecular markers that has been directly or indirectly associated to quantitative trait loci (QTL) were considered as a tool for selection in the presence of these antagonistic relationships. Aslam et al. (2011) reported several QTL across different chromosomes in association with growth curve traits. Four different regions affecting asymptotic weight, breast width, yellowness, and percent drip loss were reported in chromosome 3. Additionally, two QTL regions affecting body weight at 17 and 40 weeks of age were detected on chromosome 5. On chromosome 12, two QTL regions were found to be associated with body weight at 40 and 80 weeks, and meat quality (percent drip loss). Additional QTL were detected on different chromosomes with significant effects on breast length, and breast weight and several other meat quality traits.

More recently, several single nucleotide polymorphisms (SNPs) have been significantly associated with body weight using genome-wide association studies (GWAS). In fact, Abdalla et al. (2022) reported that 33 SNPs among a 65K markers on the commercial genotyping panel were strongly correlated with body weight in turkeys at 18 weeks of age. These markers had minor allele frequencies between 0.10 and 0.47 and their effect on body weight ranged between -0.15kg $\pm$ 0.01 and 0.12kg $\pm$ 0.03.

SELECTION FOR WALKING ABILITY

Leg disorder problems and their negative impact on bird mobility and walking ability have increased in parallel with the spectacular increase in growth rate in the last 4 or 5 decades. Leg disorders are a primary welfare concern for the turkey industry worldwide. Leg health is a fundamental element of modern turkey breeding programs. In fact, locomotion problems have become one of the most important challenges facing modern turkey industry.

Nestor et al. (1984) reported that leg scores for turkeys selected for shank width were significantly higher than the non-selected birds. Therefore, selected male turkeys had poorer walking ability than non-selected counterparts at 16 weeks of age. Similar results were observed at 20 weeks of age (Nestor et al., 1987). Emerson et al. (1991) reported that selected males for increased shank diameter, leg muscle, shank and drum bone had lower leg muscle and bone weights than non-selected counterparts. Additionally, in selected turkeys, shank and drum bone weights were lower than in non-selected counterparts. Non-selected turkey populations had lower leg scores (better walking ability) than selected turkeys. Ye et al. (1997) reported that selected male turkeys for increased shank width had poorer walking ability, shorter and narrower shanks than non-selected male turkeys at 16 weeks of age. Nestor et al. (2001) and Nestor et al. (2005) concluded that the shank width of the non-selected males was bigger compared to their selected counterparts. Additionally, walking ability scores at 16 weeks of age were lower (birds walked better) for the non-selected turkey birds.

Gait scores are directly associate with walking ability, and they have been used as phenotypes to select for leg soundness, mobility and walking ability. Using a four scale gait scoring system (1=normal; 2=slightly handicapped; 3=severely handicapped; and 4=nearly incapable of walking), Hahn et al. (2020) reported that at eight weeks of age, the walking ability of all birds in the three experimental groups which were either without any training period (control), training from weeks 2 to 8 (short-term), or training from weeks 2 to 21 (long-term) was normal (gait score of 1). At week 21 of age, the average percentage of slightly handicapped birds (gait score of 2) was similar across the three treatments classes and ranged between 40 and 43%. Similar results were observed by Kapell et al. (2017). There was a clear difference between male and female turkey birds. In fact, the males had up to 3 times higher prevalence of valgus and varus than females. Due to a pre-selection of the males at 14 weeks of age, the prevalence of valgus and varus deformities may be an underestimation compared to the females. A clear difference in prevalence was found for tibial dyschondroplasia between males and females.

A better understanding of normal gait and its influences on biomechanical aspects of leg bones has become an important motivation to prevent skeletal disorders and locomotion issues. Additionally, it has been useful to better understand the effects of common leg defects on the kinetic parameters of gait and biomechanical properties of bone. Rondon et al. (2017) reported that at 33 d, varus, valgus, twisted legs, crooked toes, and slipped tendons were observed in 4 strains of Large White turkeys. Additionally, while one strain had no twisted legs at 16 d and 5.70% of cumulative leg problems at 33 d of age, the other strains had, at least, twice as many leg problems. Furthermore, Rondon et al. (2018) noted that Femur, tibia, and tarsus-metatarsus, bone mineral content, bone mineral density, and biomechanical parameters at 145 days of age had several significant correlations with gait kinetic parameters at 92, 115 and 145 days in large white turkeys.

The heritability of leg disorders and mobility is in general low. Estimates of heritability for valgus and varus deformities, tibial dyschondroplasia, and footpad dermatitis ranged between 0.01 to 0.07, between 0.06 to 0.12, and 0.10 to 0.15, respectively (Kapell et al., 2017). Similar heritability was reported for gait scores with estimates ranging between 0.08 and 0.13.

Several studies reported a genetic association between leg disorder, gait scores and body weight in commercial turkey populations. Costa et al. (2014) reported a significant difference in the prevalence of footpad dermatitis and gait disorder at two age points (13-15 and 16-20 weeks of age). Furthermore, both footpad dermatitis and gait scores were strongly associated with body weight. Havenstein et al. (1988) reported that the estimates of the genetic correlation between body weight and various bone weight measurements were high (>.75). Kapell et al. (2017) reported genetic correlations between gait scores and body weight ranging between 0.28 to 0.51 in purebred turkey lines. On the other hand, few studies reported a weak genetic correlation between body weight and walking ability in turkey populations. Nestor et al. (1985) noted that a considerable genetic increase in body weight in male turkeys in spite of the deterioration of their walking ability which could point towards the lack of genetic association between body weight and walking ability in Turkeys. Havenstein et al. (1988) reported that the genetic correlation of 0.34 between shank width with body weight indicating that selection for body weight alone might not rise shank width enough to support the changes brought in body weight. Kapell et al. (2017) noted that there was a low genetic correlation (-0.06 to 0.08) between body weight and some leg disorders.

