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Comparative study of growth patterns in seven strains of Japanese quail using nonlinear regression modeling

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Abstract: The aim of this study was to compare the growth pattern of seven strains of Japanese quail including Wild, Italian Speckled, Tuxedo, Scarlett, English white, White button, and A&M Texas by nonlinear growth functions including Gompertz, Richards, logistic, Lopez, and Weibull functions. The body weights of the unselected randomly bred populations of these strains were measured weekly from 1 to 42 days of age and then used to fit functions. The fitness of each function was assessed by statistics including the mean square error, Akaike information criterion, Bayesian information criterion, and adjusted coefficient of determination. The results showed that Gompertz was the best function for describing the growth curve in Italian Speckled and Wild strains; however, the best function for the other strains was the logistic function. The maximum and minimum values for age and weight at the inflection point were obtained for the White button and Scarlett strains, respectively. The weight to age ratio at the inflection point was maximized for Italian Speckled. The best growth rate was observed for the Italian Speckled strain, whereas the White button strain exhibited the worst growth rate. In conclusion, the Italian Speckled strain had the best properties among the tested strains for breeding as broiler poultry.

Key words: Inflection point, growth rate, quail, nonlinear functions

1. Introduction

Optimizing the live weight of broilers at slaughter is very important for farmers to obtain maximum profit and minimum expenses of rearing. Estimation of growth for live organisms versus time is implemented by either linear or nonlinear function (1). Growth is defined as an increase in body size per time unit. This economic parameter greatly affects the broiler industry in global-scale models (2). However, continuous measurement of growth processes is an impossible task since the shape of internal organs could change differently at different phases of growth. Therefore, mathematical functions may help us to fit growth rates, describing the growth pattern in a coherent framework, which is useful for computing objectives (3,4). The growth curves extracted by fitted functions give a set of parameters that can be used to predict animal weight at a specific age over time, allowing for an accurate decision on selection (3,4). The understanding of function parameters in biological information could help develop breeding strategies parallel to changing growth patterns (5).

Growth functions could be implemented to relate body weight to either age or cumulative feed intake and predict daily energy and protein requirements of the animals (6). In a comparative study, it was shown that the Gompertz function was the best one among 11 growth functions to describe body weight (7). However, Raji et al. (8) and Ozkan and Kocabas (9) suggested that Weibull and logistic functions, in that order, were the best functions for growth in quail based on the goodness of fit. In general, most studies reported that Gompertz and Richards functions could describe the time-dependent changes of growth fairly well in Japanese quail (10–15).

Japanese quail is currently the smallest poultry species bred for meat and eggs. Characteristics including rapid growth, resistance to diseases, small body size, and limited space requirements for breeding make quails useful economic and laboratory animals for genetic and biological studies (16,17).

A variety of plumage color mutations in Japanese quails has been reported (16,18) that may be considered as different quail strains. Feather pigmentation may affect tissue color and subsequently change the consumer tendency for quail meat (19). Many Japanese quail strains were derived from wild quails. These strains have some

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specific fixed marker genes for plumage color, eggshell color, and brooding groups making similar colonies. It is supposed that these marker genes do not affect the growth pattern in poultry (12), whereas the effect of the roux plumage color mutation on growth was reported by Minvielle et al. (16). The results of several studies showed that selection of the growth function must be strain-specific (12,20). The present study was undertaken to compare growth patterns of quail strains using nonlinear functions.

2. Materials and methods

The experiment was performed in the Research Center of Special Domestic Animals (RCSDA), Research Institute at University of Zabol, Zabol, Iran. A total of 470 one-day-old Japanese quails including Wild (n = 83), Italian Speckled (n = 136), Scarlett (n = 41), Tuxedo (n = 44), White button (n = 31), English white (n = 64), and A&M Texas (n = 71) strains were obtained from the genetic stock of the RCSDA hatchery from unselected and randomly mating parents. On hatching day, all chicks were identified by wing bands, and they were fed a normal diet containing 250 g CP/kg and 2900 kcal J ME/kg. The birds had ad libitum access to feed and water throughout the experiment. A lighting schedule of 23:1 h (light:dark) was used during the experiment. Room temperature was scheduled to drop gradually from 35 °C the first week to 20–25 °C for the following weeks. Body weights of the birds were recorded weekly. The records for quails that died before 42 days of age were excluded from the analyses.

