Spanish Journal of Agricultural Research
17 (3), e0606, 10 pages (2019)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2019173-14973
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

RESEARCH ARTICLE

OPEN ACCESS

A sinusoidal equation as alternative to conventional growth functions to describe the evolution of growth in quail

Hassan Darmani-Kuhi (Darmani Kuhi, H)[1], James France (France, J)[2], Secundino López (López, S)[3] and Navid Ghavi Hossein-Zadeh (Ghavi Hossein-Zadeh, N)[1]

[1]University of Guilan, Faculty of Agricultural Sciences, Dept. Animal Science, Rasht, 41996-13776, Iran. [2]University of Guelph, Centre for Nutrition Modelling, Dept. Animal Biosciences, Guelph ON, N1G 2W1, Canada. [3]Instituto de Ganadería de Montaña, CSIC-Universidad de León, Dept. Producción Animal, Universidad de León, 24007 León, Spain.

Abstract

Aim of study: The aim of the present study was to introduce a sinusoidal equation into poultry science by applying it to temporal growth data from quail.

Material and methods: To examine the performance of the sinusoidal equation in describing the growth patterns of quail, four conventional growth functions (Gompertz, logistic, López and Richards) were used as reference in this study. Comparison of models was carried out by analysing model behaviour when fitting the curves using nonlinear regression and assessing statistical performance. Maximum log-likelihood estimation, mean squared error, Akaike and Bayesian information criteria were used to evaluate the general goodness-of-fit of each model to the different data profiles.

Main results: The selected sinusoidal equation precisely describes the growth dynamics of quail. Comparison of the growth functions in terms of the goodness-of-fit criteria revealed that the sinusoidal equation was one of the most appropriate functions to describe the age-related changes of bodyweight in quail.

Research highlights: To the best of our knowledge there are no studies available on the use of sinusoidal equations to describe the evolution of growth in quail. The sinusoidal equation used in this study represents a suitable alternative to conventional growth functions to describe the growth curves for a range of strains/lines of male and female Japanese quail.

Additional keywords: modelling; trigonometric equation; *Coturnix japonica*; poultry; nonlinear regression.

Abbreviations used: AIC (Akaike information criterion); BIC (Bayesian information criterion); MLE (maximum log-likelihood estimation); MSE (mean squared error).

Authors' contributions: HDK and NGHZ collected and analysed the data and wrote the initial draft of the manuscript. JF helped develop the functional form of the sinusoidal. SL oversaw the fitting of nonlinear functions to the growth curves. Both JF and SL edited and contributed to writing the final version of the manuscript. All authors read and approved the final manuscript.

Citation: Darmani-Kuhi, H; France, J; López, S; Ghavi Hossein-Zadeh, N (2019). A sinusoidal equation as alternative to conventional growth functions to describe the evolution of growth in quail. Spanish Journal of Agricultural Research, Volume 17, Issue 3, e0606. https://doi.org/10.5424/sjar/2019173-14973

Received: 06 Apr 2019. **Accepted:** 04 Oct 2019.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Hassan Darmani Kuhi: darmani_22000@yahoo.com; h.darmani@guilan.ac.ir

Introduction

Growth is a fundamental property of biological systems and can be defined as an increase in body size with time. Understanding of the economic importance of various traits, such as body weight, weight gain, rate of maturity, and age and weight at which maximal growth occurs, has led researchers to carry out detailed studies targeting weight-age relationships (Ersoy *et al.*, 2006). For this purpose, different mathematical growth functions have been applied and developed (Gompertz, 1825; von Bertalanffy, 1957; Richards, 1959; France *et al.*, 1996; López *et al.*, 2000). These functions can be used to determine the efficiency of nutrient utilization, which is the derivative of the relationship between body weight and dietary nutrient intake, and as response functions to predict daily energy, protein and amino acids requirements for maintenance and growth and efficiency of utilisation (France *et al.*, 1996; Darmani Kuhi *et al.*, 2009; 2011; 2012).

The general shape of the growth curve is a sigmoid form and is usually modelled using classic growth functions, which summarise the information into a few biologically interpretable parameters (Darmani Kuhi *et* *al.*, 2010; Teleken *et al.*, 2017). Modelling of animal growth has been a topic of increasing interest over the past seventy-five years. There are many studies aimed at evaluating animal growth models but, due to the nebulous nature of model development, modellers seem more willing to re-develop and adapt existing models for their own requirements than to develop new ones.

In the field of poultry science, growth modelling has been applied to the major avian species, mainly broilers and turkeys (Anthony *et al.*, 1991; Knizetova *et al.*, 1991; Maruyama *et al.*, 1998; Porter *et al.*, 2010). Much less attention has been paid to other poultry species, even though their farming is of increasing interest nowadays (Minvielle, 2004). In particular, Japanese quail (*Coturnix japonica*) is a species with many positive biological characteristics, such as small size, fast growth rate, early sexual maturity, short generation interval or less feed requirements and less susceptibility to some avian diseases than other poultry species (Vali, 2008). Laying performance (laying rate, incubation period) is also rather prospective, conferring some advantages to the farming of this species. However, there is scarcity of information on the growth traits of quail and on their modelling using non-linear equations, aspects that would result in more efficient farming programmes. Therefore, it is valuable to gain insights and knowledge on the factors influencing the productive performance of this species. The objectives of the present study were to introduce a sinusoidal equation into poultry science, to apply it to temporal growth data from quail, and to compare its fitting performance with four standard growth functions, *viz*. the Gompertz, logistic, López and Richards.

