Feeding, feed-seeking behavior, and reproductive performance of broiler breeders under conditions of relaxed feed restriction

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ABSTRACT Broiler breeders are feed restricted to optimize reproductive performance. A randomized controlled study was conducted to investigate the effect of increasing female broiler breeder BW on feeding, feed-seeking behavior, and reproductive performance. It was hypothesized that a greater BW would decrease feeding and feed-seeking behavior, and reduce reproductive performance. Ross 708 female broiler breeders (n = 36) were fed using a precision feeding system from 2 to 42 wk of age. Ten BW trajectories were created from a multiphasic Gompertz growth model that increased growth from 0 to 22.5% in the prepubertal and pubertal phases of growth, in 2.5% increments. Six unrestricted birds were not limited to a maximum BW. Body weight was evaluated as a 2-way ANOVA. Two linear regression analyses were conducted, one which included all birds and one which excluded the unrestricted birds. For the regression analyses, BW at photostimulation (22 wk of age) was used as the continuous independent variable to represent the degree of variation between trajectories. Differences were reported at $P \leq 0.05$. Body weight increased as trajectory-specific BW targets increased from 6 to 28 wk of age. Differences of BW between BW trajectories decreased during the laying period, which was a result of individual bird variation within BW trajectories. Station visit frequency decreased per kilogram increase in BW for all birds during rearing and lay, and within feed-restricted birds during lay only. The number of meals and ADFI increased with age, which reflected nutrient intake to support maintenance, growth, and reproductive requirements. Mean egg weight (**EW**) of all birds increased by 0.72 g per kilogram increase in BW from 22 to 41 wk of age. From 22 to 29 wk of age, mean EW of feed-restricted birds increased by 2.78 g per kilogram increase in BW. For every kilogram increase in BW, age at first egg comparing all birds decreased by 10.83 d. Two unrestricted birds came into lay before photostimulation. In contrast with the hypotheses, BW increased up to 22.5% above the recommended target did not reduce feeding and feed seeking behavior, or negatively impact reproductive performance.

Key words: precision livestock feeding, body weight, hunger, unrestricted feed intake, sexual maturity

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INTRODUCTION

Broiler breeders are feed restricted to control BW throughout their life cycle. In particular, broiler breeders have been restricted 25 to 50% less feed than what unrestricted birds would consume on a daily basis (Rosales, 1994; Renema et al., 2007). As a result, broiler breeders experience chronic hunger and concomitant feeding frustration that have been identified through behavioral assessments (Savory and Maros, 1993; Hocking et al., 2002; Merlet et al., 2005) and physiological parameters (Hocking et al., 1996; de Jong et al., 2002). As such, feed restriction clearly leads to poor welfare. However, unrestricted feed intake can lead to health issues related to rapid growth and obesity, which is also considered to be a welfare issue. This reiterates the paradox described by Decuypere et al. (2010) that feed restriction is required as part of broiler breeder management to optimize reproduction, but to also avoid metabolic disorders and mortality.

In the past, feed restriction has been considered crucial during rearing to optimize reproductive performance and reduce health problems (reviewed by de Jong and Guémené, 2011 and D'Eath et al., 2009). Specifically, unrestricted feed intake has advanced sexual maturity and reduced egg production (Robinson et al., 1991; Bruggeman et al., 1999; Heck et al., 2004), and obesity-related lameness and death. Recent literature reported that broiler breeders reared to be 9.1% above the recommended BW target had similar egg production compared with restricted broiler breeders (van Emous et al., 2013).

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Moreover, cumulative egg production was 39% greater for precision-fed broiler breeders reared 22% above the recommended BW target than broiler breeders reared on a standard BW curve (van der Klein et al., 2018a). This suggests there is potential to increase broiler breeder BW targets without negatively affecting reproductive performance. In turn, the degree of feed restriction may be able to be relaxed to address chronic hunger and improve bird welfare.

A sequential precision feeding (**PF**) system has been created to control individual bird feed intake based on live BW (Zuidhof et al., 2019). This PF system provides birds with multiple meals of short duration throughout the day to achieve predetermined BW targets. To date, the PF system has been used to investigate feeding and feed seeking behaviors (Girard et al., 2017; Zuidhof et al., 2017), and to precisely implement BW curves to explore the effect of various degrees of relaxed feed restriction on broiler breeder growth and reproductive performance (van der Klein et al., 2018a,b; Zuidhof, 2018; Hadinia et al., 2019). Girard et al. (2017) assessed hunger through feeding and feed-seeking behaviors of conventionally skip-a-day and PF fed broiler breeder pullets. The authors reported that precision-fed broiler breeders demonstrated less feather pecking but more object pecking than did skip-a-day-fed birds. Thus, multiple meals throughout the day did not eliminate hunger. Recent studies have demonstrated precision-fed hens reared in accordance with recommended BW trajectories produced 27 and 10.3% less eggs than daily-fed pullets (Zuidhof, 2018; Hadinia et al., 2019). Zuidhof (2018) hypothesized that for some birds, increased meal frequency of PF pullets might not provide a sufficient amount of nutrients for carcass fat deposition to support egg production. It was suggested that broiler breeder feed restriction could be relaxed during rearing, particularly when using a PF system, to increase nutrient intake before sexual maturity and increase egg production.

