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Correlation between long-bone dimensions and body mass in cats

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Summary

Body mass significantly influences morphology in both humans and animals. The relations between the body mass and osteometric measurements of the skeleton can show adaptive changes in the animal skeleton due to body mass changes. This relationship had previously been analysed in dogs. The lack of such studies in cats encouraged us to investigate this topic. Radiogrammetric measurements were performed in live animals of both sexes (16 females and 20 males) in both dorsopalmar/dorsoplantar and mediolateral projections Morphometric measurements were performed for almost all long bones, e.g. the humerus, the tibia, and the fibula. Statistical analysis was performed with the SPSS 21.0 package. It showed that the body mass affected transverse rather than longitudinal dimensions of the selected long bones. Moreover, the sexual dimorphism identified (except for the pelvis) resulted from two sex-related factors (greatest length/body mass). Step regression analysis and estimation of determination coefficients (R^2) proved that transverse dimensions, such as the smallest breadth of diaphysis in the humerus and the greatest breadth of the distal extremity in the femur, were the most suitable dimensions for body mass estimation. Body mass estimation and the calculations of height at withers, can offer a broader insight into the morphology of animals from past centuries and are important in both palaeontology and archaeozoology. Therefore, descriptions of archaeological cat species, also in terms of height at withers and body mass estimations, afford a more meaningful evaluation of their morphological structure across various historical periods.

Keywords: cat, body mass, long bone, morphometric analysis

Body size has a notable impact on an animal's life (8, 29, 31). Associated with a range of metabolic and physiological variables, body mass is of keen interest to vertebrate paleobiology (8). Almost all characteristics of life have some effect on body size (8), which is physiologically reflected in animal phenotype (8, 29). As a significant physiological variable in ecological and functional studies (13), body mass allows palaeontologists to make reasonable estimations concerning the morphology and related ecological features of fossil species. As a result, scholars may better understand the relationships between various skeletal measurements in living mammals (5).

Examination of the postcranial skeleton is particularly important in assessing body mass, as the morphology of all skeletal parts must be adapted not only to the physical forces enabling animal locomotion, but must also provide a stable framework for skeletal muscles and permanent protection for all internal organs (13). Therefore, there is a close relationship between skeletal dimensions and body mass (5, 13, 16, 17). Studies carried out in large existing and extinct carnivores proved that long bone circumference and cross-sectional geometric and articular properties are more useful in body mass prediction than longitudinal dimensions of the humerus or the femur. This assumption was explained by mechanical loading of the limbs and their locomotor behaviour (5). A study by Fariña et al. (13) carried out in mammal megafauna stressed that a statistical methodology used in body mass prediction must be influenced by the animal body size. Finally, an analysis of variance involving body mass and the diameter and length of long bones in mammals (36 species) showed that the midshaft diameter of the humerus and the femur, or the length of the metapodia, most strongly correlated with body mass (14). Humerus and femur circumferences were also successfully used for mass estimation in archaeozoological canine material from the Theodosius Harbour, Turkey (25). Not only is this relationship vital in the study of fossil mammals in paleobiology (8, 12), but it is also emphasised in zooarchaeological studies regarding visual morphology evaluation. These assessments rely on biometric data, most of which make it possible to evaluate the size of archaeological animals (1).

The estimation of animal body mass is based primarily on skeletal morphometrics (12, 30, 33, 37). These predictions use various measurements, such as the length, diameter and circumference of limb bones and the distal articular surface area of proximal limb bones (6, 18). Different formulas or factors obtained from these long-bone measurements have made it possible to predict the body mass of different animal species (3, 5, 6, 12, 25, 34, 37).