Material and methods

Data set

Twelve time course profiles representing the growth curves of six male and six female quail were obtained from two publications (Balcıoğlu *et al.*, 2005; Sezer & Tarhan, 2005), and used in the study. The growth profiles reported by Sezer & Tarhan (2005) each contained 17 data-points, with weights given at 3-day intervals from hatching to Day 48 of age. The curves described by Balcıoğlu *et al.* (2005) had weekly weight recordings from hatching to Week 8, giving 9 data-points in each profile.

Sinusoidal model

The functional form of the sinusoidal equation proposed as a growth function to describe the relationship between bodyweight and age in male and female quail is:

$$w = w_f \left[\sin\left(\frac{2\pi t}{b} + \theta \right) \right]^2$$

where w is body weight (g) at age t (d), w_f is final weight, and the parameters b and θ are real numbers. The above equation provides a versatile function that can describe a range of predominantly sigmoidal behaviour. Initial body weight (w_0) and point of inflexion (w^*, t^*) when describing sigmoidal patterns (Fig. 1) are given by

$$w_0 = w_f \left[\sin(\theta) \right]^2$$

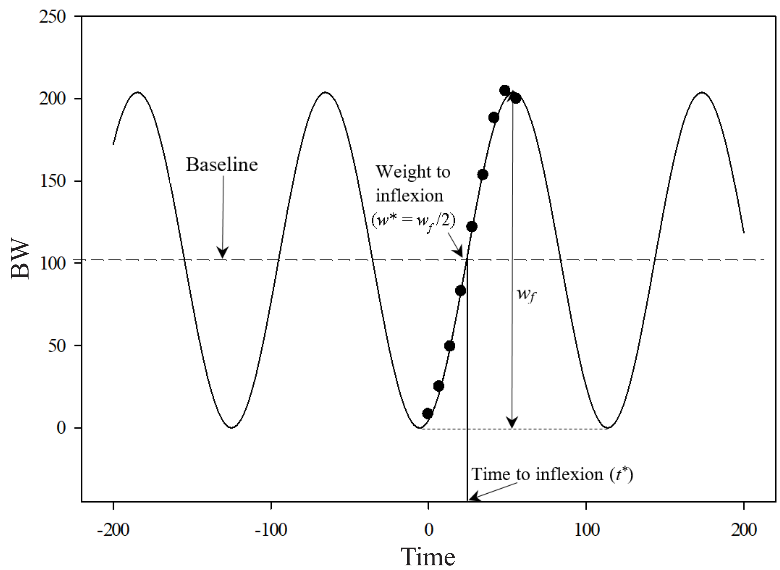

Figure 1. Graph of the sinusoidal equation showing its fit to the male data of the High line. BW is body weight (g), Time is age (d).

$$w^* = \frac{w_f}{2}$$

$$t^* = \frac{b}{2\pi}\left[\left(N + \frac{1}{4}\right)\pi - \theta\right]$$

where b and θ are positive. The integer N is given by

$$\left\lfloor \frac{\theta}{\pi} + \frac{3}{4} \right\rfloor$$

where $\lfloor x \rfloor$ denotes the greatest integer less than or equal to x.

To examine the performance of the sinusoidal equation in describing the growth patterns of quail, four conventional growth functions, *viz*. Gompertz, logistic, López and Richards (Thornley & France, 2007), were used as reference in this study (Table 1). These functions are the most common equations used to describe somatic growth curves in animals. The five non-linear functions were fitted to the growth curves using the non-linear regression procedure of SigmaPlot 12.0 (Systat Software, Inc., San Jose, CA, USA). The Marquardt-Levenberg algorithm was used for iterative estimation of the parameters of each model. Initial parameter values had to be provided to commence the iterative process. Final estimates were not affected by the initial values adopted.

Statistical analysis

Comparison of models was carried out by analysing model behaviour when fitting the curves using nonlinear regression and assessing statistical performance. Maximum log-likelihood estimation (MLE), mean squared error (MSE), Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to evaluate the general goodness-of-fit of each model to the different data profiles.

Results

Fitting behaviour of the five equations when applied to growth curves for quail of a high line (as an example) is illustrated in Fig. 2 (males) and Fig. 3 (females). The parameter estimates are given in Tables 2 and 3 for male and female quail, respectively.

As seen in Tables 2 and 3, final weight, and age and weight at point of inflexion were numerically different between males and females. With all quail strains and all the growth functions, point of inflexion occurred at an earlier age in males than in females, and both weight at inflexion and asymptotic or final weight were smaller in males than in females.

