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Evaluation of the growth of Criollo foals using nonlinear models

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ABSTRACT - The present study aimed to evaluate the growth of Criollo foals from birth to 800 days of age using Brody, Gompertz, Logistic, and Von Bertalanffy nonlinear models. The data utilized consisted of weight, height, chest circumference, and shin circumference taken from 75 foals kept in southern Brazil. Morphometric traits analyzed showed mean values ranging from 63 to 325 kg for weight, 0.92 to 1.32 m for height, 0.88 to 1.58 m for chest circumference, and 0.12 to 0.18 m for shin circumference. For the evaluated traits, all applied nonlinear models achieved convergence. The results indicated that the Brody model provided the best adjustments for weight, height, and chest circumference. Gompertz model was found to be the most suitable for describing the growth curve of shin circumference. The animals exhibited an increase in weight during the evaluated period. Height showed the most rapid increase until approximately 365 days of age, followed by a decrease, and a more homogeneous growth pattern thereafter. Chest circumference exhibited more uniform growth in animals from 365 days of age onwards, with slower growth and greater variability observed from 400 days of age. Shin circumference showed greater growth in the first months of age, remaining stable thereafter. We observed that 94 and 5% of the animals in the studied population did not meet the minimum values for height and chest circumference, respectively, according to the breed standards from 24 months of age. Our results can assist in selection and future studies with the Criollo breed.

Keywords: chest circumference, growth curve, height, horses, shin circumference, weight

1. Introduction

The population of the Criollo horse breed is increasing in Brazil, particularly in the state of Rio Grande do Sul (ABCCC, 2022). These animals are renowned not only for their endurance and hardiness but also for their prowess in various equestrian competitions. Additionally, they are known for their docility and temperament, making them ideal horses for sports, leisure, and work. In the country, approximately 500 annual events are held with Criollo horses, with the Freio de Ouro standing out as the main morphological and functional competition used for selecting Criollo horses since 1982.

The performance of horses in morphological and functional competitions depends on the good development of foals from birth (Pimentel et al., 2017). Thus, different morphometric measurements have been used to select animals with superior performance (Souza et al., 2019). Generally, individual body measurements such as height, chest circumference, and shin circumference are widely used to assess the growth of animals, as well as serving as standards for registering males and females in the Crioulo breed.

The growth of equines is highly dependent on their genetic potential and environmental factors, including management and feeding practices (Fitzhugh, 1976; Fradinho et al., 2016; Fernandes et al., 2020). According to Thompson (1995) and Barcelos et al. (2016), understanding the specific growth pattern of each breed is fundamental due to the correlation between the physical development of foals and the onset of orthopedic diseases. Furthermore, the pattern of animal development plays an extremely important role in evaluating and identifying the morphometric traits that drive the genetic improvement of every breed.

The study of growth evolution with age in different equine breeds, as well as in the same breed kept in different geographical regions, is relevant because the ideal model for one population may not be applicable to another due to differences in the animals' growth patterns (Fradinho et al., 2016; Souza et al., 2019). When analyzing growth curves, nonlinear mathematical models offer some advantages, such as good adjustments and parameters with biological interpretations (Fradinho et al., 2016; Souza et al., 2017). In general, the Gompertz, Logistic, Bertalanffy, and Brody models are commonly used in evaluations of growth curves in different equine populations (McManus et al., 2010; Fradinho et al., 2016; Souza et al., 2019; Teixeira et al., 2021).

McManus et al. (2010) demonstrated that the Weibull and Brody curves exhibited the best fit for the increase in height and weight of horses raised in the Brazilian Army. On the other hand, Fernandes et al. (2020) showed that the Logistic model is the best growth predictor in height at withers and body length in male and female Mangalarga Marchador horses from six to 176 months of age. Studying the growth curve in body weight and withers height of Campolina breed horses, Teixeira et al. (2021) reported that the Gompertz model was chosen as the most suitable. These authors emphasized that this knowledge can serve as a foundation for breeders' associations to support their strategies, focusing on the process of selection and equine evolution through growth studies with linear measurements.