The objective of the present study was to implement a variety of BW trajectories using a PF system to evaluate the effect of varying degrees of relaxed feed restriction on feeding, feed-seeking behavior and reproductive performance of broiler breeders. It was hypothesized that increased BW (a lesser degree of feed restriction) would decrease station visit frequency and meal size due to reduced hunger, whereas ADFI and meal frequency would increase because birds would be fed more to achieve greater BW targets. It was also hypothesized that egg weight (**EW**) would increase, age at first egg (**AFE**), and egg production would decrease with increasing BW.

MATERIALS AND METHODS

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

Experimental Design

The study was a completely randomized controlled study with 10 unique BW trajectories that were applied from 2 to 42 wk of age using a PF system. The trajectories were created from a 3-phase Gompertz growth model that manipulated the first 2 phases (prepubertal and pubertal) of growth. In the present study, the recommended Ross 708 BW curve (Aviagen, 2016a) was fit to the model to estimate prepubertal and pubertal growth. Trajectories differed in 2.5% increment increases of target BW gain during both the prepubertal and pubertal growth phases, which started from the Ross 708 recommended BW trajectory (CON) up to 22.5% above the recommended BW trajectory (CON+2.5%, CON+5%, CON+7.5%, CON+10%, CON+12.5%, CON+15%, CON+17.5%, CON+20% and CON+22.5%). The degree of feed restriction was relaxed to allow birds to reach increased BW targets. Three female broiler breeders were randomly assigned to each BW trajectory and 6 additional females were assigned to an unrestricted group, meaning they were fed ad libitum (not limited to a maximum BW and were given access to a meal upon every PF station visit). Each bird was considered to be an experimental unit.

Stocks and Management

Ross 708 broiler breeder pullets (n = 36) were reared in a single chamber with Ross YP males (n = 8) with a stocking rate of 3.2 birds per m^2. Males followed the Ross YP BW target (Aviagen, 2016b). All birds had access to 2 PF stations 24 h per day and ad libitum access to water throughout the experiment. On day 7, a wing tag with a radio frequency identification (**RFID**) transponder was applied to the right wing web for individual identification in the PF stations. Birds were fed commercial diets as follows: a poultry starter crumble from week 0 to 5 (2,762 kcal ME, 21% CP, and 0.99% Ca), a broiler breeder grower mash from week 6 to 26 (2,799 kcal ME, 15% CP, and 0.79% Ca), and a broiler breeder layer diet from week 27 to 46 (2,798 kcal ME, 15% CP, and 3.40% Ca). The photoschedule was 24L:0D (100 lx) from day 0 to 3 then reduced to 8L:16D (15 lx) on day 4. Light intensity was reduced to 5 lx on day 26 until the end of week 21 in attempt to reduce feather pecking. Hens were photostimulated at week 22 as the photoperiod was increased to 11L:13D (20 lx). The photoperiod increased to 12L:12D (25 lx) on week 23, then again at week 24 to 13L:11D (50 lx) for the remainder of the experiment. Each PF station had 5 green LED lights (2 lx) that illuminated the station so that birds could see their way through the station during hours of darkness, without causing photorefractoriness (Rodriguez, 2017). Temperature was set at 34.5°C on day 0 and decreased 0.5°C/d until day 22, after which it remained constant at 23.5°. A single RFID-equipped nest box (8 nesting sites) and trap nest box (10 nesting sites) were introduced to the chamber at 14 wk of age so that pullets could familiarize themselves with the nests before the onset of lay. Each

RFID nesting site was equipped with an RFID reader which identified a hen with each egg that was laid.

Precision Feeding System

The design and operation details of the PF system and individual stations have been more fully described elsewhere (Zuidhof et al., 2019). Briefly, the PF system fed birds individually based on live BW measurements compared with a target BW within the system software. Individual birds were recognized in the system through a unique RFID transponder. Each PF station consisted of a sorting and feeding stage. The sorting stage isolated each bird and recorded its live BW on entry when a decision was made: if the bird's live BW was greater than its programmed target BW, the bird was gently ejected from the station without access to a meal. If the bird's live BW was less than its programmed target BW, it was given access to feed in the feeding stage for 60 s. The BW trajectories of feed-restricted birds were automatically updated within the system software hourly.

Data Collection

Collection and recording of BW, station visit frequency, feed intake, number of meals, and meal size data has been fully described by Zuidhof et al. (2017). Briefly, BW was recorded within the PF system software on entry into the station. Station visit frequency, ADFI, the number of meals, and meal size were derived from records in the PF system database. Data collection began on week 2 to align with the time that individual feeding from the PF stations was fully implemented. Body weight was evaluated for each BW trajectory in 2-wk periods from 2 to 42 wk of age. Feeding and feed-seeking behaviors and EW were evaluated in 10 4-wk periods: 2 to 5, 6 to 9, 10 to 13, 14 to 17, 18 to 21, 22 to 25, 26 to 29, 30 to 33, 34 to 37, and 38 to 41 wk of age. Floor eggs were found beginning at 20 wk of age, and were assumed to be produced by unrestricted hens due to their high BW which could have advanced sexual maturation (Heck et al., 2004; Renema and Robinson, 2004). To ensure a precise estimate of **AFE**, the cloaca of each unrestricted hen was palpated daily to detect the presence or absence of a hard-shell egg in the shell gland from week 20 to 22. Thus, all floor eggs were appropriately identified to individual unrestricted hens. The cloaca of all hens was palpated daily from week 22 to 35. Eggs were collected, weighed, and assigned to individual hens daily.

