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ANIMAL PRODUCTION

Growth predictability models in Mangalarga Marchador horses

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ABSTRACT: *This study evaluated the suitability of the Brody, logistic, and quadratic response plateau models to describe chest and cannon girth data obtained cross-sectionally in Mangalarga Marchador horses, in order to select the best model and predict the growth and maturity of males and females of this breed. Data were collected from 230 horses aged 6 to 176 months, divided by sex and age (16 age classes). The studied models were compared according to each quality evaluator by computing the adjusted coefficient of determination (R^2_{adj}) and residual standard deviation (RSD) with R statistical software. The chest girths obtained by the models ranged from 172.06 (males) to 181.50 cm (females) (Brody), 172.51 (males) to 181.89 cm (females) (logistic), and 177.67 (males) to 183.09 cm (females) (plateau). For cannon girth, the values were 18.18 (females) to 19.33 cm (males) (Brody), 18.11 (females) to 19.41 cm (males) (logistic), and 18.70 (females) to 19.40 cm (males) (plateau). The logistic model was best suited to describe the growth in chest girth of male and female Mangalarga Marchador horses. For cannon girth growth, the model best suited for males was the logistic model, and the one best suited for females was the Brody model.*
Key words: *horses, nonlinear models, morphology.*

Modelos de previsibilidade de crescimento em cavalos Mangalarga Marchador

RESUMO: *O objetivo deste estudo foi avaliar o ajuste dos modelos Brody, Logístico e Platô de resposta quadrática aos dados de perímetros torácico e de canela em equinos Mangalarga Marchador obtidos pelo método transversal, a fim de selecionar o melhor modelo e predizer sobre o crescimento e a maturidade de machos e fêmeas desta raça. Foram utilizados dados de 230 equinos de seis a 176 meses de idade que foram divididos por sexo e em 16 classes de idade. Os modelos estudados foram comparados segundo os avaliadores de qualidade: coeficiente de determinação ajustado (R^2_{aj}) e desvio padrão residual (DPR), utilizando-se o software estatístico R. Os perímetros torácicos obtidos pelos modelos variaram de 172,06 a 181,50 cm (Brody), 172,51 a 181,89 cm (Logístico) e 183,09 a 177,67 cm (Platô) para fêmeas e machos, respectivamente. Para o perímetro de canela os valores variaram de 18,18 a 19,33 cm (Brody), 18,11 a 19,41 cm (Logístico) e 18,70 a 19,40 cm (Platô) para fêmeas e machos, respectivamente. O modelo logístico é mais indicado para expressar o crescimento em perímetro torácico de machos e fêmeas da raça Mangalarga Marchador. Já para a variável perímetro de canela, o modelo mais indicado para os machos foi o modelo Logístico e para as fêmeas o modelo de Brody.*
Palavras-chave: *equinos, modelos não lineares, morfologia.*

INTRODUCTION

The Mangalarga Marchador (MM) breed is widely distributed throughout Brazil, playing an important economic and social role. One of their most valued traits is their gait, which is known as marcha, where the animal does not lose contact with the ground when moving, which results in a comfortable ride (SANTIAGO et al., 2016).

For animals to competently move and to be desirable on the market, their body parts must have adequate shapes and sizes, in addition to good body conformation (LUCENA et al., 2016). In this sense, the morphology can affect the function of the horses, such as, chest and cannon circumferences, which have been associated with cardiorespiratory capacity and load capacity during the training of horses (MENESES et al. 2014).

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One of the most important applications of these two measures is in the definition of animal biotypes through functional ability or the conformation indices (body and dactyl-thoracic indices) described by BORTONI (1991) and CABRAL et al. (2004). According to these authors, if the Body index, greater than 90, the animal is classified as a sport- or hunter-type horse; between 86 and 88, as saddle- or riding-type horse; and less than 85, as a draft-type horse. Already the Dactyl thorax index if less than 10.5, horses are considered saddle horses with poor structure; if equal to 10.5 and up to 10.8, as saddle horses; if equal to or greater than 10.8 and up to 11.0, as light-draft horses; and equal to and above 11.5, as heavy-draft horses. In view of the importance of these characteristics, it is necessary to carry out detailed studies on the behavior of their growth over age and the identification of the best regression model to describe such growth in MM horses.

