Iranian Society of Animal Science

Journal of Livestock Science and Technologies

Shahid Bahonar University of Kerman

ISSN: 2322-3553 (Print) ISSN: 2322-374X (Online)

Paper type: Original Research

Evaluation of models for predicting the preweaning body weight in Holstein calves

Ali Moharrery[1], Hassan Rahmani[1*], and Mohammad Javad Zamiri[2]

[1]Department of Animal Science, Agricultural College, Shahrekord University, Shahrekord, Iran.
[2]Department of Animal Science, College of Agriculture, Shiraz University, Shiraz, Iran.

*Corresponding author,
Tell: +989133832260,
E-mail:
Rahmani_56@ yahoo.com

Received: 25 Jan. 2021,
Accepted: 07 Mar. 2021,
Published online: 24 Aug 2021,

Abstract This study compared six non-linear equations [Exponential growth (4 parameters), Exponential growth (Stirling), Polynomial (Cubic), Quadratic, Brody, and Sinusoidal] for prediction of pre-weaning body weights at different ages in Holstein calves. Thirty-two calves (16 males and 16 females) were randomly divided into two treatment groups and fed with starter diets containing either corn or barley as the grain source. Starter feeding began on the third day of life, and high quality alfalfa hay and fresh cow milk were fed according to the farm schedule. The calves were weighed at birth and weekly thereafter until weaning. In this manner, ten weight records, including the birth and weaning weights, constituted the data set. The results revealed that all functions mentioned earlier showed good fitness to predict weight gain in relation to age in all groups of calves. However, based on the goodness of the fit of various criteria and the statistical performance, the polynomial (cubic) function was considerably superior to other functions for predicting the calf live weight. The flexible growth functions (more parameters) very often give a closer fit to data points and a smaller residual sum of square (RSS) value than the simpler functions such as the Brody functions.

Keywords: mathematical modeling, growth function, body weight, suckling period, calf

Introduction

Dairy calves are typically fed with a fixed amount of milk or milk replacer along with free-choice starter. Starter feed intake is small during the first week of life but at some point begins to increase (Jasper and Weary, 2002; Terre et al., 2007; Stamey et al., 2012; Hill et al., 2016). The rate of increase in starter intake is affected by several factors including the amount of liquid diet consumed. With increasing emphasis on intensification of calf rearing, prediction of body weight before weaning is important in maintaining the health and viability of the calf, and better preparation of the starter diet. Among the current statistical procedures for analysis of the growth data, fitting of the nonlinear functions offers an opportunity to summarize the information contained in the entire sequence of weight-age points into a small set of parameters that can be interpreted biologically and used to derive other relevant growth traits. Mathematical models are powerful tools for improving the animal -

performance while reducing nutrient excretion to the environment (Tedeschi et al., 2005; Moharrery and Mirzaei, 2014). The relationship between weight gain and age can be explained by any one of the several functions such as the Exponential, Quadratic, Polynomial, and Brody's. Although the mathematical formulas of these equations differ, either of them produces a similar graph reflecting the generally desirable biological characteristics.

Due to the short length of suckling period or milk feeding before weaning and continuation of growth in weaned calves, the growth curve cannot reach the plateau at weaning. Therefore, the mathematical equations found in the literature cannot be fit to the growth pattern and to describe weight gain in relation to the age before weaning. Some mathematical functions may be used as alternatives in the sense that each one fits with some data sets more closely than the others. However, the form of the fitted curve must be sufficiently flexible to closely follow any trends of the data and to give a consistently good fit to the data (Darmani Kuhi et al., 2003). Therefore, the objective of the present study was to compare six mathematical models for their potential usefulness in predicting the pre-weaning weight at different ages in Holstein calves.

Materials and methods

Management, experimental design and calf weight

Thirty-two Holstein calves (16 males and 16 females) were immediately separated from their mothers at birth, randomly divided into two groups and transferred to individual pens with controlled temperature. During the first 6 hours of life, colostrum was fed three times in bottles at 10% of the live weight, after which, pasteurized fresh colostrum was fed for three consecutive days. Subsequently, pasteurized fresh milk was fed according to the farm schedule; 4 kg up to 2 weeks, 5 kg up to 6 weeks of ages, and then 4 kg up to 8 weeks of age. Milk was offered two times per day at 6.00 and 15.00 hrs. The calves were weaned at 60 days of age.