Statistical Analysis

Body weight was evaluated as a 2-way ANOVA using the MIXED procedure in SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016) with BW trajectory and period as the fixed effects. Because of model convergence issues, the rearing and laying phases were analyzed independently. Age was included in the model as a random effect with individual bird as the subject to account for within-bird variation. Two linear regression analyses were conducted using the REG procedure of SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016) to determine the relationship of BW at photostimulation with feeding and feed-seeking behaviors, EW, AFE, and cumulative egg production. Body weight at photostimulation was used as a continuous independent variable that served as a proxy for the various degrees of separation of BW trajectories throughout rearing. The first regression analysis included all birds (feed-restricted and -unrestricted birds), whereas the second analysis included feed-restricted birds (excluded unrestricted birds) to determine the effects of BW at photostimulation within feed-restricted birds only. Feeding and feed-seeking behaviors and EW were evaluated independently for each period from 2 to 42 wk of age. All means were adjusted using Tukey's pairwise comparisons to estimate significance of difference between least squares means. Differences were reported where $P \leq 0.05$. Trends were reported where $0.05 < P \leq 0.10$.

RESULTS AND DISCUSSION

A total of 5 birds were culled during the study because of poor health or lameness: a bird from each of the CON+10%, CON+17.5%, and unrestricted groups at 35, 14, and 24 wk of age, respectively, and 2 birds from the CON+22.5% group at 35 and 36 wk of age.

Body Weight

Body weight was similar across BW trajectories at 2 and 4 wk of age (Table 1). Precision-fed chicks underwent training during the first 2 to 3 wk of life as they learn how to move through and eat from the PF stations. Most chicks were eating individually from the station feeder by 2 wk of age; however, some chicks required additional training to learn how to successfully eat from the feeder. Thus, BW was similar across BW trajectories because not all birds reached their trajectory-specific BW during the training period.

As designed, BW increased from 6 to 20 wk of age as trajectory-specific BW targets increased ($P < 0.001$, Table 1). Similarly at photostimulation (22 wk of age), there was a clear effect of BW trajectory on BW ($P < 0.001$, Table 1), and differences in BW between BW trajectories increased concomitantly with BW targets (Figure 1). In particular, the unrestricted birds weighed 2,007 ± 59.1 g more than the CON birds at photostimulation. During the onset of lay, BW of the unrestricted birds remained greater than the feed-restricted birds (Table 1). However, beginning at 26 wk of age, differences of BW across feed-restricted birds began to decrease because of higher variation (Figure 2). At peak lay (approximately 30 wk of age), BW variation further decreased across BW trajectories (Figure 2). Specifically at week 30, BW of the unrestricted birds (4,591, ±160.0 g) was similar to the CON+22.5% birds (4,766, ±154.3 g), which did not differ from the BW of the remaining feed-restricted birds (Table 1; Figure 1). Body weight continued to increase with age as trajectory-specific BW targets increased

Table 1. Effect of BW trajectory[1] (W) and age (A) on BW during rearing and lay.