Advantages have been identified by using nonlinear statistical modeling as a method of analyzing animal development (CARNEIRO et al., 2014; FREITAS, 2005; GUEDES et al. 2004; MENDES et al., 2008; SILVEIRA et al. 2011; TELEKEN et al., 2017). In horses, the application of these methods allows breeders to know the adequate growth rate of foals (FRADINHO et al. 2016), to select the best animals in the herd at an early age, and to avoid the mistaken culling of animals with potential, since foals are most often sold in their first year of life (PINTO et al., 2005) and their sale is responsible for much of the gross revenue of farms (SANTOS et al., 2007).

Few studies analyzed growth in equine girths, since other traits, such as withers height, have minimum reference values as stipulated by the associations of the different breeds for granting a studbook record; thus, there are generally larger amounts of data available for such traits that can be used for studies. In addition, the limited number of studies on the growth of morphological traits in horses demonstrated the difficulty of obtaining data. As confirmed by SOUZA et al. (2019), MM horses, for example, grow until they are 5 years old, and the owners of the stud farm mostly sell the animals before reaching this age. Thus, to enable growth studies with a larger number of animals and to better understand the development of a given population, the use of cross-sectional data collection is recommended (SILVA et al., 2010; SPERANDIO et al., 2011), where the variables can be collected only once in each animal, as efficiently demonstrated by RIBEIRO et al. (2018), SOUZA et al. (2017), and SOUZA et al. (2019) in horses.

Thus, the objective of this study was to carry out a comparative evaluation of predictability models (Brody, logistic and quadratic response plateau) in order to select the best model and predict the growth of the chest and cannon perimeter of males and females of Mangalarga Marchador breed.

MATERIALS AND METHODS

The experimental data were obtained during an agricultural exhibition held in Belo Horizonte, Minas Gerais, Brazil, in 2012. A total of 230 MM animals, 96 males and 134 non-pregnant females, were divided into 16 age classes (6-8, 9-11, 12-14, 15-17, 18-20, 21-23, 24-29, 30-35, 36-41, 42-47, 48-53, 54-59, 60-71, 72-83, 84-95 and 96-176 months) and by sex (see Ribeiro et al. 2018). The animals were grouped and included in the classes according to their age to mitigate the effect of heteroscedasticity, because, in studies of growth curves, the variability usually increases as the animal gets older. Such grouping proved to be efficient because the Breusch-Pagan test performed showed no significant result.

The chest and cannon girths were measured by a single person positioned on the left side of the animal in standing position (four limbs supported and head in normal position), according to the method described by CABRAL et al. (2004) and SANTIAGO et al. (2016). The chest girth was measured with a tape measure positioned at the end of the withers (caudally to the withers), between the T8 and T9 spinal processes, with the tape running down between the intercostal space of the 8th and 9th ribs until reaching the point where the last rib meets the xiphoid process. The cannon girth was measured in the medial region of the cannon of one of the forelimbs, formed by metacarpal bones II, III, and IV.

Brody (I), logistic (II), and quadratic response plateau (III) nonlinear regression models were used to describe the growth curve of the MM horses, whose equations are as follows:

I. Brody: $Y_i = \alpha * \{1 - exp[K(t_i - \beta)]\} + \varepsilon_i$

II. Logistic: $Y_i = \frac{\alpha}{1 + exp\{K(t_i - \beta)\}} + \varepsilon_i$

III. Quadratic response plateau:

$$\begin{cases} Y_i = a + bt_i + ct_i^2 + \varepsilon_i, & se\ t_i \leq t_0 \quad (1) \\ Y_i = p + \varepsilon_i, & se\ t_i > t_0 \quad (2) \end{cases}$$

In equations I and II, Y_i is the variable under study (chest/cannon girth); α is the asymptotic value or adult girth of the animal; β is a location parameter associated with the inflection point of the model, that is, it indicates the age at which the animal changes from accelerated to decelerated growth; K is the maturity or precocity index of the model (the higher the K value is, the less time it will take for the animal to reach its adult size); t_i is the age of the animal, i = 1, 2,..., n; ε_i is the random error associated with the model, which is assumed to be random, independent, and normally distributed with a mean of zero and constant variance, $\varepsilon_i \sim N(0, \sigma^2)$. In equation III, a, b, and c are the parameters of the quadratic polynomial model, without direct practical interpretation; t_0 is the junction point of quadratic equation (1) with plateau P, indicated in expression (2). The terms Y_i , t_i and ε_i have the same meaning as in equations I and II.

