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Research Article

Models Describing Growth Characteristics of Holstein Dairy Cows Raised in Korea

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ABSTRACT

The objective of the present study was to determine the best model to describe and quantify the changes in live body weight, height at withers, height at rump, body length and chest girth of Holstein cows raised under Korean feeding conditions for 50 months. The five standard growth models namely polynomial linear regression models, regression of growth variables on the first and second-order of ages in days (model 1) and regression of growth variables on age covariates from first to the third-order (model 2) as well as non-linear models were fitted and evaluated for representing growth pattern of Holstein cows raised in Korean feeding circumstances. Nonlinear models fitted were three exponential growth curve models; Brody, Gompertz, and von Bertalanffy functional models. For this purpose, a total of 22 Holstein cows raised in Korea used in the period from April 2016 to May 2020. Each model fitted to monthly growth curve records of dairy cows by using PROC NLIN procedure in SAS program. On the basis of the results, nonlinear models showed the lower root mean square of error (RMSE) for live body weight, height at withers, height at rump, body length and chest girth (12.22, 1.95, 1.55, 4.04, 2.06) with higher correlation coefficiency (R^2) values for live body weight, height at withers, height at rump, body length and chest girth (0.99, 0.99, 0.99, 1.00, 1.00). Overall, the evaluation of the different growth models indicated that the Gompertz model used in the study seemed to be the most appropriate one for standard growth of Holstein cows raised under Korean feeding system.

(**Key words**: Holstein cow, Growth curve, Model, Body weight, Chest girth, Rump)

Ⅰ. INTRODUCTION

Growth predictions in dairy cows are considerable value to dairy husbandry researches and farm holders. As it provides useful information for the development of new strategic plans related to nutrition and genetic selection and reproduction, such as the improved management, and nutritional reinforcement, breeding technologies associated to growth and assessment of genetic makeup of the animals for growth, contributing to the progress of decision-making in a dairy farm as well as research area (Marinho et al., 2013). The shape of the growth curve in beef and dairy cows are associated with the efficacy of the productivity and longevity of the animals (Engelken, 2008).

Growth curve studies in dairy cows are already available from several countries. Additional studies are needed since the rate of growth may vary in several countries due to the practice of different feeding and management system as well as in the outlines of breeding. Each country has been developing its feeding practices reflecting its circumstances of regions and agricultural resources. Studies on growth information and the related prediction are important for decision makings such as the time for sale that directly related to the profitability of animal production. Due to the above reasons, farmers, as well as researchers, are paying more attention to develop the new strategies for maximizing growth with feeding management (Aziz et al., 2006; Darmani Kuhi et al., 2010).

Studies on growth curve estimation in dairy cows have mainly used nonlinear models which related to cow weight and age (Lopez et al., 2015; Souza et al., 2010; Vazquez et al., 2012). Different mathematical equations have also used to predict the

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lactation curves of dairy cows (Fathi-Nasri et al., 2008). The use of the mathematical model in growth curve estimation provides the information of indicators with few biological parameters that enable both interpretation and understanding of the phenomenon (Fitzhugh, 1976). The importance of growth curve estimation in dairy cows include (i) having a biological interpretation, (ii) measuring the treatment effects over time, (iii) identifying overweight cows at a younger age in a population by investigating the growth curve and limit weight, (iv) measuring the individual within or among variances of great interest in genetic analysis (Freitas, 2005).

A wide range of mathematical models have been used to estimate the growth curve in dairy cows for a well fit function model as an alternative. Therefore, in this study, we aimed to explore and compare the Polynomial linear regression model 1 and 2 and non-linear (Brody, Gompertz and von Bertalanffy) functional model for the benefit of the growth curve of Holstein dairy cows reared under Korean feeding conditions.

Ⅱ. MATERIALS AND METHODS

1. Animal feeds and feeding

A total of 22 Holstein cows were fed and raised according to Korean feeding standard for dairy cattle 2012 and 2017 (Korean feeding standard of dairy cattle, 2017). Individuals from newborn calves to heifers, mature and milking cows we were employed for lifetime growth experiment. The original data set consisted of observation from April 2016 to May 2020 in dairy cattle for 50 months, which a total of 918 measures for body weight, 851 measures for height at wither, 823 measures for height at rump, 813 measures for body length and 561 measures for chest girth for the growth estimation. The study was conducted in the experimental dairy farm, National Institute of Animal Science (NIAS), Cheonan, Republic of Korea. The study was approved by the Institutional Animal Care and Use Committee (IACUC, No. 2019-376) at the National Institutional of Animal Science (NIAS, Jeonju, Korea), Republic of Korea. During experimental periods, calves, heifers and mature animals were fed twice a day at 09.00 and 17.00, and the feeds allowances were indicated in Table 1. Lactating dairy cows was fed TMR once a day at 09:00 according to their milk production and lactating cycle and water was provided *ad libitum* (Table 2). Also, the chemical, ingredients compositions and allowances of feeds for calves, heifers, mature cows and lactating cows are shown in Table 1, 2, respectively.

