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Mathematical models to define growth patterns in indigenous horses of India

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ABSTRACT

The objective of the study was to define the nature of growth and to establish the standards of growth in Marwari, Manipuri and Zanskari horses. Mathematical functions for the prediction of growth in Marwari horses were derived utilising 1112 records of body weight. The body weight standards of Marwari horses from birth to 11 ½ years of age were defined and found to be close to that of Arabian horses. The Logarithmic, Power, S and Cubic functions were derived with respective R^2 values of 0.955, 0.833, 0.897 and 0.980 for average body weights to explain the age-weight relationship in Marwari horses from birth to 11 ½ years of age. Looking at the distribution of observed data along the course of predicted curve and goodness of fit on average body weight, the Cubic equation $\hat{Y} = 68.136 + 10.744 (x) - 0.12189 (x)^2 + 0.00044177 (x)^3$ can reliably be utilized for prediction of body weight with respect to age. Similarly, the Cubic equations with R^2 value of 0.965 and 0.958 were derived respectively for Manipuri and Zanskari horses. The two roots of Cubic function were derived to define the points of inflection of growth curve. The study indicated that the initial growth phase in Marwari, Manipuri and Zanskari continues up to the age of 73.22, 72 and 67.4 months respectively and there after it remains static; and the cubic function can reliably be used to explain the nature of growth in Marwari, Manipuri and Zanskari breeds of horses.

Keywords: Cubic, Growth, Horse, Marwari, Regression

The Marwari breed of horse is known for its elegance and bravery, but it largely remained unexplored in terms of breeding parameters until recently (Mehta *et al*. 2021). The Manipuri and Zanskari horses are well-known for their adaptation to hilly terrains and are being used for draught purpose (Mehta 2020). However, the breeds have been defined at the molecular level (Behl *et al*. 2007, Jun *et al*. 2014). Growth of an animal is an undisputed indicator of its health, vigour, productive and reproductive efficiency. The growth of an animal over and under the normal physiological body weight warns the owner to pay attention on it so as to safeguard the purpose of keeping the same. There are typical differences in the body weight of animals of different breeds at different stages of growth, such as the Thoroughbred, Marwari, Manipuri and Zanskari horses. Nevertheless, for most horse breeds worldwide, the mathematical aspects of the growth from birth to the age of ten years or more are absent. Among the few reports, Onoda *et al*. (2011) studied the male body weight of Thoroughbred colts and worked out empirical growth curve from birth to about 630 days of age. Similarly, Onoda *et al*. (2013b) presented empirical percentile growth curves with Z-scores for Japanese Thoroughbred horses utilising the age weight data from birth to 1100 days. Fernandes *et al*. (2020) reported growth curve for height at withers and body length of Mangalarga Marchador horses of 6 to 176 months of age utilising the Logistic and Quadratic response plateau non-linear regression models. However, the paper does not present age-weight relationship of Mangalarga Marchador horses. Valette *et al*. (2008) presented the use of linear and non-linear functions to describe the growth of young sport- and race-horses born in Normandy in terms of age, from birth to 24 months, and wither height. Similarly, Teixeira *et al*. (2021) presented growth curves of Campolina horses using nonlinear models. It is a known fact that the growth of large animals generally follows linear function in the initial phase of growth, the growth slows down subsequently and then it remains static for quite some time and declines towards the fag end of the life. The available literature does not include a single linear or non-linear regression model to describe this association in horses from birth to the majority of their productive life. Similar information regarding nature of growth and availability of standards of growth is largely missing. This study was therefore planned to derive a single prediction equation for the purpose and to define the standards of growth in Marwari, Manipuri and Zanskari horses.

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MATERIALS AND METHODS

Animals: A total of 1112 body weight records of Marwari horses maintained at Equine Production Campus, Bikaner from the year 1989 to 2021 were analysed for the purpose. These horses were maintained under intensive system of management with feed and water *ad lib*. The body weight of all healthy and non-pregnant animals was recorded in morning at an interval of 6 month from birth to 11½ years of age. The Manipuri and Zanskari horses maintained at the same farm, under similar managemental conditions were utilised for the present study. Body weight data of 151 Manipuri and 211 Zanskari horses, recorded every 6 months from birth to 11½ years of age was analysed.

Statistical analysis: The mathematical functions to define the nature of growth in Marwari, Manipuri and Zanskari horses were derived using logarithmic, power, S and cubic regression-curve estimation models (SPSS 26.0) given as follows:

Cubic: $\hat{Y} = b_0 + [b_1X] + [b_2X^2] + [b_3X^3]$

Logarithmic: $\hat{Y} = b_0 + b_1\log(X)$

Power: $\hat{Y} = = b_0X^{b1}$

S: $\hat{Y} = \exp(b_0 + b_1/X)$

where $\hat{Y}$, body weight in kg; X, age in months; b_0, constant and b_i, coefficients of the predictor variables, where i varies from 1 to 3. Further, $\exp(b_0 + b_1/X)$ is the value of e to the power of $(b_0 + b_1/X)$; where e is base of natural logarithm.

