



An update to the regression to estimate the body mass of extinct xenarthrans

Uma atualização na regressão para estimar a massa corporal de xenartros extintos

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In this paper, we provide an update on a regression model designed to estimate the body mass of extinct xenarthrans, particularly those from the Brazilian Intertropical Region. We utilized 84 samples from nine extant xenarthrans species (Pilosa and Cingulata), yielding excellent quality indices ($R^2 = 0.53$, %PE = 4.94, %SEE = 4.44). While there are other good options, we reinforce that this is an excellent tool for estimating the body mass of extinct xenarthrans.

Key words: Xenarthra, ordinary least square, Brazilian Intertropical Region.

No presente trabalho apresentamos uma atualização para uma regressão produzida para estimar a massa corporal de xenartros extintos, em especial os da Região Intertropical Brasileira. Utilizamos 84 amostras de nove espécies viventes de xenartros (Pilosa e Cingulata), alcançando excelentes índices de qualidade ($R^2 = 0,53$, %PE = 4,94, %SEE = 4,44). Apesar de existirem outras ótimas opções, reforçamos que esta é também uma excelente ferramenta para estimar a massa corporal de xenartros extintos.

Palavras-chave: Xenarthra, mínimos quadrados, Região Intertropical Brasileira.

1. INTRODUCTION

Since 2017, Dantas and collaborators have endeavored to estimate the body mass of extinct xenarthrans from the Brazilian Intertropical Region (BIR) [1]. Initially, they employed allometric regression utilizing the minimum width of the diaphysis of the humerus and femur [2]. A multiple factor in the femur diaphysis were employed in an attempt to determine a more realistic weight for these taxa [1, 3, 4].

Inspired by the regressions proposed by Anderson et al. (1985) [2] and Campione and Evans (2012) [5], a novel method to estimate the body mass of extinct giant sloths and armadillos was proposed using data from extant Xenarthra [6]. Although this new regression exhibited good quality indices, it faced criticism [7, 8], prompting the exploration of additional data to enhance the initial regression. Therefore, the primary objective of this study was to update and justify the utilization of the earlier Xenarthra body mass regression.

2. MATERIAL AND METHODS

We included 79 new samples belonging to extant sloths (*Bradypus torquatus* and *Bradypus variegatus*), anteaters (*Tamandua tetradactyla*, *Myrmecophaga tridactyla*), and armadillos (*Cabassous unicinctus*, *Cabassous tatouay*, *Dasypus novemcinctus*, *Dasypus septemcinctus*, and *Euphractus sexcinctus*). In total, the update comprised 84 samples (Table 1). To generate the update, we measured (in millimeter) the circumference at the minimum width of the mid-length (MWM) of the humerus and femoral diaphysis association with the body mass (in grams).

In contrast to previous paper [6], we opted for ordinary least squares (OLS) regression. This choice is based on its superior performance with allometric data compared to the reduced major axis (RMA) [9, 10]. All data underwent logarithmic transformation (base 10). The assessment of the regression quality relied on the correlation of logarithmized data, percent predicted error (% PE) [11, 12], and standard error of the estimate (% SEE) [11].

Table 1. Body mass (in g), humerus and femur circumference (in mm) of extant xenarthran species.