	Age	BW trajectory										
		CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+22.5%	UNRES
	wk	g										
Rearing	2	150	139	141	137	155	135	143	110	152	124	141
	4	368	348	368	297	373	355	349	365	403	309	367
	6	575^{g}	$591^{f,g}$	$588^{e,f,g}$	$551^{d,e,f,g}$	$632^{d,e,f}$	$647^{d,e}$	$660^{c,d}$	$669^{b,c,d}$	$690^{a,b,c}$	$709^{a,b}$	789^{a}
	8	$796^{f,g}$	799^{g}	$819^{f,g}$	$828^{f,g}$	$856^{e,f}$	$879^{d,e}$	$895^{c,d,e}$	$913^{b,c,d}$	$930^{b,c}$	952^{b}	$1,534^{a}$
	10	983^{h}	$1,002^{g,h}$	$1,031^{f,g}$	$1,049^{f}$	$1,066^{e,f}$	$1,103^{d,e}$	$1,127^{c,d}$	$1,148^{c}$	$1,167^{b,c}$	$1,195^{b}$	$2,185^{a}$
	12	$1,156^{j}$	$1,192^{i,j}$	$1,218^{h,i}$	$1,240^{g,h}$	$1,275^{f,g}$	$1,306^{e,f}$	$1,332^{d,e}$	$1,357^{c,d}$	$1,385^{b,c}$	$1,414^{b}$	$2,742^{a}$
	14	$1,323^{j}$	$1,356^{i,j}$	$1,384^{h,i}$	$1,416^{g,h}$	$1,450^{f,g}$	$1,486^{e,f}$	$1,514^{d,e}$	$1,550^{c,d}$	$1,583^{b,c}$	$1,612^{b}$	$3,139^{a}$
	16	$1,486^{j}$	$1,523^{i,j}$	$1,556^{h,i}$	$1,594^{g,h}$	$1,634^{f,g}$	$1,677^{e,f}$	$1,707^{d,e}$	$1,745^{c,d}$	$1,778^{b,c}$	$1,820^{b}$	$3,429^{a}$
	18	$1,698^{h}$	$1,739^{g,h}$	$1,779^{f,g}$	$1,819^{f}$	$1,880^{e}$	$1,910^{e}$	$1,953^{d}$	$1,994^{c,d}$	$2,038^{b,c}$	$2,072^{b}$	$3,775^{a}$
	20	$1,977^{j}$	$2,025^{i}$	$2,073^{h}$	$2,119^{g}$	$2,172^{f}$	$2,222^{e}$	$2,273^{d}$	$2,320^{c,d}$	$2,366^{b,c}$	$2,405^{b}$	$4,094^{a}$
PS[2]	22	$2,290^{k}$	$2,346^{j}$	$2,400^{i}$	$2,455^{h}$	$2,519^{g}$	$2,576^{f}$	$2,627^{e}$	$2,684^{d}$	$2,742^{c}$	$2,793^{b}$	$4,297^{a}$
Lay	24	$2,587^{k}$	$2,652^{j}$	$2,717^{i}$	$2,788^{h}$	$2,853^{g}$	$2,915^{f}$	$2,973^{e}$	$3,040^{d}$	$3,096^{c}$	$3,163^{b}$	$4,480^{a}$
	26	$2,840^{h}$	$2,929^{g}$	$2,977^{f}$	$3,054^{e}$	$3,140^{d}$	$3,141^{b,c,d,e,f,g,h}$	$3,261^{c}$	$3,339^{b}$	$3,365^{b,c,d,e,f,g,h}$	$3,313^{b,c,d,e,f,g,h}$	$4,447^{a}$
	28	$3,022^{g,h}$	$3,123^{f,h}$	$3,181^{e,g}$	$3,283^{d}$	$3,356^{c}$	$3,377^{c}$	$3,511^{b}$	$3,562^{b,c}$	$3,541^{b,c,d,e}$	$3,619^{b,c,d,e,f}$	$4,520^{a}$
	30	$3,155^{d,e,f}$	$3,285^{f}$	$3,315^{e,f}$	$3,448^{e}$	$3,528^{d}$	$3,534^{d}$	$3,686^{c}$	$3,754^{b}$	$3,702^{b,c,d,e,f}$	$3,766^{a,b,c,d,e,f}$	$4,591^{a}$
	32	$3,240^{d,e}$	$3,379^{e}$	$3,440^{d,e}$	$3,543^{c,d}$	$3,617^{b,c,d,e}$	$3,656^{b,c,d,e}$	$3,731^{b}$	$3,866^{b,c}$	$3,777^{a,b,c,d,e}$	$3,899^{a,b,c,d,e}$	$4,655^{a}$
	34	$3,341^{c,d,e,f}$	$3,478^{f}$	$3,553^{d}$	$3,657^{c}$	$3,750^{b,e}$	$3,773^{b}$	$3,855^{a,b,c,d}$	$3,996^{a}$	$3,971^{a,b,c,d}$	$4,076^{a}$	$4,642^{a}$
	36	$3,392^{b,c,d}$	$3,511^{d}$	$3,623^{d}$	$3,713^{c,d}$	$3,812^{c}$	$3,838^{c}$	$3,938^{b}$	$4,048^{a}$	$3,984^{a,b,c,d}$	$4,091^{a,b,c,d}$	$4,687^{a}$
	38	$3,428^{e,f,g}$	$3,573^{g}$	$3,647^{d,f}$	$3,769^{c,e}$	$3,865^{c}$	$3,870^{c}$	$3,997^{b}$	$4,062^{b}$	$4,045^{a,b,c,d}$	4,244[3]	$4,797^{a,b}$
	40	$3,501^{f,g,h}$	$3,600^{h}$	$3,686^{e,g}$	$3,788^{d,f}$	$3,896^{c}$	$3,937^{c}$	$4,051^{b}$	$4,132^{b}$	$4,069^{a,b,c,d,e}$	4,298[3]	$4,780^{a}$
Source		Probability										
Rearing	W	< 0.001										
	A	< 0.001										
	Wx	< 0.001										
Lay	W	< 0.001										
	A	< 0.001										
	Wx	< 0.001										

[a–j]Means within rows with no common superscript differ ($P < 0.05$). SEM are shown in the form of a heat map (Figure 2).

[1]BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) were not limited to a maximum BW.

[2]Photostimulation.

[3]BW of a single bird remaining in the BW trajectory group.

	BW trajectory										
Age (wk)	CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+22.5%	UNRES
2	0	-11	-9	-13	5	-15	-7	-40	2	-26	-9
4	0	-20	0	-71	5	-13	-19	-3	35	-59	-1
6	0	16	13	-24	57	72	85	94	115	134	214
8	0	3	23	32	60	83	99	117	134	156	738
10	0	19	48	66	83	120	144	165	184	212	1,202
12	0	36	62	84	119	150	176	201	229	258	1,586
14	0	33	61	93	127	163	191	227	260	289	1,816
16	0	37	70	108	148	191	221	259	292	334	1,943
18	0	41	81	121	182	212	255	296	340	374	2,077
20	0	48	96	142	195	245	296	343	389	428	2,117
22	0	56	110	165	229	286	337	394	452	503	2,007
24	0	65	130	201	266	328	386	453	509	576	1,893
26	0	89	137	214	300	301	421	499	525	473	1,607
28	0	101	159	261	334	355	489	540	519	597	1,498
30	0	130	160	293	373	379	531	599	547	611	1,436
32	0	139	200	303	377	416	491	626	537	659	1,415
34	0	137	212	316	409	432	514	655	630	735	1,301
36	0	119	231	321	420	446	546	656	592	699	1,295
38	0	145	219	341	437	442	569	634	617	816	1,369
40	0	99	185	287	395	436	550	631	568	797	1,279

Figure 1. Heat map of differences in BW (g) across BW trajectories from 2 to 40 wk of age, relative to the CON trajectory. Trajectories varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW. Red, yellow, and blue colors indicate low, intermediate, and high values, respectively.

postpeak production; however, differences in BW across all birds decreased (Table 1; Figure 1): by 40 wk of age, the unrestricted birds weighed 4,780 g (±146.9), which did not differ from the CON+22.5% (4,298) and CON+20% birds (4,069 ± 90.9 g). Lack of significant differences in BW during the laying period was largely due to the small sample size per BW trajectory among the feed-restricted hens (n = 3), which is why the present study focused on regression analyses rather than ANOVA.