Despite the importance of body measurements such as height, chest circumference, and shin circumference for registering males and females in the Criollo breed, there are few studies describing the evolution of these measurements across different ages. Therefore, this study was conducted to evaluate the growth of Criollo foals from birth to 800 days of age, using measurements of weight, height, chest circumference, and shin circumference. Non-linear mathematical models were employed to analyze this data and determine the function that best fits the animals' development.

2. Material and Methods

We used information of weight, height, chest circumference, and shin circumference measured from birth to 800 days of age in 75 Criollo breed foals, 41 males and 34 females. The animals originated from two properties located in the city of Jaguarão, in the state of Rio Grande do Sul, and were kept in natural pasture systems mainly composed of *Paspalum notatum*, *Andropogon lateralis*, *Coelorachis selloana*, and *Paspalum dilatatum* (Pillar et al., 2009).

After birth, the foals were initially identified based on their dams. Subsequently, after weaning, identification was conducted using data from the livestock records. Individual weight measurements were taken using a conventional 1,500-kg box scale. The foals were led into the scale individually and weighed, with the values expressed in kilograms. Height was measured in meters using a hypsometer (German model), with the foals positioned with all four limbs supported on a horizontal and even surface. The hypsometer was then raised to the highest point of the withers (spinous process of the fifth thoracic vertebra), and the reading was taken from the scale positioned on the equipment rod. Chest circumference was measured using a measuring tape, passing over the end of the withers, approximately at the level of the ninth rib, and ventrally behind the xiphoid process. The measurement was taken at the end of expiration and is expressed in meters. Shin circumference was measured with the animal positioned so that the front limbs were on a horizontal plane, planted on the ground. Using a measuring tape in meters, the shin was encircled at the level of the middle third of the third metacarpal of the left front limb.

The nonlinear models used (Brody, Gompertz, Logistic, and Von Bertalanffy) are represented by the following expressions:

$$\text{Brody} = Wt = A(1 - B\,e^{-kt})$$

$$\text{Gompertz} = Wt = A\exp(-B\,e^{-kt})$$

$$\text{Logistic} = Wt = A/(1 + B\,e^{-kt})$$

$$\text{Von Bertalanffy} = Wt = A(1 - B\,e^{-kt})^3$$

In these functions, Wt represents the variable under study (weight, height, chest circumference, and shin circumference) at age t (days). Parameter A is the asymptotic value of the trait, representing the maximum value that the trait can reach in adulthood. Parameter B is the integration constant, related to the values in the initial phase of the trait; however, there is no biological interpretation for this parameter. Parameter k is the maturity rate, understood as the change in the trait concerning its maturity; in other words, it indicates the speed at which the animal approaches adulthood.

For each trait, differences between means based on sex (male or female) were compared by performing Student's t-test, using the SAS program (Statistical Analysis System, 2008). Results were considered statistically significant when $P<0.05$. Afterwards, the analyses using the different studied nonlinear models were conducted using the same program. For each trait, the best-fit model was determined based on the following criteria: coefficient of determination (R^2), calculated as the square of the correlation between observed and estimated measures, which is equivalent to 1 (SSE/SST), in which SSE is the sum of squared errors and SST is the total sum of squares; mean squared error (MSE), calculated by dividing the sum of squared residuals by the number of observations, which is the maximum likelihood estimator of residual variance; Akaike's information criterion (AIC) (Akaike, 1974), AIC = n In (SSE/n) + 2p, in which n is the observation number, In is the natural logarithm, and p is the number of model parameters; Bayesian information criterion (BIC) (Schwarz, 1978), BIC = n In(SSE/n) + p In (n). Higher R^2 values and lower MSE, AIC, and BIC values indicate better fits test.

The parameter estimates from the most suitable model for each trait were used to obtain the lower and upper limits of the 95% confidence interval for weight, height, chest circumference, and shin circumference values over different ages.

3. Results

Morphometric measurements obtained in Criollo foals from birth to 800 days of age showed mean values ranging from 63 to 325 kg (weight), 0.92 to 1.32 m (height), 0.88 to 1.58 m (chest circumference), and 0.12 to 0.18 m (shin circumference) (Table 1). For all traits, sex did not show significant effect under the Student's *t*-test (results not shown).