Xenarthra species	SP#	Humerus Circumference (mm)	Femur Circumference (mm)	Body Mass (g)
<i>Bradypus torquatus</i>	MN 23921	27	28	4200
<i>Bradypus torquatus</i>	UFES 1918	39	40	5500
<i>Bradypus variegatus</i>	UFMG 3988	22	22	750
<i>Bradypus variegatus</i>	UFMG 3987	27	27	1400
<i>Bradypus variegatus</i>	MN 79120	25	26	5000
<i>Bradypus variegatus</i>	MN 79570	29	30	5600
<i>Bradypus variegatus</i>	MN 83742	24	25	6000
<i>Cabassous tatouay</i>	MN 79317	37	40	3100
<i>Cabassous tatouay</i>	MN 4989	35	31	4700
<i>Cabassous unicinctus</i>	LEG 1893	28	34	900
<i>Cabassous unicinctus</i>	LEG 1897	25	37	3000
<i>Choloepus didactylus</i>	ROM 31160	40	43	6200
<i>Choloepus hoffmanni</i>	ROM 89635	33	35	4500
<i>Dasyopus novemcinctus</i>	LEG 1890	19	25	283
<i>Dasyopus novemcinctus</i>	LEG 1891	22	29	600
<i>Dasyopus novemcinctus</i>	MN 4984	16	27	620
<i>Dasyopus novemcinctus</i>	LEG 1894	18	20	1000
<i>Dasyopus novemcinctus</i>	LEG 1895	31	37	1000
<i>Dasyopus novemcinctus</i>	MN 5007	19	24	1090
<i>Dasyopus novemcinctus</i>	LEG 1896	17	23	1200
<i>Dasyopus novemcinctus</i>	MN 4671	17	28	1750
<i>Dasyopus novemcinctus</i>	MN 79546	19	29	2000
<i>Dasyopus novemcinctus</i>	MN 79585	20	31	2500
<i>Dasyopus novemcinctus</i>	MN 81786	20	29	2500
<i>Dasyopus novemcinctus</i>	MN 5008	22	32	2580
<i>Dasyopus novemcinctus</i>	MN 4981	23	32	2700
<i>Dasyopus novemcinctus</i>	ROM R2385	22	30	3077
<i>Dasyopus novemcinctus</i>	MN 5009	21	30	3150
<i>Dasyopus novemcinctus</i>	LEG 1898	33	43	3400
<i>Dasyopus novemcinctus</i>	MN 79372	25	31	3500
<i>Dasyopus novemcinctus</i>	MN 83554	21	32	3500
<i>Dasyopus novemcinctus</i>	MN 5006	24	35	3555
<i>Dasyopus novemcinctus</i>	MN 4672	25	35	3970
<i>Dasyopus novemcinctus</i>	MN 5500	30	41	4000
<i>Dasyopus novemcinctus</i>	MN 79456	21	32	4000
<i>Dasyopus novemcinctus</i>	MN 79536	25	40	4000
<i>Dasyopus septemcinctus</i>	UFES 1217	19	24	510
<i>Dasyopus septemcinctus</i>	MN 63454	13	22	670

