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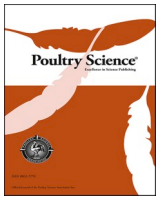

Full-Length Article

Body weight optimization of broiler breeder hens. 1. Pullet growth, feed efficiency, carcass composition, and sexual maturation

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ABSTRACT

This study aimed to evaluate the effect of early growth (**EG**) and time of maximum pubertal growth peak (**I2**) on development, feed efficiency, carcass composition, and sexual maturation of broiler breeder females. Target BW trajectories were designed by changing coefficients of a 3-phase Gompertz model fit to the recommended BW target of Ross 308 breeders, $BW = \sum_{i=1}^{i=3} g_i exp^{(-\exp(-b_i(t-I_i)))}$. In each phase *i*, biologically relevant coefficients describe the amount of BW gain (g_i), the rate of growth (b_i), and the inflection point (I_i), which is the time when the growth rate for that phase is at its maximum rate. The study consisted of a 6 × 2 factorial arrangement, with six I2 levels (*I* from phase 2) and two EG levels. The I2 coefficients were 15, 17, 19, 21 (standard), 22, and 23 in wk. The EG treatments were: EG0, where g_1 and g_2 coefficients estimated from the standard from the breeder recommended BW were unchanged; and EG20, where 20% of the gain (g_2) in phase 2 (pubertal phase) was shifted to phase 1 (g_1; prepubertal phase). Two-hundred-eighty-eight Ross 308 pullets were randomly assigned to the twelve BW growth trajectories and fed using a precision feeding system from 0 to 28 wk of age. Body composition variables were submitted to three-way ANOVA, with EG, I2, and age as fixed sources of variation. Analysis of covariance was conducted on the remaining dependent variables with EG as fixed effect, I2 as a continuous fixed effect, and age as continuous random effect. Differences were reported at $P \leq 0.05$. The BW of females followed their target BW, and ADFI differed depending on the amount of feed required to achieve their respective BW targets. Breast fleshing score was 0.2 greater in the EG20 compared to EG0. The number of juvenile primary wing feathers and age at first egg decreased by 0.4 and 0.9 d, respectively, per wk of earlier I2. Advancing I2 resulted in birds with increased carcass fat deposition from 16 to 28 wk of age. Carcass fat was 1.3- to 1.6-fold greater in the EG20 only from 4 to 16 wk of age. Early growth increased mostly pullet muscle and skeletal characteristics whereas advancing I2 advanced sexual maturity and increased carcass fat deposition around sexual maturation time.

Introduction

Genetic potential of meat-type chickens has increased considerably over the last seven decades. When comparing the broilers from 1950s to the 2000s, the growth rate increased by 400% at 56 d of age (Zuidhof et al., 2014). This genetic improvement is associated mainly with growth potential, feed intake capacity, feed efficiency, and lean deposition (Hocking and McCorquodale, 2008; Zuidhof et al., 2014; Carney et al., 2022). The same genetic potential is present in the broiler breeders, which creates a challenge to parent stock managers, because growth and reproductive traits are negatively correlated (Decuypere et al., 2010; Siegel and Dunnington, 2017). Because of that, broiler breeders are kept under quantitative feed restriction, particularly during rearing (de Jong et al., 2002). Over the past decades, evidence suggests the degree of relative feed restriction has increased (Renema et al., 2007; van Emous et al., 2015). Therefore, genetic selection and nutritional strategies in modern broiler breeders might have contributed to fat deposition being sub-optimal for reproduction (Carney et al., 2022). New feeding strategies might be necessary to accommodate changes in the degree of relative feed restriction and potential metabolic and welfare concerns.

In addition to nutritional strategies such as amino acid levels (lysine

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control) in the diets, feed restriction approach is also used for breeder feeding management. Relaxing feed restriction of broiler breeders has been done previously (Renema et al., 1999; Robinson et al., 2007; van Emous et al., 2013; van der Klein et al., 2018a; Afrouziyeh et al., 2021). Many of these studies utilized changes of BW at different times based on the breeder recommended BW target and provided useful information regarding relaxing feed restriction. However, the growth trajectory combinations tested were somewhat arbitrary (Zuidhof, 2020). A more systematic approach to change growth trajectories is to utilize multiphasic growth models with parameters that can be modified strategically. Differently from a single-phase growth model, a multiphasic growth model accounts for the existence of overlapping growth phases (Koops, 1986; Kwakkel et al., 1993; van der Klein et al., 2020; Zuidhof, 2020). Robertson (1908) was among the first to describe the existence of three cycles of growth in mammals, and later was described in the domestic fowl by Brody (1921). More recently, Afrouziyeh et al. (2021) developed a trial with several growth trajectories and utilized a triphasic Gompertz model from Zuidhof (2020). The model consisted of three distinct phases: 1) prepubertal, 2) pubertal, and 3) post-pubertal. The parameters of the triphasic model have biological relevance and because the coefficients are continuous numbers they present an opportunity for a systematic evaluation, with continuous coefficients that can be used to find an optimal BW trajectory. The early growth phase is considered the period before puberty (prepubertal), where primary development occurs in internal organs, skeletal development, feathering, and muscle growth (Lilja et al., 1985; Kwakkel et al., 1993; Kwakkel et al., 1998; Afrouziyeh et al., 2021). The subsequent phase (pubertal) corresponds to the time of sexual maturation, and as a result the development of tissues involved with the reproductive tract, such as oviduct and fat tissue (Grossman and Koops, 1988; Kwakkel et al., 1993; Afrouziyeh et al., 2021).

The recommended growth trajectories (target BW) of parent stocks are provided by the primary breeders, which are updated based on their annual genetic upgrades (Cobb-Vantress, 2020; Aviagen, 2021a). As previously discussed, a change or manipulation of these growth trajectories can affect not only growth of birds, but potentially tissue development, carcass composition, and reproductive performance (Fuller et al., 1969; Eitan et al., 2014). Additionally, the time of growth and how much the trajectory is changed also influences growth and development of birds. Recent research suggests that feed restriction in broiler breeders might be approaching a biological limit, where pullets might have insufficient fat deposition for optimal sexual development (van der Klein et al., 2018a, 2018b; Zuidhof, 2018) or reproductive capacity (Afrouziyeh et al., 2021). These authors hypothesized that current BW recommendations might not allow birds to achieve an optimal BW to maximize egg production. Therefore, this study was developed to evaluate a systematic manipulation of the first and second growth phases (prepubertal and pubertal) of broiler breeder females, with growth trajectories that were mainly above but also under the current breeder BW recommendations. The coefficients for the prepubertal and pubertal phases were manipulated to create desired growth trajectories, whereas the coefficients of the third phase (post-pubertal) were not modified.

The objective of this study was to evaluate the effect of growth shifted from pubertal to prepubertal phase (early growth; **EG**) and different inflection point levels of the pubertal phase (time of maximum pubertal growth; **I2**) on development, feed efficiency, carcass composition, and sexual maturation of broiler breeder females. We hypothesized that shifting gain from the pubertal phase to the prepubertal phase would increase pullet skeletal frame size indicators (shank and keel length), decrease feed efficiency, increase pullet fat deposition at photostimulation age, and advance sexual maturation. Additionally, we hypothesized that an earlier time of maximum pubertal growth peak would increase large yellow follicle numbers at sexual maturation age, decrease feed efficiency, increase fat deposition at sexual maturation age, and advance sexual maturation.