The calves in each group were fed with one of the two starter diets containing either corn or barley as the grain source (Table 1). Starter feeding began on the third day of life, and alfalfa hay and fresh cow milk were fed according to the farm schedule. The calves were weighed at birth and weekly thereafter until weaning. Six non-linear functions [Exponential (exp) growth (4 parameters), Exponential growth (Stirling), Polynomial (Cubic), Quadratic, Brody, and Sinusoidal] were evaluated with regard to their ability to describe the relationship between the age and body weight using the pooled data.

Table 1. Ingredients (g per kg as-fed) and chemical composition of the starter, milk and alfalfa hay

	Starter			
	Corn-based	Barley-based	Alfalfa hay	Milk
Corn	620	-		
Barley	-	620		
Rapeseed meal	30	30		
Soybean meal	260	26		
Soybean	50	50		
Calcium carbonate	9	9		
Sodium carbonate	8	8		
NaCl	5	5		
Mineral Mix[a]	10	10		
Vitamin Mix [b]	8	8		
Chemical and nutritional composition (g per kg dry matter)				
DM (g/kg) [1]	930.6	930.7	941.1	116.6
Ash[1]	76.8	80.0	81.9	67.0
CP (N × 6.25) [1]	197.1	200.4	127.5	257.3
Crude fat[1]	57.3	51.9	49.7	320.8
NFC[3]	518.3	502.7	221.2	344.8
NDF[1]	150.5	165.0	519.7	-
Metabolizable energy (MJ/kg) [2]	16.820	16.862	8.912	22.133

[a] Calcium, 64 mg; phosphorus, 30mg; magnesium, 44 mg; manganese, 4 mg; zinc, 4.6 mg; iron, 10.5 mg; copper, 1 mg; iodine, 0.025 mg; selenium, 0.037 mg; cobalt, 0.01 mg; (supplied per kilogram of mixture).
[b] Vitamin A, 1350000 IU; cholecalciferol, 80000 IU; vitamin E, 6700 IU; riboflavin, 0.85 mg; choline chloride, 7.5 mg; vitamin B_{12}, 9.3 µg; vitamin B_6, 0.873 mg; biotin, 0.013 mg; folic acid, 0.88 mg; vitamin B_5, 29.65 mg; vitamin B_3, 1.7 mg; vitamin B_1, 0.8 mg; (supplied per kilogram mixture).
ME= Metabolizable energy; CP = Crude protein; NDF= Neutral detergent fiber; NFC= Non-fiber carbohydrates.
[1] Analyzed in the laboratory.
[2] Calculated from NRC (2001) data.
[3] Calculated from other parameters from laboratory analysis.

Model description and calculations

Ten weight records, including the birth and weaning weights, constituted the data set. Some calves lost weight from one weighing to the next, but compensated their lost weight at the subsequent weighing. No clinical signs of diarrhea or pneumonia were observed, and there were no cases of lost data in this part of the experiment.

Mathematical models

To estimate the body weight (BW), six non-linear functions were fitted to the data set as follows:
Exponential growth, Double, 4 parameters:
W = a × exp × (b ×age) – (c × exp (d ×age)); (1)
Exponential growth (Stirling):
W = W_0 + a ((exp (b ×age)-1)/b); (2)
Polynomial (Cubic):
W = W_0 + (a × age + b × (age ^{2})) + (c × (age ^{3})); (3)
Quadratic:
W = a + (b × age + c × (age ^{2})); (4)
Brody (1945):
W = a × exp (b ×age); (5)
Sinusoidal:
W = a + (b ×Cos (c ×age + d)); (6)

In these functions, W denotes the expected BW at a given age, W_0 is the initial BW, and a, b, c, and d are constants.
In Brody's model, the values of a and b for each calf were obtained by plotting the natural logarithm of the live weight against the age, and then fitting the data statistically. This gave lines that could be described by a linear equation (Ln Brody):

Ln W = Ln a + (b × age); (7)

The general differential form of a growth function is dW/dAge = f (W, Age), which implies that the growth rate of a biological system is dependent on the live weight and age. A growth function, can characterize several underlying physiological or biological mechanisms or constraints (Darmani Kuhi et al., 2003).

Statistical analysis

The growth functions were fitted to the measurements of live weights at corresponding age via nonlinear procedure by using the Marquardt algorithm (SAS software, version 9.4, SAS Institute Inc, Cary, NC).
For functions with the same number of parameters, F=RSS_1/RSS_2 was calculated in which, the subscripts 1 and 2 refer to the fit with the bigger and smaller RSS values, respectively. The functions with different number of parameters were tested using the following F test (Motulsky and Ransnas, 1987):

$$F = \frac{(RSS_1 - RSS_2)/(df_1 - df_2)}{RSS_2/df_2} \quad (8)$$

where, df is the degree of freedom, and subscript 1 refers to the fit with the fewer parameters, the simpler function. The H0 means that all functions have the same RSS.