The parameters of these models were estimated by the least squares method, through which the normal equations system is obtained. Model comparison and the selection of the most appropriate model to describe the growth curve were performed based on the following model fit quality indicators:

- Residual standard deviation (RSD), calculated by the expression $\mathrm{RSD}=\sqrt{\mathrm{RMS}}$, where QME is the residual mean square (RMS). The lower the RSD is, the better the model fits.
- Adjusted coefficient of determination (R^2_{adj}), obtained by: $\mathrm{R}^2_{\mathrm{adj}} = 1 - \frac{(\mathrm{n}-1)(1-\mathrm{R}^2)}{\mathrm{n}-\mathrm{p}}$, where n is the number of observations, p is the number of parameters, and $\mathrm{R}^2 = 1 - \frac{\mathrm{RSS}}{\mathrm{TSS}}$, where RSS is the residual sum of squares and TSS is the total sum of squares. The values of R^2_{adj} range between 0 and 1, and the model with the highest R^2_{adj} has the best fit.

The Durbin-Watson test was used to assess the presence of residual dependence between measurements, evaluating whether the residual of an observation is associated with the residual of adjacent observations. The assumption of normality was confirmed by the Shapiro-Wilk test, and the assumption of residual homoscedasticity was confirmed by the Breusch-Pagan test. The variance between the animals within the same age class was calculated, making it possible to incorporate this variability into the parameter estimation process by weighting according to the inverse of the variance, when necessary.

The confidence intervals were calculated for the parameter estimates. The 95% confidence interval is defined for the parameter β_i of the model as: $CI\ (\beta_i): \hat{\beta}_i \pm t_{(v;0;025)} S(\hat{\beta}_i)$, where $\hat{\beta}_i$ is the estimate for parameter (β_i); $S(\hat{\beta}_i)$ is the standard error of the estimate; and $t_{(v;0;025)}$ is the upper quantile of Student's t distribution, setting α = 5% and the degree of freedom, $v = n - p$.

R software (R DEVELOPMENT CORE TEAM, 2018) was used to perform statistical tests, estimate model parameters, calculate confidence intervals, and plot graphs.

RESULTS AND DISCUSSION

As the first step of the regression analysis, the models were fit considering that all the assumptions were met, and after these first adjustments, residual analysis was performed. The Shapiro-Wilk, Durbin-Watson, and Breusch-Pagan tests, which had p-values > 0.05 for all models in both variables, were added to the analysis, and they reinforced that all the assumptions for fitting the regression model were met at a significance level of 5%.

The model fit quality indicators indicated that the models were efficient in describing the growth curve for the chest and cannon girths of horses, with very similar RSD values between the Brody and logistic models and adjusted coefficients of determination (R^2_{adj}) ranging from 94.73 to 96.82% for chest girth and between 89.02 and 96.09% for cannon girth in these two models (Table 1). The values of R^2_{adj} obtained by the quadratic response plateau model were lower, ranging from 82.31 to 82.47% for chest girth and 81.67 to 89.90% for cannon girth (Table 2). According to these model fit quality indicator results, the logistic model proved to be the best to describe the growth in the chest girth of males and females because it had higher R^2_{adj} values for both sexes. For cannon girth, the best nonlinear model was the Brody model for females and the logistic model for males.

Different results were reported by Souza et al. (2019) for the same breed. The authors found that the chest girth data for males did not follow a normal distribution, which precluded the application of nonlinear modeling in these animals. For the females included in their study, it was possible to use statistical models; the R^2 values ranged from 85.6 to 86.2%, and the Brody model was considered the best fit, not the logistic model as in the present study. For cannon girth, those researchers obtained R^2 values ranging from 75.85 to 86.3%, with Brody's model being considered the best for females and the logistic model being considered the best for males, which agrees with the present study. Other researchers have studied the growth of girths in foreign breeds, such as FRADINHO et al. (2016), who reported R^2 values for chest girth of 0.938 (logistic) and 0.947 (Brody) and for cannon girth of 0.859 (logistic) and 0.862 (Brody) when studying Lusitano fillies and colts. The

Table 1 - Estimates of the parameters and model fit quality indicators of the nonlinear Brody and logistic models in the description of the growth curves for chest and cannon girths in male and female Mangalarga Marchador horses.