Material and methods

The animal protocol for the study was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed the Canadian Council on Animal Care guidelines (CCAC, 2009).

Growth trajectories design

The growth trajectories which comprised the treatments were developed using a 3-phase modified Gompertz model (Zuidhof, 2020):

$$BWt = \sum_{i=1}^{i=3} g_i \times exp^{-exp^{-b_i \times (t - I_i)}} + \varepsilon_i,$$

where BWt was the BW (kg) at a given time t (wk); g_i was the total amount of gain (kg) accruing in phase i; b_i was the rate of gain for phase i; I_i was the inflection point (time of maximum growth in wk) where the gain was maximum in phase i; and ε_i is the random error for each observation of each phase i. The biologically relevant coefficients for the 9 parameters (3 per phase) were estimated using a least squares method fitting the Ross 308 female recommended target BW (Aviagen, 2021a) and are presented in Table 3. The coefficients estimated from the 3-phase Gompertz model fit exceptionally well the growth trajectories of the Ross 308 broiler breeders in relation to their age (Table 3). Therefore, to develop the target BW trajectories in the current study, coefficients were changed systematically based on (1) the g coefficients from the prepubertal (phase 1) and pubertal phase (phase 2), which represents the amount of gain in kg for each phase; and (2) the I coefficient from the pubertal phase, representing the time (in wk) where the gain was at peak. By changing the coefficients for these specific variables, a systematically evaluation of the growth trajectories was possible.

Experimental design

The trial consisted of a 6 × 2 factorial arrangement of treatments, with six coefficients for time of maximum pubertal growth peak (**I2**) and two levels of early growth (**EG**; shift gain from g_2 to g_1), totalling twelve growth trajectories. The I2 coefficient estimated for the standard breeder recommended target BW was 21 wk (Table 3), and was modified to create the treatment growth trajectories. The other five I2 levels (15, 17, 19, 22, and 23 wk) advanced or delayed the time of maximum pubertal growth phase. The EG factor was discrete with two levels: EG0, where g_1 and g_2 parameters were the estimated coefficients for the breeder recommended target (Table 3); and EG20, where 20% of the gain (396 g) in phase 2 (pubertal) was shifted to phase 1 (prepubertal). The parameters for each growth trajectory are presented in Table 4, and the BW targets are displayed in Fig. 1 by the line series. Each growth trajectory was applied to the individual bird using a precision feeding (**PF**) system; therefore, each bird was the experimental unit.

Animals and management

A total of two-hundred-eighty-eight Ross 308 pullet breeders (one-day-old) were randomly assigned to one of the twelve growth trajectories, totalling twenty-four pullets per growth trajectory at placement. Pullets from each growth trajectory were identified with a neck tag at hatch and randomly divided in three floor pens (4.5 × 5.4 m) with approximately 50 birds per feeding station. Birds were equipped with a radio frequency identification (**RFID**) wing tag at 7 d of age. All birds were fed individually using a PF system. The detailed functionality of the PF system has been described previously (Zuidhof, 2018). Briefly, all free-run birds were trained to use the PF system from placement to 13 d of age. During this time, they had free access to the feeding stations at any time. From 14 d onward, the individual feeding started, and pullets were fed according to their individual growth trajectory. Each feeding

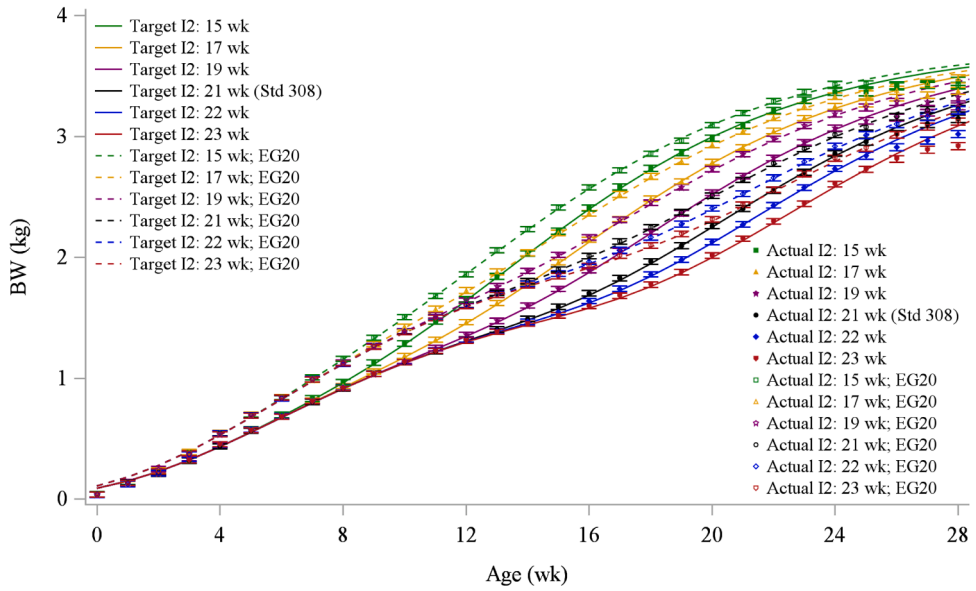

Fig. 1. Designed BW growth trajectories (target; lines) and the observed BW for each growth trajectory (actual; markers) of the Ross 308 broiler breeder females. Early growth (EG) was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1). Time of maximum pubertal growth (I2) was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Table 1
Dietary calculated nutrient composition of the commercial diets fed to the Ross 308 broiler breeders.

Nutrients, % or as follows	Starter 0 to 28 d	Developer 29 to 133 d	Pre-breeder 134 to 161 d	Breeder 1 162 to 196 d
Apparent ME, kcal/kg	2,900	2,700	2,800	2,858
Crude protein	20.0	14.9	14.7	16.0
Digestible (dig) lysine	1.00	0.51	0.51	0.64
Dig methionine	0.56	0.34	0.34	0.39
Dig total sulfur amino acids	0.84	0.61	0.60	0.65
Dig tryptophan	0.21	0.15	0.15	0.16
Dig threonine	0.73	0.50	0.50	0.56
Dig valine	0.83	0.58	0.57	0.65
Dig arginine	1.18	0.76	0.76	0.87
Dig leucine	1.51	1.07	1.04	1.20
Dig isoleucine	0.76	0.50	0.50	0.56
Available Phosphorus	0.50	0.46	0.45	0.36
Calcium	1.05	1.00	1.49	3.12

station was composed of two stages: decision stage and feeding stage. Each bird entered in the decision stage individually. First, the system identified each bird that entered the decision stage by its RFID tag. Then, birds were allowed or not to proceed to the feeding stage based on their BW measured and their respective real-time BW target. Birds that were above the target BW were gently ejected without access to feed. When its BW was less than its real-time BW target trajectory, the bird was permitted to proceed to the feeding stage. In the feeding stage, birds were allowed to consume feed for 150 s with 50 g presented in the feeder. As a consequence, the PF system provided birds (individually) with multiple visits (BW record) and meals each day based on their treatment group BW target, with no corrections for feed intake or water consumption. The target growth trajectories were updated hourly.