The R^2 statistic, utilised as the coefficient of determination to quantify the extent to which variation in Y is explained by variation in X, was calculated utilising the following derivation:

$$R^2 = \frac{RSS}{TSS};$$

where RSS is Regression (explained) Sum of Squares and TSS is the Total Sum of Squares, calculated by:

$$R^2 = \frac{\sum_{i=1}^{n}[f(Xi)-\bar{Y})]^2}{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}$$

where i varies from 1 to n and $\hat{Y}$ is the mean value of Y.

The per cent absolute deviation (%Di) of predicted values were derived by using:

$$\%\,Di = \frac{|Yi - \bar{Y}i|}{Yi} \times 100$$

where $\hat{Y}i$, observed value and $\hat{Y}i$, predicted value of i[th] body weight where I varies from 1 to n (=24)

In order to determine the maxima and minima of the cubic curve, the two roots of the cubic function were derived by differentiating the function $(b_0 + b_1X + b_2X^2 + b_3X^3)$ with respect to X.

$$f'(x)\ b_1 + 2b_2X + 3b_3X^2$$

For finding critical points, put,

$$\frac{dy}{dx} = f'(x) = 0$$

So, $b_1 + 2b_2X + 3b_3X^2 = 0$

Determinant $D = (2b_2)^2 - 4(3b_3)(b_1) = 4b_2^2 - 12\,b_3\,b_1$

Hence the wo roots; $X_1, X_2 = \frac{-2b_2 \pm \sqrt{4b_2^2 - 12b_3b_1}}{6b_3}$

The analysis of variance was carried out to study the effect of breed, sex and interaction of breed with sex (Snedecor and Cochran 1994). The breed and age group means were compared using Duncan's multiple range test (Duncan 1957).

RESULTS AND DISCUSSION

Defining the baseline: Identification and breeding of true to the breed Marwari horses had always been an issue of prime importance among the horse breeders. In order to define the body weight standards of the breed at different stages of age, 32 years data was analysed and the average annual weight from birth to 11½ years of age was measured with weight at birth, 6 and 9 years of age as 36.51±0.88, 365.68±7.07 and 366.91±6.99 kg, respectively (Supplementary Table 1). The results of analysis of variance showed that the effect of sex and period was non-significant (P>0.05) but that of interaction between sex and period was significant (P<0.01). However, the male animals were heavier than the female animals from birth to 3 years of age (Table 1). Similar standards were also worked out for the Manipuri and Zanskari horses. The Manipuri horses measured 24.56±1.52, 245.43±15.28 and 245.30±19.05 kg and the Zanskari horses measured 29.20±2.17, 289.53±11.05 and 297.89±14.23 kg respectively at birth, 6 and 9 years of age (Table 2). The Manipuri and Zanskari horses behaved similarly in the analysis of variance where the effect of sex and interaction between sex and period was non-significant (P>0.05) but that of period was significant (P<0.01).

The average six-monthly body weight of the above breeds was not available in the literature for comparison or contrast; however, the body weight data presented in Tables 1 and 2 clearly demonstrates that Manipuri ponies were the lightest, Zanskari ponies were intermediate, and Marwari horses were the heaviest of the breeds measured. Further, it is said that the Marwari breed of horses has been developed by breeding of Indian ponies having Mongolian inheritance with Arabian horses from 12[th] century onwards (Kaura 1961, Edwards 1994, Behl *et al*. 2007, Doniger 2009, Gupta *et al*. 2012). The Arabian and Mongolian inheritance in Marwari has also been confirmed by Jun *et al*. (2014) while doing whole genome sequencing and analysis of its genetic origin. The standards of body weight of Marwari were expected to be intermediate between the (Manipuri and Zanskari) ponies and the Arab horses, but the literature indicates that the adult Arab horses' weight 360 to 450 kg at adult age (Encyclopaedia Britannica 2019) which is quite similar to the present observation in Marwari horse. This clearly indicates that Indian native ponies were substantially upgraded using Arab horses leading to the development of Marwari breed of horses. This is further substantiated by the fact that in the Marwari horses, the wither height measures 150.15±0.04 cm, body length measures 151.44±0.06 cm and heart girth measures 170.02±0.19 cm (Mehta *et al*. 2021) and in the Iranian Arab horse withers height measures 149.17±0.33 cm, body length measures 148.54±0.46 cm and heart girth measures

Table 1. Average and predicted body weight of Marwari horses utilising Cubic function along with analysis of variance