Genetic selection of fast-growing strains has increased mobility problems and made natural mating impossible with serious consequences on animal wellbeing and welfare. Animal welfare has become a serious issue for the poultry industry not only for its potential relationship with productivity but also due to societal concerns. Poultry production is a global industry due to international trade. Thus, the poultry industry has to operate within the limits of national and international rules and regulations, especially those related to animal welfare. Footpad dermatitis and walking ability are two parameters often used in poultry welfare audits.

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CHAPTER 2

LINEAR THRESHOLD ANALYSIS OF MALE BODY WEIGHT AND WALKING SCORE [1]

[1] Soyalp, S., E. Hartono, S.E. Aggrey, and R. Rekaya. To be submitted to Poultry Science

ABSTRACT

Several welfare and health problems in the turkey industry are largely due to intense selection for rapid growth to reach heavier final body weights in exceedingly shorter periods of time. During the last 40 years, turkey birds have been subjective to heavily directional selection, especially for growth traits. As a consequence, body weight, breast width and weight, and other body parts have increased substantially in commercial turkey birds. However, this increases in body weight, especially due to the increase of the relative contribution of the breast, resulted in the relative decrease in the leg muscle and leg bone weights. This has resulted in mobility problems in turkey birds. Birds with leg and mobility problems often have difficulties accessing water and food which affect their growth and overall health. The current study was carried out to investigate the relationships between body weights and growth rates with walking ability in turkey birds using linear and threshold models. The data consisted in growth and walking ability traits collected on 276,059 male birds. The pedigree file included 836,785 individuals. Male birds were measured for body weight at 12 and 20 weeks of age. Also, they were measured for walking score at 20 weeks of age. For walking score, birds were scored based on a 1 (bad) to 6 (good) grading system. Due to the small number of records in classes 5 and 6, birds with walking scores of 4, 5 and 6 were grouped together resulting in only 4 classes for walking ability. Heritability estimates of walking score at 20 weeks of age ranged between 0.25 and 0.27 depending on the number of scoring classes. Heritability of body weight at 12 and 20 weeks of age was moderate and ranged between 0.44 and 0.51 with higher heritability for older age. Using the 4-class scoring system, the genetic correlation between walking scores and body weight at 12 weeks was around -0.35, indicating that heavy birds tend to have poor walking ability. Similarly, estimates of the genetic correlations between walking score and body weight at 20 weeks was -0.45, indicating a more pronounced antagonistic relationship

between body weight and walking ability. The genetic correlation between body weight at 12 and 20 weeks was positive and high (0.80). The residual correlation between walking ability and body weight at 12 and 20 weeks of age was -0.07 and -0.02, respectively. The residual correlation between body weight at 12 and 20 weeks of was 0.57. Similar results were observed when a binary classification was adopted for walking ability. Collectively, these results indicate that intensive selection for growth has resulted in heavy birds that are more prone to leg and mobility problems.

INTRODUCTION

Turkeys raised for meat production are bred to grow and gain weight very rapidly, particularly to grow more muscle in the breast and thighs. This rapid growth rate can result in severe welfare related problems, including leg disorders such as lameness, ascites (accumulation of fluids in the abdominal cavity resulting from a heart problem), reproductive impairment, and heart failure to name a few. Very heavy birds often suffer from leg weakness, joint problems, and bone fractures. Their legs may be uncapable to support their body weight, leaving them unable to access food and water, and often they suffer from hock and foot burn due to increased contact with the litter.

Over the last 40 years, genetic selection for rapid growth has been very effective in male turkey birds. Due to the heavy genetic selection, mobility problems and leg abnormalities have increased. These problems are negatively associated with the animal wellbeing and resulted in an increase in downgrading and mortality, all of which decreased the efficiency of commercial turkey production. In fact, broiler turkey growers have suffered from high mortality problems and less efficient production periods. Additionally, rapid growth has led to meat quality issues in the poultry industry. Collectively, these factors could play a determinant role in the economic viability of the turkey enterprise.

Havenstein et al. (1988) using long-term growth turkey lines selected for carcass composition were significantly heavier than in the non-selected line. Bacon et al. (1986) reported that body weight of selected male turkeys was significantly heavier than non-selected line at 16 weeks of age. Similarly, Nestor et al. (2001) noted that by 16 weeks of age, selected males for body weight (14.2 kg) were heavier than the non-selected counterparts (13.7 kg) and the absolute difference continued to increase at 20 weeks (18.2 vs 17.2 kg). Updike et al. (2005) reported that random bred control toms weighed significantly less than both the selected and fast-growing commercial toms at all ages (P<0.05). Additionally, the total breast meat yield was the lowest in random bred control toms. However, the highest breast meat yield was in the fast-growing commercial male toms. Nestor et al. (2005) reported that at 8 weeks of age, selected male turkeys for body weight were larger than non-selected counterparts. Hiscock et al. (2022) concluded that the final body weight was higher in selected turkey males compared to non-selected males. Specifically, selected males gained an average of 1.63 kg per week, which was significantly higher ($P < 0.05$) than the non-selected males (1.12 kg per week). Additionally, selected males had substantially heavier whole breast (6.08 kg) compared to non-selected male (4.74 kg). Clark et al. (2019) reported that after 50 generations of selection for increased body weight, selected turkeys are 2.5 times heavier than the non-selected counterparts. Furthermore, the magnitude of the difference in body weight increased with the age of the bird. At 5 weeks of age the selected turkeys (2.02 ± 0.03 kg) were over twice as heavy as the non-selected turkeys (0.98 ± 0.03 kg). By 16 weeks of age, the selected line (16.4 ± 0.4 kg) were approximately 2.5 times heavier than the non-selected turkeys (6.7 ± 0.4 kg).

Nestor et al. (1984) reported that the leg scores of turkeys selected for shank width were significantly higher than non-selected birds indicating a poorer walking ability than non-selected counterparts at 16 weeks of age. Similar results were observed at 20 weeks of age (Nestor et al., 1987). Emerson et al. (1991) reported that selected male turkeys for increased shank diameter, leg muscle, shank and drum bone had lower leg muscle and bone weights than non-selected counterparts. Additionally, in selected turkeys, shank and drum bone weights were lower than in non-selected counterparts. Non-selected turkey populations had a lower leg scores meaning that birds walked better than selected turkeys. Ye et al. (1997) reported that selected male turkeys for increased shank width had poorer walking ability, shorter and narrower shanks than non-selected turkeys in males at 16 weeks of age. Nestor et al. (2001) reported that shank width of the non-selected male turkey birds was greater than selected male turkey birds. Nestor et al. (2005) reported that shank width was larger in the non-selected turkeys than in the selected turkey birds in males. Also, walking ability scores at 16 weeks of age were lower (birds walked better) for the non-selected turkey birds than the selected turkey birds in males.