Assessment of the model accuracy

Several statistics can be used to determine the goodness of the fit. Here, the goodness of the fit was assessed by using six criteria: determination coefficient (R^2), residual sum of squares (RSS), the mean bias, convergence percentage (C%), the root of the mean squared error of prediction (RMSPE %), and comparison between the predicted and observed values using the paired t-test. The R^2 was calculated through linear regression analysis between the observed and predicted values; the mean bias was calculated as follows (Haefner, 1996):

$$\text{Mean bias} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad (9)$$

where, O_i is the observed value, P_i is the predicted value, and *n* is the sample size (Sarmento et al., 2006), C% indicates the convergence percentage in relation to the individual data set. The lower the RSS and mean bias values, the better the adjustment (Malhado et al., 2009). The magnitude of the error was estimated by mean square prediction error (MSPE) (Wallach and Goffinet, 1989) or by its root (RMSPE):

$$MSPE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2 \quad (10)$$

The MSPE can be separated into three components (Haefner, 1996):

$$MSPE = (\overline{P} - \overline{O})^2 + (S_p^2(1-b)^2) + ((1-r^2)S_O^2) \quad (11)$$

where, S_p^2 and S_O^2 are the variances of predicted and observed values, respectively, b is regression slope of O on P and r^2 is determination coefficient of the same equation. The first term of this equation is the mean bias (i.e., when observations' regression on predictions has a nonzero intercept). The second term is the regression bias, defined as systematic error made by the model; when it is large, there is an indication of the model inadequacies to predict the variables in question. The last term represents unexplained variation in observed values after the time that mean and the regression biases have been removed. The results of each of these three MSPE components have been presented as a percentage of the total MSPE. The RMSPE was also calculated; therefore, the MSPE could be expressed with the same units of the observed and predicted variables. If the model were perfect, the linear observations' regression (y) on predictions (x) would have an intercept equal to zero and a slope equal to one (Cannas and Atzori, 2005). As mentioned earlier, observed and predicted measurements were also compared through a paired t-test (SAS Institute Inc., Cary, NC, USA), as suggested by Mayer and Butler (1993).

Results

The descriptive statistics, mean birth weight and relative growth weight for different ages and sex are presented in Table 2. Relative growth weight in calves was highly supple, ranging from -17.8 to 28.3 g/day from the second week of age (WOA) to weaning, respectively.

Table 2. Descriptive statistics for birth weight (kg) and relative growth weight (RG; g kg^{-1} d^{-1}) in calves at different ages and sex

	n	Mean	SD	Minimum	Maximum
Both sexes					
Birth weight	32	39.32	2.281	34.80	43.80
RG in first week	32	4.1	6.28	-12.7	19.0
RG in second week	32	4.1	6.26	-17.8	15.3
RG in third week	32	11.7	4.79	1.3	23.5
RG in fourth week	32	13.8	3.85	5.1	24.0
RG in fifth week	32	13.6	2.96	5.9	18.9
RG in sixth week	32	12.3	2.94	3.5	17.6
RG in seventh week	32	12.6	3.13	5.7	19.9
RG in eighth week	32	12.7	3.90	3.8	21.8
RG at weaning	32	16.5	4.93	11.5	28.3
RG in total period	32	16.0	0.32	15.6	17.4
Male calves					
Birth weight	16	39.49	2.261	36.6	43.6
RG in first week	16	3.3	4.98	-7.4	10.6
RG in second week	16	6.2	4.31	0.0	15.3
RG in third week	16	11.3	4.98	1.3	20.3
RG in fourth week	16	14.5	4.55	5.1	24.0
RG in fifth week	16	14.4	2.42	9.6	17.9
RG in sixth week	16	11.3	2.71	3.5	14.1
RG in seventh week	16	13.5	2.92	8.4	19.9
RG in eighth week	16	12.2	4.30	3.8	21.8
RG at weaning	16	16.2	4.76	12.4	28.0
RG in total period	16	16.0	0.39	15.7	17.4
Female calves					
Birth weight	16	39.14	2.359	34.8	43.8
RG in first week	16	5.0	7.42	-12.7	19.0
RG in second week	16	1.9	7.23	-17.8	14.1
RG in third week	16	12.2	4.70	4.5	23.5
RG in fourth week	16	13.1	3.00	7.9	19.1
RG in fifth week	16	12.7	3.28	5.9	18.9
RG in sixth week	16	13.3	2.92	7.5	17.6
RG in seventh week	16	11.7	3.14	5.7	17.7
RG in eighth week	16	13.1	3.54	4.6	18.5
RG at weaning	16	16.9	5.24	11.5	28.3
RG in total period	16	15.9	0.25	15.6	16.6