All nonlinear models tested (Brody, Gompertz, Logistic, and Von Bertalanffy) aiming at describing the development of Criollo foals from birth to 800 days of age for weight, height, chest circumference, and shin circumference traits successfully converged. For weight trait, the value estimated for parameter A ranged from 315.40 (Logistic model) to 346.70 kg (Brody model) (Table 2). According to the adopted goodness-of-fit criteria (R^2, MSE, AIC, and BIC), the Brody model was slightly superior in describing the weight evolution with age. The mean predicted values with the Brody model for weight from birth to 800 days of age exhibited a curve that was similar and very close to the mean of the observed data (Figure 1). Additionally, the animals exhibited an increase in weight during the evaluated period.

Table 1 - Means and respective standard deviations of morphometric measurements of Criollo foals from birth to 24 months of age

Age (months)	Weight (kg)	Height (m)	Chest circumference (m)	Shin circumference (m)
First	63.18±12.85	0.92±0.031	0.88±0.057	0.12±0.006
6	188.88±22.81	1.15±0.038	1.32±0.062	0.16±0.007
12	246.20±31.11	1.25±0.037	1.41±0.062	0.16±0.007
18	303.63±29.17	1.29±0.041	1.54±0.055	0.17±0.008
24	325.36±39.70	1.32±0.046	1.58±0.067	0.18±0.007

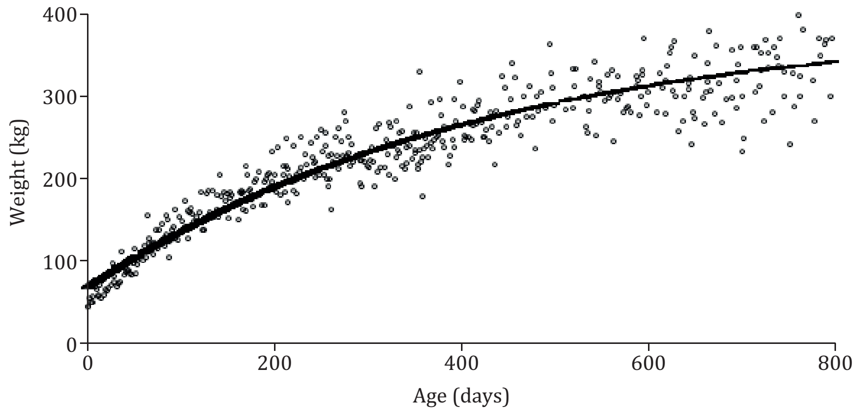

Figure 1 - Means of weights observed (•) and predicted (-) with the Brody nonlinear model for Criollo horses.

The nonlinear models estimated similar values for the parameter A for the height of foals (Table 2). The Brody nonlinear model was considered the most suitable for adjusting the height evolution of Criollo foals. Overall, accelerated growth in the height of foals was observed until 365 days of age, followed by deceleration and uniformity until 800 days of age (Figure 2).

The nonlinear models showed the same R^2 values for the chest circumference trait, along with similar MSE values for shin circumference (Table 2). Therefore, the best model was determined based on AIC and BIC criteria, indicating a slight superiority for the Brody model. Chest circumference exhibited more homogeneous growth in animals up to 365 days of age, with slower development and greater variability observed from 400 days of age onwards (Figure 2).

The best-fitting nonlinear model for shin circumference was Gompertz (Table 2), with value of 0.1800 m estimated for parameter A, within the expected range for Criollo horses at 800 days of age. An increase in shin circumference was observed in the early months of the animals' lives, which can be explained by the accelerated bone growth that occurs during this phase. After this period, there is uniformity in development (Figure 2).

Due to the need for a practical tool for breeders to monitor the growth and development of their animals, 95% confidence interval limits were obtained for weight, height, chest circumference (based on estimates obtained with the Brody model), and shin circumference (based on estimates obtained with the Gompertz model) in the Criollo breed (Table 3), complementing the graphical information of the growth curves (Figures 1 and 2).