Five nonlinear functions including the Gompertz, Richards, logistic, Lopez, and Weibull functions were fitted on live body weight to recognize the best-fitted function for each strain. Table 1 shows the functional forms of the nonlinear functions commonly used for body weight versus time analysis. In all functions, W is the body weight of the bird at age t, W_0 and W_f are respectively the expected body weight on day 0 (hatching day) and the final weight (i.e. asymptotic body weight), k is the age to approximately one-half maximum weight or maturation index, m is the shape parameter, and t_i and w_i are age and weight at inflection point, respectively.

After fitting the functions, the goodness of fit for these functions was determined using the following criteria:

$$R^2_{Adj} = 1 - \left[\left(\frac{n-1}{n-p}\right) * \left(1 - R^2_{model}\right)\right],$$

$$MSE = \frac{SSE}{n-p},$$

$$AIC = n.\ln\left(\frac{SSE}{n}\right) + 2p,$$

$$BIC = n.\ln\left(\frac{SSE}{n}\right) + p.\ln(n),$$

where:

R^2_{model} = coefficient of determination;

SSE = sum of squared errors;

SST = total sum of squares;

n = number of observations; and

p = number of parameters.

Smaller Akaike and Bayesian information criteria or mean square error (MSE) (7) and larger adjusted coefficient of determination (R^2_{Adj}) for a function represent a better fit to the data. The growth functions for each strain were fitted to the body weight data by nlme package R using a port algorithm (https://cran.r-project.org/web/packages/nlme/index.html). The statistical differences in growth parameters between strains were determined by Student's t-test. Data on absolute growth rate (AGR), age, and weight at inflection point were analyzed by GLM and least square means were used to detect the differences between strains.

3. Results

The descriptive statistics for body weight traits of the strains are presented in Table 2. The maximum and minimum values of hatching weight (day 1) are those of the Italian Speckled and Wild strains. The highest mean of body weight of 42 days was for the Italian Speckled strain, which could be due to its high hatching weight. Followed by the Italian Speckled strain, the Wild strain had a higher body weight of 42 days despite having a lower hatching weight than other strains, indicating its higher growth rate.

The estimated parameters for all functions in the quail strains are shown in Table 3. The parameter W_0, which is initial body weight, was smaller in the Gompertz function than other functions for all strains. In the Gompertz function, the value of W_0 was significant between strains ($P < 0.05$), and the highest value for W_0 was seen in Italian Speckled followed by the Wild strain while the lowest value was estimated for the Tuxedo strain. The maximum and minimum values for W_0 in the logistic function were obtained for the Italian Speckled and A&M Texas strains, respectively. The difference in W_0 parameter was statistically significant between strains in the logistic function ($P < 0.05$), while there was not a significant difference among strains in the Richards, Lopez, and Weibull functions.

The estimated values for W_f, final weight, by the Gompertz and Lopez functions were higher than those of other functions. In these functions, the Wild and Scarlett strains had the highest and lowest W_f values, respectively. The estimated W_f parameter using the Richards and logistic functions was the highest for the Italian Speckled strain while the lowest value of W_f was estimated for A&M Texas and White button strains, respectively. In the Weibull function, the highest and lowest values for W_f were observed for the Wild and Scarlett strains, respectively.

Table 1. Equations of growth curve functions, age, and weight at the inflection point used in this study.

Functions	Equation	Age at the inflection point (t_i)	Weight at the inflection point (w_i)	Reference
Gompertz	$W = W_0 \exp\left\{[1 - \exp(-k \times Age)] \ln\left(\frac{W_f}{W_0}\right)\right\}$	$\frac{1}{k}\left[\ln\left(\ln\left(\frac{W_f}{W_0}\right)\right)\right]$	$\frac{W_f}{e}$	(29)
Richards	$W = \frac{W_0 W_f}{\left[W_0^m + (W_f^m - W_0^m)e^{-kt}\right]^{1/m}}$	$\frac{1}{k} \times \ln\left(\frac{m}{(W_f^m - W_0^m)/W_0^m}\right)$	$\frac{W_f}{\sqrt[m]{m+1}}$	(30)
Logistic	$W = \frac{W_0 W_f}{[W_0 + (W_f - W_0)\exp(-k \times Age)]}$	$\frac{1}{k}\ln\left(\frac{W_f - W_0}{W_0}\right)$	$\frac{W_f}{2}$	(31)
Lopez	$W = \frac{(W_0 \times k^m) + (W_f \times Age^m)}{(k^m + Age^m)}$	$k\left(\frac{m-1}{m+1}\right)^{1/2}$	$\frac{\left[\left(1+\frac{1}{m}\right)W_0 + \left(1-\frac{1}{m}\right)W_f\right]}{2}$	(32)
Weibull	$W = W_f - (W_f - W_0)\exp[-(k \times Age)^m]$	$\frac{1}{k}\left(\left(\frac{m-1}{m}\right)^{1/m}\right)$	$W_f - (W_f - W_0)\exp\left(-\frac{m-1}{m}\right)$	33))

Table 2. The descriptive statistics of body weight traits in quail strains.