Variable	Model	Sex	----Parameter * ----				
			α	K	β	R^2_{adj}	RSD
Chest girth	Brody	Females	178.76	0.0983	-7.30	0.9475	19.90
		Males	175.33	0.0646	-15.51	0.9473	17.18
	Logistic	Females	179.13	0.0953	-6.61	0.9607	20.81
		Males	175.71	0.0770	-9.41	0.9682	17.67
Cannon girth	Brody	Females	18.40	0.0893	-11.94	0.9308	0.36
		Males	19.09	0.0684	-17.06	0.9420	0.40
	Logistic	Females	18.43	0.0738	-15.39	0.8902	0.20
		Males	19.06	0.0714	-13.87	0.9609	0.21

* α = the asymptotic value or adult girth of the animal; β = a location parameter that is associated with the inflection point of the model; K = the maturity or precocity index of the model; R^2_{adj} = adjusted coefficient of determination; RSD = residual standard deviation.

Lusitano horse is a breed that gave rise to the MM breed (CASIUCH, 2016), which could explain the similar findings of the two studies.

The chest girths obtained by the models ranged from 172.06 to 181.50 cm by the Brody model and from 172.51 to 181.89 cm by the logistic model (Table 3). For the quadratic response plateau model, the values were 183.09 and 177.67 cm for females and males, respectively (Table 2). For the cannon girth, the values ranged from 18.18 to 19.33 cm by the Brody model and from 18.11 to 19.41 cm by the logistic model. For the plateau model, the values were 18.70 and 19.40 cm for females and males, respectively (Table 2). Results for the estimates of parameter α between the models were similar. This confirmed that all correctly described the growth in chest and cannon girth of the animals, as did the fact that these values are consistent with the values reported by Souza et al. (2019) for the MM breed, which were a chest girth of 179.07 to 182.88 cm for females and a cannon girth of 18.25 to 18.76 cm for females and 18.95 to 19.41 cm for males. Conversely, Cabral et al. (2004) found chest girth values of 175.7 cm for females and 180.8 cm for males, and cannon girth values of 19 cm for females and 19.7 cm for males.

Table 2 - Estimates of the parameters and model fit quality indicators of the quadratic response plateau model in the description of the growth curves for chest and cannon girths in male and female Mangalarga Marchador horses.

Variable	Sex	----Parameter * ----						
		a	b	c	t_0	p	R^2_{adj}	RSD
Chest girth	Females	140.17	1.1918	-0.0082	72.03	183.09	0.8231	37.68
	Males	133.88	1.0473	-0.0062	83.61	177.67	0.8247	1.071
Cannon girth	Females	15.58	0.0782	-0.0004	79.67	18.70	0.8167	0.2760
	Males	15.07	0.1272	-0.0009	68.08	19.40	0.8990	0.5959

* a, b, and c are the parameters of the simple linear regression models; R^2_{adj} = adjusted coefficient of determination; RSD = residual standard deviation; t_0 = the junction point of the quadratic equation with the plateau p, i.e., the age at which animals stop growing, in months; p = plateau constant, i.e., the adult morphometric measurement reached at time t_0, in centimeters.

Table 3 - Estimated parameters and lower and upper limits of the confidence intervals (95%) for the Brody and logistic models in the description of the growth curves for the chest and cannon girths of male and female Mangalarga Marchador horses.

Model	Sex	Parameter *								
		LL	α	UL	LL	K	UL	LL	B	UL
Chest girth										
Brody	Females	176.01	178.76	181.50	0.0690	0.0983	0.1270	-12.17	-7.30	-2.43
	Males	172.06	175.33	178.60	0.0380	0.0646	0.0910	-26.00	-15.51	-5.00
Logistic	Females	176.72	179.13	181.89	0.0660	0.0953	0.1330	-13.55	-6.61	-2.04
	Males	172.51	175.71	179.32	0.0600	0.0770	0.1002	-14.12	-9.41	-5.70
Cannon girth										
Brody	Females	18.18	18.40	18.62	0.0640	0.0893	0.1140	-17.89	-11.94	-6.00
	Males	18.84	19.09	19.33	0.0420	0.0684	0.0940	-27.47	-17.06	-6.64
Logistic	Females	18.11	18.43	18.87	0.0400	0.0738	0.1230	-36.36	-15.39	-5.23
	Males	18.75	19.06	19.41	0.0540	0.0714	0.0940	-20.50	-13.87	-8.88

* α = the asymptotic value or adult girth of the animal; β = a location parameter that is associated with the inflection point of the model; K = the maturity or precocity index of the model; R^2_{adj} = adjusted coefficient of determination; RSD = residual standard deviation; LL = lower limit of the confidence interval; UL = upper limit of the confidence interval.