In the present study, differences in BW among birds reflected trajectory-specific BW targets throughout the rearing period and at the time of photostimulation; feed intake increased (the degree of feed restriction decreased) as BW targets increased. This was expected, as feed restriction is reportedly most severe from 8 to 16 wk of age when broiler breeders are restricted 25 to 30% of the intake of unrestricted birds (de Jong and Jones, 2006). There was large variation in individual bird BW within each BW trajectory from 26 to 40 wk of age. In addition, not all birds within their respective BW trajectory groups reached the same BW. The individual bird variation might have been due to a combination of using the PF system and genetic differences in mature BW. In a recent PF study, Zuidhof (2018)

	BW trajectory										
Age (wk)	CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+22.5%	UNRES
2	11.1	55.9	15.1	21.4	10.1	12.8	14.0	13.2	8.2	7.3	6.7
4	18.0	23.9	19.3	46.3	28.1	35.1	35.6	27.5	29.6	8.5	13.3
6	6.5	6.8	11.2	27.5	6.8	6.8	6.7	7.5	6.6	8.1	22.1
8	12.9	6.5	6.6	7.4	6.6	6.6	6.6	6.6	6.6	8.0	44.2
10	6.7	6.6	6.9	6.6	10.0	7.2	7.5	6.6	7.0	8.1	46.1
12	6.6	6.7	6.6	6.6	6.8	6.6	7.1	6.6	6.9	8.1	48.7
14	6.6	7.6	6.7	6.6	6.8	6.6	6.7	6.6	6.7	8.1	61.1
16	6.8	6.6	6.9	6.6	6.6	7.7	6.7	8.2	6.9	8.1	45.6
18	6.6	6.6	6.7	6.5	6.8	6.5	6.6	8.2	6.6	8.0	45.3
20	6.6	6.9	6.6	6.6	6.6	6.6	7.3	8.1	6.6	9.7	68.8
22	6.9	8.4	6.6	6.6	6.8	6.6	7.2	8.1	7.7	8.3	59.1
24	2.1	1.3	1.7	1.2	2.0	1.7	2.6	0.1	2.3	0.2	115.5
26	9.2	2.3	6.1	15.6	7.6	78.3	8.0	5.7	134.0	154.4	113.7
28	57.6	1.6	6.4	1.4	5.0	8.9	4.6	47.3	85.7	120.7	144.3
30	91.3	8.9	33.5	5.2	9.4	16.7	9.0	1.9	108.2	154.3	160.0
32	87.2	9.4	32.0	16.9	60.2	83.5	37.5	75.5	166.0	150.5	151.6
34	93.5	8.0	7.8	6.6	2.5	9.6	78.3	3.6	111.2	44.6	162.0
36	144.0	32.7	4.7	48.5	2.8	13.1	16.2	17.7	117.5	134.5	167.0
38	92.8	7.1	5.9	22.1	6.1	14.3	12.4	11.1	98.1	N/A[1]	203.7
40	77.2	16.5	7.4	8.4	14.4	5.4	16.5	9.4	90.9	N/A[1]	146.9

Figure 2. Heat map of SEM values (g) for the differences in BW across BW trajectories from 2 to 40 wk of age, relative to Figure 1. Trajectories varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW. Red, yellow, and blue colors indicate low, intermediate, and high values, respectively. [1]An SEM value was not applicable where there was 1 bird remaining in the BW trajectory group.

Table 2. Regression analysis of the effect of BW at photostimulation on the daily number of station visits for all birds[1] or feed-restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed-restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	Visits	—Visits/kg—				Visits	—Visits/kg—			
2–5	51.0	−8.6	4.14	0.121	0.047	78.6	−19.6	22.32	0.030	0.39
6–9	120.4	−23.2	5.57	0.358	<0.001	63.2	−0.3	29.48	0.000	0.99
10–13	130.3	−25.6	4.60	0.499	<0.001	64.9	0.6	23.58	0.000	0.98
14–17	126.6	−25.7	4.66	0.496	<0.001	120.1	−23.0	24.83	0.033	0.36
18–21	136.2	−27.9	5.06	0.495	<0.001	131.6	−25.9	26.55	0.037	0.34
22–25	120.2	−23.3	3.98	0.534	<0.001	167.1	−41.8	18.77	0.166	0.035
26–29	67.6	−11.1	4.26	0.185	0.014	131.7	−36.5	20.51	0.112	0.088
30–33	49.6	−7.1	4.31	0.082	0.11	146.1	−45.3	19.42	0.179	0.028
34–37	36.8	−5.0	3.44	0.069	0.11	102.2	−30.9	16.67	0.130	0.076
38–41	45.8	−8.1	3.36	0.171	0.023	129.9	−41.6	16.60	0.214	0.020

[1]BW trajectories that varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2]Excluded unrestricted birds.

hypothesized that each individual bird might have a unique optimal BW on sexual maturity, and the current recommended BW targets and concurrent growth trajectories do not sufficiently meet the optimal BW threshold of all individual birds. These differences in individual BW are detectable when using PF system due to precise feeding and BW management in accordance with a preassigned BW trajectory, which was demonstrated in the present study as there was large variation of BW among individual birds during lay within various BW trajectories (Figure 2).