For studying growth curves in dairy cows, each was weighed on a monthly basis from the birth to 50 months of age. The first measurements of height at wither and rump, body length (horizontal length between wither and pin) and chest girth besides

Table 1. The chemical compositions and daily allowances of feeds for calves, heifers and mature cows

Item	Concentrates				Mixed hay*	Corn silage
	Calf (<3mon)	Calf (<6mon)	Heifer	Mature cows (Dry)		
Chemical compositions						
Moisture (%, as fed)	12.04	11.68	10.96	11.85	8.96	73.49
Crude protein (%, DM)	20.02	16.96	13.93	18.95	11.60	10.64
Ether extracts (%, DM)	3.35	3.87	3.62	3.20	2.23	4.07
Crude fiber (%, DM)	8.00	9.28	8.21	7.09	28.7	22.59
Ashes (%, DM)	7.67	7.23	7.71	8.37	8.17	4.39
NDF (%, DM)	27.60	32.70	29.66	28.81	63.64	43.61
ADF (%, DM)	10.50	13.63	12.17	11.85	31.38	26.53
TDN (% DM)	84.49	85.92	85.86	83.78	57.21	64.9
Feeds allowances (kg/d per month of age)						
3 ~ 5 mon.	2.0~3.0		-	-	2.0	5.0
6 ~ 13 mon.	2.5~3.5		-	-	3.0	7.0
14 ~ 24 mon.	-		2.0~3.5	-	4.0	10.0
25 ~ 50 mon. (except the lactating cows)	-		-	2.0~3.5	-	4~10

* Mixed hay: Tall fescue 50%, Orchard grass 50%

Table 2. The chemical and ingredient compositions of feeds fed lactating cows (Milk Yield 30-35 kg/d)

Item	Concentrates	Alfalfa	Timothy	Mixed hay	Corn silage	TMR**
Chemical compositions						
Moisture (%, as fed)	11.55	9.78	8.62	12.20	54.08	52.52
Crude protein (%, DM)	18.95	13.01	9.65	12.41	7.76	16.75
Ether extracts (%, DM)	3.20	2.35	2.36	2.38	1.06	4.38
Crude fiber (%, DM)	7.09	31.07	32.82	32.26	7.60	18.18
Ashes (%, DM)	8.37	8.71	5.99	7.48	1.39	6.91
NDF (%, DM)	28.81	45.00	62.14	56.37	56.75	38.44
ADF (%, DM)	11.85	33.19	35.68	31.83	35.89	21.41
Ingredient compositions (%, DM)						
	43.51	10.69	9.02	14.38	20.94	

* Feed additives: Total 1.47% included sodium bicarbonate 0.20%, limestone 0.28%, and minerals & amino acid mixture 0.99%

** Total digestible nutrients (TDN) 73%, energy balance (NE_L) 1.80Mcal/kg, Milk yield 31.5kg, Milk fat 4.0%, Milk protein 3.0%, DMI 22.3kg

Table 3. Polynomial and non-linear functions used for modeling the growth curve

Model	Functional form
Polynomial linear Regression 1	$y= \beta_0+ \beta_1 t+ \beta_2 t^2+\varepsilon$
Polynomial linear Regression 2	$y=\beta_0+ \beta_1 t+ \beta_2 t^2+ \beta_3 t^3+\varepsilon$
Brody (Brody, 1945)	$y = A(1-be^{-kt}) +\varepsilon$
Gompertz (Laird, 1965)	$y = Ae^{-be^{-kt}} + \varepsilon$
von Bertalanffy (von Bertalanffy, 1957)	$y=A(1-be^{-kt})^3+\varepsilon$

β= individual measure
A= Asymptotic measure of parameter
b= proportion to A
k= rate of maturing (relative growth rate)
e= exponential (Euler's number, e=2.71828)
t= month of age
ε=residual, $\varepsilon \sim N(\mu, \sigma^2)$

weight, were taken three months after birth as the animal could stand naturally and continued every month for 50 months of age. The height of the animals was measured as the vertical distance from the top of the withers to the ground. The length of the animals was measured as the horizontal distance from the top of the withers to the ischium. The chest girth of the animals was measured as the circumstance of the animal's barrel measured immediately behind the front leg. All the measures were recorded in centimeter.

2. Growth models

The polynomial linear regression (1 and 2) and non-linear (Brody, Gompertz and von Bertalanffy) functional models used to describe the growth curve in dairy cows raised under Korean feeding management are presented in Table 3.

3. Statistical analysis

General least-squares analysis was performed to estimate regression coefficient parameters of the polynomial linear growth function for body weight, height at withers, height at rump, body length and, chest girth on age in days using PROC GLM procedure of SAS program (SAS Institute Inc, Cary, NC, USA). Parameters of nonlinear growth curve models were estimated by iteration method with Gauss-Newton or Marquardt iterative methods using PROC NLIN procedure of SAS. Model comparisons were made based the magnitude of R^2 (Model Sum of Squares/ Corrected Total Sum of Squares) and square root of mean squares of error (RMSE) which depend only on age in days as explanatory variable(s) without any other sources of variation.