Table 2 - Parameter (A, b, and k) estimates and standard error (SE), coefficient of determination (R^2), mean squared error (MSE), Akaike's information criterion (AIC), and Bayesian information criterion (BIC) according to nonlinear models studied

Trait	Model	A±SE	b±SE	k±SE	R^2	MSE	AIC	BIC
Weight	Brody	346.70±333.40	0.8332±0.8146	0.00316±0.00281	0.9866	703.2	4074.04	4087.34
	Gompertz	324.70±315.70	1.4748±1.4079	0.00508±0.00465	0.9858	740.5	4109.17	4122.96
	Logistic	315.40±308.10	2.7289±2.5296	0.00692±0.00640	0.9851	784.3	4144.80	4158.10
	Von Bertalanffy	329.70±319.90	0.4043±0.3893	0.00445±0.00405	0.9861	726.1	4096.94	4110.19
Height	Brody	1.3269±1.3168	0.2997±0.2921	0.00476±0.00438	0.8731	0.0015	−4796.94	−7783.11
	Gompertz	1.3224±1.3129	0.3463±0.3360	0.00530±0.00489	0.9988	0.0015	−4449.75	−4435.92
	Logistic	1.3187±1.3098	0.4016±0.3877	0.00583±0.00541	0.9988	0.0016	−4773.63	−4759.80
	Von Bertalanffy	1.3194±1.3093	0.1087±0.1052	0.00516±0.00472	0.9989	0.0015	−4789.22	−4775.38
Chest circumference	Brody	1.5574±1.5434	0.4400±0.4287	0.00554±0.00514	0.9997	0.0043	−4037.07	−4023.23
	Gompertz	1.5469±1.5340	0.5513±0.5328	0.00649±0.00604	0.9997	0.0045	−4008.07	−3994.23
	Logistic	1.5389±1.5268	0.6963±0.6668	0.00744±0.00695	0.9997	0.0047	−3979.55	−3965.71
	Von Bertalanffy	1.5501±1.5368	0.1703±0.1651	0.00617±0.00574	0.9997	0.0045	−4017.74	−4003.90
Shin circumference	Brody	0.1807±0.1790	0.3226±0.3118	0.00540±0.00487	0.9979	0.00005	−7281.81	−7267.97
	Gompertz	0.1800±0.1785	0.3777±0.3625	0.00605±0.00550	0.9978	0.00005	−7283.68	−7268.84
	Logistic	0.1795±0.1780	0.4441±0.4231	0.00671±0.00612	0.9978	0.00005	−7263.09	−7249.26
	Von Bertalanffy	0.1802±0.1787	0.1194±0.1149	0.00583±0.00529	0.9979	0.00005	−7275.45	−7261.61