Chest girth values for adult animals (Table 3) were higher in females (179 cm) than in males (175 cm), implying that females have a greater chest depth, i.e., long and well-arched ribs, indicating a more desirable chest girth, as recommended by the MM breed standard. These results contradicted the results found by Cabral et al. (2004), who reported that at birth, males of this breed had higher chest girth measurements than females; at 12 months, they had lower values, but when measuring the animals again in adulthood, they observed that males had a greater chest girth by approximately 5 cm. For the Quarter Horse breed, the mean chest girth of females was greater than the mean of males by approximately 2 cm according to MENESES et al. (2014). Similar results were found by MOTA et al. (2010), in which all measurements performed in females were larger than those in male Quarter Horses. These differences reported between male and female girths can be attributed to the existence of sexual dimorphism in horses (SANTOS et al., 2007; MISERANI et al. 2002). In addition, the greater chest depth, i.e., the greater chest girth found in females, may be associated with the fact that this trait is valued by breeders in the morphological evaluation during animal selection in the stud farms, as it is considered an important reproductive trait.

The cannon girth did not vary much compared to the chest girth, demonstrating that the sample variances between age classes are not heterogeneous in this trait, as also observed by FRADINHO et al. (2016). Thus, the parameter estimates for the cannon girth were not weighted (by the inverse of the variance). The asymptotic value for this variable was higher in males (19.06 cm) than in females (18.40 cm) (Table 3), suggesting that males tend to have a larger cannon girth. This may be related to the higher male body weight and height at withers observed in other growth studies on MM horses (SOUZA et al., 2017 and SOUZA et al., 2019). The same was reported by Pimentel et al. (2017) when studying Brazilian Crioulo foals, which had cannon girths of 19 cm and 18 cm for males and females, respectively, at 36 months of age.

The k parameter, which evaluates the maturity rate of the animal, or the speed in reaching the adult chest or cannon girth, was higher in females than in males, meaning that in addition to having a greater thoracic depth, they also reached this depth earlier. Although, females have smaller cannon girths, their cannon grew faster than that of males. These results may be associated not only with sexual dimorphism but also with other factors that affect animal development, such as nutrition and feeding, stressful environmental conditions, maternal age, breed, climate, year of birth, geographic location, and training (CAMPOS et al. 2007; GONÇALVES et al., 2012; MISERANI et al. 2002; SANTOS et al., 2007). One of the aforementioned factors that can most affect growth, especially in the first years of life of the animals, is nutrition, as demonstrated in the study by REZENDE et al. (2000), in which supplementing MM foals with a mineral mixture–enriched concentrate resulted in larger chest girths than nonsupplementation.

The parameters obtained in the quadratic response plateau model for both sexes (Table 2) showed that females also had larger chest girths than males (p) and reached this value at an earlier age than males (t_0). These results are consistent with those obtained by the logistic and Brody models. For the cannon girth, the values were higher in females than in males, thus differing from the results of the other models. However, there was an overestimation of age (t_0) by the plateau model (Table 3), and the age indicated by the other models was more consistent with equine growth (Figure 1), as shown in the literature on the girths of this breed, as well as other morphometric variables (SOUZA et al., 2019).

The abscissa of the inflection point of the growth curves, parameter β of the logistic model, showed negative values, suggesting that the inflection point may have occurred at an age before the first observation, which in this study was at 6 months of age. For this reason, the growth curves obtained by the models (Figure 1) did not have a sigmoidal shape.

The highest intensity and homogeneity of girth growth in the animals were observed between 6 and 24 months of age (Figure 1). There was also greater variability after 24 months of age, which may be explained by changes in the nutritional and health management of animals throughout their productive lives (SOUZA et al., 2019), in addition to the greater