<i>Euphractus sexcinctus</i>	MN 4992	31	32	1680
<i>Euphractus sexcinctus</i>	MN 5000	30	31	2070
<i>Euphractus sexcinctus</i>	MN 4994	30	28	2280
<i>Euphractus sexcinctus</i>	MN 4996	27	28	2280
<i>Euphractus sexcinctus</i>	MN 4976	29	28	2400
<i>Euphractus sexcinctus</i>	MN 5003	32	35	2520
<i>Euphractus sexcinctus</i>	MN 5001	30	32	2560
<i>Euphractus sexcinctus</i>	MN 4998	32	33	2700
<i>Euphractus sexcinctus</i>	MN 4997	32	34	2920
<i>Euphractus sexcinctus</i>	MN 4977	33	30	3030
<i>Euphractus sexcinctus</i>	MN 4999	32	34	3080
<i>Euphractus sexcinctus</i>	MN 4980	31	32	3090
<i>Euphractus sexcinctus</i>	MN 4995	34	33	3340
<i>Euphractus sexcinctus</i>	MN 4986	45	43	4450
<i>Euphractus sexcinctus</i>	MN 4993	30	33	4610
<i>Euphractus sexcinctus</i>	MN 4973	34	35	4700
<i>Euphractus sexcinctus</i>	MN 4979	35	30	5100
<i>Euphractus sexcinctus</i>	MN 4991	34	35	5200
<i>Euphractus sexcinctus</i>	MN 4990	31	32	5250
<i>Euphractus sexcinctus</i>	MN 4982	36	34	5280
<i>Euphractus sexcinctus</i>	MN 5002	33	34	5430
<i>Euphractus sexcinctus</i>	MN 4972	35	36	5500
<i>Euphractus sexcinctus</i>	MN 4988	38	39	5580
<i>Euphractus sexcinctus</i>	MN 4978	34	35	6400
<i>Myrmecophaga tridactyla</i>	MN 5073	73	71	33000
<i>Priodontes maximus</i>	ROM 46260	68	79	29500
<i>Tamandua tetradactyla</i>	LEG 1892	34	33	600
<i>Tamandua tetradactyla</i>	MN 5068	32	33	1110
<i>Tamandua tetradactyla</i>	MN 5069	33	30	2240
<i>Tamandua tetradactyla</i>	MN 4538	33	32	2620
<i>Tamandua tetradactyla</i>	MZFS1159	29	26	3820
<i>Tamandua tetradactyla</i>	UFES 1211	45	35	3875
<i>Tamandua tetradactyla</i>	MN 79361	35	30	4000
<i>Tamandua tetradactyla</i>	MN 83559	33	32	4000
<i>Tamandua tetradactyla</i>	MN 73484	32	31	4250
<i>Tamandua tetradactyla</i>	MN 79209	37	39	4500
<i>Tamandua tetradactyla</i>	MN 79287	40	32	4500
<i>Tamandua tetradactyla</i>	MN 79503	33	34	4570
<i>Tamandua tetradactyla</i>	MN 79564	33	31	5000
<i>Tamandua tetradactyla</i>	MN 79571	33	30	5000
<i>Tamandua tetradactyla</i>	MN 5515	33	32	5070
<i>Tamandua tetradactyla</i>	ROM 113857	35	30	5470
<i>Tamandua tetradactyla</i>	MN 5059	38	33	5500
<i>Tamandua tetradactyla</i>	MN 3846	36	34	5550
<i>Tamandua tetradactyla</i>	MN 5061	37	39	5850
<i>Tamandua tetradactyla</i>	MN 5056	39	40	6670

Through the application of an updated regression (see Results and Discussion), we recalculated the body masses of *Eremotherium laurillardi*, *Glossotherium phoenesis*, *Ocnotherium giganteum*, *Catonyx cuvieri*, *Valgipes bucklandi*, *Nothrotherium maquinense*, *Ahytherium aureum*, *Australonyx aquae*, *Pachyarmatherium brasiliense*, *Pampatherium humboldti*, *Holmesina paulacoutoi*, and *Holmesina criptae*.

The majority of the samples were from individuals with either the humerus or femur only. Consequently, the circumference (C) of the missing bone was estimated using the mean proportion between the humerus and femur (f/h) in individuals with partial skeletons containing both bones (Table 2).

Table 2: Proportion between humerus (h) and femur (f) used to estimate the body mass of extinct xenarthrans.

Taxon	Sample	Circumference (in mm)		Proportion (f/h)
		Femur (f)	Humerus (h)	
Pampatheriidae				
<i>H. paulacoutoi</i>	MCL 501	155	123	1.25
<i>H. criptae</i>	LPP-PV-001	126	104	1.20
<i>P. humboldti</i>	MCL 900	148	113	1.30
Mean value				1.25
Megatheriidae				
<i>E. laurillardi</i>	Port Lavaca, Texas, USA	532	398	1.35
<i>N. maquinense</i>	LEG 1454	169	140	1.20
<i>N. maquinense</i>	LEG 1359/1357	180	154	1.15
<i>N. maquinense</i>	MCL 1020	125	86	1.45
Mean value				1.28
Mylodontidae				
<i>G. phoenesis</i>	MCL 4303	313	210	1.50
Scelidotheriidae				
<i>C. cuvieri</i>	LEG 1179/1180	182	150	1.20
<i>C. cuvieri</i>	LEG s/n	370	200	1.85
<i>V. bucklandi</i>	LEG 1718/1720	277	175	1.60
<i>V. bucklandi</i>	LEG s/n	210	120	1.75
Mean value				1.60

The proportion could be determined for individuals described in the literature (*E. laurillardi*, *C. cuvieri*, *H. criptae*) [4, 13, 14]. Alternatively, it could be determined for individuals measured in collections (*N. maquinense*, *V. bucklandi*, *G. phoenesis*, *P. humboldti*, and *H. paulacoutoi*; Table 2). To estimate the body mass we used the mean values of f/h for the families (Table 2). For *P. brasiliense*, *O. giganteum*, and the Megalonychidae taxa were used the proportions found in Pampatheriidae, *G. phoenesis*, and Megatheriidae, respectively.