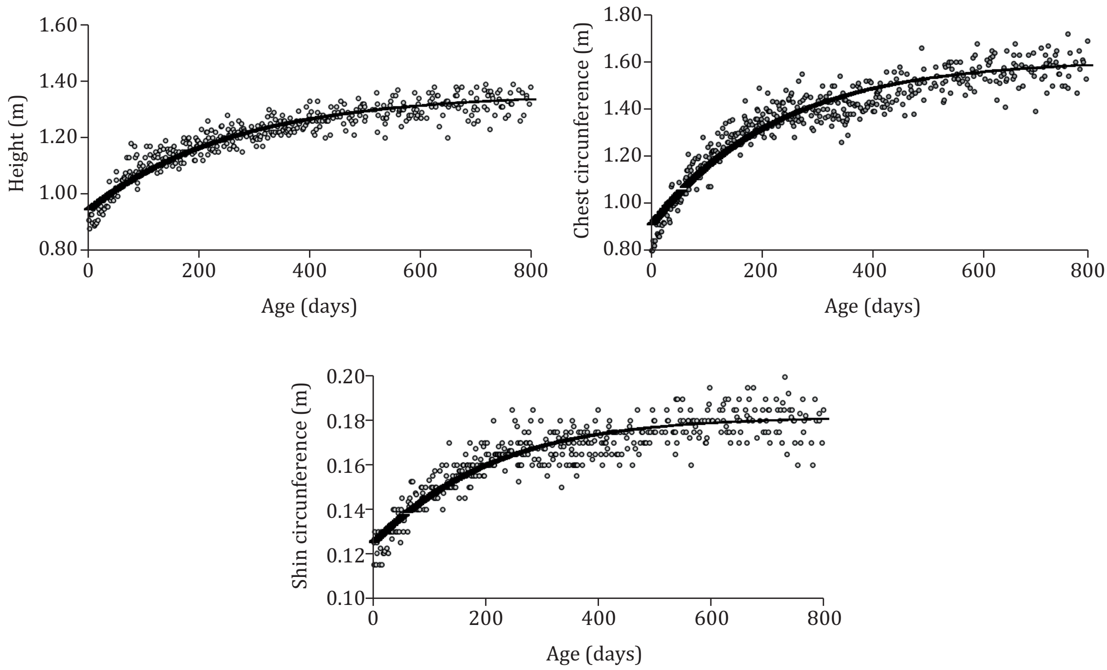

Figure 2 - Means of observed (•) and predicted (-) for height (with the Brody nonlinear model), chest circumference (with the Brody nonlinear model), and shin circumference (with the Gompertz nonlinear model) for Criollo horses.

Table 3 - Lower and upper limits of the confidence interval (95%) for weight, height, chest circumference, and shin circumference of Criollo foals according to the growth curve obtained by the best nonlinear model for each trait

Age (days)	Weight (kg)		Height (m)		Chest circumference (m)		Shin circumference (m)	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
1-90	63.73	136.08	0.90	1.09	1.09	1.15	1.08	1.17
91-180	127.10	184.73	1.04	1.17	1.13	1.30	1.14	1.18
181-270	182.51	236.17	1.14	1.24	1.26	1.42	1.15	1.20
271-360	208.92	245.06	1.21	1.26	1.39	1.48	1.15	1.21
361-450	239.37	293.63	1.24	1.29	1.41	1.54	1.16	1.22
451-540	268.15	325.76	1.26	1.31	1.45	1.58	1.15	1.23
541-630	301.65	337.42	1.29	1.33	1.48	1.60	1.16	1.23
631-800	309.79	378.98	1.30	1.35	1.52	1.64	1.17	1.24

4. Discussion

The means obtained for the evaluated traits in this study (Table 1) showed values similar to those reported for Criollo breed foals from birth to 36 months of age by Rodrigues (1999), with weight ranging from 57 to 386.8 kg, height ranging from 0.91 to 1.39 m, chest circumference ranging from 0.86 to 1.67 m, and shin circumference for females ranging from 0.13 to 0.185 m and for males ranging from 0.145 to 0.195 m. In the studied population, no differences were observed in the development between males and females for the evaluated traits, which can be attributed to the same management conditions provided to animals of both sexes, including the same diet.

A portion of the studied population did not reach the minimum values for the morphometric measurements of height (94% of animals) and chest circumference (5% of animals), required by the Brazilian Association of Criollo Horse Breeders (ABCCC, 2022) from 24 months of age. For males, the required measurements in the Criollo breed are 1.40 to 1.50 m for height, a minimum of 1.68 m for chest circumference, and 0.18 m for shin circumference. For females, a height of 1.38 to 1.48 m is required, along with a minimum of 1.70 m for chest circumference and 0.17 m for shin circumference. Animals aged 24 months or older will be eligible to receive the definitive breed registration, provided they meet the required breed standard. This significantly impacts their commercial value, making these measurements crucial for breeders.

The values of parameter A estimated for the weight trait with different nonlinear models (Table 2) indicate that Criollo foals at 800 days of age have weights within the expected normal range. This is because the animals are in an active phase of growth and in skeletal development on their way to adulthood. According to Dowdall (1982), adult Criollo horses (above 40 months of age) have an average weight of 435 kg. In a study with Mangalarga Marchador horses using the Brody, Logistic, Von Bertalanffy, and Gompertz nonlinear models, Souza et al. (2017) reported that the animals reached stability with weights ranging from 416 kg (Logistic model) to 439 kg (Brody model). These authors considered weight measurements from birth to 60 months of age, encompassing the developmental period up to adulthood. This extension of the evaluated period could explain the differences in results compared with those obtained in the present study.