There were also relevant differences among models in the growth parameters that are common to all the models (w_0, w_f, t^*, w^*). For female quail (Table 3), the overall estimates of final weight from the sinusoidal and logistic equations were lower than those from the other equations. Fitting the growth equations to both male and female data profiles mostly led to the lowest MSE, AIC, BIC and highest MLE values with the sinusoidal and Richards equations, indicating that the data are better described by these equations than by the others (Table 4). Comparing the sinusoidal with the Richards,

Table 1. Functional form of conventional growth equations used in this study.

Equation	Functional form[1]	Time at point of inflexion (t^*)	Weight at point of inflexion (w^*)
Gompertz	$w = w_0 \exp\left[\ln\left(\frac{w_f}{w_0}\right)\left(1 - \mathrm{e}^{-ct}\right)\right]$	$\frac{1}{c}\ln\left[\ln\left(\frac{w_f}{w_0}\right)\right]$	$\frac{w_f}{\mathrm{e}}$
Logistic	$w = \frac{w_0 w_f}{\left[w_0 + \left(w_f - w_0\right)\mathrm{e}^{-ct}\right]}$	$\frac{1}{c}\ln\left(\frac{w_f - w_0}{w_0}\right)$	$\frac{w_f}{2}$
Richards	$w = \frac{w_0 w_f}{\left[w_0^n + \left(w_f^n - w_0^n\right)\mathrm{e}^{-ct}\right]^{1/n}}$	$\frac{1}{c}\ln\left(\frac{w_f^n - w_0^n}{n w_0^n}\right)$	$\frac{w_f}{(n+1)^{1/n}}$
López	$w = \frac{w_0 k^n + w_f t^n}{k^n + t^n}$	$k\left[\frac{n-1}{n+1}\right]^{1/n}$	$\frac{(n+1)w_0 + (n-1)w_f}{2n}$

[1] w is body weight; t is time; w_f is final weight, w_0 is initial weight, and c, k and n are parameters that define the shape of the growth profile.

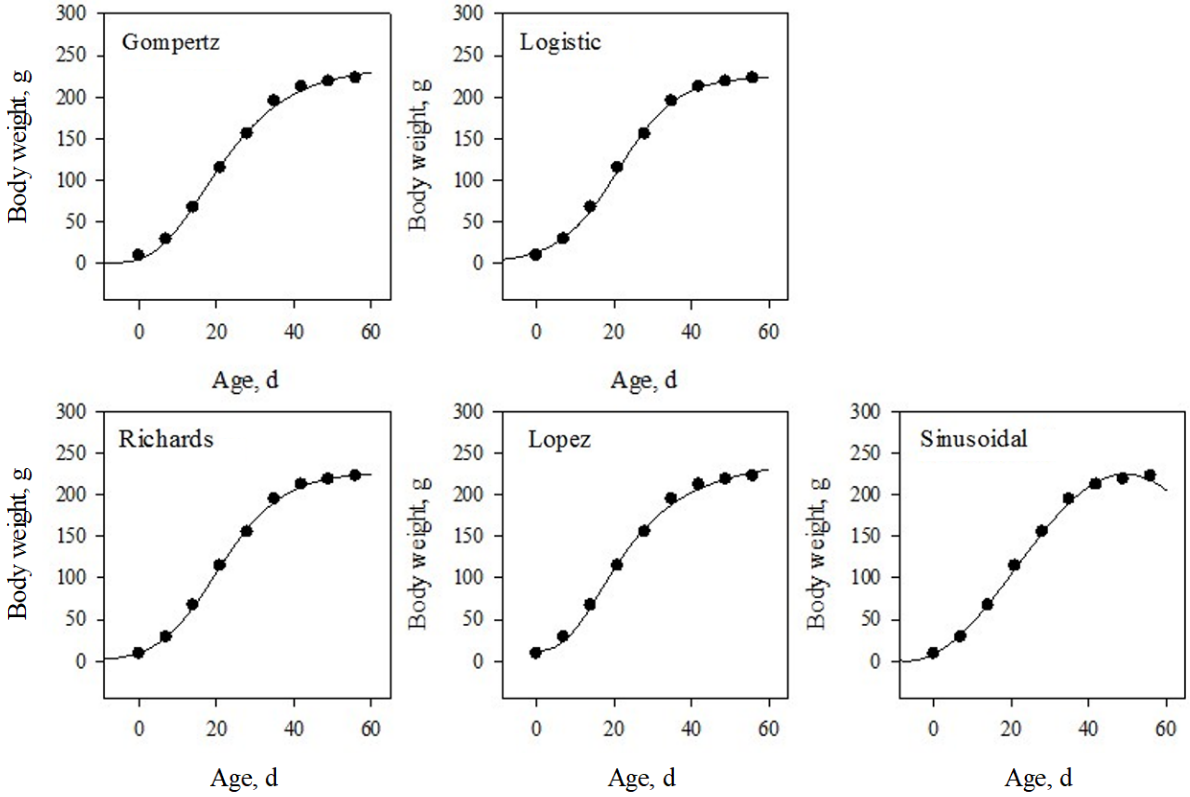

Figure 2. Plots of body weight (g) against age (d) showing the fit of different growth functions to the data for male High line quail.