Age	Male		Female		Pooled	
	Observed (Y)	Predicted (Ŷ)	Observed(Y)	Predicted (Ŷ)	Pooled(Y)	Predicted (Ŷ)
Birth*	37.00±0.94 (27)	74.03	36.12±1.41(34)	64.09	36.51±0.88 (61)	68.14
6 Month	152.27±3.91 (30)	132.61	144.77±3.49 (39)	125.12	148.03±2.62 (69)	128.31
12 Month	200.69±6.42 (32)	183.36	193.10±5.88 (42)	177.74	196.38±4.34 (74)	180.28
18 Month**††	240.07±7.50 (30)	226.83	224.42±6.16 (38)	222.54	231.32±4.83 (68)	224.62
24 Month	270.19±8.45 (27)	263.54	257.27±7.41 (37)	260.11	262.72±5.59 (64)	261.90
30 Month†	293.39±8.96 (28)	294.02	281.16±7.77 (38)	291.06	286.35±5.87 (66)	292.70
36 Month	330.59±11.07 (17)	318.82	323.41±7.58 (29)	315.97	326.07±6.24 (46)	317.58
42 Month	332.15±9.19 (13)	338.45	343.58±8.96 (26)	335.45	339.77±6.70 (39)	337.12
48 Month	338.38±11.63 (13)	353.46	352.50±10.39 (28)	350.08	348.02±7.98 (41)	351.89
54 Month	363.10±5.87 (10)	364.38	368.22±8.07 (18)	360.46	366.39±5.54 (28)	362.46
60 Month*	361.92±7.93 (13)	371.73	369.65±7.62 (26)	367.20	367.08±5.69 (39)	369.42
66 Month	370.27±9.21 (21)	376.06	357.98±6.67 (30)	370.88	363.04±5.47 (51)	373.32
72 Month	359.89±12.00 (14)	377.90	368.57±8.84 (28)	372.10	365.68±7.07 (42)	374.74
78 Month**	376.93±11.55 (22)	377.77	354.68±8.30 (30)	371.45	364.09±6.94 (52)	374.26
84 Month	383.58±14.84 (20)	376.22	358.32±8.94 (29)	369.54	368.63±8.15 (49)	372.45
90 Month	377.53±15.45 (19)	373.76	353.32±7.96 (29)	366.96	362.91±7.87 (48)	369.87
96 Month	376.25±15.81(16)	370.95	369.39±8.77 (29)	364.29	371.83±7.88 (45)	367.11
102 Month	380.32±14.32 (17)	368.30	367.48±7.75 (29)	362.15	372.22±7.17 (46)	364.73
108 Month	361.44±11.79(14)	366.35	369.55±8.77 (29)	361.12	366.91±6.99 (43)	363.30
114 Month	369.26±8.98(13)	365.64	373.83±8.74 (24)	361.80	372.22±6.42 (37)	363.41
120 Month	375.01±11.24(11)	366.70	381.45±9.54 (21)	364.78	379.23±7.27 (32)	365.62
126 Month	371.67±10.71(10)	370.05	379.24±11.93 (17)	370.66	376.44±8.39 (27)	370.50
132 Month	376.19±11.91 (10)	376.24	375.99±13.48 (15)	380.04	376.07±9.21 (25)	378.63
138 Month	374.87±11.16 (8)	385.80	375.10±17.34 (12)	393.51	375.01±11.08 (20)	390.58

Effect of sex significant *(P<0.05) and **(P<0.01); Effect of Period significant †(P<0.05) and ††(P<0.01). Body weight in kg.

169.45±0.50 cm (Gharahveysi *et al*. 2008). Almost similar measurements of wither height (145 to 155 cm) of the Arabian horses have been described by United States Equestrian Federation (2008). Thus, the Marwari horses can well be compared with Arabian horses in terms of biometric and body weight standards.

The analysis of variance indicated that the effect of sex and period was non-significant (P>0.05) but that of interaction between sex and period was significant (P<0.01) in Marwari horses. However, the male animals were heavier than the female animals from birth to 3 years of age. This superiority of males over females was not observed in subsequent age classes, in spite of the fact that a smaller number of males are maintained then the females, most probably due to the fact that the stallions become reproductively active at this age and their energy is diverted towards reproductive activities (Table 1). The interaction of sex with period was significant probably because the two sexes were influenced by the non-genetic factors like feed, fodder, management, climate etc. in different manner. The results of analysis of variance of Manipuri and Zanskari horses were quite similar where the effect of sex and interaction between sex and period was non-significant (P>0.05) but that of period was significant (P<0.01). The significant effect of period can well be attributed to the fact these animals were brought from their native tract, which is high altitude land with cold climate and they were bred at Bikaner which is a desertic place with very climate. Further, the number of animals in different periods in Manipuri ranged from 4 to 33 and that in Zanskari ranged from 6 to 61, this could also be one of the reasons amounting to significant effect of period in these two breeds. No comparable study was available in literature.