Ⅲ. RESULTS AND DISCUSSION

Over the past decades, mathematical equations have been used to measure the growth curve in farm animal for improving their selection traits. Particularly, these mathematical equations have been used in different features of management in producing meat animals for describing the ideal feeding program and determining the optimum slaughtering age. The suitable growth curve model is useful to apply directly on the point of the curve and estimate the growth status for an individual cow. So, it is important to consider a best fitting growth curve by changing the growth curve parameters. The literature review has shown that there is a wide range of growth curve model has been developed, according to how perfectly they fit the data. Most of the recent study, applying nonlinear functions to model the growth curve reported the data from Holstein cows and used routine nonlinear models, but studies on the growth curve of dairy cattle, especially using comparative models, are sparse in the literature. Therefore, in this study, we used Polynomial linear regression model and nonlinear model for model goodness of fit the data (Bahreini Behzadi et al., 2014).

The asymptotic mature size (A) and rate of maturing (k) values are considered as the important parameters in growth curve analysis. The parameters of linear model were estimated using the least squares method for each cow and the observed growth curve parameters (A, b and k) for Brody, Gompertz and von Bertalanffy growth function (live body weight) of Holstein cows raised in Korea were estimated using maximum likelihood method for each animal. The means and populations standard errors of the parameters are shown in Table 4. The live body weight estimated using the linear and nonlinear models growth function parameters are shown in Fig. 1.

Comparison of the models for body weight, based on the R^2 values, the Gompertz model had a higher R^2 value (1.00) let to fit an improved fit of data compared to Polynomial linear regression models 1 and 2 (0.99 and 0.99), Brody (0.99), and von Bertalanffy (0.99) model, also the Gompertz model showed the lower RMSE (12.22) value for the goodness fit model explaining the growth curve of the Holstein cows. Our study results are agreed with Won et al. (2017) who previously reported on growth curve analysis of Holstein cows. With the estimates of the parameters (k) of the models, animal can be selected by the rate of maturing, because those with higher maturity rate are earlier than those with lower maturity rate. In the animal production trait, maturity rate is an important parameter for animal selection (Brown et al., 1976).

The body measurement allows us to draw conclusion about maturity rate and may also serves as significant selective consideration for animal production (Bene et al., 2007). The growth curve was usually measured of height at withers, height at rump, body length and chest girth. The height of animal at a given age could be used to predict its growth curve as well as its mature rate. The height at withers was estimated using the least squares means of the linear and nonlinear functional parameter for Holstein cows raised in Korea are shown in Fig. 2. The estimated value for the height at withers of the Holstein cow growth models by using Polynomial linear regression models and nonlinear models are summarized with their RMSE and R^2 values in

Table 4. Estimation of growth parameters of body weight for Holstein cows in Korea using linear and different non-linear models

Model	Linear model				RMSE Min~Max	R^2 Min~Max
	β_0	β_1	β_2	β_3		
Polynomial linear regression 1	-6.2395 ± 49.3962	0.9517 ± 0.16280	-0.000306 ± 0.0000901	-	11.63~41.68	0.96~0.99
Polynomial linear regression 2	-51.1132 ± 60.9181	1.1693 ± 0.3808	-0.0005 ± 0.0005	0.20 ± 0.55	11.08~38.67	0.97~0.99
Model	Nonlinear model				RMSE Min~Max	R^2 Min~Max
	A±SE	b±SE	k±SE			
Brody	863.93 ± 108.5687	1.0245 ± 0.0214	0.0014 ± 0.000214	-	24.90~126.04	0.95~0.99
Gompertz	739.66 ± 61.2605	3.0092 ± 0.2921	0.0034 ± 0.000386	-	12.22~122.40	0.95~1.00
von Bertalanffy	757.25 ± 67.2278	0.6947 ± 0.0533	0.0027 ± 0.000338	-	14.69~122.96	0.95~0.99