Feed was formulated based on recommendations of the primary breeders (Aviagen, 2021b) in a three-phase feeding program for the rearing period and one layer diet phase until the end of this study (28 wk). All birds from all treatments were fed the same commercial diets throughout the study in a crumble form (corn-wheat-soybean-canola meal basis). Further nutrient information is shown in Table 1. Water was provided *ad libitum* with nipple type drinkers. Photoschedule and temperature management procedures followed the breeder recommendations (Aviagen, 2019) and is further described in Table 2. Photostimulation occurred at 21 wk of age (25 lx), 11L:13D, and increased one hour per week until 13L:11D (40 lx) and then maintained until the end of the study (28 wk; Table 2).

Table 2
Photoschedule of the Ross 308 broiler breeders.

Age (d)	Light (h)	Dark (h)	Intensity (lux)
0 to 2	23	1	50
3	19	5	50
4	16	8	50
5	14	10	30
6	12	12	30
7	11	13	20
8	10	14	20
9	9	15	20
10 to 146	8	16	10
147 to 153	11	13	25
154 to 160	12	12	40
161 to 196	13	11	40

Table 3
Estimated coefficients of the 3-phase Gompertz model[1] used to generate the standard target BW trajectories for the Ross 308 broiler breeder females.

	Ross 308 target		
Parameter	Estimate	SEM	P > |t|
g_1 (kg)	1.7709	0.0622	<.0001
b_1	0.1887	0.0090	<.0001
I1 (wk)	5.83	0.2248	<.0001
g_2 (kg)	1.9798	0.0732	<.0001
b_2	0.1880	0.0057	<.0001
I2 (wk)	21.0	0.1518	<.0001
g_3 (kg)	0.3663	0.0375	<.0001
b_3	0.1259	0.0188	<.0001
I3 (wk)	47.3	0.7689	<.0001
Mature BW	4.117		
Fit statistics			
BIC	-351.4		
R^2	0.9999		
RMSE	0.01588		

Abbreviations: BIC, Bayesian Information Criterion; R^2, coefficient of determination; RMSE, root mean square error.

[1] General model form: $BWt = \sum_{i=1}^{i=3} g_i \times exp^{-exp^{-b_i \times (t - Ii)}}$, where BWt was BW at time t (wk); g_i was the total amount of gain (kg) accruing in phase i; b_i was the rate of growth in phase i; Ii was the inflection point for phase i (wk), or the age at which growth for that phase reached its maximum growth rate.

Data collection

From 14 d onward, the PF system recorded individual feed intake (**FI**) and BW at every visit to the feeding stations. The FI during the training period (0 to 13 d of age) was calculated at the pen level (and assumed to be equal within pen), where manual BW of each bird was measured daily. Daily median BW and average daily feed intake (**ADFI**) were calculated weekly. Median BW (daily) and total daily feed intake were calculated and utilized for the cumulative feed conversion ratio (**FCR**) calculations at 7, 15 and 22 wk of age.

Breast fleshing score and pubic bone spacing were evaluated in all birds by the same individual evaluator every two weeks starting at 15 wk until 21 wk of age. A 5-point scale modified from the breeder 3-point scale (Aviagen, 2018) was utilized for fleshing score, where 0 represented undersized breast (very concave V shape) and 4 represented oversized breast (very convex U shape). Pubic bone spacing was measured using a finger scale and converted to millimetres afterwards. The progression of juvenile feathers to adult feathers was recorded by counting the remaining juvenile primary wing feathers of all birds at 15, 17, and 19 wk of age. Dorsal tract feather maturity was evaluated at 25 wk of age, using a 2-point scale, as shown in Fig. 2: 1 – dorsal feather maturity not completed, where most dorsal tract feathers had the sheath structure present (70% or more) maintaining the cyclical shape until the papilla; and 2 – full dorsal feather maturity, where the sheath was not present and growth process was completed in all dorsal tract feathers (Prum and Williamson, 2001). The median BW data per bird recorded in the PF system was utilized for BW at photostimulation age (**BWPS**) and BW at first egg (**BWFE**). Daily cloacal palpation was used to detect the presence of an egg in the shell gland and thus to determine the age at first egg (**AFE**). This method was used because each bird was the experimental unit, and therefore avoiding overlooked laying information. Since birds were place in a free-run pens, conventional egg collection would result in the first day of lay going unnoticed due to the possibility of floor eggs. Palpations were done early morning to detect hard-shelled eggs and late afternoon to detect soft-shelled eggs in the shell gland in order to avoid missing eggs laid overnight (during the scotophase). The presence of hard-shelled eggs determined eggs laid in the same day of the palpation and soft-shelled eggs determined eggs laid in the next day of the palpation.

Breast muscle (*Pectoralis major* plus *Pectoralis minor*), abdominal fat pad (fat tissue adhering to the proventriculus, gizzard and the abdominal wall), shank length (tibiotarsus measured from the hock to the footpad), and keel length (distance from the hypocleido-clavical joint to the caudal end of the sternum) were evaluated in five birds per growth trajectory at sexual maturation age (n=60). Age at sexual maturation was defined as the age of first egg laid (in days). In the birds dissected at sexual maturation age, oviduct weight (infundibulum to vagina), ovary components (the largest yellow follicle (**F1**), large yellow follicles (≥ 10 mm) number and weight, ovary weight), and chemical carcass composition were also evaluated (n=60).

Carcass chemical composition was determined using the whole carcass method (crude fat, protein, ash, and dry matter) as described by Noetzold et al. (2024). Briefly, individual birds were pressure-cooked in individual pots for 3 h. For the pressure-cooking process, water was added to the pots before cooking and lost during cooking process. The amount of water remaining in the pots after cooking was accounted and subtracted from the carcass weight. After cooking, the whole bird was homogenized using an industrial blender; samples were collected from each bird (140 mL) and oven-dried at 60°C for 72 h, with a second oven-dry process at 105°C overnight (15 h). For the carcass ash content (mineral content), samples were overnight (12h) combusted at 600°C. Carcass nitrogen was determined by the combustion method using a Leco TruMac N determinator (Leco Corporation, St. Joseph, Michigan, USA), and carcass CP was estimated by multiplying nitrogen content by 6.25 (Mutucumarana et al., 2015). Carcass lean was calculated by

Table 4
Estimated coefficients of the 3-phase Gompertz model[1] for early growth (EG)[2] and time of maximum pubertal growth (I2)[3] of Ross 308 broiler breeder females.

	EG0 [2]						EG20 [2]					
	I2											
Growth Parameter	15	17	19	21	22	23	15	17	19	21	22	23
g_1 (kg)			1.7709						2.1669			
b_1				0.1887								
I1 (wk)				5.83								
g_2 (kg)			1.9798						1.5838			
b_2				0.1880								
I2 (wk)	15.0	17.0	19.0	21.0	22.0	23.0	15.0	17.0	19.0	21.0	22.0	23.0
g_3 (kg)				0.3663								
b_3				0.1259								
I3 (wk)				47.3								

[1] General model form: $BWt = \sum_{i=1}^{i=3} g_i \times exp^{-exp^{-b_i \times (t - Ii)}}$, where BWt was BW at time t (wk); g_i was the total amount of gain (kg) accruing in phase i; b_i was the rate of growth in phase i; Ii was the inflection point for phase I (wk), or the age at which growth for that phase reached its maximum growth rate.