SD: standard deviation

Growth data from both treatment groups and both sexes at different ages were pooled and compared for the effect of treatment, sex and their interaction (Table 3). Body weight at different WOA was not affected by the treatment, sex or their interactions (*P* > 0.05).

Table 3. Mean body weight (kg) at different weeks of age

WOA	Sex		Treatment		Interaction effect*	RMSE
	Male	Female	Corn	Barley		
Birth weight	39.49	39.14	39.31	39.33	0.238	2.332
1	40.24	40.38	40.39	40.23	0.326	2.226
2	42.01	40.93	41.20	41.74	0.323	2.213
3	45.48	44.55	45.11	44.91	0.856	2.310
4	50.36	48.88	49.75	49.49	0.829	3.074
5	55.74	53.44	54.78	54.40	0.679	3.758
6	60.36	58.66	59.65	59.38	0.924	4.396
7	66.37	63.73	65.06	65.031	0.928	5.207
8	72.39	69.85	71.13	71.11	0.782	6.189
Total	81.11	78.56	80.89	78.79	0.616	6.554

*Probability for sex × diet interaction.
RMSE = Root Mean Square of Error

Estimated values of the parameters for functions are presented in Table 4. All functions could be fitted by nonlinear regression during the pre-weaning period. The convergence percentage (C%) for all six functions was 100%.

Table 4. Mean model parameters for calf weight, coefficient of determination (R^2), residual sum of squares (RSS), and convergence percentage (C%) in seven mathematical models describing calf weight before weaning

Model	W0	a	b	c	d	Adj R^2	RSS	C%
Exp. growth (4 params)	-	35.143	0.0126	-1.4×10^{14}	-31.054	0.9997	9424	100
Exp. growth (Stirling)	37.300	0.3488	0.0178	-	-	1.0000	9578	100
Polynomial (Cubic)	39.920	-0.1553	0.0211	-0.00015	-	1.0000	9073	100
Quadratic	-	38.195	0.223	0.0065	-	0.9997	9381	100
Brody	-	35.973	0.0121	-	-	0.9999	9771	100
Ln Brody	-	3.595	0.117	-	-	0.9996	11493	100
Sinusoidal	-	56.676	-7.823	3.560	-3.276	0.9780	72312	100

a, b, c, d: mean parameters of each model. Refer to text for more detail.

The RSS values, as a criterion for the goodness of the fit, showed that the Polynomial (cubic) had the lowest RSS value and was able to demonstrate a suitable fit; nonetheless, other functions provided a perfect fit. The Brody function, as a two-parameter function, showed the best fit, and within the three-parameter functions (Exponential growth Stirling and Quadratic), the Quadratic function showed a smaller RSS value. Amongst the four-parameter functions, the Sinusoidal function possessed the largest value. Based on the present data, the Polynomial function with lower RSS value and higher coefficient of determination (R^2) resulted in a better fit to the data, being superior to other functions.

The accuracy of body weight predictions, assessed by six functions through computing the mean bias and MSPE, is presented in Table 5. The portion of unexplained variation as a component of MSPE remained high for all functions (more than 98%). According to the mean bias, Ln Brody, Polynomial and Quadratic were superior to other functions. However, prediction of body weight variations was improved by Ln Brody function. This is illustrated by RMSPE decreasing from 1.16% to 0.04% (Table 5). In this manner, the regression bias remained constant (0.0% of MSPE). Furthermore, comparison between three-parameter functions revealed the superiority of Quadratic to Exponential growth Stirling, due to the lower mean bias and RMSPE% in the Quadratic function. Among the four-parameter functions, the Sinusoidal function showed the highest RMSPE%.