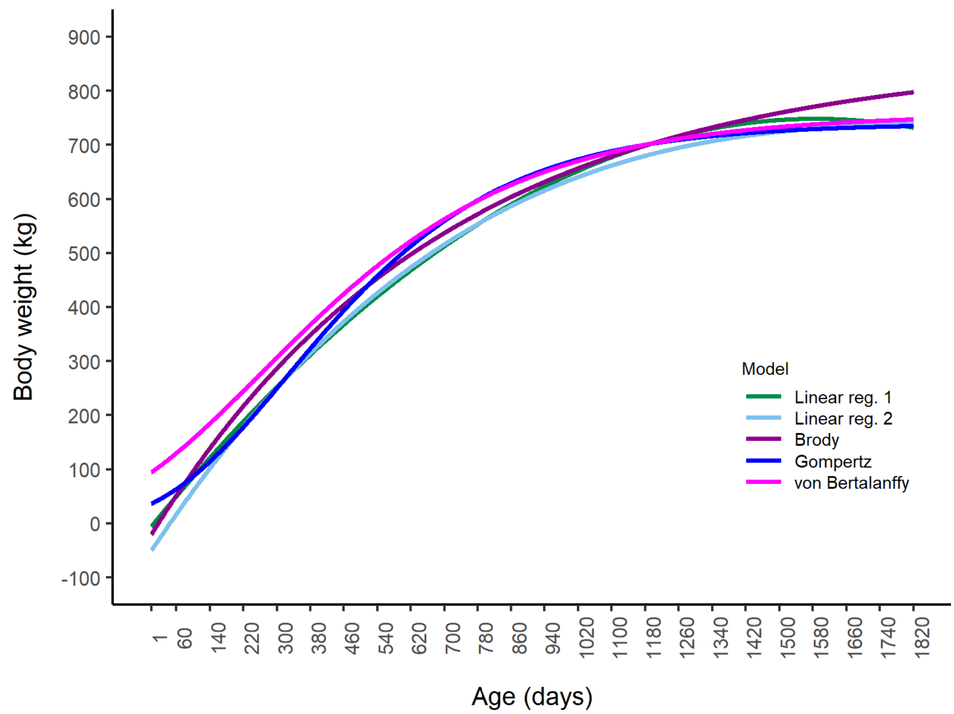

Fig. 1. Estimation of growth parameters for live body weights of Holstein cows raised in Korea for 50 months of age using linear and nonlinear functional models live body weights instead of live weights (Linear reg.1, Polynomial linear regression 1; Linear reg.2, Polynomial linear regression 2; Brody, brody equation; Gompertz. Gompertz equation; von Bertalanffy, von Bertalanffy equation)

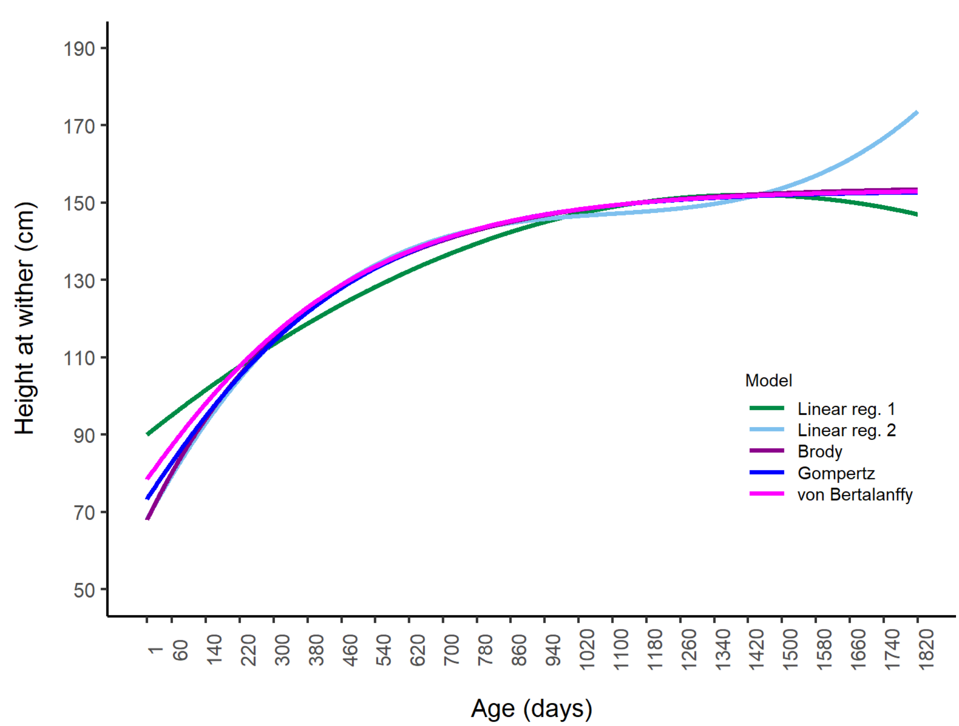

Fig. 2. Estimation of growth parameters for height at withers of Holstein cows for 50 months using linear and nonlinear functional models (Linear reg.1, Polynomial linear regression 1; Linear reg.2, Polynomial linear regression 2; Brody, brody equation; Gompertz. Gompertz equation; von Bertalanffy, von Bertalanffy equation)

Table 5. Estimation of growth parameters for height at withers in Holstein cows in Korea using linear and different non-linear models

Model	Linear model				RMSE Min~Max	R^2 Min~Max
	β_0	β_1	β_2	β_3		
Polynomial linear regression 1	89.8795 ± 3.6557	0.0878 ± 0.0091	0.000031 ± 0.0000052	-	1.69~4.51	0.94~0.98
Polynomial linear regression 2	67.8588 ± 8.7490	0.2035 ± 0.0403	-0.0001 ± 0.0580	0.000000055 ± 0.000000018	1.61~3.06	0.98~0.99
Model	Nonlinear model				RMSE Min~Max	R^2 Min~Max
	A±SE	b±SE	k±SE			
Brody	154.21 ± 5.1997	0.5615 ± 0.0484	0.0026 ± 0.000570	-	1.95~102.05	0.39~0.98
Gompertz	153.11 ± 4.6989	0.7390 ± 0.0749	0.0030 ± 0.000636	-	1.96~21.35	0.97~1.00
von Bertalanffy	153.44 ± 4.8393	0.2245 ± 0.0215	0.0029 ± 0.000613	-	1.96~3.28	0.97~1.00