In order to understand the growth pattern, mean comparison was carried out using Duncan's multiple range test and it was observed that in Marwari breed, the body weight averages with respect to 24 age classes were defined under 10 homogenous subsets. The subsequent body weights were significantly higher than the respective preceding body weights till 3 years of age, commensurating with first 7 subsets. The subsequent body weights overlapped with preceding ones (Supplementary Table 1). The results indicated that right from birth to 3 years of age the growth was substantial and it slowed down thereafter. During 4th and 5th year there was slight overlapping and thereafter the differences amongst last 15 age-classes was non-significant defining the flatness of the curve or cessation of further growth. This happens in most animals that the growth slows down when the productive life starts and it remains more or less static thereafter. In Manipuri and Zanskari, the body weight averages with respect to 24 age classes were defined by 7 and 11 homogenous subsets (Table 2) and the overlapping of subsequent body weight

Table 2. Average and predicted body weight of Manipuri and Zanskari horses derived using Cubic function

Age	Manipuri		Zanskari	
	Observed (Y)	Predicted (Ŷ)	Observed (Y)	Predicted (Ŷ)
Birth	24.56±1.52^{a} (9)	52.73	29.20±2.17^{a} (10)	55.39
6 Month	106.33±8.15^{b} (9)	92.74	121.08±4.42^{b} (12)	106.76
12 Month	136.44±8.21b^{c} (9)	127.08	154.46±5.42^{c} (13)	150.59
18 Month	161.89±8.61^{cd} (9)	156.19	189.08±7.85^{d} (13)	187.43
24 Month	191.57±7.10^{de} (7)	180.46	234.11±6.59^{e} (9)	217.87
30 Month	212.33±8.47^{ef} (6)	200.32	256.11±6.46^{ef} (9)	242.46
36 Month	218.17±5.76^{efg} (6)	216.18	262.50±14.04^{efgh} (8)	261.77
42 Month	232.67±15.07^{efg} (3)	228.46	259.83±17.12^{efg} (6)	276.37
48 Month	225.00±19.64^{efg} (4)	237.57	298.75±18.36^{ghijk} (4)	286.84
54 Month	239.50±47.50^{efg} (2)	243.94	310.75±18.26^{ijk} (4)	293.73
60 Month	239.67±23.18^{efg} (3)	247.97	282.40±18.45^{fghijk} (5)	297.62
66 Month	229.07±17.56^{efg} (5)	250.08	281.28±9.33^{fghijk} (13)	299.07
72 Month	245.43±15.28^{fg} (6)	250.70	289.53±11.05^{fghijk} (13)	298.65
78 Month	254.92±12.18^{fg} (5)	250.22	278.96±8.19^{fghij} (11)	296.93
84 Month	253.13±14.93^{fg} (5)	249.08	274.32±8.70^{fghi} (11)	294.48
90 Month	246.60±13.59^{fg} (7)	247.68	296.83±8.57^{ghijk} (10)	291.87
96 Month	242.24±14.07^{fg} (7)	246.45	300.43±14.11^{hijk} (9)	289.65
102 Month	256.20±12.91^{fg} (9)	245.79	310.72±13.86^{ijk} (8)	288.41
108 Month	245.30±19.05^{fg} (9)	246.12	297.89±14.23^{ghijk} (8)	288.70
114 Month	253.62±14.26^{fg} (9)	247.87	293.13±12.72^{fghijk} (8)	291.11
120 Month	266.90±16.44^{g} (7)	251.44	293.48±11.87^{fghijk} (8)	296.18
126 Month	262.83±17.22^{fg} (6)	257.25	318.25±12.30^{ijk} (8)	304.50
132 Month	260.00±12.74^{fg} (5)	265.72	321.06±24.08^{k} (6)	316.63
138 Month	264.92±16.36^{g} (4)	277.26	312.00±21.06^{ijk} (5)	333.14

Values with different superscripts differed significantly ($P<0.05$) Body weight in kg.

over preceding body weight was much higher in these two pony breeds as compared to the Marwari breed because of a smaller number of observations as well as due to the small size and lesser body weight of these animals as compared to the Marwari animals.