Table 5. Evaluation of the mathematical models used to calculate the calf weight

Model	Mean bias	MSPE	Components of MSPE, %			RMSPE %
			Mean bias	Regression bias	Unexplained variation	
Exp. growth (4 params)	0.0156	2.045	0.76	0.17	99.07	1.430
Exp. growth (Stirling)	-2.26×10^{-8}	1.424	0.00	0.00	100.0	1.195
Polynomial (Cubic)	-17×10^{-11}	0.964	0.00	0.00	100.0	0.982
Quadratic	1.42×10^{-10}	1.346	0.00	0.00	100.0	1.160
Brody	-0.0355	3.711	0.96	0.47	98.57	1.926
Ln Brody	-825×10^{-14}	0.0016	0.00	0.00	100.0	0.040
Sinusoidal	-2.4×10^{-7}	79.727	0.00	0.00	100.0	8.929

MSPE = mean squared error of prediction.
RMSPE = root of the mean squared error of prediction.

Whenever the functions fit the data with sensible values, using statistical calculations is essential to decide which function must be accepted. As a common rule, the more complicated function (the one with more parameters) fits better with the data. Additionally, the goodness-of-it was assessed using F test (Motulsky and Ransnas, 1987). The calculated F tests, based on the RSS value, for the functions with the same and with different number of parameters are presented in Table 6. The Polynomial function, as a four-parameter equation, was assumed to be superior to other functions. However, the Exponential growth (also 4 parameters) was 3.13% superior to Polynomial, and in 41% of the cases, there were no significant differences between these functions (Table 6). The Brody function was not superior to other functions.

Comparisons between three-parameter functions showed that in 88% of cases the Quadratic function was similar to Exponential growth Stirling, but Quadratic function showed 6.25% more superiority compared to the Exponential growth Stirling function (P<0.05). The Sinusoidal function, as a four-parameter function, showed more than 84% similarity to the Exponential growth Stirling, Quadratic and Brody functions.

Table 6. Statistical significances among different models based on residual sums of squares

Model	Exp. Growth (4 Params)	Exp. growth (Stirling)	Polynomial Cubic	Quadratic	Brody	Sinusoidal
Exp. Growth (4 Params)	----	21.88*	3.13	9.38	84.38	78.13
	----	78.12ǂ	40.62	90.62	15.62	15.62
	----	40.63ǂ	6.25	18.75	96.88	84.38
Exp. growth (Stirling)	0.00	----	0.00	3.13	84.38	0.00
	78.12	----	21.87	87.49	15.62	87.50
	59.38	----	12.50	25.00	100.00	87.50
Polynomial Cubic	56.25	78.13	----	75.00	96.88	81.25
	40.62	21.87	----	25.00	3.12	18.75
	93.75	87.50	----	100.00	100.00	100.00
Quadratic	0.00	9.38	0.00	----	96.88	0.00
	90.62	87.49	25.00	----	3.12	90.62
	81.25	75.00	0.00	----	100.00	87.50
Brody	0.00	0.00	0.00	0.00	----	0.00
	15.62	15.62	3.12	3.12	----	84.37
	0.00	0.00	0.00	0.00	----	78.13
Sinusoidal	6.25	12.50	0.00	9.38	15.63	----
	15.62	87.50	18.75	90.62	84.37	----
	15.63	12.50	0.00	12.50	21.88	----

* Percentage of the cases in which the model specified in the column was significant (P < 0.05) superior to the model specified in the row.
ǂ Percentage of the cases in which the model specified in the column had no significant difference (P > 0.05) compared to the model specified in the row.
ǂ Percentage of the cases in which the sums of squares of the model specified in the column was smaller than the model specified in the row.

Further evaluation of the mathematical functions was performed by comparing the observed and predicted values of the body weight (Table 7). The difference between the predicted and observed values was the lowest in Ln Brody function, however, no significant difference was found between the observed and predicted values for all the functions (P>0.7; paired t-test). Regression between the observed and predicted values showed that all functions had very low *a* value and value equal to 1 for slopes (b). However, the lowest SE and the highest coefficient of correlation (r) were found for the Polynomial function.

Table 7. Evaluation of mathematical functions for weight prediction in calves during the suckling period

Model	Pred. - Obs.	a	b	SE	r	p
Exp. Growth (4 params)	-0.0156	0.2337	0.9662	0.0759	0.9956	0.8370
Exp. growth (Stirling)	2.26×10^{-8}	0.0000	0.9999	0.0637	0.9970	1.0000
Polynomial (Cubic)	-17×10^{-11}	1.5×10^{-11}	1.0000	0.0523	0.9979	1.0000
Quadratic	1.42×10^{-10}	4.99×10^{-10}	1.0000	0.0618	0.9971	1.0000
Brody	-0.0355	0.5299	0.9913	0.1022	0.9921	0.7281
Ln Brody	-825×10^{-14}	-2.2×10^{-10}	1.0000	0.0021	0.9887	1.0000
Sinusoidal	-2.4×10^{-7}	-0.0004	1.0000	0.4759	0.8107	1.0000

a and b: the intercept and the slope of linear regression between observed and predicted values for weight prediction (kg) subjected to the paired t-test.
SE: standard error of estimate.
r: correlation coefficient.
P: probability of the differences between predicted and observed values when subjected to the paired t-test.