Existing data point towards a negative relationship between growth and body weight traits and walking ability in turkeys. Several studies showed clear difference between selected and non-selected animals often under experimental conditions. Additionally, walking ability, a discrete trait, is often analyzed as a continuous response in clear violation to its distributional form. The aim of this study is to investigate the relationship between growth traits and walking ability using a large commercial data and the appropriate statistical modeling approach.

MATERIALS AND METHODS

DATA

Data for turkey birds hatched between 2009 to 2018 were provided by Hendrix Genetic (Canada). The population consisted of 276,059 turkey birds. Pedigree information was available for 836,785 turkey birds. Birds were measured for body weight at 12 and 20 weeks of age. Additionally, they were measured for walking scores at 20 weeks of age using a 1 to 6 scoring system. Score 1 means extremely lateral deviation whereas scores 4, 5, and 6 indicate birds without any leg lateral deviation. Scores 2 and 3 indicated birds with intermediate lateral leg deviation. Due to the small number of observations with walking ability scores of 5 and 6, birds with these sores were joined by those with sore 4 making a unique class (score 4). Thus, our final data set included only 4 walking classes (class 1=score 1; class 2=score 2; class 3=score 3; and class 4=scores 4, 5, and 6).

MODEL AND ANALYSIS

After editing, the data consisted of 75,094 birds recorded for 3 traits: body weight at 12 weeks (BW12), body weight at 20 weeks (BW20) and walking ability at 20 weeks (WA). Birds with original walking ability of 4, 5, and 6 were grouped into one class (class 4) to ameliorate the representation of leg incidences in different score classes. Additionally, a second analysis where walking ability was expressed as a binary trait (0 if original WA score is <4 and 1 otherwise) was carried out. This second analysis reduces the uncertainties associated with the 6-class scoring system and could provide easy and practical answers to producers. Descriptive statistics of the data were obtained using different packages of R. A threshold-linear mixed model similar to that one used by Rekaya et al. (2013) was implemented for the joint analysis of the categorical (leg problems) and linear growth traits. The threshold-linear mixed model used was:

$$y_{ijk} = H_{ik} + \beta_k * (age)_{jk} + u_{jk} + e_{ijk} \qquad [1]$$

where y_{ijk} was the observed phenotype for BW12, and BW20 (k=1,2), or the liabilities for walking ability (k=3) for bird j, H_i was the fixed effect of the hatch week class i, β_k is the regression coefficient of bird age for trait k (only for growth traits), $(age)_{jk}$ is the age of bird j for trait k, u_{jk} is the random additive effect of bird j for trait k, and e_{ijk} is the random residual term. Assuming normality conditionally on the model parameters, the joint distribution of the discrete response (WA) and continuous traits (BW12 and BW20) is expressed in matrix notation as:

$$\mathbf{y} \mid \boldsymbol{\beta}, \mathbf{u}, \mathbf{R_0} \sim \mathrm{N}(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u}, \mathbf{R_0} \otimes \mathbf{I}) \qquad [2]$$

where $\boldsymbol{y} = (\boldsymbol{y}_1', \boldsymbol{y}_2', \boldsymbol{l}' \ )'$ is the vector of continuous responses ($\boldsymbol{y_i}$) and liabilities ($\boldsymbol{l}$); $\boldsymbol{\beta}$ and $\mathbf{u}$ are vectors of systematic and random effects, respectively; and $\mathbf{R_0}$ is a 3 × 3 residual (co)variance. **X** and **Z** are known incidence matrices with the appropriate dimensions.

When the walking ability was classified as binary, the residual covariance matrix, $\mathbf{R_0}$, is not completely random due to the fixation of the third diagonal element (corresponding to the binary trait) to 1. Consequently, the direct sampling of $\mathbf{R_0}$ is not feasible. To overcome this problem of sampling of the residual (co) variance, the methods described by Rekaya et al. (2013) were used.

The multiplication of model [2] by a diagonal matrix $\mathbf{D} = \mathbf{D_0} \otimes \mathbf{I}$, where $\mathbf{D_0}$ is an 3 x 3 diagonal matrix and **I** is an identity matrix with appropriate dimensions, yields an equivalent model:

$$\mathbf{y}^* = \mathbf{X}\boldsymbol{\beta}^* + \mathbf{Z}\mathbf{u}^* + \mathbf{e}^* \qquad [3]$$

where

$\boldsymbol{\beta}^* = (\boldsymbol{\beta}_1^{*\prime}, \boldsymbol{\beta}_2^{*\prime}, \dots, \boldsymbol{\beta}_t^{*\prime})'$,

$\mathbf{u}^* = (\boldsymbol{u}_1^{*\prime}, \boldsymbol{u}_2^{*\prime}, \dots, \boldsymbol{u}_t^{*\prime})'$,

with $\boldsymbol{\beta}_i^* = \boldsymbol{\beta}_i d_{ii}$ and $\boldsymbol{u}_i^* = \mathbf{u}_i d_{ii}$, where $\boldsymbol{\beta}_\mathbf{i}$ and $\mathbf{u_i}$ are vectors of fixed and random effects for the trait *i* in the identifiable model in [2], respectively, and d_{ii} is the diagonal element *i* of matrix $\mathbf{D_0}$. However, model in [3] is not identifiable because of **D** is not known. The residual (co)variance matrix of the non-restricted model in [3] given by:

$$\mathrm{var}(\mathbf{e}^*) = \mathbf{DRD}' = \Sigma = \Sigma_0 \otimes \mathbf{I}, \qquad [4],$$

a non-restricted residual (co)variance matrix, where **R** is the original restricted residual (co)variance matrix in [2], and Σ_0 is a 3 x 3 residual (co)variance matrix of the non-identifiable model in [4]. Thus, estimates of the restricted residual covariance matrix, **R**, could be easily obtained using equation [4] and the non-restricted matrix Σ_0. The lack of restriction in Σ

facilitates enormously the Bayesian implementation via Markov Chain Monte Carlo (MCMC) methods. However, in order to obtain the parameters of the identifiable model in [2] from the draws of the non-identifiable parameters, **D** needs to be defined. The identifiable parameters, based on expressions in [3] and [4], can be retrieved as:

$\boldsymbol{\beta}_i = \frac{1}{d_{ii}} \boldsymbol{\beta}_i^*$; [5]

$\mathbf{u}_i = \frac{1}{d_{ii}} \boldsymbol{u}_i^*$; [6]

$\mathbf{R} = \mathbf{D}^{-1}\sum\mathbf{D}'^{-1}$ and $\mathbf{R_0} = D_0^{-1} \sum_0 D_0^{-1}$ [7].

Given that the diagonal elements of $\mathbf{R_0}$ corresponding to the binary responses are fixed to 1, the last diagonal element of the matrix $\mathbf{D}_0$ must be equal to the square root of their corresponding elements in $\sum_0$, and the first 2 diagonal elements of $\mathbf{D}_0$ corresponding to the continuous traits are set equal to one as indicated by Rekaya et al. (2013).

To complete the Bayesian formulation, the following prior were assumed to the unknown in the model.

$p(\boldsymbol{\beta}^*) \sim U[-10^6,10^6]$

$p(\mathbf{u} \mid \mathbf{A},\mathbf{G}) \sim N(0, \mathbf{A}\otimes\mathbf{G_0})$

and for the elements of matrix $\mathbf{G_0}$,

$p(g_{ii}) \sim U[0,10^5]$ for i = 1,2, 3

and $p(g_{ij}) \sim U\left[-\sqrt{\sigma_{u1}^2\sigma_{u2}^2}, \sqrt{\sigma_{u1}^2\sigma_{u2}^2}\right]$ for i ≠ j = 1,2, 3

where **A** is the additive genetic relationship between birds, $\mathbf{G_0}$ is the additive genetic (co)variance matrix, and g_{ii} is the genetic variance for the trait *i*. Similar priors are assumed for $\sum_0$ but with 10^6 for the upper bound of the uniform distribution for the diagonal elements.

The resulting full conditional distributions needed for the implementation of Gibbs sampling for the systematic and random effects, liabilities, and genetic and residual (co)variance matrices were in closed form being normal, truncated normal and scaled inverted

Wishart, respectively. A unique chain of 100,000 samples was implemented where the first 30,000 samples were discarded as burn-in period based on visual inspection of the behavior of the chain. In each iteration of the sampling the process, the transformations indicated in in equations [5], [6] and [7] were applied to draws of the non-identified model in order to obtain samples corresponding to the identifiable parameters in model [2]. Computer software developed by Rekaya et al. (2013) was used for analysis.

RESULTS AND DISCUSSION

Tables 2.1 presents a summary description of the three traits analyzed in this study when walking ability was classified into four classes. Across the four walking ability classes, there were non-significant differences in the phenotypic averages of body weight at 12 or 20 weeks of age; although there was a slight decreasing trend. Body weight (SD) at 12 weeks of age ranged between 8.3 kg (0.99 kg) and 8.4 (0.99 kg) across the 4 classes. Similarly, body weight (SD) at 20 weeks ranged between 15.7 kg (1.40 kg) to 16.3 kg (1.48 kg). For both growth traits, there was substantial variation within and across walking ability classes (Table 2.1). When walking ability was classified as binary, similar distribution for the three traits was observed both in the trend and magnitude of the differences (Table 2.2).

Estimates of the heritabilities and genetic and residual correlation for the three traits using a linear-threshold model are presented in Table 2.3. The heritability of growth traits was moderate to high ranging between 0.44 and 0.51. For walking ability, the point estimate of heritability was 0.25. The genetic and residual correlations between walking ability and growth traits were moderate (-0.45 to -0.35) and weak (-0.07 to -0.02), respectively (Table 2.3). The genetic and residual correlations between the two growth traits were, as expected, moderate to high.

These results clearly indicate that, at least at the genetic level, selection for heavier birds at 12 or 20 weeks of age will lead to an increase in walking ability problems. Furthermore, the problem tends to accentuate with the age of the bird. These results seem to indicate that fast growing birds will allocate large portion of nutrients to accrue muscle and fat deposition at the expense of skeleton development. Even when enough nutritional resources are available the problem persists due to the unbalance between the rate of growth and skeleton maturity and the biological limitations on the amount of feed a bird can eat. Several studies have shown similar results. In facts, Nestor et al. (1984) reported that there was a negative genetic correlation breast meat yield and walking ability (-0.43) in selected male turkey birds for body weight at 16 weeks of age. Nestor et al. (1987) reported that walking ability had a high negative genetic correlation (-0.52) with body weight in selected male turkey birds at 20 weeks of age. Ye et al. (1997) reported that the negative phenotypic association (-0.34) was between breast yield and walking ability in selected male turkey at 16 weeks of age. Nestor et al. (2005) reported that in the selected turkey birds in males there was a negative genetic correlation (-0.29) between body weight and walking ability at 20 weeks of age.

However, other studies found a positive relationship between growth traits and walking ability. Nestor et al. (2010) reported that there was a positive genetic correlation (0.36) between breast meat and walking ability in selected male turkey birds. Leishman et al. (2023) reported that body weight had a positive correlation with walking ability (0.47) in selected male turkey birds.

Table 2.4 presents the average breeding values for the three traits across the four walking ability classes. As expected, the breeding values for walking ability increased with the class score due to the adopted scoring system. For the growth traits, the opposite was observed with average breeding values decreasing with the increase in walking ability scores. The rate of decay in the average breeding values for growth traits was more pronounced for body weight at 20 weeks. These results are in complete concordance with the estimates of the genetic correlation presented in Table 2.3. Because the negative relationships between walking ability and growth traits is far from being perfect (-1), there are still ample opportunities to selection fast growing birds with reasonable walking ability. This is well supported by the spread of breeding values for growth traits across the four scoring classes.