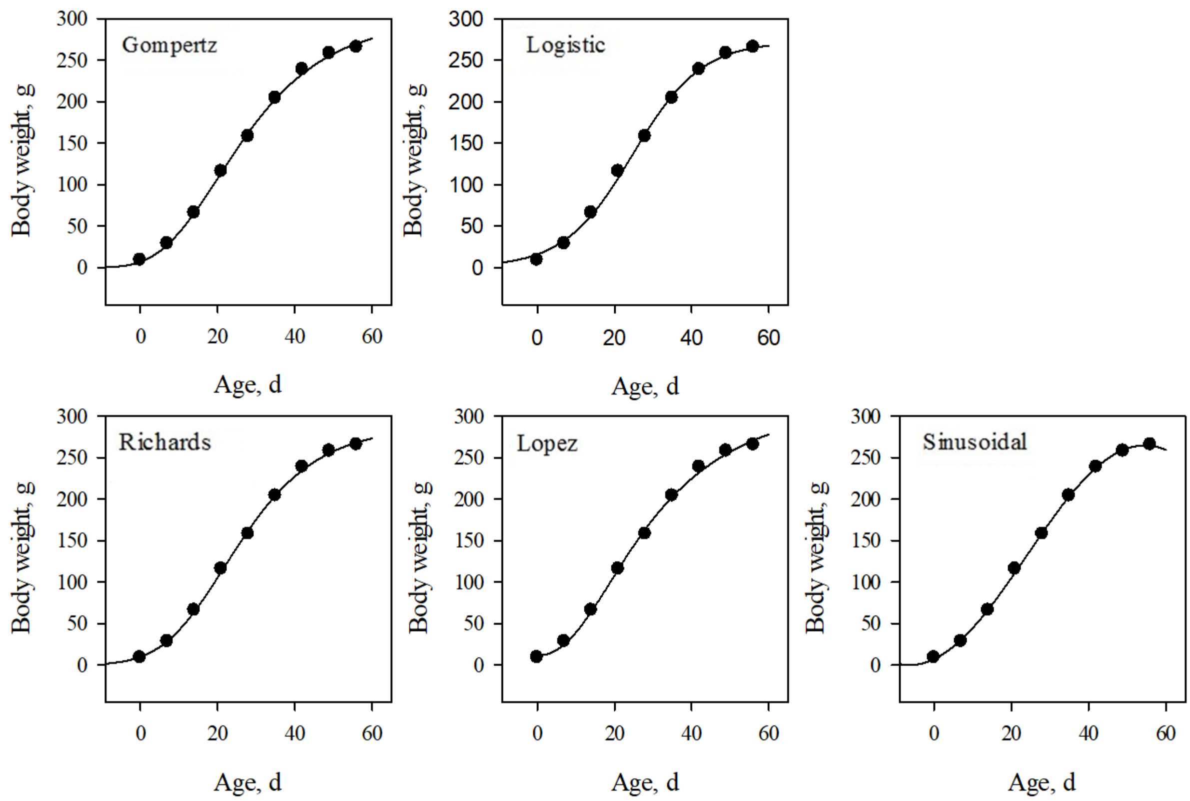

Figure 3. Plots of body weight (g) against age (d) showing the fit of different growth functions to the data for female High line quail.

Table 2. Parameters for the male data profiles estimated using the different growth equations.

Parameters[1]	Gompertz	Logistic	Richards	López	Sinusoidal
		Control line (N = 323), Balcıoğlu *et al.* (2005)			
w_0	4.47	10.62	11.28	13.36	5.91
w_f	186.1	175.3	174.5	192.8	173.3
c	0.0755	0.1250	0.1326	-	-
n	-	-	1.153	2.69	-
k	-	-	-	24.26	-
b	-	-	-	-	226.8
θ	-	-	-	-	3.327
t^*	17.43	21.94	22.41	18.15	21.65
w^*	67.00	87.65	89.71	69.74	86.65
R^2	99.33	99.82	99.80	99.15	99.91
		High line (N = 180), Balcıoğlu *et al.* (2005)			
w_0	4.86	13.27	10.19	12.53	8.39
w_f	236.2	224.5	228.1	250.6	225.0
c	0.0813	0.1314	0.1093	-	-
n	-	-	0.5616	2.50	-
k	-	-	-	23.07	-
b	-	-	-	-	225.6
θ	-	-	-	-	3.336
t^*	16.68	21.07	19.50	16.46	21.22
w^*	85.02	112.27	103.17	84.03	112.51
R^2	99.73	99.84	99.88	99.57	99.71
		Low line (N = 138), Balcıoğlu *et al.* (2005)			
w_0	3.45	9.26	8.53	11.09	5.84
w_f	168.5	159.7	160.6	174.9	159.8
c	0.0803	0.1311	0.1227	-	-
n	-	-	0.8367	2.71	-
k	-	-	-	23.25	-
b	-	-	-	-	226.2
θ	-	-	-	-	3.334
t^*	16.91	21.26	20.74	17.44	21.35
w^*	60.66	79.85	77.65	62.72	79.89
R^2	99.61	99.93	99.93	99.57	99.67
		Brown (N = 24), Sezer & Tarhan (2005)			
w_0	4.28	10.19	8.30	11.62	4.43
w_f	194.7	178.0	182.2	207.1	172.6
c	0.0778	0.1341	0.1125	-	-
n	-	-	0.6151	2.49	-
k	-	-	-	24.12	-
b	-	-	-	-	204.0
θ	-	-	-	-	3.302
t^*	17.23	20.89	19.76	17.14	20.28
w^*	70.08	89.00	83.56	70.13	86.32
R^2	99.82	99.93	99.96	99.84	99.91