There was a weak association between the relative growth rate (g kg^{-1} d^{-1}) and birth weight (P<0.05) with only less than 7% of the variation in the total relative growth rate being explained by the variation in birth weight (Table 8). Significant negative correlations were found between the birth weight and relative growth rate from birth at first week of age (r = -0.482, P = 0.0053), where birth weight accounted for 21% of the variation in relative weight gain (Table 8). The weak correlation between the birth weight and relative weight gain before weaning (r = 0.291, P = 0.106) indicated that there was no association between these parameters.

Table 8. Linear regression of relative growth rate (RG, g kg-1 d-1) on calf birth weight (BIR, kg) at different ages during the suckling period

Sex and age	Equation ± SEM	*P*	R2
First week			
Both sexes	RG = 56.213 (17.345) – 1.325 (0.440) BIR	0.0053	0.21
Male	RG = 23.595 (22.614) – 0.515 (0.571) BIR	0.0548	0.05
Female	RG = 24.283 (25.206) – 2.026 (0.643) BIR	0.0071	0.37
Fourth week			
Male	RG = 39.794 (20.153) – 0.641 (0.510) BIR	0.2292	0.04
Female	RG = -8.982 (11.933) + 0.565 (0.304) BIR	0.0844	0.14
Sixth week			
Both sexes	RG = 31.183 (8.609) – (0.480 (0.219) BIR	0.0359	0.11
Male	RG = 36.479 (10.714) – 0.637 (0.771) BIR	0.0339	0.23
Female	RG = 24.073 (12.658) – 0.276 (0.323) BIR	0.4069	0.05
Total weaning period			
Both sexes	RG = 14.205 (0.960) + 0.045 (0.024) BIR	0.0765	0.07
Male	RG = 12.802 (1.587) + 0.081 (0.040) BIR	0.0636	0.17
Female	RG = 15.542 (1.103) + 0.010 (0.028) BIR	0.7288	0.01

Discussion

Nonlinear functions have been used extensively to model animal growth (Thornley and France, 2007). In modern commercial dairy farms, prediction of body weight in suckling calves is vital in all aspects of calf rearing such as provision of nutrients for optimal growth. Assuming an appropriate growth function, the accuracy of function parameters depends on the accuracy of the data. The data set of the current study was collected from male and female calves reared on two types of starter diets from birth to weaning.

Growth curves are often nonlinear sigmoidal functions parameterized to include an asymptote and an inflection point. However, in suckling dairy calves growth will continue sharply after weaning and does not plateau at weaning time, i.e., the growth curve is not sigmoidal with an asymptote and inflection point. Thus, mathematical functions such as Gompertz, logistic, Lopez, Richards which describe the sigmoidal growth curve cannot fit to the data during the suckling period. Cumulative growth curves from birth to weaning exhibiting the typical rising trend observed in rapidly growing young calves can be described by hyperbolic equations such as Bordy (1945) and Exponential growth curve. Sinusoidal curve, used in this experiment, can describe the patterns of exhibiting faster early growth and a fairly low but variable point of inflection. This function also can describe a wide range of hyperbolic shapes when there is no point of inflection. Since the sinusoidal function is periodic, we only need consider its behavior over a particular interval, e.g., the ascending pattern of the curve (Darmani Kuhi et al., 2018).

Notwithstanding, a simple function with lower parameters seems to be better and easier to use by animal scientists. As a general rule, when comparing the fits of two functions, the first step is to examine the best-fit value of each function to make sure they are scientifically valid. Based on the values of adjusted coefficient of determination (R^2), none of the functions was significantly better than the others, a finding also reported in broiler chickens (Darmani Kuhi et al., 2003). If two functions fit the data with sensible values, they should be compared with the goodness-of-the fit as quantified by RSS. Therefore, another comparison among the functions was based on the RSS values. Based on this criterion, Polynomial cubic and Sinusoidal functions obtained the best and worst fits, respectively.