The estimation of body mass based on long-bone measurements has mainly been conducted in domestic carnivore species, particularly dogs (5). A special formula has been applied to archaeological dog remains to predict their body mass and facilitate comparisons with modern breeds (24). That study aimed to estimate body mass based on canine archaeozoological remains from the Yenikapi Metro and Marmaray excavations (early Byzantine – late Byzantine period, 4th-15th century AD), using humerus and femur measurements (midshaft circumference). The formula is as follows: body mass in grams = $10^{(2.88 \times \log(f)) - 3.4}$ and body mass in grams = $10^{(2.47 \times \log(h)) - 2.72}$, where log (f) is the femur circumference at the midpoint of the shaft and log (h) – is the humerus circumference at the midpoint of the shaft.

For cats, there are no studies on body mass-long bone morphometrics, except for a general assessment of the Fissipedia suborder performed by Alexander et al. (2).

In this study, long-bone measurements were taken from cats of different breeds by radiogrammetric methods, and correlations between these measurements and body mass were evaluated.

Material and methods

This study involved 36 adult cats (aged 2-4 years): 16 females and 20 males. The weight range of the animals used in the experiment is presented in Table 1. The animals were patients of the Department of Surgery, Faculty of Veterinary Medicine, Istanbul University-Cerrahpaşa, and were diagnosed with diseases not indicating any pathologies of the locomotor system morphology. Their owners agreed for radiographs to be performed. Data on the animals' age, sex, and height at the withers, together with radiological examination of all bones of the left thoracic and pelvic limb, allowed us to perform a quantitative and qualitative analysis of the results. After obtaining data on a cat's age, sex, and body mass, radiographs covering all bones of its left thoracic and pelvic limbs were taken. Radiographic imaging was performed in both dorsopalmar/dorsoplantar and mediolateral projections (Fig. 1 and 2). During radiography of the long bones, the cassette's horizontal angle did not exceed 5 degrees, and imaging was conducted from a maximum distance of 1 meter with an optimal focus distance of 90 degrees (36).

The basic framework for morphometric measurements was based primarily on a study by von den Driesch (9).