Daily Station Visits

All Birds (Feed Restricted and Unrestricted) As BW increased among all birds, motivation to seek for feed decreased during the rearing period and toward the end of lay. The number of daily station visits decreased significantly from 2 to 29 wk of age over a range of 8.6 to 27.9 visits per kilogram increase in BW, and from 38 to 41 wk of age by 8.1 visits per kilogram increase in BW (Table 2). There was no effect of BW on the number of daily station visits from 30 to 37 wk of age (Table 2).

Feed-Restricted Birds (Excluding Unrestricted) By contrast, motivation to search for feed decreased as BW increased among feed restricted birds during the laying period. The number of daily station visits significantly decreased by 41.8, 45.3, and 41.6 visits per kilogram increase in BW from week 22 to 25, 30 to 33, and 38 to 41, respectively (Table 2). The number of station visits of the feed-restricted birds tended to decrease by 36.5 and 30.9 visits for every kilogram increase of BW during week 26 to 29 ($P = 0.088$) and 34 to 37 ($P = 0.076$), respectively (Table 2). However, there was no effect of BW at photostimulation on the number of daily station visits during the rearing period. (Table 2).

When unrestricted birds were included in the analysis, there was a strong reduction in feed-seeking behavior during rearing and toward the end of lay as BW increased. This was expected as the unrestricted birds were not limited to a maximum BW and were able to consume more feed relative to the feed-restricted birds during the rearing period, which in turn might have

Table 3. Regression analysis of the effect of BW at photostimulation on the number of meals for all birds[1] or feed-restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed-restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	Meals	—Meals/kg—				Meals	—Meals/kg—			
2–5	5.4	1.8	0.62	0.216	0.006	−3.7	5.5	2.87	0.126	0.069
6–9	−7.9	5.8	0.60	0.747	<0.001	8.0	−0.5	2.18	0.002	0.81
10–13	−8.4	5.8	0.27	0.935	<0.001	0.2	2.4	0.82	0.248	0.008
14–17	−5.3	4.4	0.31	0.864	<0.001	2.3	1.4	0.64	0.151	0.045
18–21	−2.2	3.8	0.34	0.793	<0.001	2.2	2.1	1.05	0.132	0.062
22–25	−2.6	4.7	0.69	0.611	<0.001	−9.1	7.4	1.82	0.398	<0.001
26–29	7.2	3.1	1.11	0.201	0.010	−10.6	10.2	3.68	0.236	0.010
30–33	−0.3	4.7	1.37	0.284	0.002	0.8	4.4	3.02	0.079	0.15
34–37	1.8	3.2	1.17	0.209	0.011	8.9	0.5	2.27	0.002	0.83
38–41	6.9	1.2	0.77	0.074	0.15	12.2	−0.9	3.31	0.003	0.78

[1]BW trajectories that varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2]Excluded unrestricted birds.

Table 4. Regression analysis of the effect of BW at photostimulation on ADFI for all birds[1] or feed-restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed-restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	——g——	—g/kg—				——g——	——g/kg——			
2–5	25.5	5.5	2.11	0.181	0.013	−11.1	20.1	10.44	0.129	0.066
6–9	−25.9	35.3	3.96	0.719	<0.001	68.2	−2.1	19.36	0.000	0.91
10–13	−42.7	41.5	1.95	0.936	<0.001	−19.9	32.3	8.55	0.364	<0.001
14–17	−20.1	32.4	2.17	0.877	<0.001	9.3	20.5	3.55	0.572	<0.001
18–21	12.7	26.8	2.22	0.825	<0.001	7.1	29.3	6.23	0.470	<0.001
22–25	46.7	23.4	3.28	0.630	<0.001	−67.6	69.1	9.76	0.667	<0.001
26–29	128.2	9.8	3.76	0.184	0.014	−4.1	62.7	8.11	0.705	<0.001
30–33	143.9	10.6	3.27	0.260	0.003	32.7	55.1	10.18	0.540	<0.001
34–37	128.0	7.7	3.65	0.137	0.044	42.8	41.9	10.65	0.402	<0.001
38–41	117.0	10.1	2.91	0.300	0.002	58.4	33.8	10.78	0.299	0.005

[1]BW trajectories that varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2]Excluded unrestricted birds.

induced satiety and reduced motivation to search for feed. However, this was not observed among the feed-restricted birds only. Thus, breeders reared to achieve a BW up to 22.5% above the recommended target were feed restricted to a point that did not appear to reduce hunger, which increased motivation to seek for feed. Inconsistent with the hypothesis, BW increased up to 22.5% above the recommended BW target (lesser degree of feed restriction) did not appear to station visit frequency and therefor reduce hunger during the rearing period.

Meal Frequency and Average Daily Feed Intake

In general, the number of meals and ADFI increased as BW increased.

All Birds (Feed Restricted and Unrestricted) The number of meals consumed by all birds increased over a range of 1.8 to 5.8 meals per kilogram increase in BW from 2 to 37 wk of age (Table 3). From 2 to 27 wk of age, the range of ADFI increased from 5.5 to 41.5 g per kilogram increase in BW (Table 4).

Feed-Restricted Birds (Excluding Unrestricted) Within feed-restricted birds, the number of meals consumed increased significantly by 2.4, 1.4, 2.1, and 10.2 meals per kilogram increase in BW from 10 to 13, 14 to 17, 22 to 25, and 26 to 29 wk of age, respectively. In addition, the number of meals consumed by feed-restricted birds tended to increase during week 2 to 5 ($P = 0.069$) and 18 to 21 ($P = 0.062$). Average daily feed intake increased per kilogram increase in BW throughout the rearing and laying periods, with the exception of week 6 to 9 (Table 4).