Mathematical function for defining the standards: In order to define the observed trend of change in body weight with respect to age, eleven mathematical functions, viz. Linear, Logarithmic, Inverse, Quadratic, Cubic, Compound, Power, S, Growth, Exponential and Logistic were utilised and four non-linear regression models, viz. Logarithmic, Cubic, Power and S having R^2 value of ≥ 0.80 were selected for deriving the equations utilising entire data set of Marwari breed presenting the body weight at 6 months' interval. The R^2 values have been presented in Table 3 and the goodness-of-fit along the course of data has been presented in Supplementary Fig.1. The best fit as per R^2 values was Power regression equation followed closely by S, Cubic and Logarithmic equations. However, the observation of regression plot (Supplementary Fig. 1) indicated that the mathematical closeness of fit depicted in terms of R^2 may not be the correct way to proceed further and hence these four models were retested on average values of body weight taken at 6 months interval to find out the best fit. The resultant R^2 values for Logarithmic, Power, S and Cubic regression models were 0.955, 0.883, 0.897 and 0.980 respectively (Table 3). The goodness-of-fit of Cubic equation is also evident from the Fig. 1(A). However, in order to visualise the distance of individual observation from the respective predicted value, another static absolute deviation of predicted values from the observed values was drawn and the same is presented in Supplementary Table 1 for all four prediction models used in the study. The observed values had minimum deviation from the predicted values in 6 (Logarithmic), 17 (Cubic), 0 (Power) and 1 (S) classes out in all 24 classes, reaffirming the findings depicted in terms of R^2 as well as physical observation of the regression plot. In Manipuri ponies, utilising the average body weights with respect to age, the Cubic, Logarithmic, Power and S regression model had R^2 values of 0.959, 0.969, 0.874 and 0.914 respectively [Table 3, Fig. 1 (B)]. Similar exercise was done for the Zanskari horses utilising the average body weight with respect to age and the Cubic, Logarithmic, Power and S regression model had R^2 values of 0.953, 0.938, 0.869 and 0.901 respectively [Table 3, Fig. 1 (C)].

The growth of any species follows a peculiar trend over age and the same needs to be defined statistically, so as to make the standard observations usable and applicable at several places e.g. planning, breeding, health, management. In order to define the growth phase, the Logarithmic, Cubic, Power and S functions were tried utilising entire data set presenting the body weight of Marwari animals at 6 months' interval. The R^2 values obtained were 0.807,

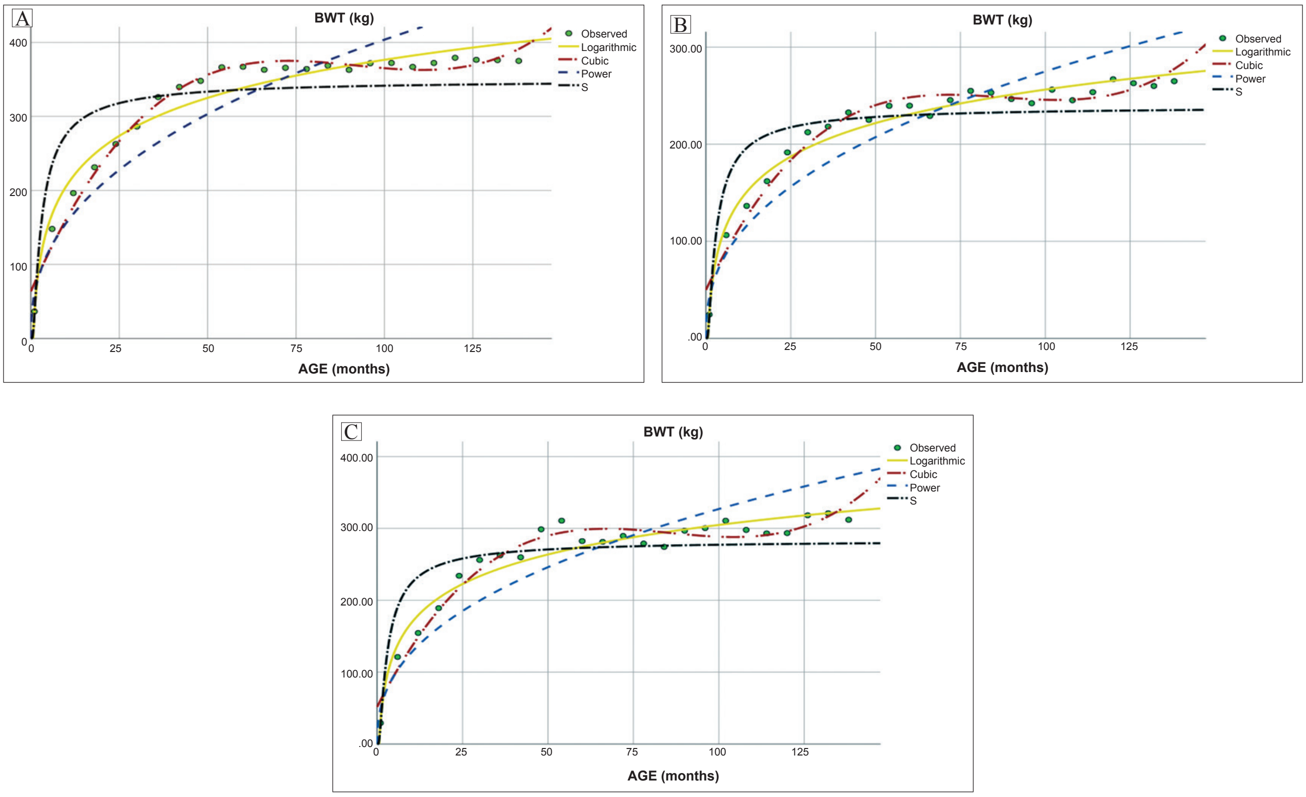

Fig. 1. Fitting of regression models on average values of body weight of horses taken a 6 months interval; (A) Marwari horse, (B) Manipuri horse and (C) Zanskari horse.

