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MORPHOMETRIC CHARACTERISTICS OF THE CERVICAL, THORACIC, AND LUMBAR VERTEBRAE OF THE BROWN BEAR (*URSUS ARCTOS*): SEXUAL DIMORPHISM AND SIZE VARIATION

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ABSTRACT

The vertebral column plays a significant structural and functional role in supporting the brown bear's (*Ursus arctos*) greater body mass, locomotion, and behavioral ecology. However, detailed morphometric observations of the ursid axial skeleton remain limited. This presented study delivers an extensive morphological and morphometric analysis of the cervical, thoracic, and lumbar vertebrae in eight adult brown bears from the Belitsa Dancing Bear Sanctuary, Bulgaria. Five males and three females (24–39 years; 100–300 kg) were examined. Each vertebra was measured for width, length, and height using digital calipers, and statistical analyses were performed to evaluate the influence of sex, body weight, and age. The typical vertebral formula (C7–T14–L6) was found in seven individuals, while one female exhibited a T15/L5 configuration with a constant thoracolumbar total of 20 vertebrae. Sexual dimorphism was evident, with males possessing significantly larger vertebrae across multiple regions. Markedly distinct differences were identified at T7 and L5. Body weight had a clear effect, with heavier bears demonstrating significantly larger vertebral dimensions. Occasional intervertebral ossifications were observed and excluded from quantitative evaluation. This evidence points to strong functional links between vertebral morphology, biomechanical demands, and life-history characteristics in brown bears. This analysis delivers baseline anatomical data relevant for evolutionary interpretation, comparative morphology within Carnivora, and clinical assessment of spinal pathology in captive and wild bears.

Key words: brown bear, morphometry, spine, vertebrae, size variation.

Introduction

The brown bears (*Ursus arctos*) are among the largest terrestrial carnivores. They possess clear ecological adaptability, broad geographical distribution in Eurasia and North America, and notable variation in body size and morphology among the representatives of the family (Haroldson *et al.*, 2021; Nowak, 1991; Swenson *et al.*, 2021). A wide range of behaviors is enabled by the musculoskeletal system of this species, such as digging, climbing, wrestling, and load bearing during bipedal posture. All its powerful locomotion depends on the organization and biomechanical properties of the vertebral column. The functional and evolutionary morphology of the extant species of bears has been extensively researched with respect to the craniodental structure, feeding mechanics, and ecological adaptation (Christiansen, 2007, 2008; Figueirido *et al.*, 2008; Sacco & Van Valkenburgh, 2004), but in-depth investigations on the axial skeleton and vertebral morphometry are limited.

In mammals, the major support for the epaxial and hypaxial muscle groups, spinal cord protection, force transmission from the limbs, and trunk stabilization in general are enabled by the vertebral column. The variations in vertebral morphology are strongly connected to the locomotor specialization, posture, and body mass distribution (Ewer, 1998; Martín-Serra *et al.*, 2015). Most of the studies on the Carnivora have predominantly focused on felids and canids, focusing on the functional adaptations associated with predation, efficient movement, and agility (Barycka, 2007; Figueirido *et al.*, 2011). In contrast, the ursids demonstrate a plantigrade stance, strong trunk, and specific behavioral ecology, which suggest differences in vertebral architecture that merit targeted examination (Huber, 2022; Kitchener, 1994).

The sexual dimorphism of the brown bears is well observed and documented, as the males are generally larger, heavier, and with more robust musculature than females (Haroldson *et al.*, 2021; Swenson *et al.*, 2021). These differences may extend to the bones of the spine, especially in the regions subject to great biomechanical loading, like the thoracic and lumbar segments. However, sexual dimorphism in vertebral morphology of *Ursus arctos* has not been systematically quantified and investigated in detail. The existing investigations and study results on bears generally address the skull and the dentition from an anatomical perspective (Christiansen, 2007; Figueirido *et al.*, 2008; Ruzhanova-Gospodinova *et al.*, 2024; Yu *et al.*, 2007) or show broad evolutionary overviews without detailed morphometric analysis of the spine (Kitchener, 1994; Kumar *et al.*, 2017; Wayne *et al.*, 1989; Wagner, 2010). The available clinical reports of spinal pathology, including spondylosis and intervertebral disc disease, underline the need for a deeper knowledge of the structural characteristics of the vertebrae in this species (Hadžiomerović *et al.*, 2019; Wagner *et al.*, 2005).