Strain / age	Mean*	SD	Min	Max
Wild (n = 83)				
1	8.450	1.119	5.990	11.900
7	23.494	5.128	14.360	34.120
14	51.348	12.505	23.980	77.100
21	87.224	17.444	41.090	121.080
28	137.353	21.361	66.690	181.900
35	173.592	23.200	95.000	218.200
42	207.799	29.735	107.600	273.700
Italian Speckled (n = 136)				
1	9.626	1.028	6.760	11.670
7	22.052	4.387	12.380	34.190
14	54.297	13.542	18.550	80.450
21	93.933	22.755	31.720	137.880
28	140.364	25.840	48.300	187.400
35	181.135	26.762	83.700	241.300
42	212.755	30.326	103.400	293.100
Scarlett (n = 41)				
1	8.990	1.095	6.310	10.780
7	21.910	3.904	12.010	29.850
14	53.461	11.286	27.020	75.250
21	93.108	15.548	57.260	125.470
28	142.073	18.732	90.400	170.400
35	177.490	21.055	119.800	212.900
42	197.083	24.439	131.500	240.900
Tuxedo (n = 44)				
1	9.416	1.300	6.620	12.770
7	20.022	3.862	12.000	31.130
14	47.010	14.475	22.210	74.450
21	85.897	22.813	44.850	129.780
28	137.102	29.045	61.900	194.200
35	178.527	31.240	96.700	241.800
42	206.757	34.398	96.700	286.400
White button (n = 31)				
1	8.525	1.184	6.620	11.600
7	18.253	3.366	11.970	23.720
14	39.040	11.090	17.930	59.920
21	70.292	20.056	28.720	105.630
28	111.574	30.394	48.320	163.770
35	144.720	37.649	65.600	230.800
42	174.223	39.730	74.300	253.000
English white (n = 64)				
1	8.706	1.372	6.390	12.250

Table 2. (Continued).

7	20.244	5.222	12.650	39.100
14	43.653	11.882	21.850	75.100
21	75.733	19.576	36.760	118.650
28	120.659	26.178	42.900	165.900
35	157.725	30.717	61.500	211.900
42	186.864	35.493	70.900	245.300
A&M Texas (n = 71)				
1	8.834	1.411	6.810	12.780
7	19.183	3.925	12.930	32.260
14	43.318	10.707	20.690	71.720
21	77.194	19.100	31.620	123.370
28	122.717	26.165	61.500	174.900
35	161.668	29.979	82.600	234.400
42	186.803	32.048	87.100	262.300

* n: Number of quails; SD: standard deviation; Min: minimum; Max: maximum.

There was a significant difference among strains for W_f, k, and m parameters in all fitted functions (Table 3). The lowest and highest values for the m parameter were estimated respectively for the Wild and Tuxedo strains (except for the Richards function). In the Richards function, A&M Texas and then the Tuxedo strain showed the highest value of the m parameter and the difference between these strains was not significant.

Table 4 shows the goodness of fit criteria for all functions in the seven quail strains. In all strains (except the Italian Speckled and Wild strains), the logistic function had the lowest AIC, BIC, and MSE values and the highest R^2_{Adj}; thus, this function could be the best for describing growth curves of these strains. According to four goodness of fit criteria, the Gompertz function is the worst function for the Tuxedo and A&M Texas strains, while the Lopez function was the worst function for the English white, White button, and Scarlett strains (Table 4). The values of AIC and BIC for the Gompertz function were the lowest for the Italian Speckled and Wild strains, but the R^2_{Adj} value for these strains was the highest using the Weibull and Richards functions, respectively. The goodness of fit by MSE value for Italian Speckled and Wild strains was the lowest in the Gompertz and Richards functions, respectively. In the Wild strain, the difference of BIC criteria between the Gompertz and Richards functions was higher than the differences of MSE and R^2_{Adj} criteria, and the Gompertz function had the lowest BIC. Therefore, the Gompertz function was the best function for describing growth curves of the Italian Speckled and Wild strains.