0.845, 0.832 and 0.821 respectively for Logarithmic, Power, S and Cubic functions. Lower R^2 values were expected because the model tries to accommodate the entire variation present in the data set and gives a predicted value of each observation. The results presented that the Power regression equation to be the best fit followed closely by S, Cubic and Logarithmic equations. However, the aim of present investigation was to define the standards of growth and to derive a single equation for predicting the body weight during most part of the life. Thus, in order to achieve this the average values of body weight with respect to the 24 age classes encompassing birth to 11 ½ years of age were worked out and the four selected models, viz. Logarithmic, Cubic, Power and S functions were tested. As expected, the R^2 values improved significantly in Marwari (0.883-0.980), Manipuri (0.874-0.969) and Zanskari (0.869-0.953). Based on the R^2 values and observation of curve fitting to the average data (Fig.1), the Cubic function was selected as the best to define the age-weight relationship in studied breeds of horses. Comparable study is not available in the literature. However, in Japanese Thoroughbred horse empirical percentile growth curves using Z-scores were developed for defining the age-body weight and age-wither height relationship (Onoda *et al.* 2011, Onoda *et al.* 2013a, 2013b). In this study, for age-body weight relationship the data from birth to 1100 days (~3 years) of age was utilised and for the age-wither height relationship the data from birth to 800 days was utilised. Contrary to this, the present investigation tries to explain the age-body weight relationship from birth to 11½ years (~4197 days). Fernandes *et al*. (2020) perhaps covered the longest part of life, i.e. from 6 to 176 months of age and reported growth curve for height at withers and body length of Mangalarga Marchador horses utilising the Logistic and Quadratic response plateau nonlinear regression models. However, the paper doesn't present age-weight relationship of Mangalarga Marchador horses. The mathematical functions used in the present study were also used by Valette *et al.* (2008) in sports- and race-horses born in Normandy. However, the study covers a very narrow age group, i.e. from birth to 18 months of age and the relationship worked out is between age and wither height. Hossein-Zadeh and Ghorbani (2018) carried out similar study in Caspian horses measured from birth to 32 weeks of age and reported that the Brody function was the best model for fitting the growth curve of body weight, body length and wither height in females and all horses.

Cubic function for defining the standards: When the Cubic, Logarithmic, Power and S regression models were derived, the first age class was defined as having the numerical value of 1 rather than 0, because the Logarithmic, Power and S regression models do not accept the value 0 in the input format for the variable, but the fact remains that by replacing 0 with 1 in the first age class, the age of the animal is read as 1 month instead of 0 month, which is basically the first weight of animals when it is born. However, in order to overcome this, the cubic model, which accepts 0 in the input format for the variable, was

Table 3. Regression equations and R^2 values for the prediction of body weight in different breeds and sexes of horses

Model	Breed / Sex	Equation	R^2
Data set - Observed body weight			
Logarithmic	Marwari	$\hat{Y} = 26.239 + 76.335 \log(x)$	0.807
Power	Marwari	$\hat{Y} = 56.601 (x)^{0.432}$	0.845
S	Marwari	$\hat{Y} = \exp [5.807 + (-2.350/x)]$	0.832
Cubic	Marwari	$\hat{Y} = 63.055+11.191(x) + (-0.13042) (x)^2+ 0.00048527 (x)^3$	0.821
Data set - Average body weight			
Logarithmic	Marwari	$\hat{Y} = 35.137+74.120 \log(x)$	0.955
Power	Marwari	$\hat{Y} = 60.405 (x)^{0.412}$	0.883
S	Marwari	$\hat{Y} = \exp [5.857+ (-2.380/x)]$	0.897
Cubic	Marwari	$\hat{Y} = 63.757 + 10.952(x) + (-0.12466) (x)^2+ 0.00045282 (x)^3$	0.980
Logarithmic	Manipuri	$\hat{Y} = 27.087 + 49.766 * \log(x)$	0.969
Power	Manipuri	$\hat{Y} = 42.125 (x)^{0.407}$	0.874
S	Manipuri	$\hat{Y} = \exp [5.477 + (-2.385/x)]$	0.914
Cubic	Manipuri	$\hat{Y} = 50.011 + 7.286 (x) + (-0.08600) (x)^2+0.00032717 (x)^3$	0.959
Logarithmic	Zanskari	$\hat{Y} = 31.735 + 59.305 * \log(x)$	0.938
Power	Zanskari	$\hat{Y} = 49.389 (x)^{0.411}$	0.869
S	Zanskari	$\hat{Y} = \exp [5.649 + (-2.392/x)]$	0.901
Cubic	Zanskari	$\hat{Y} = 51.610 + 9.403 (x) + (-0.11513) (x)^2+ 0.00044782 (x)^3$	0.953
Recommended equations			
Cubic	Marwari	$\hat{Y} = 68.136 + 10.744 (x) + (-0.12189) (x)^2+ 0.00044177 (x)^3$	0.984
Cubic	Marwari Male	$\hat{Y} = 74.031 + 10.444 (x) + (-0.11604) (x)^2+ 0.00041106 (x)^3$	0.979
Cubic	Marwari Female	$\hat{Y} = 64.089 + 10.907 (x) + (-0.12515) (x)^2+ 0.00045955 (x)^3$	0.981
Cubic	Manipuri	$\hat{Y} = 52.733 + 7.162 (x) + (-0.08440) (x)^2+0.00032090 (x)^3$	0.965
Cubic	Zanskari	$\hat{Y} = 55.392 + 9.223 (x) + (-0.11272) (x)^2+ 0.00043819 (x)^3$	0.958