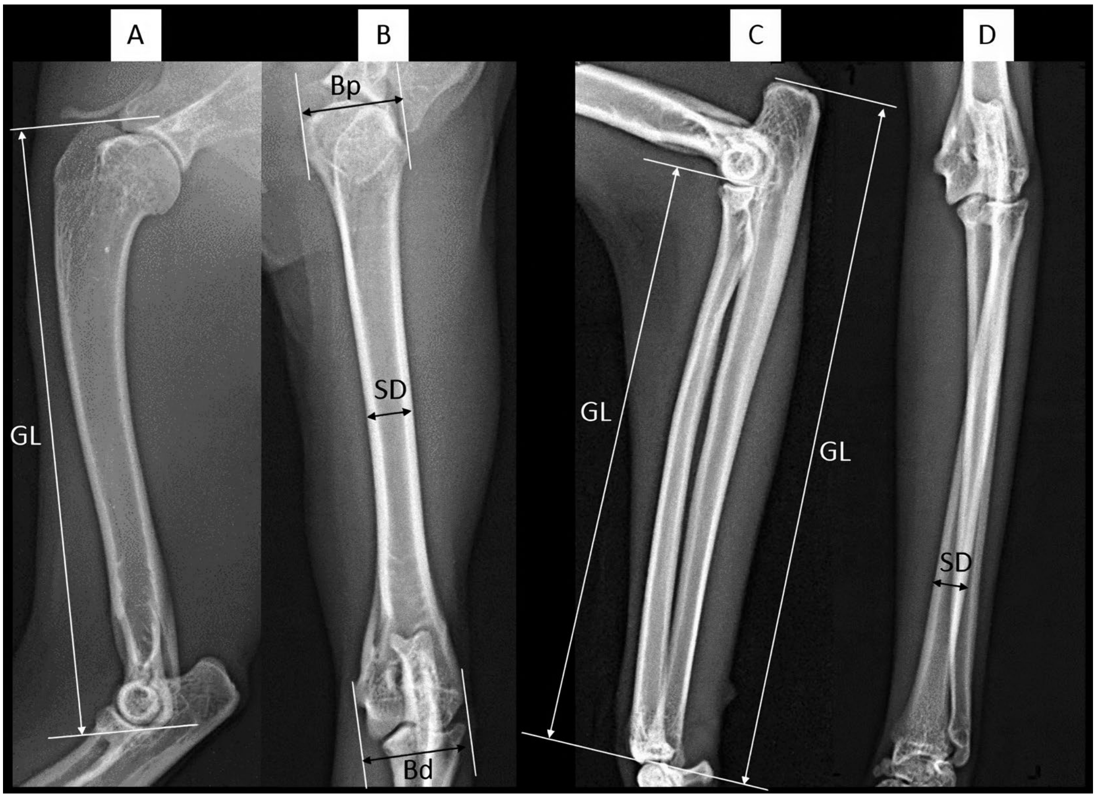

Fig. 1. Morphometric measurements based on radiographic images. A – Humerus greatest length (GL); B – Humerus smallest breadth of diaphysis (SD); C – Radius greatest length (GL-left), Ulna greatest length (GL-right); D – Radius smallest breadth of diaphysis (SD)

Morphometric measurements of the humerus, radius, ulna,

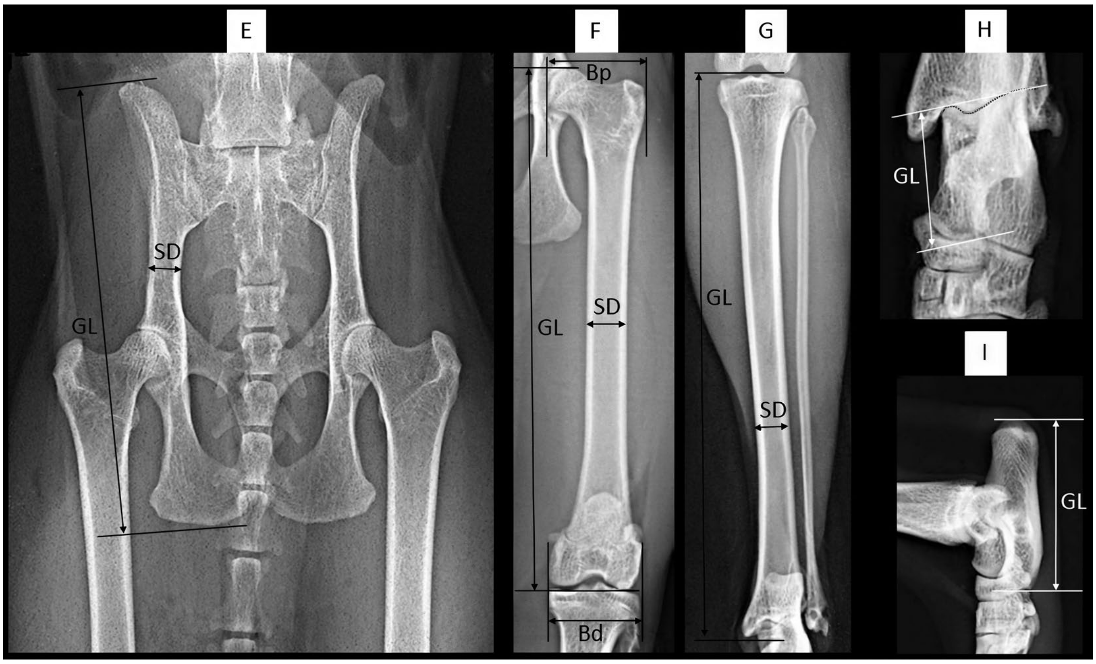

Fig. 2. Morphometric measurements based on radiographic images (continued). E – *Os coxae* greatest length of one half (GL), *Os coxae* smallest breadth of the shaft of ilium (SD); F – Femur greatest length (GL), Femur smallest breadth of diaphysis (SD); G – Tibia greatest length (GL), Tibia smallest breadth of diaphysis (SD); H – Talus greatest length (GL); I – Calcaneus greatest length (GL)