During rearing, nutrients are allocated toward structural muscle and skeletal development (Kwakkel et al., 1993, 1995). Just before sexual maturation, there is a shift in nutrient allocation toward reproductive organ development in preparation of lay (Hadinia et al., 2019). Thus, the number of meals and nutrient intake of all (feed restricted and unrestricted) and feed-restricted (excluding unrestricted) broiler breeders in the present study reflected increased BW targets to support prepubertal growth during rearing, pubertal growth toward the end of rearing and egg production throughout the laying phase.

Table 5. Regression analysis of the effect of BW at photostimulation on meal size for all birds[1] or feed-restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed-restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	——g——	—g/kg—				——g——	—g/kg—			
2–5	5.6	−0.4	0.29	0.048	0.218	6.3	−0.6	1.48	0.007	0.668
6–9	12.1	−1.0	0.47	0.126	0.042	10.1	−0.2	2.43	0.000	0.939
10–13	12.0	−0.8	0.33	0.157	0.023	6.6	1.3	1.59	0.027	0.409
14–17	13.2	−1.0	0.33	0.206	0.008	8.2	1.1	1.52	0.019	0.491
18–21	13.5	−0.9	0.28	0.264	0.002	8.5	1.1	1.32	0.026	0.422
22–25	15.0	−1.4	0.37	0.321	<0.001	12.7	−0.5	1.68	0.003	0.780
26–29	12.4	−0.6	0.55	0.042	0.263	15.7	−1.9	2.41	0.025	0.428
30–33	18.8	−1.4	0.83	0.090	0.096	16.9	−0.7	3.52	0.002	0.838
34–37	16.7	−0.6	0.80	0.017	0.486	10.3	1.9	3.21	0.015	0.554
38–41	15.7	−0.2	0.81	0.001	0.854	9.6	2.2	3.68	0.016	0.550

[1]BW trajectories that varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2]Excluded unrestricted birds.

Table 6. Regression analysis of the effect of BW at photostimulation on egg weight (EW) for all birds[1] or feed-restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed-restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	—g—	—g/kg—				—g—	—g/kg—			
18–21	61.1	−3.9	8.00	0.105	0.68	-	-	-	-	-
22–25	48.6	0.7	0.33	0.022	0.031	42.6	3.1	1.52	0.031	0.044
26–29	52.2	1.1	0.26	0.021	<0.001	48.7	2.5	0.93	0.010	0.008
30–33	57.1	0.7	0.28	0.010	0.011	54.8	1.7	1.07	0.004	0.12
34–37	60.5	0.5	0.22	0.006	0.033	60.3	0.5	0.89	0.001	0.54
38–41	61.7	0.6	0.22	0.011	0.006	61.1	0.9	0.93	0.001	0.35

[1]BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2]Excluded unrestricted birds.

Meal Size

From 6 to 25 wk of age, meal size of all birds (feed restricted and unrestricted) decreased significantly over a range of 0.8 to 1.4 g per kilogram increase in BW (Table 5). By contrast, there was no effect of BW on meal size of feed-restricted (excluding unrestricted) birds (Table 5). Including unrestricted birds in the analysis reduced meal size. This suggests unrestricted birds reached a point of satiety during rearing and leading up to peak egg production because they received feed on every station visit, which in turn decreased motivation to consume large meals. In contrast with the presented hypothesis, increased BW among feed-restricted birds (lesser degree of feed restriction) did not reduce hunger and motivation to eat during the rearing period.

Egg Weight

All Birds (Feed Restricted and Unrestricted) Egg weight increased with BW. Specifically, EW increased by 0.7, 1.1, 0.7, 0.5, and 0.6 g per kilogram increase in BW from 22 to 25, 26 to 29, 30 to 33, 34 to 37, and 38 to 41 wk of age, respectively (Table 6). Egg weight was not affected by BW during week 18 to 21 because 2 unrestricted hens that were similar in BW came into lay during that period (Table 6).

Feed-Restricted Birds (Excluding Unrestricted) Similarly, EW increased as BW increased during the beginning of lay within the feed-restricted birds only. Egg weight increased by 3.1 and 2.5 g per kilogram increase in BW from 22 to 25 and 26 to 29 wk of age, respectively (Table 6). There was no effect of BW at photostimulation on EW from 30 to 41 wk of age (Table 6).

Egg weight is known to increase with BW over time (McDaniel et al., 1981). In the present study, EW of feed-restricted birds increased up to 29 wk of age which coincided with the time BW began to plateau. By contrast, when the unrestricted birds were included with the feed-restricted birds in the analysis, EW increased with BW throughout the entire lay period. Literature has reported that heavy BW hens produce heavier eggs before, after, and during peak production compared with medium and light BW hens (Sun and Coon, 2005). Moreover, previous studies that used the PF system reported EW increased with age (van der Klein et al., 2018a, b). In the present study, EW may have been similar across feed-restricted birds because of frequent meals that provided a sufficient amount of nutrients in small portions throughout the day.