rerun utilising the numerical value of 0 month in the first age class and the prediction equations for the Marwari, Manipuri and Zanskari horses were derived with R^2 values of 0.984, 0.965 and 0.958, respectively (Table 3). The predicted values were also derived for the Marwari, Manipuri and Zanskari horses and are presented in Tables 1 and 2 and the goodness-of-fit presented in Supplementary Fig 2. Still, it is the weakness of the cubic function that even after going up to the 3 roots of the variable, the first 2 classes contribute about 80-90% to the error in prediction. Nevertheless, the accuracy of prediction was about 98% in Marwari and 96% in Manipuri and Zanskari horses, which is quite high. Thus, the recommended cubic equations (Table 3) can reliably be used for the prediction of body weight in Marwari, Manipuri and Zanskari horses. There is no report in the literature regarding the use of cubic function or any other regression model to define this kind of relationship in the equines. However, Hassen *et al*. (2004) analysed the body weight data of bulls and heifers of purebred Angus cattle and found that the cubic effect of age showed the best fit. Mehta *et al*. (2010) analysed the growth data of Indian camel breeds from birth to 20 years of age utilising linear, quadratic, cubic, exponential and Gompertz functions and recommended the cubic equation $Y = 73.2592 + 9.9072 X - 0.0631X^2 + 0.000128 X^3$ for the prediction of body weight with respect to age with R^2 value 0.994. Though the effect of sex was largely non-significant among the Marwari horses, however, the males were heavier to females till 3 years of age, so separate regression equations were derived for precise estimation of body weight in the two sexes of Marwari breed. The equations and predicted values have been presented in Tables 1 and 3.

Defining the points of inflection or Minima and Maxima: The growth of any animal species observes a specific trend over the lifespan. In order to document the change in incremental growth of the Marwari horses mean comparison was carried out. The post-hoc test revealed that the subsequent 6 monthly body weights were significantly ($P<0.05$) higher than that of preceding body weights till 3 years of age; and the subsequent age groups differed non-significantly ($P>0.05$). In order to obtain a precise estimate, the growth curve was analysed for finding out the points of inflection of the growth curve. In the present study, the maxima and minima for the Marwari horses were worked out at 73.22 and 110.72 months; for Manipuri at 72.00 and 103.33 months and for Zanskari at 67.40 and 104.08 months. The growth of livestock species follows a standard pattern, there is an initial phase of steady and significant increase in the body weight of animals; this is followed by a static phase in which the body weight remains more of less stable; and the same is followed by slight decline during the fag end of the life. The cubic regression has three roots, in the depicted growth curve of horses, there was one real and two imaginary roots. These roots define the maxima and minima of the growth curve. The maxima define the highest point of the curve, where the value is highest and the minima defines the second point where the value is minimum. The two roots (X_1, X_2) of cubic function were derived to define the points of inflection of growth curve. The respective values clearly defined that the first phase of growth in Marwari and Manipuri continues up to the age of about 6 years and up to the age of 5½ years in Zanskari horses there after it remains static till about 8-9 years of age. The post hoc test also endorses the same fact. The study indicates that the initial weight gain continues up to the age of about 6 years and the cubic function can reliably be used to explain the nature of growth in Marwari, Manipuri and Zanskari breeds of Indian horses.

The study presents the standards of growth of Marwari, Manipur and Zanskari horses from birth to 11½ years of age. The body weight standards of Marwari horses were found to be very close to Arabian horses. The cubic regression equations with R^2 values of 0.98, 0.965 and 0.958 were derived respectively for Marwari, Manipuri and Zanskari horses. The growth of Marwari, Manipuri and Zanskari horses continued till 73.22, 72 and 67.40 months of age, thereafter it remained static till 8-9 years of age. The study statistically defines the standards of growth of Marwari, Manipuri and Zanskari horses and make the standard observations usable in planning, breeding, health and management of the respective indigenous horse breeds.

REFERENCES

Behl R, Behl J, Gupta N and Gupta S C. 2007. Genetic relationships of five Indian horse breeds using microsatellite markers. *Animal* **1**: 483–88.