Age and weight at the inflection point of all strains using different growth functions are shown in Table 5. In the Gompertz function, the highest and lowest values of age and weight at inflection point were for the White button and Scarlett strains and the differences between the highest and lowest values were significant ($P < 0.05$). The age and weight at the inflection point value for the Italian Speckled strain by the Gompertz function (the best function for this strain) were 25.141 days and 124.093 g, respectively. The age at the inflection point for the Italian Speckled strain has a significant difference with the lowest and highest values of this parameter ($P < 0.05$), but the weight at the inflection point of this strain was only significant with the lowest value ($P < 0.05$).

The ranges of age and weight at the inflection point for the Richards function varied from 22.864 (Scarlett strain) to 27.037 days (White button strain) and from 106.668 (Scarlett strain) to 125.851 g (Wild strain), respectively. The difference between the highest and lowest values was statistically significant ($P < 0.05$). The age and weight at the inflection point for the Wild strain in the best function (Richards function) were obtained as 26.042 days and 125.851 g, respectively. The Scarlett and White button strains have the lowest and highest age and weight at the inflection point compared to other strains in the logistic function. The age at inflection point value for Tuxedo, Scarlett, English white, White button, and A&M Texas in the logistic function were 25.383, 22.925, 25.913, 29.029, and 25.811 days, respectively. Again, the difference between Scarlett and White button strains and all other strains was significant ($P < 0.05$). The estimated weight at the inflection point for Tuxedo, Scarlett, English white, White button, and A&M Texas in the best function (logistic function) was estimated to be 116.451, 107.172, 108.185, 129.633, and

Table 3. Growth parameters for quail strains in fitted functions.