When the walking ability was classified as binary (0=No walking ability problems; 1= walking ability problems), there has been little change in the estimates of heritabilities and correlations (Table 2.5). In fact, the heritabilities were almost identical to the estimates obtained using the 4-class scoring system for walking ability. The heritability of walking ability increased by 0.02 (0.27 vs 0.25). For the growth traits, heritability decreased by 0.01 for BW12 and remained the same for BW20. No noticeable change was observed in the estimates for the genetic and residual correlation (Table 2.5). These results seem to support the binary classification of walking ability removing, thus, the potential errors and inconsistencies associated with a 6-class scoring system.

CONCLUSIONS

Due to the heavy selection for growth during the last 40 years, turkey birds are reaching heavy weights at a very early age. This situation has created an unbalance between body growth and skeleton maturity resulting in birds with leg and mobility problems. In this study, we showed the presence of moderate negative genetic correlation between waking ability and growth traits and that antagonist association increases with the age of the bird. This negative association persist even when walking ability was classified as binary. Our results showed a substantial variation in growth trait phenotypes within and across walking ability classes indicating the possibility for additional genetic improvement of growth traits without, at least, further deterioration in walking ability. Using a 6-class system to score birds for walking ability might not be the most appropriate. This is due to the potential inaccuracies (misclassification) and the likely inconsistencies across evaluators. Our results showed that a more simplified scoring system (e.g., 4 classes) or even a binary classification could be sufficient.

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TABLES

Table 2.1: Summary statistics of body weights across walking ability classes.

		MEAN		SD	
	N	BW 12	BW 20	BW 12	BW 20
CLASS 1	27753	8.418	16.295	0.989	1.484
CLASS 2	31153	8.368	16.188	0.986	1.428
CLASS 3	14554	8.306	15.949	1.002	1.416
CLASS 4	1634	8.302	15.711	0.992	1.406

CLASS 1= birds with walking ability score of 1; CLASS 2= birds with walking ability score of 2; CLASS 3; birds with walking ability score of 3; CLASS 4; birds with walking ability scores of score 4, 5 and 6. N= the total number of observations.

Table 2.2: Summary statistics of body weights when walking ability was classified as binary.

		MEAN		SD		MAX		MIN	
	N	BW12	BW20	BW12	BW20	BW12	BW20	BW12	BW20
CLASS 1	58906	8.392	16.238	0.989	1.456	11.00	20.80	3.45	10.85
CLASS 2	16188	8.306	15.925	0.991	1.417	11.95	31.20	3.65	11.00

CLASS 1= birds with walking ability score of 1; CLASS 2= birds with walking ability scores of 2, 3, 4, 5 and 6. N=the total number of observations

Table 2.3: Estimates of heritability(diagonal), genetic, and residual correlations(off-diagonal) between body weight and walking ability traits.

Trait	WS	BW 12	BW 20
WS	0.25	-0.35	-0.45
BW 12	-0.07	0.51	0.80
BW 20	-0.02	0.57	0.44

WS= walking ability score at 20 weeks of age; BW12= body weight at 12 weeks of age; BW20=body weight at 20 weeks of age.

Table 2.4: Distribution of breeding values across the differences walking ability classes.

				MAX		MIN	
Trait	WS	BW 12	BW 20	BW 12	BW 20	BW 12	BW 20
CLASS 1	-0.156	0.058	0.116	11.75	22.85	5.05	10.85
CLASS 2	0.082	-0.005	-0.019	12.00	31.20	3.45	11.35
CLASS 3	0.299	-0.083	-0.200	11.95	20.80	3.85	11.00
CLASS 4	0.532	-0.167	-0.393	11.25	20.15	3.65	11.65

CLASS 1= birds with walking ability score of 1; CLASS 2= birds with walking ability score of 2; CLASS 3; birds with walking ability score of 3; CLASS 4; birds with walking ability scores of scores 4, 5 and 6.

Table 2.5: Estimates of heritability(diagonal), genetic, and residual correlations(off-diagonal) between body weight traits and walking ability defined as a binary response.

	WS	BW 12	BW 20
WS	0.27	-0.34	-0.44
BW 12	-0.10	0.50	0.80
BW 20	-0.07	0.57	0.44

WS= walking ability score at 20 weeks of age; BW12= body weight at 12 weeks of age, BW20=body weight at 20 weeks of age

Table 2.6: Average breeding values for body weights and binary walking ability response.

	WS	BW 12	BW 20
CLASS 1	-0.136	0.050	0.092
CLASS 2	0.107	-0.025	-0.054

CLASS 1= birds with walking ability scores of 1, 2, and 3; CLASS 2= birds with walking ability scores of 4, 5 and 6

CHAPTER 3

GROWTH DISTRIBUTION AND ITS EFFECTS ON THE RELATIONSHIP BETWEEN BODY WEIGHT AND WALKING SCORE [1]

[1] Soyalp, S., E. Hartono, S.E. Aggrey, and R. Rekaya. To be submitted to Poultry Science