Doniger W. 2009. *The Hindus: An Alternative History*. Penguin Group, London.

Duncan D B. 1957. Multiple range tests for correlated and hetrosedastic means. *Biometrics* **13**: 164–76.

Edwards E H. 1994. *The Encyclopedia of the Horse*. Dorling Kindersley, 1st edn, New York.

Encyclopaedia Britannica 2019. The Editors of Encyclopaedia. "Arabian horse". Encyclopedia Britannica, 14 Feb. 2019, https://www.britannica.com/animal/ Arabian-horse. Accessed 9 December 2022.

Fernandes T J, de Souza F A C, Ribeiro R A, Cunha F O, Meirelles S L C, de Moura R S and Muniz J A. 2020. *Ciência Rural*, *Santa Maria* **50**: 1–8. doi.org /10.1590/0103-8478cr20200140

Gharahveysi S, Kashan N E J, Gerami A and Torshizi R V. 2008. Estimation of genetic parameters on conformation traits of the Iranian Arab horse's population. *Pakistan Journal of Biological Sciences* **11**: 280–84.

Gupta A K, Tandon S N, Pal Y, Bhardwaj A and Chauhan M. 2012. Phenotypic characterization of Indian equine breeds: A comparative study. *Animal Genetic Resources* **50**: 49–58.

Hassen A, Wilson D E, Rouse G H and Tait R G. 2004. Use of linear and non-linear growth curves to describe body weight changes of young Angus bulls and heifers. Iowa State University Animal Industry Report. *A.S. leaflet* R1869.

Hossein-Zadeh N G and Ghorbani A. 2018. Modelling the growth curves for body weight and some biometric traits in Caspian horses (*Equus ferus caballus*) using non-linear mixed models. *Mammalian Biology* **93**: 5–12.

Jun J H, Cho Y S, Hu H, Kim H M, Jho S, Gadhvi P *et al*. 2014. Whole genome sequence and analysis of the Marwari horse breed and its genetic origin. *BMC Genomics* **15**: 1–10.

Kaura R L. 1961. Breeds of horses and donkeys, . *Indian Breeds of Livestock (Including Pakistan Breeds)*. (Ed.) Kaura R L. Prem Publisher, Lucknow.

Mehta S C, Bapna D L and Bhure S K. 2010. Mathematical functions for the prediction of growth in Indian dromedary genotypes. *Indian Journal of Animal Sciences* **80**: 148–51.

Mehta S C. 2020. Breeding strategies for conservation of indigenous breeds of equines. *International webinar on 'Present and future trends in conservation and breeding technologies to enhance production in indigenous animals'*. Veterinary College and Research Institute, Tirunelveli, Tamil Nadu, India, p. 23–43.

Mehta S C, Talluri T R, Legha R A, Pal Y and Tripathi B N. 2021. Phenotypic trend, breeding value and heritability of biometric traits in Marwari horses. *Indian Journal of Animal Sciences* **91**: 476–80.

Onoda T, Yamamoto R, Sawamura K, Inoue Y, Matsui A, Miyake T and Hirai N. 2011. Empirical growth curve estimation using sigmoid sub-functions that adjust seasonal compensatory growth for male body weight of Thoroughbred horses. *Journal of Equine Science* **22**: 37–42.

Onoda T, Yamamoto R, Sawamura K, Inoue Y, Murase H, Nambo Y, Tozaki T, Matsui A, Miyake T and Hirai N. 2013a. Empirical growth curve estimation considering multiple seasonal compensatory growths of body weights in Japanese Thoroughbred colts and fillies. *Journal of Animal Science* **91**: 5599–604.

Onoda T, Yamamoto R, Sawamura K, Murase H, Nambo Y, Inoue Y, Tozaki T, Matsui A, Miyake T. and Hirai N. 2013b. Empirical percentile growth curves with Z-scores considering seasonal compensatory growths for Japanese Thoroughbred horses. *Journal of Equine Science* **24**: 63–69.

Snedecor G W and Cochran W G. 1994. *Statistical Methods.* pp. 398-419. Affiliated East-West Press Pvt. Ltd., New Delhi.

SPSS 26.0 IBM Corp. Released 2019. *IBM SPSS Statistics for Windows*, Version 26.0. Armonk, NY: IBM Corp.

Teixeira G L, Fernandes T J, Muniz J A, Caetano de Souza F A, Silva de Moura R and Melo R M P S. 2021. Growth curves of campolina horses using nonlinear models. *Livestock Science* **251**: 104631. https://doi.org/10.1016/j.livsci.2021.104631.

United States Equestrian Federation 2008. *Chapter AR: Arabian, Half-Arabian and Anglo-Arabian Division*, Rule Book.

Valette J P, Robert C and Denoix J M. 2008. Use of linear and non-linear functions to describe the growth of young sport- and race-horses born in Normandy. *Animal* **2**: 560–65.