Evaluating the growth curves of Campolina horses from 7 to 203 months of age and using nonlinear models, Teixeira et al. (2021) reported higher values for parameter A (adult weight) than those obtained in the present study. These authors estimated values ranging from 528.13 kg (Logistic model) to 532.96 kg (Von Bertalanffy model) for females and from 492.79 kg (Logistic model) to 496.41 kg (Brody model) for males. Besides the breed effect, according to Fradinho et al. (2016), high weight values can be obtained due to genetic improvements and feeding practices.

For weight, R^2 showed high values with little variation among the studied models, indicating a good fit (Table 2). The AIC penalizes models that overfit the data due to higher parameterization, while the BIC penalizes models based on the number of observations, providing greater preference for less parameterized models compared with AIC (Blasco, 2017). As lower AIC and BIC values reflect better fits, in this study, the Brody model exhibited slight superiority compared with the others and obtained lower values for MSE, indicating a better fit.

Similar to the findings in the present study, Souza et al. (2017) analyzed males and females of the Mangalarga Marchador breed and reported R^2 values above 0.91 for males (Von Bertalanffy model) and 0.92 for females (Brody model). When assessing the growth of four different groups of horses from six months to adulthood, McManus et al. (2010) found the best fits with Brody and Weibull models for the group of mixed-breed horses raised by the Brazilian Army, with R^2 values of 0.55 for females and 0.92 for males. On the other hand, when comparing nonlinear models including Brody, Logistic, Von Bertalanffy, Gompertz, and Richards, Fradinho et al. (2016) indicated that the Richards model as the most suitable for describing the growth curve of Lusitano horses from birth to 42 months of age.

Unlike the findings of the present study, Teixeira et al. (2021) reported the nonlinear Gompertz model as the most suitable for representing the growth curve of body weight in the Campolina horse breed, for both sexes, with R^2 values above 95%. On the other hand, Souza et al. (2019) obtained better fits with the Logistic models for weight of Mangalarga Marchador horses. As emphasized by Fradinho et al. (2016), animal growth is influenced by several factors, highlighting the necessity of identifying the growth pattern of different breeds.

The values of parameter k estimated for weight with the nonlinear models used in this study (Table 2) were higher than the value reported by Fradinho et al. (2016). These authors evaluated Lusitano horses from birth to 42 months of age and obtained a value of 0.0010 for this parameter. This difference can be justified by the fact that Brazilian horse breeds tend to be smaller in size than the Lusitano breed, which has a later and larger growth pattern.

The observed growth of foals in the present study (Figure 1) is consistent with the expected patterns for equines. When examining the weight of Thoroughbred foals, Garcia et al. (2011) observed a period of rapid growth in the first 30 days of age, gradually decreasing as age advanced, representing 10% of the expected adult body weight at birth and 79% at 540 days of age. For Pantaneiro breed, Santos et al. (2007) described more pronounced growth in the early months of life. Evaluating Criollo foals from birth to 24 months of age, Moraes (2016) reported a higher increase in weight up to six months of age, with a pause between the fifth and sixth month due to the stress of weaning and dietary changes. However, these authors observed uniform growth up to 24 months, a pattern similar to what we observed in our study.

In the Criollo breed, height is one of the criteria established for receiving the definitive registration. Therefore, from the age of 24 months, the animal must meet the measurement according to the current breed standard. In the studied population, parameter A of height showed similar values across the different models tested. This parameter is related to the expected measurement at maturity and exhibits early maturation, being associated with bone development. It is worth noting that the values obtained for this parameter varied from 1.3187 m (Logistic model) to 1.3269 m (Brody model), falling below the minimum requirement set by the breed, both for males and females, likely due to these being young animals in an extensive system.