Function	Function parameters			
	W_0 (SE)*	W_f (SE)	k (SE)	m (SE)
Gompertz				
Italian Speckled	6.320 (0.779)^{a}	300.000 (10.490)^{a}	0.058 (0.003)^{b}	-
Tuxedo	4.356 (1.294)^{b}	290.400 (19.820)^{ab}	0.061 (0.005)^{b}	-
Wild	6.483 (0.906)^{a}	304.800 (13.750)^{a}	0.055 (0.003)^{b}	-
Scarlett	4.464 (0.958)^{b}	249.200 (9.200)^{e}	0.069 (0.004)^{a}	-
English white	5.512 (1.208)^{ab}	285.600 (21.240)^{ac}	0.054 (0.004)^{b}	-
White button	5.058 (1.952)^{ab}	270.000 (36.460)^{ade}	0.053 (0.008)^{b}	-
A&M Texas	5.552 (0.984)^{ab}	270.100 (15.700)^{bcd}	0.058 (0.004)^{b}	-
Richards				
Italian Speckled	7.620 (1.370)^{a}	277.781 (18.617)^{a}	0.070 (0.012)^{b}	0.200 (0.186)^{cd}
Tuxedo	8.330 (2.271)^{a}	236.586 (17.825)^{b}	0.113 (0.031)^{a}	0.777 (0.454)^{ab}
Wild	8.094 (1.541)^{a}	271.740 (22.154)^{a}	0.073 (0.015)^{b}	0.279 (0.233)^{bd}
Scarlett	8.496 (1.704)^{a}	217.587 (9.029)^{b}	0.115 (0.020)^{a}	0.711 (0.303)^{ab}
English white	8.389 (1.940)^{a}	227.518 (21.736)^{b}	0.095 (0.027)^{ab}	0.648 (0.419)^{abc}
White button	7.369 (3.201)^{a}	218.052 (41.495)^{b}	0.088 (0.046)^{ab}	0.548 (0.713)^{abc}
A&M Texas	8.365 (1.644)^{a}	213.926 (13.057)^{b}	0.115 (0.026)^{a}	0.867 (0.386)^{a}
Logistic				
Italian Speckled	11.580 (0.739)^{a}	237.800 (4.137)^{a}	0.120 (0.004)^{bc}	-
Tuxedo	9.188 (1.284)^{b}	229.900 (7.507)^{a}	0.127 (0.007)^{ab}	-
Wild	11.270 (0.838)^{a}	234.800 (5.039)^{a}	0.118 (0.004)^{c}	-
Scarlett	9.721 (0.967)^{b}	211.500 (4.149)^{b}	0.134 (0.006)^{a}	-
English white	9.583 (1.106)^{b}	214.500 (7.245)^{b}	0.118 (0.006)^{c}	-
White button	8.837 (1.793)^{b}	200.559 (12.208)^{b}	0.117 (0.011)^{c}	-
A&M Texas	8.805 (0.951)^{b}	210.300 (5.724)^{b}	0.124 (0.006)^{abc}	-
Lopez				
Italian Speckled	9.939 (1.679)^{a}	373.461 (33.473)^{a}	37.314 (3.321)^{ac}	2.040 (0.125)^{b}
Tuxedo	11.286 (3.008)^{a}	305.534 (35.554)^{b}	31.667 (3.268)^{bde}	2.487 (0.278)^{a}
Wild	9.861 (1.917)^{a}	389.416 (47.225)^{a}	40.125 (4.788)^{a}	2.006 (0.147)^{b}
Scarlett	10.869 (2.241)^{a}	269.806 (18.364)^{b}	27.967 (1.804)^{e}	2.414 (0.194)^{a}
English white	10.439 (2.495)^{a}	323.454 (50.072)^{ab}	37.204 (5.324)^{ad}	2.219 (0.239)^{ab}
White button	9.763 (4.028)^{a}	301.821 (82.659)^{ab}	37.439 (9.364)^{ab}	2.242 (0.423)^{ab}
A&M Texas	10.759 (2.181)^{a}	285.700 (29.032)^{b}	32.785 (2.985)^{bc}	2.426 (0.221)^{a}
Weibull				
Italian Speckled	9.614 (1.659)^{a}	271.701 (15.829)^{a}	0.029 (0.002)^{cd}	1.918 (0.094)^{b}
Tuxedo	10.810 (2.980)^{a}	237.100 (16.110)^{b}	0.033 (0.002)^{b}	2.271 (0.198)^{a}
Wild	9.637 (1.888)^{a}	275.200 (21.800)^{a}	0.028 (0.002)^{d}	1.911 (0.113)^{b}
Scarlett	10.330 (2.211)^{a}	216.500 (8.030)^{c}	0.036 (0.001)^{a}	2.163 (0.132)^{a}
English white	10.230 (2.456)^{a}	234.500 (22.520)^{bc}	0.029 (0.003)^{bd}	2.099 (0.180)^{ab}
White button	9.459 (3.986)^{a}	220.900 (39.340)^{bc}	0.029 (0.005)^{bd}	2.103 (0.319)^{ab}
A&M Texas	10.450 (2.151)^{a}	217.600 (12.820)^{bc}	0.032 (0.002)^{bc}	2.246 (0.159)^{a}

* W_0: predicted body weight on day 0 (hatching day); W_f: predicted final weight or asymptotic body weight; k: age to approximately one-half maximum weight or maturation index; m: shape parameter; SE: standard error.
Values within the same column with a different superscripted letter have a significant difference ($P < 0.05$).

Table 4. The goodness of fit criteria for fitted growth functions in the quail strains.

Strain	Criteria	Gompertz	Richards	Logistic	Lopez	Weibull
Italian Speckled	AIC*	8482.645	8483.386	8494.114	8484.559	8483.332
	BIC	8502.079	8507.679	8513.548	8508.852	8507.624
	R^2_{Adj}	92.507	92.509	92.417	92.500	92.510
	MSE	431.330	431.363	436.708	431.894	431.338
Tuxedo	AIC	2814.592	2812.592	2810.807	2814.566	2813.481
	BIC	2829.513	2831.243	2825.727	2833.217	2832.132
	R^2_{Adj}	90.691	90.781	90.805	90.722	90.755
	MSE	536.048	530.872	529.500	534.285	532.407
Wild	AIC	5040.077	5040.569	5045.227	5044.319	5043.037
	BIC	5057.536	5062.393	5062.686	5066.143	5064.861
	R^2_{Adj}	93.671	93.676	93.615	93.636	93.450
	MSE	339.802	339.508	342.827	341.706	340.954
Scarlett	AIC	2413.085	2408.254	2406.973	2413.659	2409.996
	BIC	2427.723	2426.551	2421.611	2431.956	2428.294
	R^2_{Adj}	94.935	95.036	95.042	94.942	95.006
	MSE	257.938	252.760	252.502	257.566	254.300
English white	AIC	4052.848	4051.902	4050.485	4054.478	4053.538
	BIC	4069.267	4072.426	4066.905	4075.002	4053.538
	R^2_{Adj}	89.300	89.346	89.357	89.285	89.308
	MSE	491.529	489.407	488.944	492.229	491.197
White button	AIC	2018.835	2020.052	2018.408	2020.422	2020.283
	BIC	2032.355	2036.952	2031.927	2037.321	2037.183
	R^2_{Adj}	84.944	84.928	84.974	84.902	84.912
	MSE	628.016	628.693	626.780	629.763	629.361
A&M Texas	AIC	4448.329	4443.538	4441.642	4447.787	4445.761
	BIC	4465.164	4464.581	4458.477	4468.830	4466.804
	R^2_{Adj}	90.414	90.525	90.542	90.444	90.482
	MSE	446.948	441.776	440.974	445.569	443.757