[2] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).

[3] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Fig. 2. Dorsal track feathers from broiler breeder hens. Mature feather (left) and an immature feather (right), where the sheath structure was presented maintaining the cyclical shape until the papilla.

adding the protein plus water results. Crude fat content was determined using a modified AOAC (2006) method as follows: approximately 0.5 to 1g sample was added to pre-weighed 16 × 125 mm glass tube; 10 mL of hexane solvent was added to the sample. Tubes were then weighed, agitated for sample homogenization with hexane, and left for 24 h for solvent extraction. Samples were then centrifuged for 10 min at 1500 rpm, and the supernatant hexane (70 to 80%) was moved to a second pre-weighed test tube. The second test tube was weighed and placed under a stream of nitrogen in a warm water bath (40 to 60°C) for hexane evaporation. Tubes containing residual fat were then weighed. Sample correction weight was applied based on the amount of hexane transferred to the second tube, considering that the amount of fat was homogeneous across the total amount of solvent.

Additionally, carcass composition was estimated serially on individual birds utilizing a dual-energy X-ray absorptiometry method (Lunar Prodigy Scanner, GE Medical Systems Lunar, Madison, USA) with the *small animal* settings and the enCORE 2011, software version 13.60. Four birds per growth trajectory (n=48) were live scanned at specific ages (4, 8, 12, 16, 20, 22, 24, 26, and 28 wk). Detailed description of the scan procedure was described previously (Noetzold et al., 2024). Briefly, live birds were moved to a scanning dark room (2 to 3 lx), where prior to each scan, birds were secured without sedation with a fabric restraint to avoid movements. One scan was performed per bird at each time period. All scan images were analyzed using the *Custom* option in the *Analysis* menu from the enCORE software. The whole body of each bird, without identifying specific body parts, was selected in the region of interest (ROI) option. After analysis, the total body lean, fat, and mineral content (ash) were estimated from the DXA scans and results were exported from the database and corrected with the regression estimations recommended for breeders by Noetzold et al. (2024).

Statistical analysis

Analysis of variance and analysis of covariance were conducted using the MIXED procedure of SAS (Version 9.4, SAS Institute Inc., Cary, NC). Weekly BW, ADFI and serial carcass composition estimation variables were analyzed in a three-way ANOVA, where EG, I2, and age were considered as discrete sources of variation. Pen was included in the model as a random source of variation and the individual bird as the subject to account for within-bird variation. Analysis of covariance was conducted on BWPS, BWFE, AFE, ovary components, carcass composition, and body components at sexual maturation, with EG as discrete source of variation and I2 as continuous predictor variable. The GLIMMIX procedure was used to analyze breast fleshing score, pubic bone spacing, and juvenile primary wing feathers using a Poisson distribution, whereas a binary distribution was used for dorsal feather maturity. The results were presented as means ± SEM. Pairwise comparisons were used to estimate weekly significant differences for the BW three-way interaction (EG × I2 × age), and body fat and ash two-way interactions (EG × age and I2 × age) by the PDIFF option of the LSMEANS statement (reported as different when $P \leq 0.05$). For the remaining variables, pairwise differences between means within each age were determined using Tukey's HSD test and were reported as different where $P \leq 0.05$. Trends were reported when $0.05 < P \leq 0.10$.

Results and discussion

Body weight

Weekly BW followed target growth trajectories closely for most of the study period (0 to 28 wk; Fig. 1). Bird BW started to diverge around 3 wk of age and was by design maintained until the end of the study (Supplementary Table 1).

Feed intake

Average daily feed intake started to differ after 4 wk of age due to the EG factor until 12 wk of age (Supplementary Table 2 and Fig. 3A). For the I2 factor, ADFI differed distinctly per growth trajectory from 10 to 20 wk of age, and later from 24 to 28 wk of age (Supplementary Table 2 and Fig. 3B). Contrarily from a conventional system, where the flock is fed a given amount of feed (calculated per bird) per day or in a skip-a-day regime (Sweeney et al., 2022), the current study kept birds on their own target BW by feeding multiple meals per bird throughout the day.

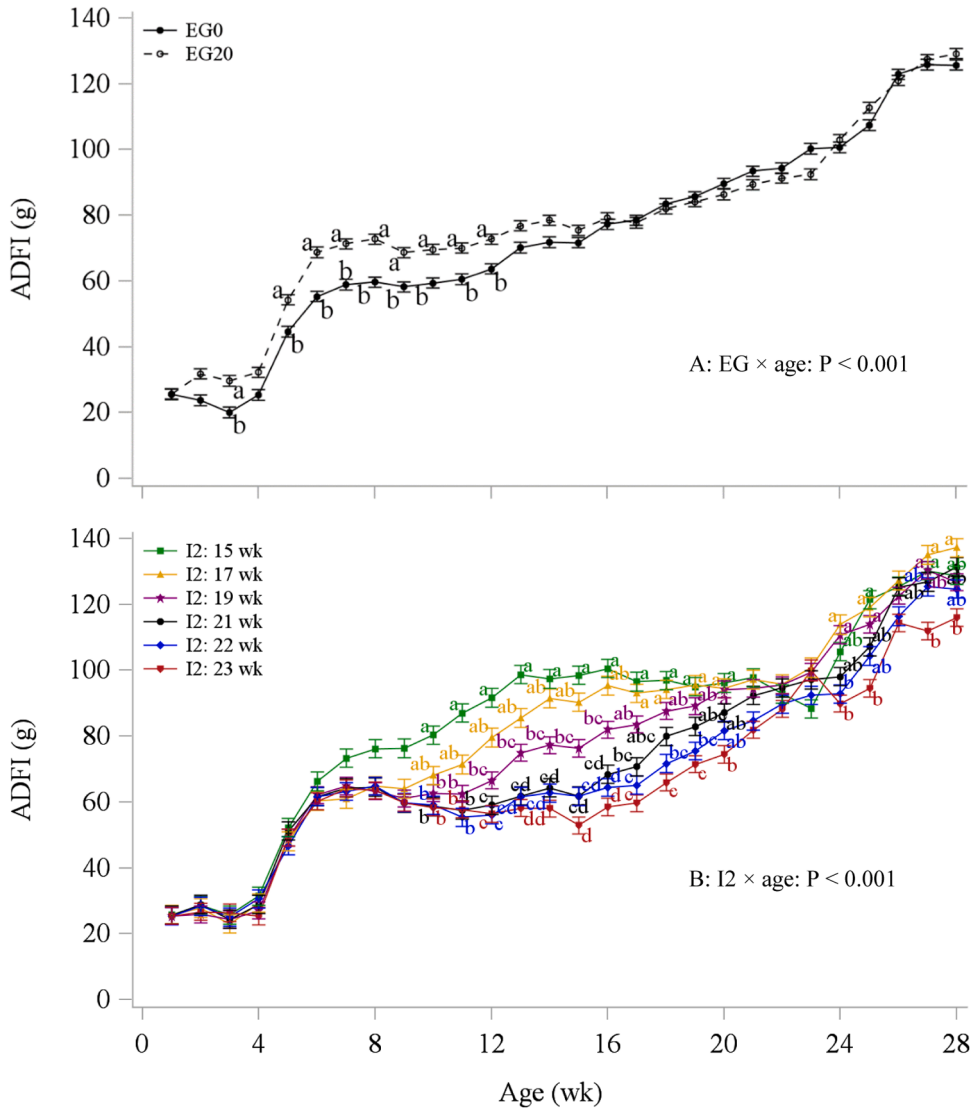

Fig. 3. Effect of time and early growth (EG, A), and time of maximum pubertal growth (I2, B) on feed intake of Ross 308 pullets. Early growth was either Standard (EG0) estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1). Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Table 5
Effects of early growth (EG)[1] shift and time of maximum pubertal growth (I2)[2] on cumulative feed conversion ratio (FCR) at 7, 15, and 21 wk of age of Ross 308 broiler breeder pullets.