ABSTRACT

The productivity of poultry has almost tripled in the last 100 years due to the use of both enhanced feeding strategies and intense genetic selection. The most phenomenal and distinguishable changes in commercial turkey populations compared to their ancestors has been the fast growth, the increased body weight, and the higher percentage of breast muscle. Unfortunately, these successes led to serious mobility problems for modern turkey birds. The current study was carried out to investigate the potential non-linear relationship between growth rate and mobility. The data consisted of body weights at 12 and 20 weeks of age and walking ability at 20 weeks of age collected on 276,059 male turkey birds. The pedigree file included 836,785 individuals. For walking ability, birds were scored based on a 1 (bad) to 6 (good) grading system. Due to small numbers, birds with walking scores of 4, 5 and 6 were group into one mobility class (score 4). The growth rates at three different age periods (0 to 12, 12 to 20 and 0 to 20 weeks) were calculated. Each bird was assigned to one of the quartiles of the of growth rate distribution for each age period. The incidence rate of the different walking ability scores across the different quartiles of the growth rate distributions showed similar pattern across the different age periods. Between the first and fourth quartiles, the incidence of score 1 (bad walking ability) increased by 31, 18, 33% for the first, second and third age periods, respectively. For acceptable and good walking ability scores (scores 4, 5, and 6), the incidence decreased by 55, 66, and 72% between the first and fourth quartiles for the first, second and third age periods, respectively. Estimates of the heritability of walking ability between the different quartiles of the growth distributions and age periods ranged between 0.21 and 0.28. The genetic correlations between adjacent growth rate quartiles were high and

decayed as the interval between quartiles increased. The highest genetic correlations, across periods, was between first and second quartiles (0.83 to 0.86) and between the third and fourth quartiles (0.86 to 0.88). The lowest correlations were between walking scores in the first and forth quartiles of the growth rate distributions and ranged between 0.75 to 0.77.

The magnitude of the variations of the incidence of the walking scores and the relatively moderate to high estimates of the genetic correlations between walking ability scores across the different growth rate quartiles seem to point towards a potential non-linear relationship between growth and mobility.

INTRODUCTION

Enormous genetic progress has been achieved for growth and feed efficiency in turkey populations due to heavy directional selection. This genetic selection success has resulted in decreased feed conversion rate, reduced age to slaughter, and increased breast meat yield. Unfortunately, this success has led to some unintended consequences including decreased reproductive performance (impossibility of natural mating), skeletal abnormalities, and increased carcass fatness. The significant reduction in the number of days to market weight and the disproportional increases in breast meat yield resulted in substantial increase in the incidences of various skeletal abnormalities, leg weakness, and locomotion problems (pododermatitis, fractured femurs, fractured tibia, tibial dyschondroplasia, and spondylolisthesis). In fact, leg problems, especially tibial dyschondroplasia, have been observed in almost half of growing turkey birds.

These leg problems resulting in poor bird walking abilities and raised the stakeholders concerns about the welfare of growing turkey birds leading to a broad welfare assessment of the turkey broiler production chain.

Clark et al. (2019) reported that after 50 generations of selection for increased body weight, selected turkeys were 2.5 times heavier than the non-selected counterparts. Furthermore, the magnitude of the difference in body weight increased with the age of the bird. At 5 weeks of age, the selected turkeys (2.02 $\pm$ 0.03 kg) were over twice as heavy as the non-selected turkeys (0.98 $\pm$ 0.03 kg). By 16 weeks of age, the selected line turkeys (16.4 $\pm$ 0.4 kg) were approximately 2.5 times heavier than the non-selected turkeys (6.7 $\pm$ 0.4 kg). Nestor et al. (2008) reported that the body weight between 8 to 20 weeks ranged from 5.82 kg to 19.57 kg and 4.86 kg to 17.47 for male and females, respectively. Rafat et al. (2011) reported that body weight of turkeys measured at 8, 10 and 12 weeks of age ranged from 560 to 1,228 g. Updike et al. (2005) reported that random bred control male toms weighed significantly less than both the selected and fast-growing commercial male toms at all ages *(P*<0.05). Additionally, the total breast meat yield was the lowest in random bred control male toms. Hiscock et al. (2022) concluded that selected turkey males final body weight was higher than their non-selected counterparts. Specifically, selected males grow at a weekly rate of 1.63 kg, which was significantly higher (P < 0.05) than the 1.12 kg for non-selected males. Additionally, selected males had heavier whole breast weight (6.08 kg) compared to non-selected males (4.74 kg).

Nestor et al. (1984) reported that the leg scores for turkeys selected for shank width were significantly higher than the non-selected birds. Therefore, selected male turkeys had poorer walking ability than non-selected counterparts at 16 weeks of age. Similar results were observed at 20 weeks of age (Nestor et al., 1987). Emerson et al. (1991) reported that selected male turkeys for increased shank diameter, leg muscle, shank and drum bone had lower leg muscle and bone weights than non-selected counterparts. Additionally, in selected turkeys, shank and drum bone weights were lower than in non-selected counterparts. Non-selected turkey populations had a lower leg scores indicating that birds walked better than selected turkeys. Ye et al. (1997) reported that selected male turkeys for increased shank width had poorer walking ability, shorter and narrower shanks than non-selected turkeys in males at 16 weeks of age. Nestor et al. (2001) reported that shank width of the non-selected male turkey birds was greater than selected male turkey birds.

Although there is a consensus about the negative relationships between growth traits and walking ability in turkey, the assumption that such relationships are linear, as assumed in all the reported studies, is less clear. In fact, it is reasonable to postulate that the relationship between growth and walking ability may be non-linear. This assumption is biologically well-supported as mobility problems will not be present until the bird weight (growth rate) exceeds a certain threshold. The aim of this study is to investigate the potential non-linearity in the relationships between growth and walking ability.

MATERIALS AND METHODS

DATA

Data for turkey birds hatched between 2009 to 2018 were provided by Hendrix Genetic (Canada). The population consisted of 276,059 animals. The pedigree included 836,785 turkey birds. Three traits (body weights at 12 and 20 weeks and walking ability at 20 weeks) were used in this study. All birds were scored for walking ability using the 6-class (1 to 6) scoring system. A score of 1 indicates an extreme lateral deviation, and scores of 2 and 3 indicate an intermediate lateral deviation of the legs. Scores of 4, 5, and 6 indicate slight to no lateral deviation of the legs. Due to the small number of animals with scores of 4, 5, and 6, birds with these scores were joined into one class (class 4). After this change, walking ability was classified based on a 4-class scoring system. After editing, the data consisted of 75,094 birds recorded for 3 traits: body weight at 12 weeks (BW12), body weight at 20 weeks (BW20) and walking ability at 20 weeks (WA). Birds with original walking ability of 4, 5, and 6 were grouped into one class (class 4) to ameliorate the representation of leg incidences in different score classes.