The F-test compares the fit of two equations, where the more complex equation (the one with more parameters) fits better than the simple one (i.e., a smaller RSS), although there is no need for statistical calculations to reject a function, if the best-fit parameters of that function make no scientific sense (Darmani Kuhi et al., 2003). Therefore, if the more complex function is inferior (higher RSS) to the simpler function, it should be rejected with a conclusion that the simpler function fits better. This would happen very rarely, due to the fact that the curve generated by the more complex function would always have a lower RSS, simply because it is more flexible with more inflection points.

Based on the F-test criterion, Polynomial cubic, Exponential growth (4 parameters) and Sinusoidal functions were superior to other functions (Table 6). Although flexible functions always have a statistically significant parameter estimate, this should not be the sole criterion in selecting a function. According to the mean bias (Table 4), the ranking of the functions was: Polynomial > Quadratic > Exponential growth (Stirling) > Sinusoidal > Exponential growth (4 parameters) > Brody > Ln Brody.

Whereas the Polynomial and Quadratic functions resulted in the lowest mean bias value and therefore the best fit, nonetheless, when RMSPE% values were used to compare the functions, Polynomial function had the least value, suggesting that this function was best for predicting the body weight. Moreover, convergence percentage is another criterion to compare the functions, but in the present study, all function met the 100% convergence. Therefore, this criterion cannot help to distinguish fitness priority among functions. However, it should be noted that such divergent findings, related to the function comparison criteria and the best function choice, are quite common in the literature (Forni et al., 2009; Malhado et al., 2009; Silva et al., 2012; Moharrery and Mirzaei, 2014). The sinusoidal, has a variable point of inflection and the ability to approach the final weaning weight along either a gradual or an abrupt trajectory, and describes a wide range of hyperbolic shapes when there is no point of inflection (Darmani Kuhi et al., 2018).

Relative growth rate (grams gain per kilogram live weight per day) between birth and weaning can be used as an index of the genetic effects on the efficiency of utilization of nutrient for gain in metabolically active tissues. This is because, during this period, the stored fat is a small proportion of total weight gain (Trenkle and Marple, 1983; Bailey, 1989) and the efficiency of gain would not be greatly influenced by variations in the composition of gain.

Calves in the present study recorded 16 g kg^{-1} d^{-1} relative growth rates at weaning which is 52% higher than the relative growth rates in Holstein calves recording 100 kg weight at weaning (Bailey and Mears, 1990). The calves in the present study were 8.6% smaller at birth (39.3 vs. 43 kg) compared to those in the study by Bailey and Mears (1990). The absence of a significant relationship between the birth weight and relative weight gain suggests that factors controlling the *in utero* growth differ from those controlling the subsequent growth to weaning. Because birth weight is highly heritable (Preston and Willis, 1970; Woldehawariat et al., 1977), the factors controlling the birth weight must have an important genetic component, although cow age also has a significant effect (Preston and Willis, 1970). It seems likely that regardless of the multitude of the factors that affect the growth rate *in utero*, their combined effect would be primarily to regulate the energy flow to the fetus (Meltror, 1983). If the genetic effects on fetal growth were exercised through regulation of the efficiency of utilization of energy for growth, then a significant correlation between the birth weight and relative growth rate from birth to weaning would have been expected. However, such a relationship was not found.

Conclusions

Comparison of six functions, in terms of the goodness of the fit criteria, revealed that the Polynomial cubic function was the most appropriate functions for describing the calf growth during the suckling period. The flexible growth functions (more parameters) very often give a closer fit to data points and a smaller RSS value than the simpler functions such as the Brody functions. Divergent findings of function comparison criteria, with respect to the best function choice, was also found in the present study. It seems that the paired t-test, calculated for both predicted and observed values of the functions along with RMSPE%, is an appropriate criterion for the evaluation of functions. However, it requires special attention to characterize the growth patterns of calves under different environmental conditions or nutritional regimes. Thus, further studies are needed to examine the most approppriate function, in which the growth function parameters and growth characteristics would provide more accurate outputs for calf rearing purposes.

Acknowledgement

The authors are grateful to the staff members of Shahrekord University Research Department for their assistance in this research.

References

Bailey, C.B., 1989. Rate and efficiency of gain, body composition, nitrogen metabolism, and blood composition of growing Holstein steers given diets of roughage or concentrate. *Canadian Journal of Animal Science* 69, 707-725.

Bailey, C.B., Mears G.J., 1990. Birth weight in calves and its relation to growth rates from birth to weaning and weaning to slaughter. *Canadian Journal of Animal Science* 70, 157-173.