Table 2. Continued.

Parameters[1]	Gompertz	Logistic	Richards	López	Sinusoidal
			White (N = 23), Sezer & Tarhan (2005)		
w_0	4.84	11.20	7.53	11.15	5.58
w_f	203.7	186.6	195.1	221.1	182.0
c	0.0781	0.1339	0.0980	-	-
n	-	-	0.3549	2.36	-
k	-	-	-	24.08	-
b	-	-	-	-	207.3
θ	-	-	-	-	3.318
t^*	16.88	20.55	20.96	16.41	20.11
w^*	73.33	93.30	82.90	71.64	90.99
R^2	99.90	99.84	99.95	99.92	99.81
			Wild (N = 24), Sezer & Tarhan (2005)		
w_0	5.39	11.58	11.61	8.46	5.93
w_f	200.2	183.1	190.3	218.3	177.6
c	0.0763	0.1311	0.0998	-	-
n	-	-	0.4254	2.31	-
k	-	-	-	24.38	-
b	-	-	-	-	208.6
θ	-	-	-	-	3.325
t^*	16.83	20.55	18.74	16.33	19.98
w^*	72.05	91.53	82.70	70.24	88.82
R^2	99.88	99.87	99.95	99.87	99.91

[1] w_f is final weight, w_0 is initial weight, t^* is time to inflexion, w^* is weight at inflexion, and c, n, k, b and θ are parameters. R^2 = percentage of variance explained for by the model. N = number of birds for each line.

Table 3. Parameters for the female data profiles estimated using the different growth equations.

Parameters[1]	Gompertz	Logistic	Richards	López	Sinusoidal
			Control line (N = 296), Balcıoğlu *et al.* (2005)		
w_0	5.23	11.93	11.82	13.25	4.52
w_f	232.2	212.0	212.3	247.2	203.7
c	0.0642	0.1118	0.1107	-	-
n	-	-	0.9775	2.48	-
k	-	-	-	29.1	-
b					238.6
θ					3.291
t^*	20.77	25.21	25.14	20.61	24.15
w^*	83.6	106.0	105.7	83.1	101.9
R^2	99.26	99.60	99.52	99.02	99.76
			High line (N = 172), Balcıoğlu *et al.* (2005)		
w_0	6.88	15.98	9.89	11.67	7.27
w_f	297.1	272.6	287.2	335.2	264.6
c	0.0655	0.1123	0.0781	-	-
n	-	-	0.2691	2.18	-
k	-	-	-	29.6	-
b					243.8
θ					3.308
t^*	20.25	24.72	21.78	18.80	24.01
w^*	107.0	136.3	118.5	99.3	132.3
R^2	99.86	99.73	99.88	99.72	99.95

Table 3. Continued.

Parameters[1]	Gompertz	Logistic	Richards	López	Sinusoidal
		Low line (N = 134), Balcıoğlu *et al.* (2005)			
w_0	4.58	10.908	8.18	10.46	4.65
w_f	212.2	193.9	200.3	230.0	188.0
c	0.0651	0.1127	0.0888	-	-
n	-	-	0.4975	2.38	-
k	-	-	-	29.1	-
b					243.3
θ					3.300
t^*	20.67	25.04	23.21	20.04	24.29
w^*	76.4	96.9	88.9	74.2	94.0
R^2	99.8	99.85	99.91	99.74	99.92
		Brown (N = 30), Sezer & Tarhan (2005)			
w_0	6.11	12.13	7.44	9.77	4.13
w_f	275.7	229.8	261.6	337.3	222.8
c	0.0571	0.1110	0.0668	-	-
n	-	-	0.1761	2.05	-
k	-	-	-	37.0	-
b					244.3
θ					3.278
t^*	23.41	26.00	23.94	21.94	25.23
w^*	99.3	114.9	104.1	93.5	111.4
R^2	99.85	99.72	99.85	99.82	99.87
		White (N = 30), Sezer & Tarhan (2005)			
w_0	6.02	12.61	7.91	10.73	4.73
w_f	260.0	226.0	247.3	302.3	217.3
c	0.0640	0.1181	0.0767	-	-
n	-	-	0.2321	2.14	-
k	-	-	-	31.3	-
b					227.3
θ					3.290
t^*	20.73	23.95	23.69	19.46	23.06
w^*	93.6	113.0	100.6	88.3	108.6
R^2	99.89	99.77	99.90	99.86	99.91
		Wild (N = 29), Sezer & Tarhan (2005)			
w_0	7.11	14.17	8.64	11.05	6.10
w_f	262.7	231.4	253.7	311.7	221.5
c	0.0653	0.1179	0.0745	-	-
n	-	-	0.1722	2.04	-
k	-	-	-	30.7	-
b					225.0
θ					3.308
t^*	19.67	23.14	20.45	18.14	22.16
w^*	94.6	115.7	100.8	87.6	110.7
R^2	98.84	99.69	99.84	99.78	99.90