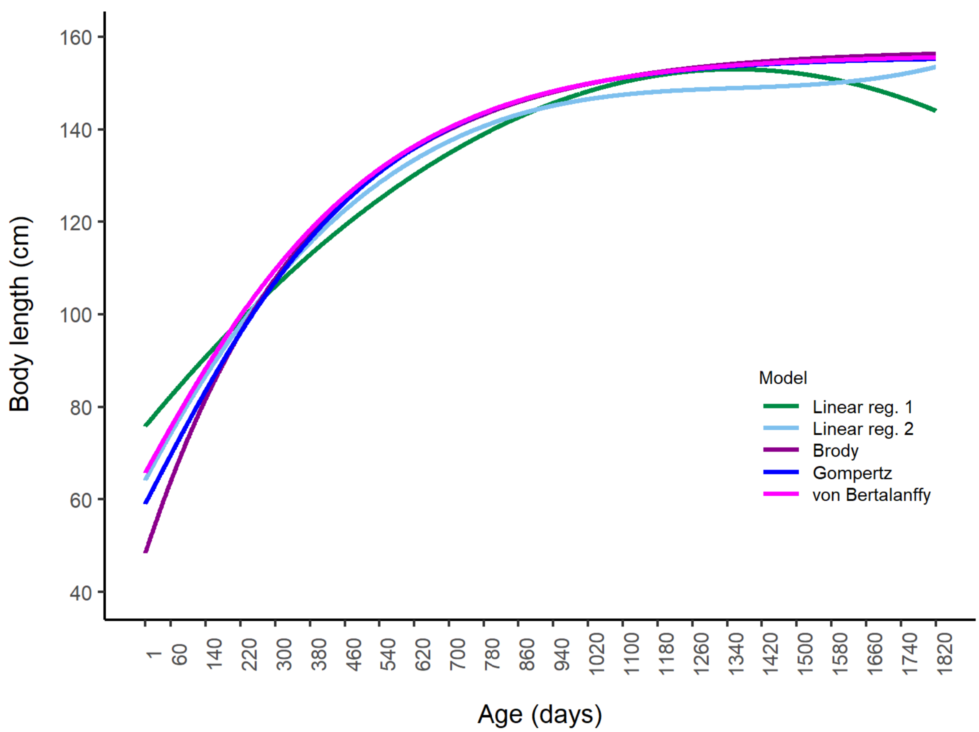

Fig. 3. Estimation of growth parameters for heights at rump of Holstein cows in Korea for 50 months of age using linear and nonlinear functional models (Linear reg.1, Polynomial linear regression 1; Linear reg.2, Polynomial linear regression 2; Brody, brody equation; Gompertz. Gompertz equation; von Bertalanffy, von Bertalanffy equation)

Table 5. From the study result, Gompertz and von Bertalanffy model indicated a higher R^2 (1.00) value with lower RMSE (1.96) value that confirmed an improved fit of data compared with other linear and nonlinear models. Among the study, the estimated values for the nonlinear models were higher as compared with Polynomial linear regression model and seemed to be overestimated.

The height at rump is an extremely important measure due to easiness and good proportion to other body measurements. According to Anderson (2008), it is a useful reference point for the design of the growth curve traits. RMSE and R^2 of the observed for height at rump was estimated by the Polynomial linear regression and nonlinear functional models. The parameter (height at rump) of linear model was estimated using the least squares method for each animal and those of non-linear model

Table 6. Estimation of growth parameters of height at rump for Holstein cows using linear and different non-linear models

Model	Linear model				RMSE Min~Max	R^2 Min~Max
	β_0	β_1	β_2	β_3		
Polynomial linear regression 1	88.078 ± 4.5583	0.1115 ± 0.0126	0.0000471 ± 0.0000054	-	1.72~4.52	0.92~0.99
Polynomial linear regression 2	63.31 ± 10.5754	0.24 ± 0.0461	-0.00022 ± 0.0000554	0.000000056 ± 0.000000019	1.03~3.06	0.97~0.99
Model	Nonlinear model				RMSE Min~Max	R^2 Min~Max
	A±SE	b±SE	k±SE			
Brody	153.71 ± 4.3708	0.6563 ± 0.0936	0.0035 ± 0.000545	-	1.70~3.32	0.97~0.99
Gompertz	153.24 ± 4.2004	0.8742 ± 0.1515	0.0041 ± 0.000588	-	1.55~3.25	1.00~1.00
von Bertalanffy	153.38 ± 4.2500	0.2645 ± 0.0430	0.0039 ± 0.000572	-	1.60~3.26	1.00~1.00