Tab. 1. Body mass range (kg)

	Total	Males	Females
Min.	2.00	2.35	2.00
Max.	6.34	6.34	4.15

Tab. 2. Body mass values (kg)

Sex	Statistical parameter	Body mass
Female	N	16
	Mean	3.21 ± 0.73[a]
Male	N	20
	Mean	4.28 ± 0.97[b]
Both	N	36
	Mean	3.80 ± 1.02

Explanation: [a, b] – differences between means indicated by different letters in the same line are significant (P < 0.05)

femur, tibia, talus, and calcaneus involved the following variables:

1. greatest length (GL),
2. smallest breadth of diaphysis (SD),
3. greatest breadth of the proximal extremity (Bp),
4. greatest breadth of the distal extremity (Bd).

Morphometric measurements of *os coxae*:

1. greatest length of one half (GL),
2. smallest breadth of the shaft of ilium (SD).

After obtaining morphometric measurements from radiographic images, statistical analyses were conducted using the SPSS 21.0 package (Version 21.0, SPSS Inc., Chicago, IL, USA). Initially, the influence of the animals' sex on long-bone measurements was examined, and attempts were made to statistically demonstrate the effect of sexual dimorphism.

Factor calculations were performed by directly scaling body mass to the bone length (GL) (body mass/GL), using morphometric measurements for the estimation of body mass. Due to low values of R^2 (coefficient of determination) in regression formulas, we employed a factor calculation, a method widely used in zooarchaeology based on long-bone morphometry (11, 15, 19, 20, 23, 27, 32, 35), as a foundation for this study.

Results and discussion

The results of our study confirmed significant differences ($P < 0.05$) in the average body mass of male and female cats. Male individuals had greater body mass than female ones (Tab. 1 and 2).

Morphometric measurements of the humerus, radius, and ulna from the thoracic limbs, as well as *os coxae*, femur, and tibia from the pelvic limbs, made it possible to calculate factors obtained from scaling morphometric measurements to body mass, as presented in Table 3 and 4. In the measurement of long bones, longitudinal measurements (GL) were used alongside transverse measurements (SD, Bp, Bd). Sexual dimorphism was observed in the morphometric measurements of both thoracic and pelvic limbs, except for the *os coxae* SD value. Differences between males and females were significant at $P < 0.05$. Therefore, due to sexual dimorphism, factor calculations were presented separately for each sex.

As the transverse measurements of the thoracic limb bone, the humerus, and the pelvic limb bone, the femur, are influenced more by body mass, the metrical values of Bp, SD, and Bd for these two bones were used in regression analyses for calculations.

In addition to factor calculations, in order to estimate body mass, we conducted a regression analysis, specifically, a stepwise regression analysis aimed at creating models with the highest determination coefficients with the least number of factors. Statistical modelling (stepwise regression analysis) relied on both longitudinal and transverse measurements of bones (GL, Bp, SD, Bd). The determination coefficient (R^2) in the regression formulas was found to be very low when based on the GL measurement. Transverse measurements

Tab. 3. Morphometric values for the thoracic limb (cm, except factor)