Effect		Cumulative FCR (g/g)					
		7 wk	SEM	15 wk	SEM	22 wk	SEM
		g/g					
EG	EG0	2.423	0.02	3.454	0.02	4.001[b]	0.02
	EG20	2.418	0.02	3.491	0.02	4.074[a]	0.02
Linear coefficients		g/g/wk					
I2 × EG	EG0	-0.0061	0.009	0.032	0.008	-0.016	0.009
	EG20	0.0070	0.006	0.032	0.005	-0.007	0.006
Source of variation		P-value					
EG		0.12		0.79		0.053	
I2		0.91		< 0.001		0.011	
EG × I2		0.12		0.99		0.29	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Therefore, feed intake was expected to change over time between the several growth trajectories. The PF system allowed or restricted individual birds based on their target BW for them to achieve a given growth trajectory.

Feed efficiency

Cumulative FCR was similar between EG0 and EG20 at 7 and 15 wk of age. At 22 wk of age, the EG0 had 0.07 points lower FCR when compared to EG20 (Table 5). For every wk of earlier time of pubertal growth (I2), cumulative FCR at 15 wk of age decreased by 0.032 g/g. However, FCR increased by 0.016 g/g at 22 wk of age for every wk of earlier I2 (Table 5). A lower and greater feed efficiency was expected in the growth trajectories heavier and lighter than the recommended breeder BW target, respectively. This was expected because relaxing feed restriction shows an increase in BW and increase maintenance ME requirement (Teofilo et al., 2022). Also, relaxing feed restriction can potentially increase fat deposition, which has a higher energetic cost than protein deposition (Sakomura et al., 2003).

Table 6
Effects of early growth (EG)[1] shift and time of maximum pubertal growth (I2)[2] on breast fleshing score, pubic bones spacing, juvenile primary wing feathers, and back feather maturity percentage of Ross 308 from 15 to 21 wk of age.

Effect		Fleshing score[3]	SEM	Pubic bones space	SEM	Juvenile primary feathers	SEM	Dorsal feather maturity[3]	SEM
		— mean —		— mm —		— n —		— % —	
EG	EG0	2.00[b]	0.02	23.0[b]	0.37	4.9	0.13	46.8	5.6
	EG20	2.20[a]	0.02	24.5[a]	0.37	3.7	0.13	54.1	5.7
Age	15	2.08	0.02	22.2[b]	0.88	5.3[a]	0.15	n/a	n/a
	17	2.12	0.03	21.7[b]	0.44	5.0[a]	0.16	n/a	n/a
	19	2.10	0.03	23.0[b]	0.53	2.6[b]	0.15	n/a	n/a
	21	2.11	0.02	28.2[a]	0.44	n/a	n/a	n/a	n/a
Linear coefficients		— unit/wk —		— mm/wk —		— n/wk —		— %/wk —	
EG × I2	EG0	-0.0564	0.01	-1.1579	0.16	0.4167	0.06	-2.064	2.7
	EG20	-0.0784	0.01	-0.5924	0.11	0.2333	0.05	-4.903	1.9
Source of variation		P-value							
EG		0.044		0.002		0.19		0.25	
I2		< 0.001		< 0.001		0.011		0.012	
EG × I2		0.65		< 0.001		0.44		0.30	
Age		0.72		< 0.001		< 0.001		n/a	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).
[3] Breast fleshing score was measured in a 5-point scale (0 to 4), where 0 represented undersized (very thin), and 4 represented oversized (very wide).
[4]Measured at 25 wk of age.

Pullet development and sexual maturation

Shifting 20% of EG from pubertal to the prepubertal phase (EG20) increased the breast fleshing by a score of 0.2 and 1.5 mm of the pubic bones spacing compared to the EG0 treatment during the 15 to 21 wk period (Table 6). Breast fleshing score also increased by 0.06 per wk of earlier I2 (Table 6). An interaction between EG and I2 showed that pubic bones spacing increased by 1.16 mm per wk of earlier I2 with a EG0, while this increase was lower (0.59 mm/wk of earlier I2) in the EG20 treatment (Table 6). The number of juvenile primary wing feathers was not influenced by the EG factor. However, the earlier I2 decreased by 0.4 the number of juvenile primary wing feathers per wk from 15 to 19 wk of age. Additionally, for every wk of earlier I2, the maturity of dorsal feathers increased by 2.06% (Table 6).

The age at first egg was not influenced by the EG factor. However, advancing the time of maximum pubertal growth decreased the AFE by 0.9 d/wk (Table 7). Interactions between EG and I2 for the BWPS and BWFE demonstrated increased of 119.5 g and 79.3 g per wk of earlier I2 at EG0 treatment, whereas for the EG20, the BW increased by 97 g and 58.8 g wk of earlier I2 for BWPS and BWFE, respectively (Table 7). In the current study, earlier time of maximum pubertal growth advanced the sexual maturation age. As further shown in Fig. 4, this was related to greater pullet BW, which might also be related to body composition (see carcass composition section).

Table 7
Effects of early growth shift (EG)[1] and time of maximum pubertal growth (I2)[2] on age at first egg (AFE), body weight at photostimulation (BWPS), and body weight at first egg (BWFE) of age of Ross 308 broiler breeder pullets.