All studied taxa were categorized as juveniles, subadults, or adults based on the stage of epiphysis–diaphysis fusion in both the humerus and femur. Juveniles exhibit a clear separation between the epiphysis and diaphysis. Subadults display a visible scar between the epiphysis and diaphysis. Adults show complete fusion of both epiphyses to the diaphysis.

3. RESULTS AND DISCUSSION

3.1 Criticism to the earlier regression

The initial criticisms of the Xenarthra regression [6, 7] focused on its creation involving the use of only five samples and the estimation of body mass for extinct xenarthrans significantly heavier than those included in the regression. Subsequently, Barbosa et al. (2023) [8] raised new criticisms, suggesting that: (i) the use of the MWM is problematic for estimating the body mass

of extinct xenarthrans; (ii) the database used was phylogenetically restricted; and (iii) the %PE of the original proposition [6] regression was “high”.

Dantas (2022) [6] and Dantas (2022) [15] acknowledges that five samples constitute a low number. Nevertheless, he defends the use of a limited sample size, asserting that the quality indices are moderate (rather than high), considering it a viable option, especially because it was constructed using data from extant Xenarthra. Furthermore, he demonstrated that the circumference and minimum width at the mid-length of the diaphysis are proportional in a sample comprising both extant and extinct xenarthrans. This is supported by the high correlations and similar slopes, suggesting that their volume could also increase proportionally with a strong correlation, which was also observed across all mammals [5].

We observed an overlook criticism regarding the use of MWM to estimate the body mass of extinct xenarthrans [8]. This criticism is directed at the utilization of allometric regressions created using data from non-xenarthrans [16], resulting in an overestimation of body mass. This stimulates the proposition of the development of a specific regression using data from extant xenarthrans [16], which was subsequently implemented [6].

Ultimately, the regression was not phylogenetically restricted; it incorporated data from the focus group [17], which exhibited distinctive humerus and femur morphologies. Consequently, it is a favorable choice for proposing estimations within this specific group of extinct mammals.

3.2. Xenarthra body mass regression updated

The updated regression (1) (Figure 1) exhibited a moderate correlation ($R^2 = 0.53$), low %PE (4.94), and low %SEE (4.44). The correlation was lower than the regression originally proposed [6]. Nevertheless, the %PE and %SEE exhibited excellent values, surpassing those obtained using multiple bones [18, 19].

$$\log_{10}BM = -1.0 + 2.5 * \log_{10}C_{(h+f)} \quad (1)$$

The significant advantage of this regression line is the utilization of one or two bones (humerus and/or femur) from the same individual. This practice prevents the amalgamation of bones from distinct individuals of varying ontogenetic stages and sexes (male/female). The regression facilitates the estimation of body mass of numerous individuals, generating a substantial number of samples. This, in turn, has contributed to a more comprehensive understanding of the body mass variation within these taxa.