[1] w_f is final weight, w_0 is initial weight, t^* is time to inflexion, w^* is weight at inflexion, and c, n, k, b and θ are parameters. R^2 = percentage of variance explained for by the model. N = number of birds for each line.

Table 4. Comparison between the general goodness-of-fit of the models for the male and female data profiles based on various statistical criteria[1].

Statistical criterion[2]	Sinusoidal *vs.* Gompertz	Sinusoidal *vs.* Logistic	Sinusoidal *vs.* López	Sinusoidal *vs.* Richards
		Male		
MLE	66.7	66.7	83.3	66.7
MSE	66.7	66.7	83.3	66.7
AIC	66.7	66.7	83.3	66.7
BIC	66.7	66.7	83.3	66.7
		Female		
MLE	100	100	100	100
MSE	100	100	100	100
AIC	100	100	100	100
BIC	100	100	100	100

[1]Numbers in the table are the percentage of cases in which the fits of the sinusoidal equation to the data were superior to the others according to the specified criteria in the rows. [2]MLE=maximum log-likelihood estimation, MSE=Mean squared error, AIC =Akaike information criterion, BIC=Bayesian information criterion.

the sinusoidal equation was superior to the Richards for 66.7% of the male data profiles, whereas for the females it was superior to the Richards in all cases. The López, Gompertz and logistic equations led to an inferior fit when compared to the sinusoidal. Inferiority of the three aforementioned equations occurred in less cases with the male data profiles than with the female ones, which is in agreement with the results obtained for the Richards equation. The Richards showed a statistically better fit to male than to female growth curves when compared to the sinusoidal. In general, the sinusoidal was the best model compared to Richards, logistic, Gompertz and López (Table 4).

Discussion

Quail farming is generating much interest in many parts of the world as it provides low energy/high protein meat of high biological value. It also offers an opportunity for poultry farmers to undertake a new and profitable enterprise (Minvielle, 2004). In addition to its lean meat, the quail's egg is lower in cholesterol compared to that of the chicken (Musa *et al.*, 2008).

Growth curves are useful tools to represent the evolution of body weight during the growing period and to provide useful and practical information for breeding and feeding purposes (Maruyama *et al.*, 1998; Aggrey, 2004). Growth curves may be used for pre-selection of animals as they can be applied to prediction of future growth at any age (Anthony *et al.*, 1991, 1996; Tekel *et al.*, 2005). Brody (1945) suggested that final or mature weight, rate of attainment of mature weight, and standardised age at which an animal attains the point of inflexion (maximum growth rate) of the curve are parameters that can be suitable and relevant objectives for genetic improvement (Raji *et al.*, 2014). Different mathematical functions have been used to describe growth curves. Furthermore, accurate estimation of daily weight gain using growth functions will allow for better calculation of the bird's energy and nutrient requirements, and thus the formulation of more fit-for-purpose diets. The most commonly used animal growth functions are Brody (Brody, 1945), von Bertalanffy (von Bertalanffy, 1957), Richards (Richards, 1959), logistic (Nelder, 1961) and Gompertz (Laird, 1965).

To the best our knowledge there is little information available on the use of trigonometric (such as the proposed sinusoidal) functions (Darmani Kuhi *et al.*, 2018) to describe the evolution of growth in poultry. In this study, a sinusoidal equation was evaluated with regard to its ability to describe the relationship between body weight and age in quail. Fitting performance observed with the sinusoidal was compared with four standard growth functions, *viz*. the Gompertz, logistic, López and Richards. The sinusoidal equation has the ability to describe a range of different curve shapes.