*Mean square error (MSE), Akaike information criterion (AIC), Bayesian information criterion (BIC), adjusted coefficient of determination (R^2_{Adj}).

107.645 g, respectively. The highest age and weight at the inflection point in the Lopez and Weibull functions were observed for the Wild strain, while the lowest values for age and weight at inflection point were for the Scarlett and A&M Texas strains, respectively. The age and weight differences at the inflection point were not significant between strains in the Weibull function, but they were significantly different in some strains in the Lopez function.

Table 5. Age and weight at the inflection point using different growth functions for quail strains.

Function	t_i* (days)	W_i (g)
Gompertz		
Italian Speckled	25.141 (0.066)^{b}	124.093 (0.395)^{a}
Tuxedo	25.335 (0.171)^{b}	116.016 (0.746)^{ab}
Wild	25.712 (0.084)^{b}	120.983 (0.457)^{a}
Scarlett	20.806 (0.094)^{c}	95.409 (0.473)^{b}
English white	27.399 (0.210)^{ab}	120.784 (1.277)^{a}
White button	30.127 (0.465)^{a}	127.710 (3.076)^{a}
A&M Texas	26.917 (0.162)^{ab}	117.656 (1.075)^{ab}
Richards		
Italian Speckled	24.049 (0.033)^{bc}	117.833 (0.159)^{ab}
Tuxedo	25.232 (0.098)^{ab}	117.541 (0.396)^{ab}
Wild	26.042 (0.079)^{a}	125.851 (0.619)^{a}
Scarlett	22.864 (0.070)^{c}	106.668 (0.387)^{b}
English white	26.184 (0.059)^{a}	110.465 (0.311)^{b}
White button	27.037 (0.183)^{a}	106.771 (0.837)^{b}
A&M Texas	25.525 (0.055)^{ab}	110.237 (0.293)^{b}
Logistic		
Italian Speckled	25.121 (0.030)^{b}	121.417 (0.142)^{ab}
Tuxedo	25.383 (0.078)^{b}	116.451 (0.405)^{ab}
Wild	25.666 (0.042)^{b}	119.716 (0.245)^{ab}
Scarlett	22.925 (0.057)^{c}	107.172 (0.359)^{b}
English white	25.913 (0.071)^{b}	108.185 (0.324)^{b}
White button	29.029 (0.356)^{a}	129.633 (4.327)^{a}
A&M Texas	25.811 (0.060)^{b}	107.645 (0.250)^{b}
Lopez		
Italian Speckled	24.207 (0.070)^{b}	116.847 (0.422)^{b}
Tuxedo	24.116 (0.137)^{b}	106.788 (0.599)^{b}
Wild	30.749 (0.342)^{a}	162.388 (2.627)^{a}
Scarlett	21.718 (0.203)^{b}	98.729 (1.119)^{b}
English white	26.716 (0.211)^{ab}	107.909 (1.203)^{b}
White button	25.427 (0.188)^{ab}	100.263 (0.868)^{b}
A&M Texas	24.945 (0.163)^{ab}	104.498 (0.868)^{b}
Weibull		
Italian Speckled	25.204 (0.093)^{a}	133.230 (1.164)^{a}
Tuxedo	24.620 (0.113)^{a}	113.205 (0.513)^{a}
Wild	27.522 (0.191)^{a}	145.417 (1.855)^{a}
Scarlett	22.807 (0.190)^{a}	106.346 (1.054)^{a}
English white	25.992 (0.182)^{a}	113.431 (1.198)^{a}
White button	26.578 (0.171)^{a}	105.408 (0.820)^{a}
A&M Texas	24.381 (0.058)^{a}	102.859 (0.280)^{a}

* t_i and W_i are age and weight at the inflection point, respectively. Values within the same column with a different superscripted letter have a significant difference ($P < 0.05$).