The brown bear's ecological, evolutionary, and veterinary importance justifies the necessity of a comprehensive morphological and morphometric documentation and characterization of the vertebral column. This kind of data enables the understanding of the functional locomotion and mechanical adaptation, supports clinical assessment of spinal disease or trauma in both captive and wild individuals, and contributes to comparative assessments within the Carnivora (Christiansen, 2007; Slater *et al.*, 2010). This study provides a detailed morphological and morphometric observation and analysis of the cervical, thoracic, and lumbar vertebrae of the brown bear. The objectives were to describe the specific characteristics of each vertebral region, to quantify key morphometric parameters, and to assess differences related to sex and body size. The obtained data intend to expand the anatomical knowledge of the *Ursus arctos* and to establish a basis for future functional, clinical, and comparative studies of the vertebral column in bears.

Materials and Methods

Animals and specimens

The vertebral columns of eight adult brown bears (*Ursus arctos*) from the Dancing Bears Park / Belitsa Bear Sanctuary (Bulgaria) were included in the present study. All animals died of natural causes while in captivity, and none of the animals were euthanized for the purpose of this research. The data related to the sex, age, and body weight were obtained from the sanctuary's medical records at the time of death. The specimens included consisted of five males and three females, aged

24-39 years, with body weights ranging from 100 to 300 kg (Table 1). All bears were fully mature individuals.

Table 1: Characteristics of the examined brown bears

№	Gender	Age, years	Weight, kg
1.	Male	29	300
2.	Male	31	300
3.	Male	32	200
4.	Male	33	206
5.	Male	34	250
6.	Female	24	130
7.	Female	37	120
8.	Female	39	100

Preparation of specimens

Following necropsy, the vertebral columns were carefully isolated, defleshed, and cleaned of surrounding soft tissues. The vertebrae were subsequently boiled and immersed in a 10% hydrogen peroxide solution to remove residual organic material and to whiten the bones for 12 to 24 hours, depending on the size and remaining soft tissues. After processing, the vertebrae were air-dried, labelled, and stored in laboratory conditions until examination. The preparation of the specimens was conducted at the Department of Anatomy, physiology, and animal sciences at the Faculty of Veterinary Medicine, University of Forestry, Bulgaria. The study included the cervical, thoracic, and lumbar vertebrae of each specimen, as every vertebra was visually inspected prior to measurement.

Exclusion criteria

In several individuals, partial or complete ossification between neighboring vertebrae was observed. The vertebrae that showed bony fusion or abnormal adhesion were excluded from morphometric analysis and were not measured as separate anatomical units. Only morphologically normal, fully separated vertebrae were included.

Measurements

The morphometric analysis was performed on each spinal region using standard osteometric protocols for mammalian vertebrae. For each vertebra, the following parameters were recorded: vertebral width (at the most prominent edges), vertebral body length, and vertebral height (at the most prominent edges) (Figure 1), following conventions used in comparative vertebral and axial skeleton studies (Sheng *et al.*, 2009).

Measurements were obtained using digital calipers with an accuracy of 0.01 mm. Each measurement was performed three times and averaged to minimize observational error, in accordance with recommended practices in morphometric studies (Martín-Serra *et al.*, 2015).