A comparison among models involves a contrast of the parameter estimates obtained with each model. The greatest discrepancy between models was observed in initial weight, as the smallest values of w_0 were obtained with the Gompertz and sinusoidal equations and the largest with the logistic and López. Reported hatching chick weights (Daikwo *et al.*, 2011; Farghly *et al.*, 2015) are closer to the values estimated with the Gompertz and sinusoidal equations. Relative differences among models were narrower for final (asymptotic) weight, with López and Gompertz giving the greatest and sinusoidal the smallest values. Average reported mature weights for male and female Japanese quail (Balcıoğlu *et al.*, 2005; Raji *et al.*, 2014) are closer to the estimates obtained with the sinusoidal equation. As for age and weight at point of inflexion, López and Gompertz estimated earlier ages and lighter weights at inflexion, in contrast to the logistic and sinusoidal for which values of both parameters were higher. With all five functions the estimates of age and weight for females at point of inflexion, in theory related to the onset of sexual maturity, were substantially lower than the values reported for hens at the onset of laying or first egg age (Zelenka *et al.*, 1984; Steigner *et al.*, 1992). Furthermore, all the functions represented the differences between males and females, and the different comparisons among quail lines/strains. Males reached the point of inflexion at an earlier age than females, with lighter weights and lower growth rates at that age, and showed a smaller final weight and consequently a shorter growth period than female quail (Steigner *et al.*, 1992; Du Preez & Sales, 1997). The comparison between heavy and light lines of quail within the same sex was similar with all the models.

Comparison of the models based on their behaviour and statistical performance showed that all functions gave a suitable fit to the data profiles. In general, assessment of the growth models based on the statistical criteria indicated some relevant differences between the functions for describing future growth of quail. In spite of the fact that the appropriateness of the models was dependent on the data and sex, the estimated statistical criteria demonstrate the suitability and superiority of the sinusoidal equation over the others. The comparison of growth functions in terms of the goodness-of-fit criteria revealed that the sinusoidal was the most appropriate for describing the age-related changes of bodyweight in quail. Nevertheless, selection of the best function requires special attention to characterise the growth patterns of animals under different environmental conditions (Dogan *et al.*, 2010). This is especially important when a particular data set is obtained under certain specific conditions (for a given bird strain, for particular feeding regimes, or when quail are farmed in certain climatic or environmental conditions) that were not defined precisely (Darmani-Kuhi *et al.*, 2003; Beiki *et al.*, 2013). Therefore, it is advisable to compare different functions to fit prior to model selection.

In conclusion, the sinusoidal equation is a suitable alternative to conventional growth functions to represent the growth curves for a range of strains/lines of male and female Japanese quail.

References

Aggrey SE, 2004. Modelling the effect of nutritional status on pre-asymptotic and relative growth rates in a random-bred chicken population. J Anim Breed Genet 121: 260-268. https://doi.org/10.1111/j.1439-0388.2004.00462.x

Anthony NB, Emmerson DA, Nestor KE, Bacon WL, 1991. Comparison of growth curves of weight selected populations of turkeys, quail and chickens. Poult Sci 70: 13-19. https://doi.org/10.3382/ps.0700013

Anthony NB, Nesto KE, Marks HL, 1996. Short-term selection for four-week body weight in Japanese quail. Poult Sci 75: 1192-1197. https://doi.org/10.3382/ps.0751192

Balcıoğlu MS, Kızılkaya K, Yolcu Hİ, Karabağ K, 2005. Analysis of growth characteristics in short-term divergently selected Japanese quail. S Afr J Anim Sci 35: 83-89.

Beiki H, Pakdel A, Moradi-Shahrbabak M, Mehrban H, 2013. Evaluation of growth functions on Japanese quail lines. J Poult Sci 50: 20-27. https://doi.org/10.2141/jpsa.0110142

Brody S, 1945. Bioenergetics and Growth. Reinhold Publishing Corp., NY, USA.

Daikwo SI, Dim NI, Momoh MO, 2011. Hatching characteristics of Japanese quail eggs in a tropical environment. Int J Poult Sci 10: 876-878. https://doi.org/10.3923/ijps.2011.876.878

Darmani Kuhi H, Kebreab E, López S, France J, 2003. An evaluation of different growth functions for describing the profile of live weight with time (age) in meat and egg strains of chicken. Poult Sci 82: 1536-1543. https://doi.org/10.1093/ps/82.10.1536

Darmani Kuhi H, Kebreab E, López S, France J, 2009. Application of the law of diminishing returns to estimate maintenance requirement for amino acids and their efficiency of utilization for accretion in young chicks. J Agric Sci 147: 383-390. https://doi.org/10.1017/S0021859609008442

Darmani Kuhi H, Porter T, López S, Kebreab E, Strathe AB., Dumas A, Dijkstra J, France J, 2010. A review of mathematical functions for the analysis of growth in poultry. World Poult Sci J 66: 227-239. https://doi.org/10.1017/S0043933910000280

Darmani Kuhi H, Rezaee F, Faridi A, France J, Mottaghitalab M, Kebreab E, 2011. Application of the law of diminishing returns for partitioning metabolizable energy and crude protein intake between maintenance and growth in growing male and female broiler breeder pullets. J Agric Sci 149: 385-394. https://doi.org/10.1017/S0021859611000062

Darmani Kuhi H, Kebreab E, France J, 2012. Application of the law of diminishing returns to partitioning metabolizable energy and crude protein intake between maintenance and growth in egg-type pullets. J Appl Poult Res 21: 540-547.