According to the best function for each one of the strains (Table 4), the White button and Scarlett strains exhibited the highest and lowest values of age and weight at the inflection point, respectively (Table 6). As can be seen from Table 6, the weight to age ratio at the inflection point for all strains in the best function was the highest in the Italian Speckled strain, followed by the Wild strain. This ratio could be a criterion to show the growth rate of strains. Accordingly, breeding of Italian Speckled and Wild strains could be useful for meat poultry due to having a higher weight to age ratio.

AGR at different ages for all strains was estimated using the best function for each strain and results are presented in Table 7. The highest and lowest AGR for the ages of 1, 7, and 14 days were estimated for the Italian Speckled and White button strains, respectively. The Scarlett and Tuxedo strains had the highest values of AGR at 21 and 28 days, respectively, while the lowest values for these ages were obtained for the White button strain. The highest AGR at ages 35 and 42 days was related to the Wild strain, followed by the Italian Speckled strain. The lowest AGR values were estimated for Scarlett at ages of 35 and 42 days. As seen in Table 6, the Italian Speckled and Wild strains have the highest AGR at most ages while the White button and A&M Texas strains have the lowest values, suggesting that the Italian Speckled and Wild strains are appropriate for meat production.

4. Discussion

Table 1 showed that the standard deviation of body weights increased with increasing age in all strains. Increase of the standard deviation with time is expected for time series data (8). Similar results were reported by Aggrey (5), Nahashon et al. (21), and Raji et al. (8).

The growth curve parameters by the Richards function were estimated for Wild, brown, and white quail strains. The W_0, W_f, m, and k values for the Wild strain were reported to be within the ranges of 8.461–8.630, 190.319–253.835, 0.170–0.424, and 0.074–0.099, respectively (12). Moreover, results for the Wild strain (with Richards as the best function) in this study were within the ranges of reported data (except W_f, which was higher than in other reports). The reported W_0 and k parameters for white and brown strains are in agreement with those of the present findings, but the reported W_f and m values for brown and white strains were smaller than ours. Different growth parameters among different studies could result from different genotypes, environmental conditions, and fitted functions for strains (22).

The goodness of fit for functions is generally performed using MSE and R^2_{Adj} criteria, where the function with the smallest MSE is assumed to have the best fit for the data (23). According to the overall goodness of fit criteria, the

Table 6. Age and weight at inflection point in the best function for quail strains.

Strains	t_i* (days)	W_i (g)	W_i/t_i
Italian Speckled	25.141 (0.066)^e	124.093 (0.395)^b	4.94
Tuxedo	25.383 (0.078)^d	116.451 (0.405)^d	4.59
Wild	25.712 (0.084)^c	120.983 (0.457)^c	4.71
Scarlett	22.925 (0.057)^f	107.172 (0.359)^f	4.67
English white	25.913 (0.071)^b	108.185 (0.324)^e	4.17
White button	29.029 (0.356)^a	129.633 (4.327)^a	4.66
A&M Texas	25.811 (0.060)^{bc}	107.645 (0.250)^{ef}	4.17

Values within the same column with a different superscripted letter have a significant difference (P < 0.05).
* t_i and W_i are age and weight at the inflection point, respectively.

Table 7. The predicted absolute growth rate (AGR) of strains using the best-fitted function at various ages.

Strains			Growth rate (g)				
	1	7	14	21	28	35	42
Italian Speckled	1.979 (0.027)^a	3.443 (0.057)^a	5.465 (0.102)^a	6.265 (0.114)^b	6.080 (0.111)^b	5.244 (0.128)^a	4.405 (0.126)^a
Tuxedo	1.200 (0.048)^c	2.388 (0.100)^{bc}	4.802 (0.180)^c	6.920 (0.201)^a	7.050 (0.195)^a	4.959 (0.225)^{ab}	2.689 (0.222)^b
Wild	1.712 (0.035)^b	3.374 (0.073)^a	5.080 (0.131)^{bc}	6.016 (0.146)^{bc}	6.002 (0.142)^b	5.332 (0.164)^a	4.511 (0.161)^a
Scarlett	1.166 (0.050)^{cd}	2.647 (0.104)^b	5.365 (0.186)^{ab}	6.994 (0.208)^a	6.198 (0.202)^b	3.757 (0.233)^c	1.977 (0.222)^c
English white	1.031 (0.040)^e	2.231 (0.083)^c	4.185 (0.149)^{de}	5.842 (0.167)^{cd}	6.162 (0.162)^b	4.798 (0.187)^b	2.767 (0.184)^b
White button	0.951 (0.058)^e	1.939 (0.119)^{cd}	3.730 (0.214)^e	5.384 (0.240)^d	5.720 (0.232)^b	4.594 (0.268)^b	3.014 (0.264)^b
A&M Texas	1.080 (0.038)^{de}	2.194 (0.079)^d	4.336 (0.141)^d	6.070 (0.158)^{bc}	6.258 (0.154)^b	4.551 (0.177)^b	2.721 (0.174)^b