Bone	Sex	Statistical parameter	GL	SD	Bp	Bd	Factor
Humerus	Female	N	16	16	16	16	16
		Mean	9.68 ± 0.61[a]	0.75 ± 0.06[a]	1.82 ± 0.12[a]	1.87 ± 0.13[a]	0.33 ± 0.07[a]
	Male	N	20	20	20	20	20
		Mean	10.39 ± 0.62[b]	0.82 ± 0.07[b]	2.08 ± 0.14[b]	2.09 ± 0.13[b]	0.41 ± 0.08[b]
	Both	N	36	36	36	36	36
		Mean	10.08 ± 0.71	0.79 ± 0.07	1.96 ± 0.18	1.99 ± 0.17	0.38 ± 0.09
Radius	Female	N	16	16			16
		Mean	9.32 ± 0.57[a]	0.49 ± 0.07[a]			0.34 ± 0.07[a]
	Male	N	20	20			20
		Mean	10.07 ± 0.55[b]	0.56 ± 0.05[b]			0.42 ± 0.09[b]
	Both	N	36	36			36
		Mean	9.74 ± 0.67	0.53 ± 0.07			0.39 ± 0.09
Ulna	Female	N	16				16
		Mean	10.94 ± 0.61[a]				0.29 ± 0.06[a]
	Male	N	20				20
		Mean	11.81 ± 0.56[b]				0.36 ± 0.07[b]
	Both	N	36				36
		Mean	11.43 ± 0.72				0.33 ± 0.08

Explanations: n – number of individuals; mean – mean value; GL – greatest length; SD – smallest breadth of the shaft of diaphysis; Bp – greatest breadth of the proximal end; Bd – greatest breadth of the distal end (Bd); [a, b] – differences between means indicated by different letters in the same line are significant ($P < 0.05$)

Tab. 4. Morphometric values for the pelvic limb (cm, except factor)

Bone	Sex	Statistical parameter	GL	SD	Bp	Bd	Factor
Coxae	Female	N	16	16			16
		Mean	8.06 ± 0.41[a]	0.57 ± 0.05[a]			0.40 ± 0.08[a]
	Male	N	20	20			20
		Mean	8.73 ± 0.35[b]	0.61 ± 0.06[a]			0.49 ± 0.11[b]
	Both	N	36	36			36
		Mean	8.43 ± 0.5	0.59 ± 0.06			0.45 ± 0.1
Femur	Female	N	16	16	16	16	16
		Mean	10.22 ± 0.62[a]	0.88 ± 0.07[a]	2.15 ± 0.2[a]	2.09 ± 0.13[a]	0.31 ± 0.07[a]
	Male	N	20	20	20	20	20
		Mean	11.27 ± 0.66[b]	0.97 ± 0.08[b]	2.42 ± 0.17[b]	2.31 ± 0.12[b]	0.38 ± 0.08[b]
	Both	N	36	36	36	36	36
		Mean	10.81 ± 0.83	0.93 ± 0.09	2.30 ± 0.23	2.21 ± 0.16	0.35 ± 0.08
Tibia	Female	N	16	16			16
		Mean	11.05 ± 0.61[a]	0.78 ± 0.07[a]			0.29 ± 0.06[a]
	Male	N	20	20			20
		Mean	11.65 ± 0.55[b]	0.86 ± 0.05[b]			0.37 ± 0.08[b]
	Both	N	36	36			36
		Mean	11.38 ± 0.65	0.82 ± 0.7			0.33 ± 0.08

Explanations: n – number of individuals, mean: mean value; GL – greatest length; SD – smallest breadth of the shaft of ilium/diaphysis; Bp – greatest breadth of the proximal end; Bd – greatest breadth of the distal end (Bd); [a, b] – differences between means indicated by different letters in the same line are significant ($P < 0.05$)

were more effective in such formulas. The highest determination coefficient (R^2) was obtained in stepwise regression formulas containing „SD" from humerus measurements and „Bd" from femur measurements. These determination coefficients (R^2) had a moderate effect level. The formulas are provided below:

Body mass (kg) = (humerus SD ∗ 10.347) – 4.326; n = 36, R^2 = 0.533

Body mass (kg) = (femur Bd ∗ 5.086) – 7.441; n = 36, R^2 = 0.656

Body mass has a significant impact on the morphological manifestation of the animal's life (8, 29). The phenotype, closely associated with the animal's living environment, has been a consistent focus for palaeontologists in visual morphological predictions (5). Body mass, along with height at withers, constitutes a fundamental element of visual morphology and is closely related to skeletal morphometrics. Body mass estimations, both in palaeontology and archaeology, considerably help in determining the structural characteristics of animals and understanding their life history (3, 5-7, 12, 25, 30, 33, 34, 37). Our study focused on the logical estimation of body mass in cats based on skeletal morphometrics. While the existing estimation formulas have generally gained prominence in fossil species (6, 7, 12, 37), the visual morphological features of archaeological cats have not received equal attention. Although morphometric evaluations of archaeozoological cat remains have been conducted by numerous researchers (10, 14, 21, 22, 28), information about visual morphological features (such as body mass or height at withers) is lacking. This is likely due to the fact that regression formulas or factors related to cats have not been developed. In our previous study, the estimation of height at withers in cats was accomplished through regression analysis, thus providing logical formulas and insights into the structural characteristics of these animals. Similarly, body mass prediction formulas for canine remains were developed and used in archaeozoological practice, showing that the humerus and femur midshaft circumference is most suitable for this purpose, as observed by Anyonge (5) and Wroe et al. (37). Therefore, in this study, we sought to develop estimation formulas for body mass, one of the morphological features of cats.

In the estimation of height at withers and body mass in mammals (including dogs and cats), the following measurements are typically used: the length, diameter, and circumference of long bones, and the surface area of the proximal limb bone distal articular surface (5, 7, 12, 18). Different formulas or factors derived from these long-bone measurements have facilitated the estimation of body mass for wild-living and domesticated animal species both in palaeontologic and zooarchaeologic studies (3, 5-7, 12, 25, 34, 37).

While the estimates for the height at withers generally make use of longitudinal measurements of bones (11, 19, 20, 25-27, 32), for body mass estimation, transverse measurements, especially shaft circumference and joint circumference, are reported to be more effective (3-5). This is because the mechanical load imposed on the extremities as a consequence of the animal's body mass is reflected in the bones (5). The results of the stepwise regression analysis applied in this study support this view. Both humerus and femur GL, SD, Bp, and Bd values, commonly employed in body mass predictions (3-5), were used in the stepwise regression here. The highest coefficient of determination (R^2) in predicting body mass was obtained for SD in the humerus and for Bd in the femur. Due to the impossibility of taking shaft circumference measurements in two-dimensional radiographic images, only Bp, SD, and Bd transverse measurements were used. The low coefficient of determination (R^2) in the regression formulas obtained was probably influenced by the small sample size (n = 36). It is anticipated that expanding it would increase the coefficient.

Even though Alexander et al. (2) provided a general assessment within the Fissipedia suborder, referring to an evaluation based on body mass-long bone morphometrics (shaft circumference), no formula based on a logical estimation of the body mass of domestic cats has been developed. This study contributes to filling this gap.

In addition to regression analyses, another estimation factor obtained was the body mass/GL ratio based on long-bone measurements. In our previous study on height at withers, a factor calculation based on the height at withers/GL ratio was employed. Although it was not a regression analysis, the study established it as the easiest estimation factor for each bone. This aspect was found to be of equivalent value to commonly used estimation methods based on factor usage in archaeological studies. However, stepwise regression analyses indicate that transverse measurements of bones are more effective in evaluating body mass estimations than longitudinal measurements.

In summary, this study determined the effectiveness of transverse measurements of the long bones, specifically SD (for the humerus) and Bd (for the femur). Thus far, body mass estimation has not received as much attention as height at withers estimation, having been limited to some archaeological species (e.g., dogs – Anyonge, 1993). The results obtained using this method have only been compared with those related to modern breeds (Onar, 2005). Thanks to our study, it may now be possible to estimate body mass in cats by modern methods. Since radiogrammetric data are considered to provide more accurate results than classical data, analysing body mass estimations with morphometric values based on the same method should lead to more precise predictions of visual morphology. In the identification of archaeological cat species, estimating both height at withers and body mass affords a more meaningful assessment of the phenotype. This is believed to have benefits for both different cat populations and comparison of species over various periods.

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