Darmani Kuhi H, Shabanpour A, Mohit A, Falahi S, France J, 2018. A sinusoidal function and the Nelder-Mead simplex algorithm applied to growth data from broiler chickens. Poult Sci 97: 227-235.

Dogan N, Emre K, Mehmet ZF, Tulin A, 2010. Comparison of non-linear growth functions to describe the growth in Japanese quail. J Anim Vet Adv 9: 1961-1966. https://doi.org/10.3923/javaa.2010.1961.1966

Du Preez JJ, Sales J, 1997. Growth rate of different sexes of European quail (*Coturnix coturnix*). Br Poult Sci 38: 314-315. https://doi.org/10.1080/00071669708417994

Ersoy E, Mendeş M, Aktan S, 2006. Growth curve establishment for American Bronze turkeys. Arch Tierzucht 49: 293-299. https://doi.org/10.5194/aab-49-293-2006

Farghly MFA, Mahrose KhMA, Abou-Kassem DE, 2015. Pre and post hatch performance of different Japanese quail egg colors incubated under photostimulation. Asian J Poult Sci 9: 19-30. https://doi.org/10.3923/ajpsaj.2015.19.30

France J, Dijkstra J, Dhanoa MS, 1996. Growth functions and their application in animal science. Ann Zootech 45: 165-174. https://doi.org/10.1051/animres:19960637

Gompertz B, 1825. XXIV. On the nature of the function expressive of the law of human mortality, and on a new method of determining the value of life contingencies. Phil Trans R Soc 115: 513-585. https://doi.org/10.1098/rstl.1825.0026

Knizetova H, Hyanek J, Knize B, Roubicek J, 1991. Analysis of growth curves in fowl. I. Chickens. Br Poult Sci 32: 1027-1038. https://doi.org/10.1080/00071669108417427

Laird AK, 1965. Dynamics of relative growth. Growth 29: 249-263.

López S, France J, Dhanoa M.S, Mould F, Dijkstra J, 2000. A generalized Michaelis-Menten equation for the analysis of growth. J Anim Sci 78: 1816-1828. https://doi.org/10.2527/2000.7871816x

Maruyama K, Potts WJE, Bacon WL, Nestor KE, 1998. Modeling turkey growth with the relative growth rate. Growth Develop Aging 62: 123-139.

Minvielle F, 2004. The future of Japanese quail for research and production. World Poultry Sci J 60: 500-507. https://doi.org/10.1079/WPS200433

Musa U, Haruna ES, Lombin LH, 2008. How to start quail production. In: Quail production in the tropics, 1st ed. Nat Vet Res Inst Press, Vom, Nigeria, 1014 pp.

Nelder JA, 1961. The fitting of a generalization of the Logistic curve. Biometrics 17: 89-110. https://doi.org/10.2307/2527498

Porter T, Kebreab E, Darmani Kuhi H, López S, Strathe AB, France J, 2010. Flexible alternatives to the Gompertz equation for describing growth with age in turkey hens. Poult Sci 89: 371-378. https://doi.org/10.3382/ps.2009-00141

Raji AO, Alade NK, Duwa H, 2014. Estimation of model parameters of the Japanese quail growth curve using Gompertz model. Arch Zootec 63: 429-435. https://doi.org/10.4321/S0004-05922014000300004

Richards FJ, 1959. A flexible growth function for empirical use. J Exp Bot 10: 290-300. https://doi.org/10.1093/jxb/10.2.290

Sezer M, Tarhan S, 2005. Model parameters of growth curves of three meat-type lines of Japanese quail. Czech J Anim Sci 50: 22-30. https://doi.org/10.17221/3991-CJAS

Steigner JW, Nestor KE, Lilburn MS, 1992. Growth and development of lines of Japanese quail (*Coturnix coturnix japonica*) divergently selected for body weight at 4 weeks of age. Comp Biochem Physiol A: Physiol 102: 389-393. https://doi.org/10.1016/0300-9629(92)90152-G

Tekel N, Sireli HD, Elicin M, Elicin A, 2005. Comparison of growth curve models on Awassi lambs. Ind Vet J 82: 179-182.

Teleken JT, Galvão AC, Robazza WD, 2017. Comparing non-linear mathematical models to describe growth of different animals. Acta Sci, Anim Sci 39: 73-81. https://doi.org/10.4025/actascianimsci.v39i1.31366

Thornley JHM, France J, 2007. Mathematical models in agriculture: Quantitative methods for the plant, animal and ecological sciences, 2nd edn. CAB Intnal, Wallingford, UK. https://doi.org/10.1079/9780851990101.0000

Vali N, 2008. The Japanese quail: a review. Int J Poult Sci 7: 925-931. https://doi.org/10.3923/ijps.2008.925.931

von Bertalanffy L, 1957. Quantitative laws for metabolism and growth. Q Rev Biol 32: 217-231. https://doi.org/10.1086/401873

Zelenka DJ, Cherry JA, Nir I, Siegel PB, 1984. Body weight and composition of Japanese quail (*Coturnix coturnix japonica*) at sexual maturity. Growth 48: 16-28.