Effect		AFE	SEM	BWPS	SEM	BWFE	SEM
		— d —		— g —			
EG	EG0	172.0	0.63	2,586[b]	5.1	3,045[b]	8.5
	EG20	171.7	0.62	2,783[a]	5.1	3,161[a]	8.5
Linear coefficients		— d/wk —		— g/wk —			
EG × I2	EG0	0.868	0.31	-119.5	1.44	-79.3	4.2
	EG20	1.247	0.22	-97.0	1.02	-58.8	3.0
Source of variation		P-value					
EG		0.22		< 0.001		< 0.001	
I2		< 0.001		< 0.001		< 0.001	
EG × I2		0.22		< 0.001		< 0.001	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Similarly to the growth phases described in this report (early growth or prepubertal, pubertal, and post-pubertal growth) feather growth also goes through different stages of development. Feather development in commercial broiler breeders under a variety of BW trajectories have not been fully studied. The juvenile primary wing feathers are among the industry evaluations commonly conducted during the moment of transfer from the pullet house to the laying house and are generally the first to moult (Leeson and Walsh, 2004), and are more closely associated to sexual maturation, where there is a natural decrease of juvenile primary wing feather as birds age (Marble, 1934; Alfaro-Wisaquillo et al., 2021). Therefore, fewer juvenile primary wing feathers indicate closer approximation to sexual maturity. In the current study, in addition to the decreased number of juvenile primary wing feathers as pullets aged, there was a decrease in feather numbers with the advancing of I2 (heavier BW trajectories during pubertal development), indicating that sexual maturation would be reached earlier with the earlier I2. This assumption was confirmed with the earlier AFE in pullets raised in the earlier I2 growth trajectories. Additionally, dorsal feather maturity was increased as the I2 was advanced at 25 wk of age. Dorsal tract (back) feather maturity is also among the industry evaluations in broiler breeder hens. However, no literature has yet been published assessing dorsal track feather maturity of broiler breeder hens. In parallel to the number of juvenile primary wing feathers, feather maturation stages may also indicate reproductive status in chickens, which has been reported in wild birds previously (Hawkins et al., 2012; Chen et al., 2015). Additionally, spatial widening of pubic bones followed a similar pattern to feather development in the present study, with greater pubic bone spacing in the advanced I2 growth trajectories. Pubic bones spreading has long been used in the industry for estimating flock progression toward sexual maturity (Fattori et al., 1993; Satterlee and Marin, 2004). The development of the secondary sex characteristics (pubic bones opening, feather growth, and comb and wattle development) are reported to be influenced by hormones related to sexual maturity, such as estrogens and androgens (Parkes and Emmens, 1944; Eitan et al., 1998; Widelitz et al., 2019). However, no hormones related to feather and sexual maturity were reported in the current study.

The advanced sexual maturity (measured as AFE) in pullets as the time of maximum pubertal growth (I2) occurred earlier may have been due to thresholds achieved in BW and body composition. A minimum BW threshold (±2 kg at 21 wk of age) for sexual maturation has been

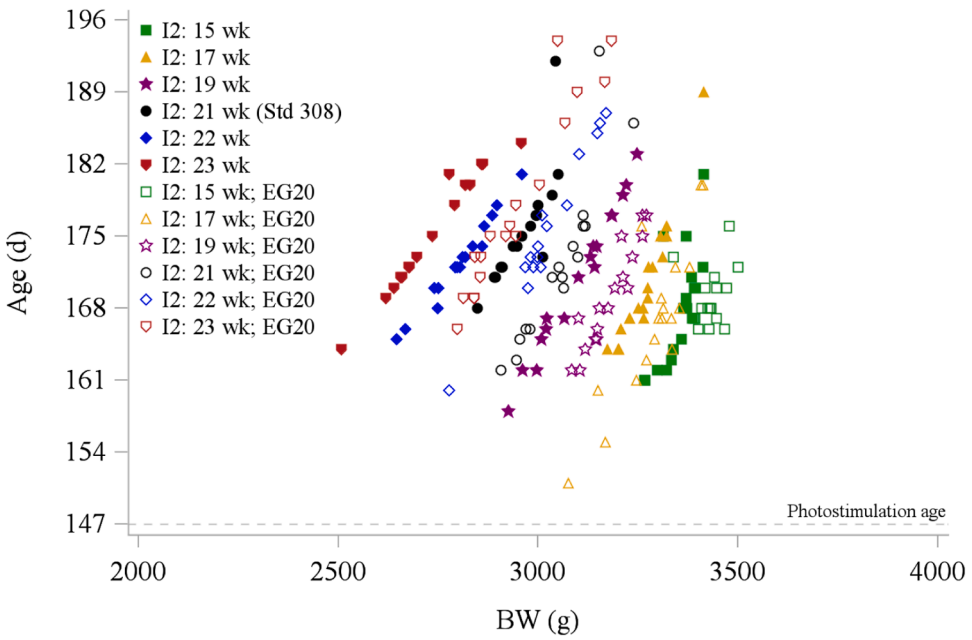

Fig. 4. Effect of early growth (EG) and time of maximum pubertal growth (I2) on age and body weight at sexual maturation of Ross 308 pullets. Early growth was either Standard (filled symbols), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1). Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

reported previously in broiler breeder hens (Lewis and Gous, 2006; Lewis et al., 2007). However, van der Klein et al. (2018a, 2018b) have found that despite reaching a minimum recommended BW threshold around the time of photostimulation, lighter hens had lower performance compared to heavier hens, suggesting that the minimum BW threshold might have changed. Alternatively, carcass fat content has decreased over the last decades due to improvements in the genetic FCR potential of broiler breeders (Caldas et al., 2018; Zuidhof, 2018; Carney et al., 2022), indicating that strategically relaxing feed restriction might improve reproductive capacity through carcass fat thresholds (see carcass composition section). The current findings indicate that sexual maturity, feather maturity, and development of secondary sex characteristics are affected by BW, and might also be affected by fat carcass composition.

Body components and ovary development

Body components and frame size measured at sexual maturation age are shown in Table 8. Abdominal fat pad increased 2.15 g and 0.02% for every wk of earlier I2. Breast muscle at sexual maturation increased by 59 g and 1.04-fold in EG20 compared to EG0 (Table 8). Interaction tendencies between EG and I2 factors (P = 0.093) suggest a greater breast weight and yield for every wk of earlier I2 for the EG0 (28.3 g and 0.27%/wk) when compared to the EG20 treatment (18.8 g and 0.04%/wk; Table 8). Earlier I2 increased shank length by 0.97 mm/wk and tended to increase keel length by 1.06 mm/wk of earlier I2 (P = 0.058; Table 8). Additionally, EG20 birds had keel length 5.6 mm greater than EG0 birds (Table 8).

In the present study, breast muscle was greater with EG20 treatment at the sexual maturation age, whereas the abdominal fat content was affected only by the time of maximum pubertal growth (I2). Shifting gain from the pubertal to the prepubertal phase of broiler breeders seems to have a greater influence in muscle and skeletal growth when compared to the fat tissue growth. These results are consistent with the concept of allometric growth, which defines that the different parts of the body grow at different rates during animal development (Huxley, 1932). Although both breast and abdominal fat yield increase in a greater rate than the carcass weight as breeders became heavier (Zuidhof, 2005), the abdominal fat pad has a later development when compared to the breast muscle, where fat is associated with the pubertal

Table 8
Effects of early growth (EG)[1] shift and pubertal growth spurt (I2)[2] on abdominal fat pad (AFP), breast muscle, shank length, and keel bone length at the age of sexual maturation.

Effect	EG	AFP	SEM	Breast	SEM	AFP	SEM	Breast	SEM	Shank	SEM	Keel	SEM
			g				%				mm		
EG	EG0	49.9	2.4	716[b]	10.0	1.72	0.08	24.6[b]	0.3	99.8	0.8	113.6[b]	1.2
	EG20	47.7	3.0	775[a]	9.8	1.56	0.10	25.6[a]	0.2	100.9	0.8	119.2[a]	1.2
Linear coefficients			g/wk				%/wk				mm/wk		
EG × I2	EG0	-2.147	1.4	-28.27	5.6	-0.0238	0.05	-0.2665	0.1	-0.9733	0.5	-1.0592	0.6
	EG20	-3.871	1.1	-18.75	3.7	-0.0960	0.04	-0.0420	0.1	-0.6047	0.3	-0.1165	0.4
Source of variation							P-value						
EG		0.27		0.026		0.20		0.021		0.51		0.028	
I2		< 0.001		< 0.001		0.017		0.026		< 0.001		0.058	
EG × I2		0.23		0.093		0.14		0.10		0.42		0.13	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

phase in chickens (Carney et al., 2022; van Eck et al., 2024). This indicates that feeding strategies around puberty is more successful to change fat deposition around sexual maturity in breeders.