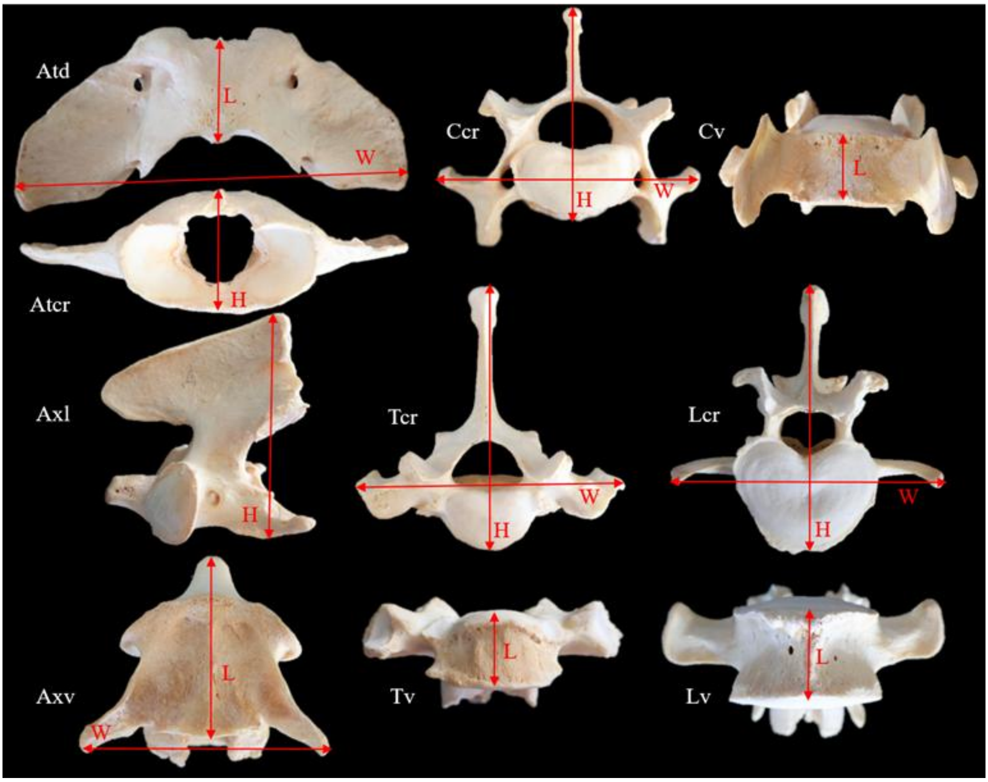

Figure 1: Measurement points of the vertebrae of the brown bear: L – length; W – width; H – height; Atd – atlas, dorsal view; Atcr – atlas, cranial view; Axl – axis, lateral view; Axv – axis ventral view; Ccr – cervical, cranial view; Cv – cervical, ventral view; Tcr – thoracic, cranial view; Tv – thoracic, ventral view; Lcr – lumbar, cranial view; Lv – lumbar, ventral view.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (version 19) to assess the influence of sex, body weight, and age on vertebral morphometry. Sex-related differences in vertebral dimensions were tested separately for each vertebral level. This was done using exact Mann-Whitney U tests, comparing measurements obtained from male (n=5) and female (n=3) bears. Vertebra-specific approach was used due to the anatomical characteristics of individual vertebrae, especially in the cervical and thoracolumbar regions. Descriptive statistics are presented as medians.

Associations between vertebral dimensions and body weight or age were assessed using Spearman's rank correlation coefficients, which are appropriate for ordinal or non-normally distributed data (Zar, 2010). Correlation analyses were conducted independently for each vertebral level. To reduce the risk of false-positive results arising from multiple comparisons, p-values were adjusted using the Benjamini–Hochberg false discovery rate procedure (Benjamini & Hochberg, 1995). Statistical significance was accepted at $p < 0.05$.

Ethical statement

This study was conducted on the skeletons of animals that died of natural causes. No experimental procedures were performed on live animals. A permission issued by the sanctuary was obtained prior to specimen examination (Permission № 1972/28.05.2024).

Results

Sample characteristics and vertebral formula

The typical vertebral formula of C7-T14-L6 was recorded in seven individuals. In one of the adult female bears, a numerical variation. This bear possessed 15 thoracic and 5 lumbar vertebrae, while maintaining a constant thoracolumbar total of 20 vertebrae. This established variation was interpreted as a redistribution within the thoracolumbar segment rather than a pathological anomaly. Morphometric evaluation was conducted according to anatomical vertebral position in all animals. Vertebrae exhibiting fusion or excessive ossification between adjacent segments were excluded from measurement.