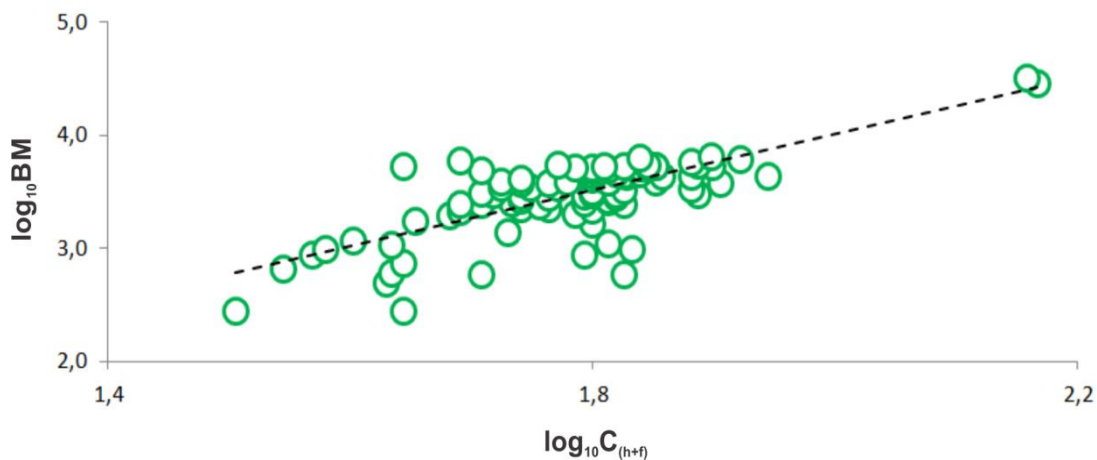


Figure 1: Ordinary least squares of log of body mass (in g) and log of the sum of femur (f) and humerus (h) circumferences (C).

3.3. New xenarthrans body mass estimations for the Late Pleistocene of BIR

Utilizing the updated regression, we proposed new estimations for Late Pleistocene giant sloths and armadillos from the BIR. In Comparison with earlier propositions (Table 3), the body mass of armadillos was similar, except for those proposed elsewhere [8], which, on average, were double our estimations (Table 3).

Table 3. Mean estimated body mass for adult individuals of 12 xenarthrans taxa (exception to *Ahytherium aureum* and *Catonyx cuvieri*, juvenile - J; and *Au. aquae*, subadult - S) that lived in the late Pleistocene of Brazilian Intertropical Region and comparison with previous estimates.

Taxa	Mean±sd (min-max)	Dantas (2022) [6]	Barbosa et al. (2023) [8]	
			method 1	method 2
<i>P. brasiliense</i>	68±28 (43-94)	56	89	151±5
<i>H. criptae</i>	80	74	-	-
<i>H. paulacoutoi</i>	94±34 (61-129)	114	176±33	194±10
<i>Pa. humboldti</i>	108	98	240±55	215±103
<i>N. maquinense</i>	134±64 (57-270)	157±20	-	109±35
<i>A. aureum</i>	214±29 (172-236) ^J	186	-	-
<i>Au. aquae</i>	296 ^S	226	-	-
<i>V. bucklandi</i>	703±227 (274-1,065)	462±127	731±120	522±193
<i>C. cuvieri</i>	901±197 (617-1,171)	598±17	776±162	558±357
<i>G. phoenesis</i>	936	463	-	825±189
<i>O. giganteum</i>	1,188±300 (837-1,590)	842	1,721±526	1,226±282
<i>E. laurillardi</i>	3,144±1,993 (968-5,969)	2,014±205	4,486±185	2,725±1,803

Estimates for the giant sloths *N. maquinense*, *A. aureum*, *Au. aquae*, *V. bucklandi*, and *C. cuvieri* were comparable on average (Table 3). Exceptions were noted in previous estimations [6] for *G. phoenesis*, *O. giganteum*, and *E. laurillardi*, which were, on average, ~44% lower than our estimations, but similar to other results [8].

4. FINAL REMARKS

In this paper, we update the Xenarthra regression [6], which now includes 84 samples and excellent indices of quality ($R^2 = 0.53$, %PE = 4.94, %SEE = 4.44). We agree that regression using multiple bones is a good option to propose the body mass of extinct xenarthrans; however, owing to the limitation of complete skeletons, to avoid a general estimation using bones of individuals with ontogenetic stages and sexes, and to have a large number of samples, we reinforce that Dantas' Xenarthra regression is a viable and excellent option.

Finally, we updated the body mass estimations made for giant sloths and armadillos in the Brazilian Intertropical Region.

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