Shank and keel length are considered to be indirect indicators of skeletal frame size (Kwakkel et al., 1998; Robinson et al., 2007). Frame size is influenced mainly by the level of feeding in early growth phase, but also to a lesser extend by pubertal growth period (Wilson et al., 1995; de Beer and Coon, 2009). Afrouziyeh et al. (2021) in a similar experimental design on Ross 708 breeders, used five I2 levels, from Standard I2 to 20% earlier I2 in a 5% range (0%, 5%, 10%, 15%, and 20%). Corroborant with the current study, Afrouziyeh et al. (2021) observed that shank length increased with the earlier I2. Skeletal frame size might provide birds with a foundation for a successful egg production period, associated with eggshell integrity (Hanlon et al., 2022) and nutrient availability for egg production (Wilson et al., 1995; Hudson et al., 2000).

Reproductive organs (ovary and oviduct) and ovary morphology at sexual maturation age are shown in Table 9. Early growth and the time of maximum pubertal growth did not affect F1 weight, LYF weight, and total ovary weight. An interaction tendency between EG and I2 ($P = 0.10$) showed a decreased of LYF number by 0.12 per wk of earlier I2 in the EG0 treatment, whereas the number of LYF increased 0.07 per wk of earlier I2 in hens raised in the EG20 treatment (Table 9). Oviduct weight tended to be 1.1 g greater in birds from the EG0 compared to EG20 birds ($P = 0.096$). For every wk of earlier I2, ovary and oviduct percentage decreased was by 0.05 and 0.02%, respectively.

In the present study, despite the considerable contrast between the BW across the treatment groups (Fig. 1), only minor differences were observed in the F1 weight, and large yellow follicular weight and number. In contrast to the current study, Renema et al. (2007) utilizing four growth trajectories (Low, Standard, Moderate, and High) observed a greater F1 weight in the Low growth trajectory feeding group, which was attributed to the greater feeding level of that group at the sexual maturation moment. In the past, follicular development in broiler breeders was mainly attributed to the BW and energy intake (Hocking, 1993; Hocking, 2004). However, this relationship may be lessened in modern broiler breeders. While feeding level continues to impact follicular development in modern breeders (Carney et al., 2022; Stephens et al., 2022), BW should be evaluated concurrently with body composition because pullets raised to a similar BW may differ in carcass composition (Zuidhof, 2018; Carneiro et al., 2019), which can affect follicular development and subsequent egg production. Additionally, improvements in genetic traits related to the reproduction in the female lines over the years (Tavárez and Solis de los Santos, 2016) may have resulted in improved follicular recruitment and growth stability compared to three decades ago. Nowadays, major differences found in follicular growth appears largely at extreme scenarios (e.g. ad libitum *vs.* feed restricted birds; Francoeur et al., 2021; Carney et al., 2022; Stephens et al., 2022).

Carcass composition

Carcass composition measured at sexual maturation age is shown in Table 10. Carcass lean and ash were 91 g and 8.2 g greater in EG20 birds raised when compared to EG0, respectively. Similarly, body ash percentage was 0.14 % greater in the EG20 treatment when compared to birds raised in the EG0 treatment. An interaction tendency between EG and I2 ($P = 0.074$) showed that for every wk of earlier I2, body lean percentage of EG0 birds increased by 0.50% compared with only 0.11% in EG20 birds (Table 10). Body fat (weight and percentage) was only affected by the time of maximum pubertal growth, where for every wk of earlier I2, body fat was increased by 19.5 g and 0.44%, respectively (Table 10). Total carcass fat composition estimations from 4 to 28 wk of age are shown in Fig. 5. Only the main effects (EG and I2) × age were reported because no statistical differences were found in the highest interaction (EG × I2 × age) and in the EG × I2 interaction. Overall carcass fat deposition increased overtime, where EG20 birds had approximately 1.3- to 1.6-fold greater carcass fat content from 4 to 16 wk of age; but this difference was not observed at 20 wk onward (Fig. 5A). On the other hand, the time of maximum pubertal growth did not influence total carcass fat deposition at 4 and 8 wk of age but increased in birds with the earlier I2 from 16 to 28 wk of age (Fig. 5B). At 22 wk of age, the most delayed I2 (I2 = 23 wk) had birds with 7.7% carcass fat compared to 11.3% from the I2 of 15 wk (Fig. 5B). Carcass fat composition is usually inversely proportional to the lean composition, as demonstrated at the sexual maturation time (Table 10). Similarly, lean composition estimation over time showed contrary pattern to the carcass fat composition (data not shown).

The first growth phase of birds (early growth) appears to be the most influential to the skeletal development in chickens (Wilson et al., 1995; Kwakkel et al., 1998; Afrouziyeh et al., 2021). In the current study, EG20 birds demonstrated greater mineral deposition at sexual maturity. In addition, ash percentage estimated over time was greater in the EG20 treatment at 4 and 8 wk of age (Supplementary Fig. 1A). However, the pubertal growth phase can also influence mineral deposition, as observed in the present study, and reported previously (Renema et al., 2007). Despite greater mineral percentage observed as the I2 was delayed after 22 wk of age (Supplementary Fig. 1B), ash weight increased as the I2 was advanced after 12 wk of age (Supplementary Fig. 1D).

A minimum carcass fat composition is expected for pullets to commence egg production (Summers et al., 1987; de Beer and Coon, 2009; van Emous et al., 2013). Afrouziyeh et al. (2021) suggested that the minimum fat composition threshold for sexual maturity is below 8% in modern broiler breeders. In the current trial, the upper end I2 treatment (EG0, I2 = 15 wk), the recommended Ross 308 BW target (EG0, I2 = 21 wk), and the lower end I2 treatment (EG0, I2 = 23 wk), yielded 11.3%, 8.8%, and 7.5% carcass fat composition at 22 wk of age,

Table 9
Effects of early growth (EG)[1] shift and pubertal growth spurt (I2)[2] on the largest yellow follicle (F1), large yellow follicles (number and g), ovary (g and % of BW), and oviduct (g and % of BW) at the age of sexual maturation.

Effect		F1	SEM	LYF No.	SEM	LYF weight	SEM	Ovary	SEM	Oviduct	SEM	Ovary	SEM	Oviduct	SEM
		g		n		g						%			
EG	EG0	11.9	0.19	6.7	0.22	44.8	1.2	50.0	1.2	61.6	1.3	1.7	0.04	2.11	0.04
	EG20	11.8	0.20	6.7	0.24	44.3	1.4	49.6	1.4	60.5	1.3	1.6	0.05	2.01	0.04
Linear coefficients		g/wk		n/wk		g/wk						%/wk			
EG × I2	EG0	-0.0363	0.10	0.1181	0.12	0.1631	0.7	0.1034	0.6	-0.8375	0.6	0.0513	0.02	0.0246	0.02
	EG20	0.0081	0.07	-0.0685	0.09	-0.7803	0.5	-0.7933	0.5	0.1969	0.4	0.0121	0.02	0.0482	0.01
Source of variation		P-value													
EG		0.61		0.14		0.19		0.20		0.096		0.17		0.18	
I2		0.77		0.69		0.36		0.29		0.31		0.014		< 0.001	
EG × I2		0.65		0.10		0.17		0.17		0.11		0.12		0.26	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

Table 10
Effects of early growth (EG)[1] shift and time of maximum pubertal growth (I2)[2] on carcass total body lean, fat, and mineral content (ash) of Ross 308 broiler breeder pullets at sexual maturation age.