Sex differences

Sex-related differences were assessed separately for each vertebral level. Mann-Whitney U tests indicated that males generally exhibited larger vertebral dimensions than females, which is valid across most vertebrae (Table 2). The strongest and most consistent differences in width, length and height were observed in thoracic vertebra T7 and lumbar vertebra L5 (exact p=0.036). This indicates particularly marked sexual dimorphism of these segments. Width and height scale robustly with sex, while length shows the same trend but with greater variability, expressed with fewer vertebra reaching significance. Identical p-values of p=0.036, across several vertebral levels reflect the small sample size (n=5 vs 3) and subsequent similar rank distributions. Table 2 presents a summary of sex-related patterns in the three spine regions and median vertebral dimensions are illustrated on Figure 2.

Table 2: Summary of sex-related differences in vertebral metrics in different spinal regions. „Yes" means that there are consistent significant sex-related differences in male medians being greater than female medians across multiple vertebral levels within the region. „Partial" means that there is consistent directional trend with statistical significance observed in fewer vertebrae.

Region	Width	Length	Height	Vertebrae with consistent sex difference*
		male > female		
Cervical	Yes	Yes	Partial	C1-C7
Thoracic	Yes	Partial	Yes	T1-T10 (**strongest at T7**)
Lumbar	Yes	Partial	Partial	L1, L3, L5 (**strongest at L5**)

** Consistent = same direction of effect across sexes (at least two of their dimensions are simultaneously significant), supported by Mann-Whitney U tests.*

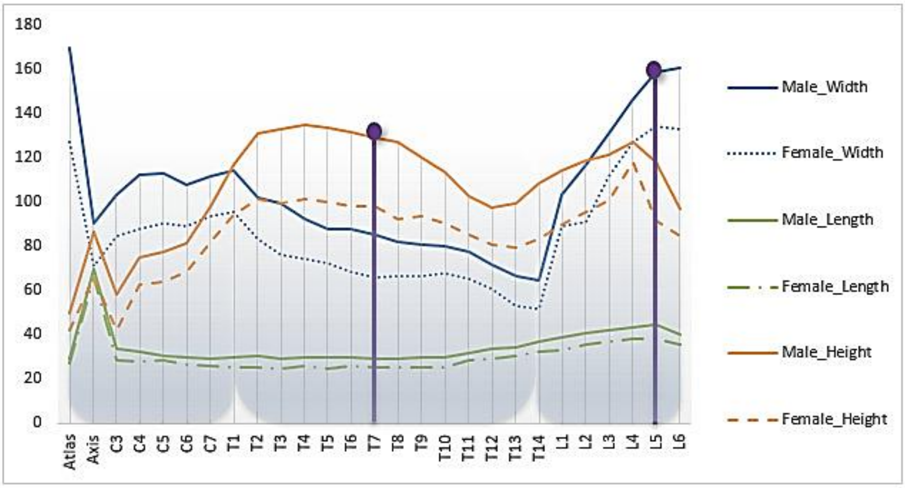

Figure 2: Median vertebral dimensions by sex along the spine, measured in millimeters (mm). Vertical markers highlight the simultaneous significance of T7 and L5 width, length and height (Mann-Whitney U test, p=0.036).

Influence of body weight

Spearman's correlation analysis showed positive associations between body weight and vertebral dimensions in all vertebral levels. Correlation coefficients were generally moderate to strong ($\rho \approx 0.5$-0.8), especially in cervical area, which indicates that heavier bears tended to exhibit larger vertebral dimensions. Due to the limited sample size, not all correlations reached statistical significance, but the overall pattern of positive correlation was consistent across the vertebra. Table 3 presents the correlation score in relation to weight and age for selected vertebrae C1 and C2 (because of their specific morphology), T7 and L5 (because they showed most clear sexual dimorphism). Figure 3 illustrates the direct positive correlation between selected vertebrae width and animal weight. Width was prioritized in figure because it is the strongest and most statistically defensible parameter. It showed clearest sexual dimorphism and strongest correlations with body weight (often with effect size > 0.7), the length and height dimensions showed greater variability between vertebral levels.