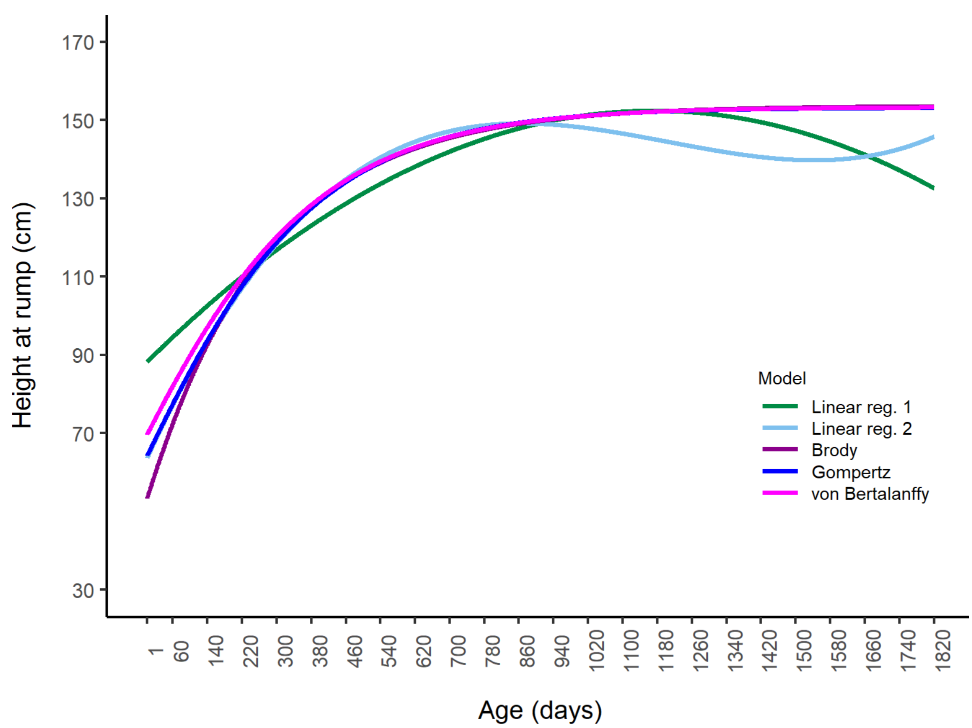

Fig. 4. Estimation of growth parameters for body length of Holstein cows in Korea for 50 months of age using linear (a) and nonlinear (b) functional models (Linear reg.1, Polynomial linear regression 1; Linear reg.2, Polynomial linear regression 2; Brody, brody equation; Gompertz. Gompertz equation; von Bertalanffy, von Bertalanffy equation)

were estimated using maximum likelihood method for each animal. The means and populations standard errors of the parameters are shown in Fig. 3. The average A, b and k parameters of the nonlinear for height at rump of cows from the selected models with their RMSE and R^2 are summarized in Table 6. The best estimation based on R^2 values showed that Gompertz model had a higher R^2 (1.00) with lower RMSE (1.55) values than that of Polynomial linear regression, Brody and von Bertalanffy models and it would be more convenient to measure the height at rump.

Body length may be a reference measurement in the design of stable growth curve analysis in dairy cattle. The estimated body length using the least squares means of the linear and nonlinear functional parameter for Holstein cows are shown in Fig. 4. The estimated growth curve parameters (A, b and k) for body length of Holstein cows from the two.

Polynomial models and three nonlinear models with their

Table 7. Estimation of growth parameters of body length for Holstein cows raised in Korea using linear and different non-linear models

Model	Linear model				RMSE Min~Max	R^2 Min~Max
	β_0	β_1	β_2	β_3		
Polynomial linear regression 1	75.6656 ± 4.6004	0.1140 ± 0.0130	0.000042 ± 0.0000077	-	3.20~8.02	0.91~0.97
Polynomial linear regression 2	63.9464 ± 9.6307	0.1805 ± 0.0567	-0.00013 ± 0.000072	0.000000032 ± 0.000000026	2.77~8.15	0.94~0.98
Model	**Nonlinear model**				**RMSE Min~Max**	**R^2 Min~Max**
	A±SE	b±SE	k±SE			
Brody	157.27 ± 8.2968	0.6946 ± 0.0977	0.0026 ± 0.000842	-	4.04~26.46	0.31~0.97
Gompertz	155.71 ± 7.5138	0.9731 ± 0.1481	0.0031 ± 0.000922	-	4.11~26.47	0.96~1.00
von Bertalanffy	156.16 ± 7.7331	0.2893 ± 0.0428	0.2645 ± 0.000894	-	4.08~26.46	0.96~1.00