Despite the Brody model showing the lowest R^2 value (0.87) compared with the other tested models (Table 2), the AIC and BIC criteria displayed lower values, indicating a better fit. Similar results were reported by Hossein-Zadeh and Ghorbani (2018), who studied the height evolution from birth to 210 days of age in Caspian horses and identified the Brody model as the best fit. On the other hand, when assessing the height of Thoroughbred horses, Fradinho et al. (2016) identified the Richards model as the best fit. A similar outcome was reported by Santos et al. (2007), with the Richards model being the most suitable for describing the height evolution from birth to adulthood in Pantaneira breed animals. Recently, Fernandes et al. (2020) indicated the Logistic model as the most suitable for describing the height from 7 to 176 months of age in Mangalarga Marchador horses, and Teixeira et al. (2021) chose the Gompertz model as the most appropriate for describing the height of Campolina breed animals from 7 to 203 months of age.

The faster increase in height of foals up to around 365 days of age, as observed in this study (Figure 2), is expected since horses undergo rapid growth in their first year of life (NRC, 2007). At birth, the height of horses can be around 60% of that of an adult horse, reaching 90% of this value by the time the animal turns 365 days of age. When evaluating biometric data of Chilean Criollo foals from birth to three years of age, Porte (2000) observed a higher growth rate in height up to 180 days of age. Garcia et al. (2011) reported height progression from birth to 540 days of age in Thoroughbred horses, with height at birth representing 63% of the expected adult height, reaching 95% at 540 days of age. Similar results were reported by Pimentel et al. (2017) when evaluating Criollo foals from birth to 36 months of age, finding horses that reached an average height of 1.34 m at 24 months, representing 95.71% of the height of a horse above 40 months of age.

In the evaluated population, the Brody model showed slightly superior fit compared with other models for the chest circumference trait. Souza et al. (2017) evaluated the chest circumference of Mangalarga Marchador horses from six to 176 months of age using Brody and Logistic nonlinear models and indicated the Logistic model as the most suitable. The value of parameter A estimated for chest circumference with the Brody nonlinear model (1.5574m) is similar to that described by Pimentel et al. (2017), who found chest circumference values for Criollo foals at 24 months of age ranging from 1.47 to 1.60 m.

Higher chest circumference values have been reported in the literature for other horse breeds. When evaluating morphologically the Brasileiro de Hipismo breed, Godoi et al. (2013) observed an average chest circumference of 1.70 m for animals of 22 to 25 months of age, within the expected range for the breed, which can reach 1.82 m in adult age. Similarly, Souza et al. (2017) obtained values of 172.06 cm (adult males) and 183.09 cm (adult females) when assessing the chest circumference of Mangalarga

Marchador horses from six to 176 months of age. According to Souza et al. (2019), the allometric growth of different body tissues, such as bone and muscle, tends to be greater in the early years of life of Mangalarga Marchador horses, which can result in different patterns of body growth compared with other breeds.

The chest circumference in the studied population exhibited more homogeneous growth in the first 365 days of age (Figure 2). This measurement is directly related to the size of the animal and its cardiorespiratory capacity, that is, small and medium-sized horses have slower development, while larger ones have higher values (Fradinho et al., 2016). In Criollo breed horses, the chest should be broad, wide, deep, with well-spaced and muscular connections, as well as arched and deep ribs. Generally, animals with a smaller chest circumference suffer impairments in their cardiorespiratory capacity and have lower physical vigor (Zamborlini et al., 1996; McManus et al., 2005).

Part of studied population exhibited height and chest circumference below the expected values for Criollo foals with 24 months of age. The animals were kept in an extensive production system, with irregular feeding, which may have masked their true developmental potential during this period. It is worth noting that from birth to two years of age, proper nutritional management is essential for the animal's bone and muscle development, and dietary restrictions can lead to consequences in the foals' body development, causing variations over time. Inadequate feeding conditions negatively contribute to initial growth rates, which should be high, becoming irregular and slower, which is unfavorable for the development of morphometric traits (Gonçalves et al., 2012).