MODEL AND ANALYSIS

Growth rates between 0 and 12 weeks, 0 and 20 weeks, and 12 and 20 weeks were computed for all birds. Based on the distribution of growth rate within each of the three periods, birds were clustering in one of four discrete classes (1=1st quartile; 2=2sd quartile; 3=3rd quartile; and 4=4th quartile). Walking ability within each of the four classes of growth distribution for each period were used to assess its relationship with growth rates. Summary statistics of the data were obtained using different packages of R.

Additionally, for each period (0-12; 0-20; and 12-20 weeks) walking ability scores within a growth rate class (4 classes) were considered as different traits. A multivariate threshold model was used to jointly analyze the 4 discrete traits for each period separately in order to assess their genetic parameters. At the liability scale, the following model was used:

$$l_{ijk} = H_{ik} + u_{jk} + e_{ijk} \qquad [1]$$

where l_{ijk} was the non-observed liability for walking ability in growth rate class *k* (*k*=1- 4) for bird *j*, H_i was the fixed effect of the hatch week class *i*, u_{jk} is the random additive effect of bird *j* for trait *k*, and $e_{ijk}$is the random residual term.

Assuming normality conditionally on the model parameters, the joint distribution of the liabilities can be expressed in matrix notation as:

$$\boldsymbol{l} \mid \boldsymbol{\beta}, \mathbf{u}, \mathbf{R_0} \sim \mathrm{N}\,(\mathbf{X}\boldsymbol{\beta} + \mathbf{Zu}, \mathbf{R_0} \otimes \mathbf{I}) \qquad [2]$$

where $\boldsymbol{l} = (\boldsymbol{l}'_1, \boldsymbol{l}'_2, \boldsymbol{l}'_3, \boldsymbol{l}'_4)'$ is the vector of liabilities for the four traits, **β** and **u** are vectors of systematic and random effects, respectively; and $\mathbf{R_0}$ is a 4 × 4 residual (co)variance. **X** and **Z** are known incidence matrices with the appropriate dimensions.

Because a given bird will have a walking ability score only in one of the four growth rate classes, the residual covariances between traits cannot be estimated and they were set to zero resulting in a diagonal matrix $\mathbf{R_0}$.

Flat bounded prior were assumed for the fixed effects, and the classical multivariate normal distribution for the additive effects (p ($\mathbf{u}$ | $\mathbf{A}$, $\mathbf{G}$) ~ N(0, $\mathbf{G_0} \otimes \mathbf{A}$)). For the genetic ($\mathbf{G_0}$) and residual ($\mathbf{R_0}$) covariance matrices, flat bounded priors were assumed. The resulting full conditional distributions needed for the implementation of Gibbs sampling for the systematic and random effects, liabilities, and genetic covariance matrix, and the diagonal element of $\mathbf{R_0}$ were in closed form being normal, truncated normal, scaled inverse Wishart, and scaled inverse Chi Square distributions, respectively. A unique chain of 100,000 samples was implemented where the first 30,000 samples were discarded as burn-in period based on visual inspection of the behavior of the chain. Computer software developed by Rekaya et al. (2013) was used for analysis.

RESULTS AND DISCUSSION

Table 3.1 presents a summary of the growth rate distribution for the 0 to 12-week period. From the lowest to the highest quartiles, the growth rate increased by almost 24% from 0.080 to 0.099 kg. The coefficient of variation ranged between 1 and 4% with the lowest values corresponding to the intermediate quartiles indicating a sharp distribution with relatively heavy tails. Similar trends were observed for the growth rate distributions for the other periods (0 to 20 and 12 to 20 weeks) as shown in Tables 3.2 and 3.3.

Table 3.4 presents the incidence rate of the different walking ability scores across the different quartiles of the growth rate distribution for the 0 to 12-week period. Within a growth rate quartile, score 2 (class 2) has the highest incidence and it ranged between 41 to 41.8%. The lowest incidence was observed for scores 4, 5 and 6 (class 4) with an incidence rate ranging between 1.3 and 2.9. Across quartiles and except for class 2, there were clear differences in the incidence of the different classes. In fact, there was a 31% increase in the incidence of class 1 (score 1) and a 55% decrease in the incidence of class 4 (scores 4,5, and 6) between the first and four quartiles (Table 3.4). There was a 36% decrease in the incidence of class 3 (score 3) between the first and the four quartiles.

For the 12 to 20 week (Table 3.5) and 0 to 20 week (Table 3.6) of age periods, the same trend was observed compared to the 0 to 12 week of age period. Except for class 2 (walking score of 2), there were significant differences in the incidence for walking scores across growth rate quartiles and age periods. The incidence of class 1 (score 1) increased by 18% (Table 3.5) and 33% (Table 3.6) between the first and fourth quartiles for both periods. However, the incidence of good mobility scores (class 4) decreases by 66% and 72% between the first and fourth quartiles for the same two periods (Tables 3.5 and 3.6).

Estimates of heritabilities and genetic correlations, using a multivariate threshold model, between walking ability classes across the four growth rate quartiles for the 0-12, 12-20, and 0-20-week periods are presented in Tables 3.7, 3.8, and 3.9, respectively. Across the different growth rate quartiles and periods, the heritability of walking ability ranged between 0.21 and 0.28. The highest heritability was observed for the fourth growth quartiles across periods. There was higher similarity between the estimates of heritability of walking ability between the first and second growth rate quartiles and between the third and fourth quartiles. The genetic correlations between adjacent growth rate quartiles are always high (>0.80) and decayed as the interval between quartiles increased (Tables 3.7-3.9). The highest genetic correlation, across periods, was between first and second quartiles (0.83 to 0.86) and between the third and fourth quartiles (0.86 to 0.88). The lowest correlations were between walking ability scores in the first and forth quartiles of the growth rate distributions and ranged between 0.75 to 0.77.