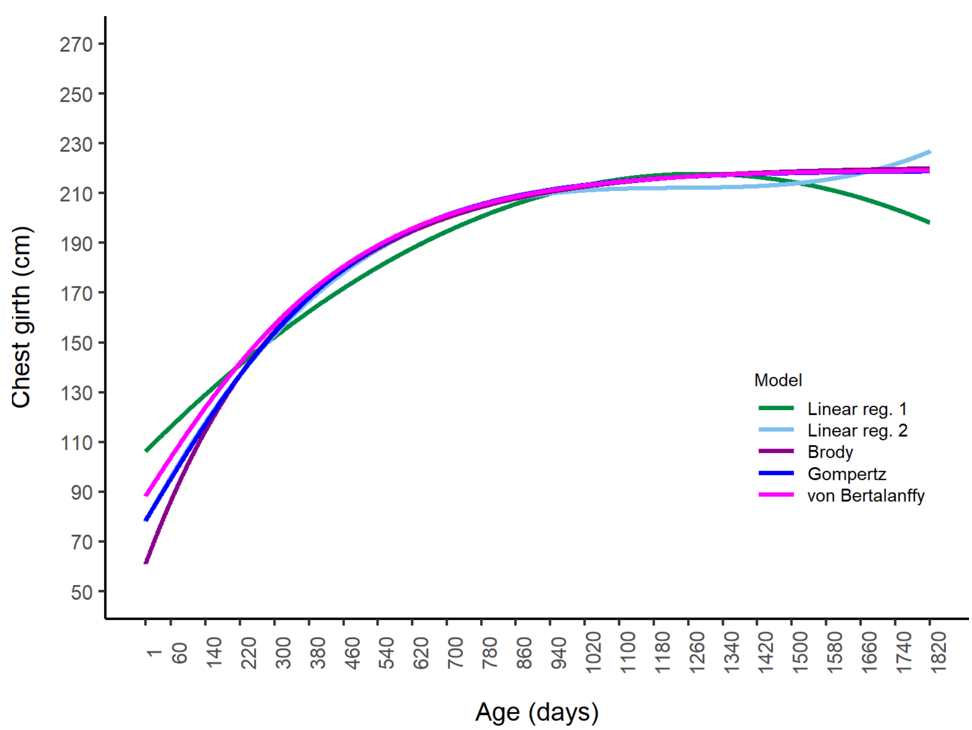

Fig. 5. Estimation of growth parameters for chest girth of Holstein cows raised in Korea for 50 months of age using linear nonlinear functional models (Linear reg.1, Polynomial linear regression 1; Linear reg.2, Polynomial linear regression 2; Brody, brody equation; Gompertz. Gompertz equation; von Bertalanffy, von Bertalanffy equation)

RMSE and R^2 are shown in Table 7. Comparison of the models based on the R^2 values, the Gompertz von Bertalanffy model showed the higher R^2 value (1.00) with lower RMSE (4.11 and 4.08 respectively) value as compared to Polynomial linear regression model 1 and 2 (0.97, 3.20 and 0.98, 2.77 respectively), and Brody (0.96, 4.04) models. So, this model confirms the goodness fit model explaining the growth curve of the Holstein cows. From the results, the Gompertz and von Bertalanffy models had a higher R^2 values (0.99) with lower RMSE (9.89) value than those of other models. This can be a result of negative correlation between the asymptotic mature length and growth rate parameters of the cows.

Body weight is closely associated with other growth measurements; especially chest girth is one of most accepted satisfactory predictor of live body weight analysis in animals (Lukuyu et al., 2016;

Table 8. Estimation of growth parameters of chest girth for Holstein cows raised in Korea using linear and different non-linear models

Model	Linear model				RMSE Min~Max	R^2 Min~Max
	β_0	β_1	β_2	β_3		
Polynomial linear regression 1	105.9813 ± 6.292	0.1744 ± 0.0205	0.000068 ± 0.000012	-	2.53~7.00	0.95~0.99
Polynomial linear regression 2	77.5825 ± 11.758	0.3233 ± 0.0629	0.00026 ± 0.000080	0.00000007 ± 0.00000030	2.20~5.01	0.96~1.00
Model	Nonlinear model				RMSE Min~Max	R^2 Min~Max
	A±SE	*b*±SE	*k*±SE			
Brody	220.68 ± 7.4346	0.7260 ± 0.0776	0.0029 ± 0.000454	-	2.06~6.34	0.96~1.00
Gompertz	219.17 ± 7.0475	1.0318 ± 0.1298	0.0035 ± 0.000504	-	2.22~6.13	1.00~1.00
von Bertalanffy	219.61 ± 7.1548	0.3051 ± 0.0363	0.0033 ± 0.000485	-	2.15~6.12	0.99~1.00

Lesosky et al., 2012). The estimated chest girth was using the least squares means of the nonlinear functional parameter for Holstein cows in Korea are shown in Fig. 5. The observed growth curve parameter (A, b and k) values for chest girth of Holstein cows from the selected models with their RMSE and R^2 are shown in Table 8. Among the results, the Gompertz model was highly significant and it had a high R^2 (1.00) with low RMSE (2.22) value, showings very good performance on the validation data set with 95 % prediction accuracy. Because the model does not consider sex or age to stratify results, it is very amenable to transfer onto a weight tape that can be used for all ages of Holstein cows raised in Korea. The mature size, rate of maturity and coefficient of determinations of body measurements of Holstein cows in Korea were fitted by nonlinear models. Among the results, the rate of maturity estimates of body measurements revealed lower RMSE values with higher coefficient of determination. It indicated that this tool could have the potential impact for small farm holders to use the accurate growth curve of animal traits to plan feeding strategies for productivity, as well as accurate estimates of slaughter weight at market, which is the primary determinant of market price.