Brody, S., 1945. Bioenergetics and Growth. Rheinhold Publishing Corporation., New York, USA.

Cannas, A., Atzori A.S., 2005. Development and evaluation of a model to predict sheep nutrient requirements and feed utilization. *Italian Journal of Animal Science* 4 (Suppl. 1), 15-33.

Darmani Kuhi, H., Kebreab, E., Lopez, 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. *Poultry Science* 82, 1536–1543.

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. *Poultry Science* 97, 227–235.

Forni, S., Piles, M., Blasco, A., Varona, L., Oliveira, H.N., Lobo, R.B., Albuquerque, L.G., 2009. Comparison of different non-linear functions to describe Nellore cattle growth. *Journal of Animal Science* 87, 496–506.

Haefner, J.W., 1996. Modeling Biological Systems. Principles and Applications. Chapman & Hall, New York, USA.

Hill, T.M., Quigley, J.D., Bateman, H.G., Suarez-Mena, F.X., Dennis, T.S., Schlotterbeck, R.L., 2016. Effect of milk replacer program on calf performance and digestion of nutrients in dairy calves to 4 months of age. *Journal of Dairy Science* 99, 8103–8110.

Jasper, J., Weary, D.M., 2002. Effects of *ad libitum* milk intake on dairy calves. *Journal of Dairy Science* 85, 3054–3058

Malhado, C.H.M., Carneiro, P.L.S., Affonso, P.R.A.M., Souza, J.R., Sarmento, J.L.R., 2009. Growth curves in Dorper sheep crossed with the local Brazilian breeds, Morada Nova, Rabo Largo, and Santa Ines. *Small Ruminant Research* 84, 16–21.

Mayer, D.G., Butler, D.G., 1993. Statistical validation. *Ecological Modelling* 68, 21-32.

Mellor, D.J., 1983. Nutritional and placental determinants of foetal growth rate in sheep and consequences for the newborn lamb. *British Veterinary Journal* 139, 307-324.

Moharrery, A., Mirzaei M., 2014. Growth characteristics of commercial broiler and native chickens as predicted by different growth functions. *Journal of Animal and Feed Science* 23, 82–89.

Motulsky, H.J., Ransnas, L.A., 1987. Fitting curves to data using nonlinear regression: A practical and nonmathematical review. *FASEB Journal* 1, 365–374.

NRC, 2001. Nutrient Requirements of Dairy Cattle. 7th ed. National Academy Press, Washington, DC, USA.

Preston, T.R., Willis, M.B., 1970. Intensive Beef Production. Pergamon Press, Oxford, UK.

Sarmento, J.L.R., Regazzi, A.J., Souza, W.H., Torres, R.A., Breda, F.C., Menezes, G.R.O., 2006. Study of growth curve of Santa Ines sheep. *Revista Brasileira de Zootecnia* 35, 435–442.

Silva, L.S.A., Fraga, A.B., Silva, F.L., Beelen, P.M.G., Silva, R.M.O., Tonhati, H., Barros, C.C., 2012. Growth curve in Santa Ines sheep. *Small Ruminant Research* 105, 182–185.

Stamey, J.A., Janovick, N.A., Kertz, A.F., Drackley, J.K., 2012. Influence of starter protein content on growth of dairy calves in an enhanced early nutrition program. *Journal of Dairy Science* 95, 3327–3336.

Tedeschi, L.O., Fox, D.G., Saniz, R.D., Barioni, L.G., Mederios, S.R., Boin, C., 2005. Mathematical models in ruminant nutrition. *Scientia Agricola* 62, 76-91.

Terre, M., Devant, M., Bach, A., 2007. Effect of level of milk replacer fed to Holstein calves on performance during the preweaning period and starter digestibility at weaning. *Livestock Science* 110, 82–88.

Thornley J.H.M., France J., 2007. Mathematical Models in Agriculture. Quantitative Methods for the Plant, Animal, and Ecological Sciences. 2nd ed. CAB International. Wallingford, UK.

Trenkle, A., Marple, D.N., 1983. Growth and development of meat animals. *Journal of Animal Science* 57 (Suppl.2), 273-283.

Wallach, D., Goffinet, B., 1989. Mean squared error of prediction as a criterion for evaluating and comparing system models. *Ecological Modelling* 44, 299-306.

Woldehawariat, G., Talamantes, M.A., Pettyt, R.R., Cartwright, T.C., 1977. A summary of genetic and environmental statistics for growth and conformation characters of beef cattle. Texas Agricultural Experiment Station Technical, Report No. 103, Texas.