These results clearly show that heavy selection for growth rate across the different age periods has led to a substantial increase in mobility problems for turkey birds. This is the case even for birds within the lowest quartiles of the growth rate distributions indicating that all birds (even those with the lowest growth rate) have already crossed the threshold for maintaining a healthy balance between growth and skeleton integrity. This is likely due a larger allocation of nutritional resources to support breast meat yield than bone and skeleton development. As growth rate increases, the situation becomes more dire as the incidence of bad walking ability (score 1) increased by around 25% and good mobility scores (4, 5, and 6) decrease by more than 50%. These results are in concordance with those reported by previous studies (Emerson et al., 1991; Ye et al., 1997; Updike et al., 2005; and Hiscock et al., 2022). Although the patterns of incidence of the different walking scores are the same across the different growth rate quartiles and periods, the magnitude of the variations are not similar indicating a likely non-linear relationship between growth and walking ability. The relatively moderate to high estimates of the genetic correlations between walking ability scores across the different growth rate quartiles seem to indicate some genetic difference between these traits. This is an additional evidence that the relationship between walking ability and growth rates is not linear.

CONCLUSIONS

Heavy selection for growth rate during the last 40 years has led to a significant unbalance between body weight and skeletal maturity. Turkey birds are reaching market weight at a very early age resulting in substantial increase in mobility problems. Although there are significant differences in the incidence of the different walking ability scores within a specific growth rate quartile and age period, the magnitude of these differences varies across quartiles and age periods potentially indicating a non-linear relationship between growth and mobility problems. This result is further supported by the less than perfect genetic relationships between walking scores across growth rate quartiles (moderate genetic correlations). Thus, a better modeling of the association between growth and walking ability is needed. Changepoint (breakpoint) models could be an appropriate approach to deal with this potential non-linear relationship between growth and mobility in turkey birds.

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TABLES

Table 3.1: Summary of growth rate distribution of turkey birds within the 0 to 12 week of age period.

Quantile	N	MEAN	SD	MIN	MAX
1	18690	0.080	0.003	0.036	0.085
2	18820	0.087	0.001	0.085	0.090
3	18802	0.092	0.001	0.090	0.095
4	18782	0.099	0.003	0.095	0.134

N= Number of birds

Table 3.2: Summary of growth rate distribution of turkey birds within the 12 to 20 week of age period.

Quantiles	N	MEAN	SD	MIN	MAX
1	18714	0.131	0.011	0.034	0.145
2	18662	0.152	0.004	0.145	0.158
3	18886	0.164	0.003	0.158	0.170
4	18832	0.181	0.009	0.170	0.550

N= Number of birds.

Table 3.3: Summary of growth rate distribution of turkey birds within the 0 to 20 week of age period.

Quartiles	N	MEAN	SD	MIN	MAX
1	18734	0.102	0.004	0.075	0.107
2	18807	0.110	0.0017	0.107	0.113
3	18770	0.116	0.0016	0.113	0.119
4	18783	0.124	0.004	0.119	0.228

N= Number of birds

Table 3.4: Incidence of walking ability scores (%) across the different quartiles of the growth rate distribution for the 0 to 12 week of age period.

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
CLASS 1	32.4	35.2	37.5	42.6
CLASS 2	41.2	41.7	41.8	41.0
CLASS 3	23.3	20.5	18.6	14.9
CLASS 4	2.9	2.5	1.9	1.3

CLASS 1= birds with walking score of 1; CLASS 2= birds with walking score of 2; CLASS 3= birds with walking score of 3; and CLASS 4= birds with walking scores of 4, 5, and 6

Table 3.5: Incidence of walking ability scores (%) across the different quartiles of the growth rate distribution for the 12 to 20 week of age period.

	1^{st} Quartile	2^{nd} Quartile	3^{rd} Quartile	4^{th} Quartile
CLASS 1	34.9	35.4	36.2	41.1
CLASS 2	39.1	41.3	43.0	42.3
CLASS 3	22.7	20.8	18.7	15.2
CLASS 4	3.2	2.3	1.9	1.1

CLASS 1= birds with walking score of 1; CLASS 2= birds with walking score of 2; CLASS 3= birds with walking score of 3; and CLASS 4= birds with walking scores of 4, 5, and 6

Table 3.6: Incidence of walking ability scores (%) across the different quartiles of the growth rate distribution for the 0 to 20 week of age period.

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
CLASS 1	32.6	34.2	37.3	43.5
CLASS 2	39.3	42.0	42.6	41.8
CLASS 3	24.3	21.3	18.3	13.4
CLASS 4	3.6	2.3	1.5	1.0

CLASS 1= birds with walking score of 1; CLASS 2= birds with walking score of 2; CLASS 3= birds with walking score of 3; and CLASS 4= birds with walking scores of 4, 5, and 6

Table 3.7: Heritability and genetic correlations between the four discrete traits for walking ability defined based on the quartiles of growth rate between 0 to 12 weeks.

Trait	1	2	3	4
1	0.23	0.85	0.78	0.76
2		0.21	0.81	0.79
3			0.26	0.87
4				0.26

Table 3.8: Heritability and genetic correlations between the four discrete traits for walking ability defined based on the quartiles of growth rate between 12 to 20 weeks.

Trait	1	2	3	4
1	0.22	0.86	0.79	0.75
2		0.23	0.81	0.77
3			0.27	0.88
4				0.28

Table 3.9: Heritability and genetic correlations between the four discrete traits for walking ability defined based on the quartiles of growth rate between 0 to 20 weeks.

Trait	1	2	3	4
1	0.22	0.83	0.77	0.77
2		0.22	0.82	0.79
3			0.26	0.86
4				0.26

CHAPTER 4

CONCLUSIONS

Heavy selection for growth in turkey has led to disproportionate relationships between skeleton maturity and body weight. This situation has resulted in an increase in mobility and leg soundness problems in commercial turkey birds.

Our results showed a moderate heritability for growth at 12 and 20 weeks and a relatively low heritability for walking ability. The negative genetic correlation between body weights and walking ability found agrees with the observed decay in turkey bird mobility. Based on the results of this study, it seems that 4-class scale or even a binary classification of walking ability is at least as good as 6-class system. The genetic correlation between walking ability across different growth rate classes seem to indicate a non-linear relationship between growth and leg problems. To reduce, or at least avoid a further deterioration of leg soundness in turkey, walking ability should be included in the selection index.