Ⅳ. CONCLUSION

Selecting a flexible and accurate model to predict the growth curve in animal can improve the outcome of researches, and assure that its application can be useful for farmers. On the basis of our results, Gompertz is the best fitted model based on RMSE and R^2 values which is suitable to describe the growth characteristics of Holstein dairy cows raised in Korea. Although, Gompertz model is the most suitable one due to its accuracy in predicting mature weight, which is an important for reproduction efficiency and feeding strategies. Hence, this finding can be useful for Korean farmers and researchers to optimize the Holstein dairy cattle management and production efficiency.

Ⅴ. ACKNOWLEDGEMENT

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Ⅵ. REFERENCES

Anderson, N. 2008. Dairy cow comfort tie stall dimensions. Infosheet January 2008, OMAFRA, Ontario, Ministry of Agriculture, Food and Rural Affairs, Guelph, ON, Canada.

Aziz, M.A., Shalaby, N.A., El-Shafie, O.M., Mahdy, A.T. and Nishida, A. 2006. Comparison between the shapes of lactation curve of Egyptian buffalo milk yield estimated by the incomplete gamma function and a new model. Livestock Research for Rural Development. 18:1-9.

Bahreini-Behzadi, M.R., Aslaminejad, A.A., Sharifi, A.R. and Simianer, H. 2014. Comparison of mathematical models for describing the growth of Baluchi sheep. Journal of Agricultural Science and Technology.

16:57-68.

Bene, S., Nagy, B., Nagy, L., Kiss, B., Polgár, J.P. and Szabó, F. 2007. Comparison of body measurements of beef cows of different breeds. Archives of Animal Breeding(Ach. Tierz. Dummerstorf). 50:363-373.

Brody, S. 1945. Bioenergetics and growth: With special reference to the efficiency complex in domestic animals. Rheinhold Publishing, New York, USA. pp. 1-1023.

Brown, J.E., Fitzhugh Jr, H.A. and Cartwright, T.C. 1976. A comparison of nonlinear models for describing weight-age relationships in cattle. Journal of Animal Science. 42:810-818.

Darmani-Kuhi, H., Porter, T., López, S., Kebreab, E., Strathe, A.B., Dumas, A., Dijkstra, J. and France, J. 2010. A review of mathematical functions for the analysis of growth in poultry. World's Poultry Science Journal. 66:227-240.

Engelken, T.J. 2008. Developing replacement beef heifers. Theriogenology. 70:569-572.

Fathi-Nasri, M.H., France, J., Odongo, N.E., López, S., Bannink, A. and Kebreab, E. 2008. Modelling the lactation curve of dairy cows using the differentials of growth functions. The Journal of Agricultural Science. 146:633-641.

Fitzhugh, H.A. 1976. Analysis of growth-curves and strategies for altering their shape. Journal of Animal Science. 42:1036-1051.

Freitas, A.R. 2005. Curvas de crescimento na producão animal. Revista Brasileira de Zootecnia. 34:786-795.

National Institute of Animal Science. 2017. Korean feeding standard. pp. 200-234.

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

Lesosky, M., Dumas, S., Conradie, I., Handel, I.G., Jennings, A., Thumbi, S., Toye, P. and Bronsvoort, B.M. 2012. A live weight-chest girth relationship for accurate dosing of east African shorthorn zebu cattle. Tropical Animal Health Production. 45:311-316.

López, S., France, J., Odongo, N.E., McBride, R.A., Kebreab, E., Al-Zahal, O., McBride, B.W. and Dijkstra, J. 2015. On the analysis of Canadian Holstein dairy cow lactation curves using standard growth functions. Journal of Dairy Science. 98:2701-2712.

Lukuyu, M.N., Gibson, J.P., Savage, D.B., Duncan, A.J., Mujibi, F.D.N. and Okeyo, A.M. 2016. Use of body linear measurements to estimate live weight of crossbred dairy cattle in smallholder farms in Kenya. Springer Plus. 5:1-14.

Marinho, K.N.S., Freitas, A.R., Falcão, A.J.S. and Dias, F.E.F. 2013. Nonlinear models for fitting growth curves of Nellore cows reared in the Amazon Biome. Revista Brasileira de Zootecnia. 42:645-650.

Souza, L.A., Caires, D.N., Carneiro, P.L.S., Malhado, C.H.M. and Filho, R.M. 2010. Curvas de crescimento em bovinos da ra¸ca Indubrasil criados no Estado do Sergipe. Revista Ciência Agronômica. 41:671-676.

Vázquez, J.A., Lorenzo, J.M., Fuciños, P. and Franco, D. 2012. Evaluation of non-linear equations to model different animal growths with mono and bisigmoid profiles. Journal of Theoretical Biology. 314:95-105.

Von Bertalanffy, L. 1957. Quantitative laws in metabolism and growth. The Quarterly Review of Biology. 32:217-231.

Won, J.I., Lim, H.J., Kim, T.I., Park, J.J., Dang, C.G. and Yoon, H.B. 2017. Estimation of growth curve parameters for evaluation of growth characteristics of Korean holstein cow. Journal of Agriculture & Life Science. 51:135-140.

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