Values within the same column with a different superscripted letter have a significant difference (P < 0.05).

Gompertz function was the best function for describing the growth curve of the Italian Speckled and Wild strains. In comparative studies of various growth functions, it has been shown that the Gompertz and Richards functions reflect weight changes rather the age in Japanese quail well (7,10,12,13,15), which is in agreement with results of this study for the Italian Speckled and Wild strains. The logistic function was the best for most of the strains (Tuxedo, Scarlett, English white, White button, and A&M Texas), which is in line with the results of Raji et al. (8). However, Ozkan and Kocabas (9) reported the Weibull function as the best function for describing the growth curve of Japanese quail in Nigeria (8), which is opposed to this study's findings.

Selection of a flexible function with the least complexity among the available functions is necessary for researchers when choosing an appropriate growth function. For example, the Gompertz and Logistic functions are simple and fit well to short time series data such as growth records of animal species (6), but the Richards function has an additional parameter and is more complex than the Gompertz and logistic functions. This function can fit well into complex patterns, but it requires a long time series and has fitting difficulty (24).

Growth curves are often nonlinear sigmoidal functions with an asymptote and an inflection point (25). Assuming an appropriate growth function, the accuracy of function parameter estimation depends on the accuracy of the data (4).

The weight and age at inflection point by the Gompertz function were reported to be 81.70 g and 14.95 days, respectively (7). The ranges of weight and age at the inflection point for quails varied within the ranges of 74.85–89.89 g and 18.74–21.22 days by Gompertz function (11,26), smaller than the estimated age and weight at the inflection point for all strains in the present study. Age and weight at inflection point were obtained higher for brown strain females (12), but White button had the highest age and weight at the inflection point in the present study.

Italian Speckled followed by the Wild strain presented the highest AGR at most ages. The difference of daily gain of the quail strains was reported in other research, such that males of white and females of wild quails were better than other strains with respect to growth rate (12). The average values for AGR were reported as 3.56 g (7,12,14), which is smaller than the AGR at the age of 35 days for all strains (Table 7). It was reported that absolute growth rate of all quail strains increased until about week 3, which is the age of maximum accumulation, and thereafter a rapid decline occurred (27). This result is consistent with our findings for the Italian Speckled and Scarlett strains while opposing the findings for the remaining strains (Wild, Tuxedo, English white, and White button; Table 7). The absolute growth rate of the Wild, Tuxedo, English white, White button, and A&M Texas strains increased until about week 4, then decreased to 42 days.

The differences between growth rates in the early part of the developmental period for strains could represent correlated differences in final weight. In this study, the White button strain with lower AGR had a lower 42-day body weight (Table 1), which is in line with the results of Sezar and Tarhan (28).

Various sets of gene lines and strains could represent the differences in early and late growth of the lines (12). This was reported in quail (5). As confirmed by analyses of different lines (20), the choice of the function must be strain-specific. The findings of the present study showed that it is necessary to apply a strain-specific function for describing a growth curve.

In conclusion, five functions were compared in terms of the goodness of fit criteria for seven quail strains and it was found that the Gompertz and logistics functions were the best for describing growth curves in Italian Speckled, Wild, and other strains, respectively. For most of the strains, simple functions (fixed inflection point) represent the best descriptions of age-related changes in weight. The results suggest that it is necessary to pay attention to the characteristics of the growth patterns of different strains under various environmental conditions. Italian Speckled followed by the Wild strain showed the highest weight to age ratio at the inflection point and absolute growth rate compared to other strains. Therefore, these strains could be considered as broiler poultry. Furthermore, age and weight at the inflection point and growth rate at different ages in strains could be used as effective criteria in breeding strategies.

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