For shin circumference, the best fit was obtained with the Gompertz nonlinear model (Table 2), differing from what was reported by Souza et al. (2017) for Mangalarga Marchador breed horses, in which the Brody and Logistic models were the most suitable to describe the development of shin circumference from six to 176 months of age. On the other hand, Fradinho et al. (2016) reported better fits for the shin circumference measured from birth to 42 months of age in Lusitano breed using Richards nonlinear model, with values for parameter A of 21.4 cm for males and 19.3 cm for females. The accelerated bone growth that occurs primarily in the first months of foals' lives explains the increase in shin circumference observed during this phase (Figure 2). Generally, the skin, the area related to the metacarpal bones and tendons, should be short, with strong, well-defined tendons, and correctly aligned in Criollo breed animals (ABCCC, 2022).

In general, all studied traits showed the same pattern over time, with greater stability and homogeneity from 180 to 400 days of age (Figures 1 and 2). Santos et al. (2007) described greater variability in the growth of Pantaneiro horses in the early months of life, which reduces with age. For Quarter Horse breed, Mota et al. (2010) reported greater regularity in growth up to 570 days of age for height and chest circumference traits. In general, nutrition and management are factors that directly influence morphometric measurements. The nutritional management provided to the animals during this phase is of paramount importance for consistency in the growth curve and, consequently, for good bone and muscle development (Gonçalves et al., 2012).

Despite the existence of studies involving morphometric measurements in horses using nonlinear models (McManus et al., 2010; Fradinho et al., 2016; Souza et al., 2017), research on the Criollo breed remains limited, particularly concerning chest and shin circumference traits, for which there are no studies on growth curve modeling. Understanding the evolution of relevant traits in horses, such as morphometric measurements, provides a better insight into the animals' developmental process, enabling improvements in nutritional, sanitary, genetic and welfare management (Souza et al., 2017).

To provide a practical contribution to assist professionals and breeders in monitoring the growth of Criollo animals, 95% confidence interval limits were obtained for the evaluated traits across different age groups (Table 3). Similar results have been presented in the studies by Fradinho et al. (2016) with the Lusitano breed, Souza et al. (2017) with the Mangalarga Marchador breed, and Teixeira et al. (2021) with the Campolina breed. Despite the importance of the obtained results, mainly enabling a more careful selection of foals, further supplementation of the information presented in Table 3 is expected in future studies, encompassing a larger number of animals, as the limits of this table were estimated based on the sample used in this work.

5. Conclusions

The present study provides an insight into the growth of Criollo foals from birth to 800 days of age. The Brody model showed the best fit for describing the evolution of weight, height, and chest circumference. However, for shin circumference, the Gompertz model was the most suitable.

The animals showed an increase in weight during the evaluated period. Accelerated height growth was observed in the first 365 days of foal's lives, followed by a decrease and homogeneity until 400 days of age. Chest circumference exhibited more homogeneous growth in animals up to 365 days of age, with slower and more variable growth observed from 400 days of age onwards. Shin circumference showed significant growth in the early months of age, remaining stable until 800 days of age. Some individuals in the evaluated population did not meet the minimum values required by the breed standard for height and chest circumference traits at 24 months of age.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: Martins, M. C.; Souza, J. S. and Boligon, A. A. **Data curation:** Martins, M. C.; Souza, J. R. M.; Rodrigues, W. B. and Boligon, A. A. **Formal analysis:** Martins, M. C.; Souza, J. S. and Boligon, A. A. **Funding acquisition:** Boligon, A. A. **Investigation:** Martins, M. C.; Souza, J. S. and Boligon, A. A. **Methodology:** Martins, M. C.; Souza, J. S. and Boligon, A. A. **Project administration:** Boligon, A. A. **Supervision:** Souza, J. S.; Pimentel, A. M. H. and Boligon, A. A. **Validation:** Martins, M. C.; Souza, J. S. and Boligon, A. A. **Visualization:** Martins, M. C.; Souza, J. S. and Boligon, A. A. **Writing – original draft:** Martins, M. C.; Souza, J. S.; Souza, J. R. M.; Rodrigues, W. B.; Pimentel, A. M. H. and Boligon, A. A. **Writing – review & editing:** Martins, M. C.; Souza, J. S.; Souza, J. R. M.; Rodrigues, W. B.; Pimentel, A. M. H. and Boligon, A. A.

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