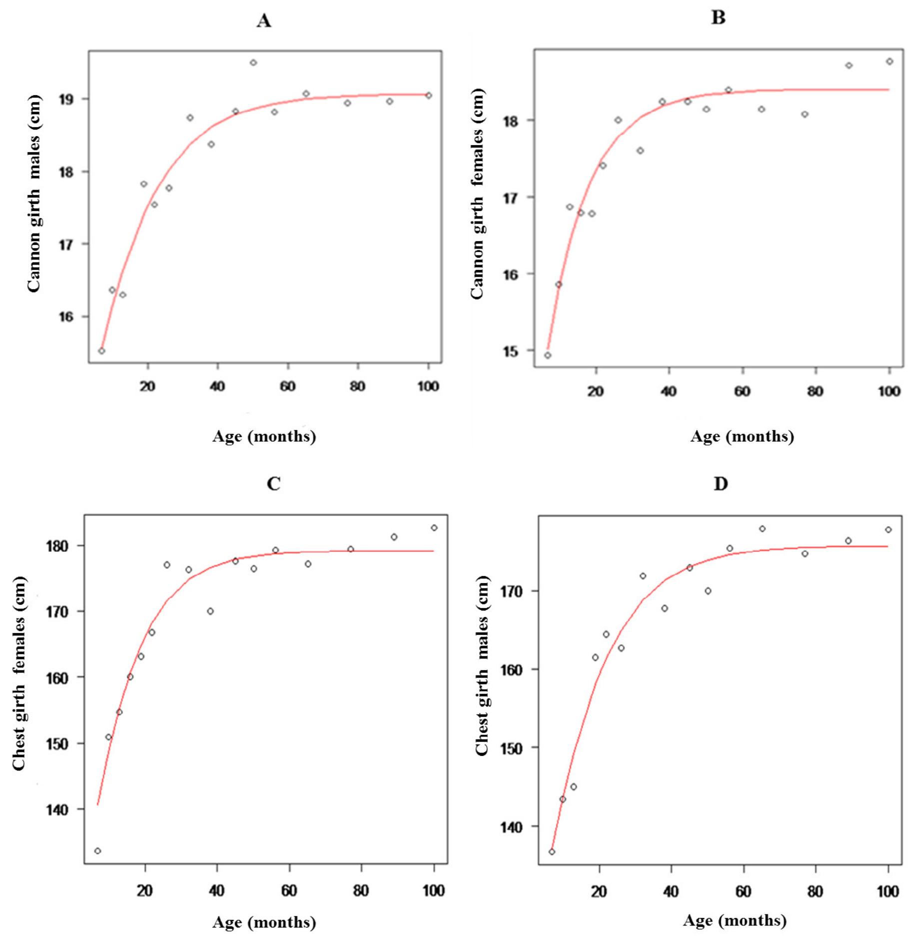

Figure 1 - Growth curve for the cannon girth of Mangalarga Marchador horses obtained by the logistic model for males (A) and Brody model for females (B). Growth curve for the chest girth obtained by the logistic model for females (C) and males (D).

heterogeneity between individuals of the same breed compared to other horse breeds (SANTIAGO et al., 2016). At approximately 60 months of age, the growth curve for both sexes stabilized (Figure 1), demonstrating that the chest and cannon girths of MM animals grow until this age. In contrast, Pimentel et al. (2017), when studying Brazilian Crioulo colts and fillies, observed that the cannon girth in females did not grow after 24 months of age, unlike what was observed for the MM breed, thus demonstrating that the variation between different genetic groups may interfere with the growth pattern.

To follow the animal development, table 3 provides the reference values, with lower and upper limits to the 95% confidence level for the growth curve. The breeders and professionals of horses can compare the measurements of his animals with the growth pattern recommended by the model most appropriate in describing the development of these variables. To obtain the lower limit (population percentile of 2.5%) of a given characteristic, just look at table 3 and replace the LL values in the respective model indicated, with t_i being the age of your animal. To obtain the average estimate (population percentile 50%), it is simply replaced the estimated values parameter obtaining the upper limit (population percentile 97.5%) estimated for the characteristic at the age of interest just replacing the UL values.

CONCLUSION

The logistic model is best suited to track the chest girth growth of male and female MM horses. For cannon girth, the model of best fit for males was the logistic model, and for females was the Brody model.

Girth growth is more intense and homogeneous at the age of 6 to 24 months in the MM breed and stabilizes at 60 months in both sexes. The females are more precocious than males in reaching their adult chest and cannon girths.

Based on the confidence intervals of the parameters in the indicated models and the growth pattern verified in this research for animals Mangalarga Marchador, breeders and professionals of horses of this breed can monitor the development of their animal, in thoracic and shin girth, over time, in order to establish guidelines for the management and selection of your animals.

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BIOETHICS AND BIOSSECURITY COMMITTEE APPROVAL

The study was approved by the Research Ethics Committee of the Universidade Federal de Lavras under record number 039/12.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The funding sponsors had no role in the study design; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the design and writing of the manuscript. All authors critically reviewed the manuscript and approved the final version.

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