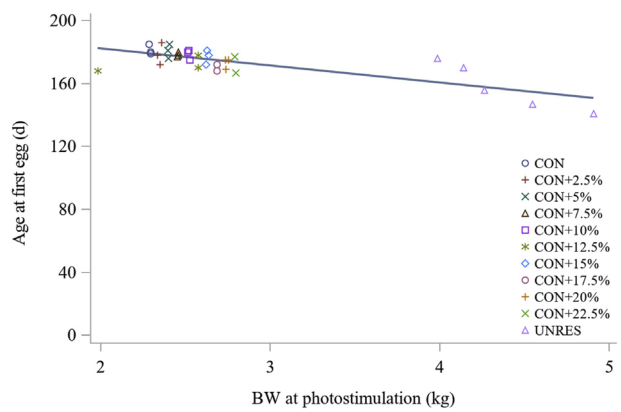

Figure 3. Regression analysis of the effect of BW at photostimulation on age at first egg ($R^2 = 0.616$, $P < 0.001$). Body weight trajectories that varied in prepubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW.

Age at First Egg

All Birds (Feed Restricted and Unrestricted) Sexual maturity advanced as BW increased. Age at first egg decreased by 10.8 d (±1.54 d) per kilogram increase in BW ($P < 0.001$, Figure 3).

Feed-Restricted Birds (Excluding Unrestricted) Sexual maturity was not advanced as BW at photostimulation increased among feed-restricted birds. Age at first egg tended to decrease by 8.8 d (±5.13 d) per kilogram increase in BW ($R^2 = 0.103$, $P = 0.10$).

Two unrestricted hens came into lay before photostimulation on day 141 and 147, during week 20 and 21, respectively. The remaining unrestricted and feed-restricted hens came into lay from day 170 to 181, during week 24 and 25. Body weight above the recommended targets advanced sexual maturity, which is consistent with Heck et al. (2004) who reported ad libitum-fed broiler breeders came into lay at 20 wk of age before photostimulation. Renema et al. (1999) photostimulated broiler breeder pullets at 21 wk of age, and reported ad libitum pullets reaching sexual maturity 13.6 d earlier than feed-restricted pullets. By contrast, Robinson et al. (1991) reported that when photostimulated at 22 wk of age, ad libitum broiler breeders reached sexual maturity on day 180.5, which was similar to feed-restricted broiler breeders (day 183.3). Notably, one of the CON+12.5% birds weighed 1,981 g at photostimulation which was 593 g less than the average BW of the other birds in the CON+12.5% group. Moreover, the light CON+12.5% bird reached sexual maturity 2 and 10 d before the birds that followed the same BW trajectory, and around the same time as birds in the CON+22.5%, CON+20%, and CON+17.5% groups (Figure 3). This suggests that each bird has a unique optimum BW trajectory and BW threshold to reach sexual maturity.

Egg Production

There was no effect of BW trajectory on cumulative egg production of all birds (feed restricted and unrestricted; data not shown; $R^2 = 0.074$, $P = 0.13$) or within feed-restricted (excluding unrestricted) birds (data not shown; $R^2 = 0.011$, $P = 0.60$). On average throughout the laying period, unrestricted hens produced 104.4 eggs/hen and CON hens produced 98.7 eggs/hen. Egg production has been reported to decrease as BW increases (Yu et al., 1992; Heck et al., 2004). Feed-restricted broiler breeders produced 29.7% more eggs during the lay period than ad libitum hens (Robinson et al., 1991); however, there have been genetic changes to modern breeder birds because this research was reported. High BW hens produced 129.4 eggs/hen from 32 to 55 wk of age, which was 1.39 times more than standard BW hens (van der Klein et al., 2018b). The authors suggest that increased egg production of high BW hens may have been due to strict control of meal size and increased meal frequency through the PF system in combination with recent genetic change to modern breeder lines. Similarly in the present study, controlled feed allocation and increased meal frequency through the PF system may have altered fat deposition and reduced variation in egg production across all birds. Thus, there is potential to increase BW 22.5% above the recommended BW target without affecting egg production of precision-fed hens.

Animal research is evolving to maximize the value of research while reducing the number of animals required to conduct that research. The present study used an innovative experimental design with the specific goal of reducing the number of birds required to conduct the experiment. This randomized controlled study with a total of 36 birds was designed for regression analysis. Although some ANOVA was conducted, it was not the primary focus. The current design insured against sample size problems such as mortality in specific groups within the design. Thus, the loss of birds from a single BW trajectory had minimal impact on the overall regression analysis.

In conclusion, station visit frequency was a suitable indicator of feed-seeking motivation that could be used to describe hunger. Station visit frequency of feed-restricted (excluding unrestricted) birds decreased during the laying period as BW increased; however, this was not observed during the rearing period. By contrast, when unrestricted birds were included in the analysis, station visits frequency decreased during rearing as BW increased. This means that hunger and motivation to seek for feed was not reduced of birds fed to achieve a BW that ranged of 2.5 to 22.5% above the recommended BW target during rearing, whereas unrestricted birds that were given feed on every station visit reached a point of satiety which decreased motivation to seek for feed. Meal frequency, ADFI, and meal size more closely reflected an increase in nutrient intake to support growth, maintenance, and reproductive requirements. Age at first egg and cumulative egg production were not significantly affected by increased BW at photostimulation; however, 2 unrestricted hens came into lay before photostimulation at 20 and 21 wk of age. Thus, there is potential to increase broiler breeder BW targets and reduce the degree of feed restriction without reducing reproductive performance. The BW results of the present study indicated that optimal BW trajectories may strongly depend on the individual broiler breeder. Larger future studies are recommended to confirm the effects of increased BW within BW trajectories, and whether genetic potential may influence hunger and feed and feed-seeking motivation.

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DISCLOSURES

The authors declare no conflicts of interest.

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