Effect		Lean	SEM	Fat	SEM	Ash	SEM	Lean	SEM	Fat	SEM	Ash	SEM
		g						%					
EG	EG0	2,640[b]	20.1	262	7.7	93.5[b]	1.63	90.7	0.51	8.89	0.26	3.21[b]	0.048
	EG20	2,731[a]	21.4	271	7.7	101.7[a]	1.63	90.1	0.50	8.90	0.26	3.35[a]	0.048
Linear coefficients		g/wk						g/wk					
EG × I2	EG0	-51.765	10.8	-19.541	3.9	-1.4391	0.82	0.4977	0.21	-0.4437	0.13	0.0299	0.024
	EG20	-54.557	7.6	-13.828	2.7	-1.5933	0.58	0.1086	0.15	-0.2694	0.09	0.0179	0.017
Source of variation		P-value											
EG		0.050		0.18		0.049		0.10		0.19		0.043	
I2		< 0.001		< 0.001		< 0.001		0.006		< 0.001		0.050	
EG × I2		0.80		0.14		0.85		0.074		0.19		0.62	

[1] Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1).
[2] Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

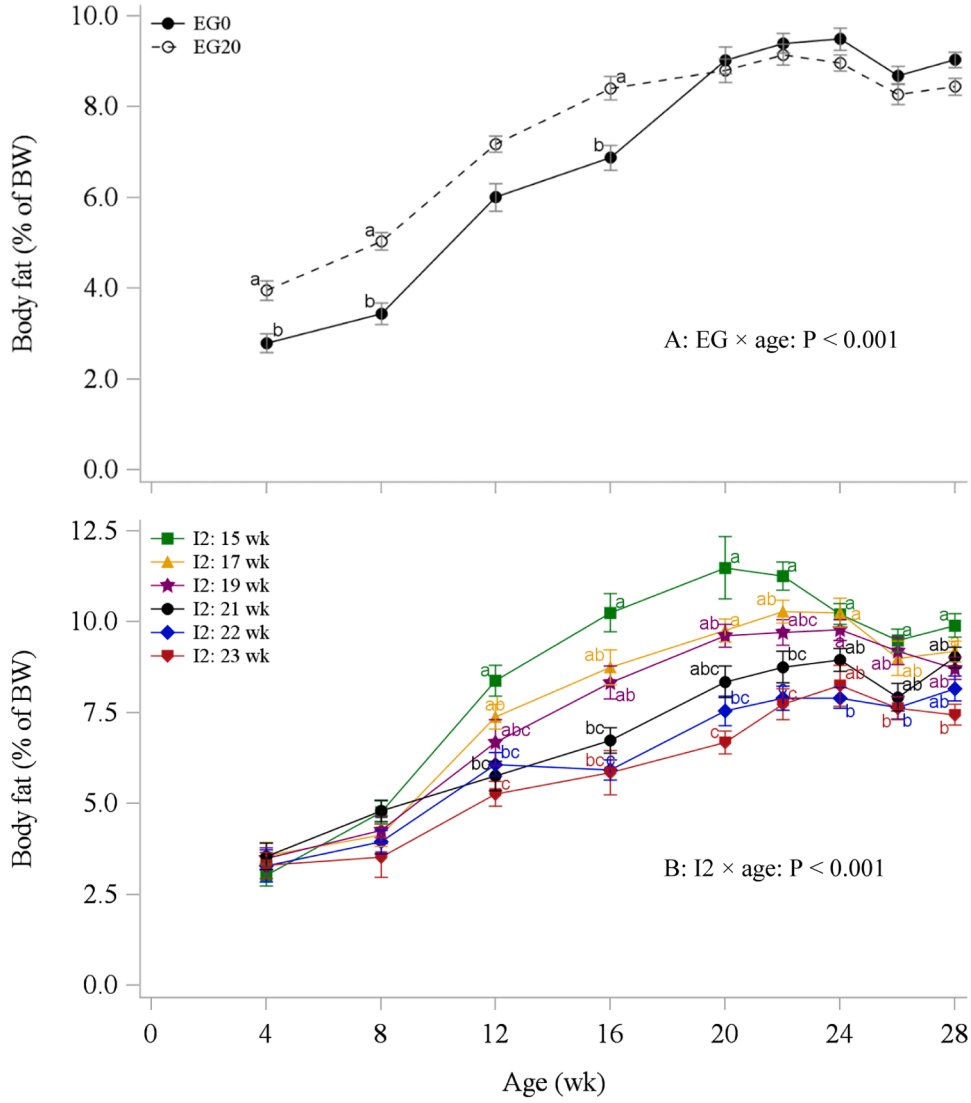

Fig. 5. Effect of time and early growth (EG, A), and time of maximum pubertal growth (I2, B) on body fat percentage of Ross 308 broiler breeder females from 4 to 28 wk of age. Early growth was either Standard (EG0), estimated from the Ross 308 breeder-recommended standard BW gain; or 20% shifted (EG20), where 20% gain (kg) of the pubertal phase (g_2) was shifted to prepubertal phase (g_1). Time of maximum pubertal growth was advanced (15, 17, and 19 wk) or delay (22 and 23 wk) based on the Ross 308 standard inflection point (21 wk).

respectively (Fig. 5B). It seems that the carcass composition of 7.5% was enough for all pullets to commence egg production. However, breeders raised in the treatments with delayed I2 (lower BW and lower carcass fat), had their sexual maturation delayed when compared to the earlier I2 treatments. As observed, the mechanism behind earlier sexual maturation in the current trial is linked to BW and carcass composition

in response to the I2 factor. Thus, indicating that the current results were influenced by the carcass fat levels and not only BW. Both BW and body composition can be confounded by the fact that birds with different body composition can perform differently at a similar BW. In the current trial, the EG factor demonstrated changes in BW but a lack of fat deposition differences at the photostimulation and sexual maturation age, which suggests that body composition is an important indicator to sexual development and maturity in modern broiler breeders. In a straightforward manner, body weight and carcass fatness are positively correlated (Sakomura et al., 2003; Heijmans et al., 2023). Nonetheless, as shown in the current trial, the time of gain can also determine fatness level around the sexual maturation age. Further investigation from the current trial will describe egg laying persistence and its relationship to the body weight and body composition.

In conclusion, shifting gain from the pubertal to the prepubertal phase in broiler breeder pullets increased skeletal development (keel length and mineral content), breast fleshing and yield, and carcass fat composition before 16 wk of age. The earlier time of maximum pubertal growth (I2) advanced feather maturation of pullets, advanced sexual maturity, and influenced carcass composition before, during and after sexual maturity. Furthermore, relaxing feed restriction during the early growth phase of breeder pullets decreases feed efficiency. Appropriate growth trajectory recommendations can be made after the laying cycle is evaluated.

Disclosures

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.psj.2024.104414.

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