Table 3: Spearman correlation coefficient (rho) of body weight and vertebral dimensions of selected vertebrae. W-width, L-length, H-height.

Vertebra	Dimensions	ρ (Weight)	p-value
Atlas	W	0.467	0.243
	L	0.587	0.126
	H	**0.898**	**0.002**
Axis	W	0.563	0.146
	L	**0.934**	**0.001**
	H	0.659	0.076
T7	W	0.491	0.217
	L	0.602	0.114
	H	0.491	0.217
L5	W	**0.719**	**0.045**
	L	**0.743**	**0.035**
	H	0.623	0.099

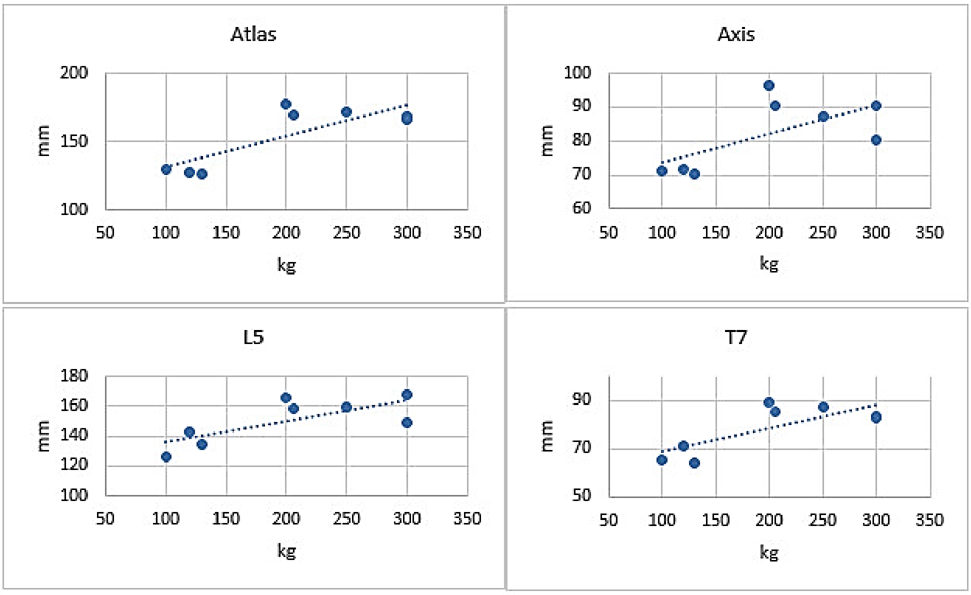

Figure 3: Association between selected vertebrae width (in millimeters) and animal weight (in kilograms).

Influence of age

Associations between age and vertebral dimensions were weaker and less consistent than those observed for body weight. Most vertebral levels showed low to moderate correlation coefficients, often with negative direction (Table 4). There is only a trend, because no significance was reached. This suggests that age-related variation in vertebral size may be largely mediated by body mass rather than age.

Table 4: Spearman correlation coefficient (rho) of age and vertebral dimensions of selected vertebrae. W-width, L-length, H-height.

Vertebra	Dimensions	ρ (Age)	p-value
Atlas	W	0.095	0.823
	L	-0.667	0.071
	H	-0.643	0.086
Axis	W	-0.143	0.736
	L	-0.500	0.207
	H	-0.690	0.058
T7	W	0.071	0.867
	L	-0.036	0.933
	H	-0.524	0.183
L5	W	-0.333	0.420
	L	0.000	1.000
	H	-0.167	0.693

Summary of main findings

Male brown bears showed larger bones of the vertebral column than females, with pronounced dimorphism in T7 and L5. The higher body weight and adult age were both associated with clearly bigger vertebral dimensions, showing a strong association between vertebral solidity and overall body size. Numerical variation in the thoracolumbar region was detected in one female bear, but it maintained a constant thoracolumbar total, indicating anatomical variability within otherwise stable regional segmentation.

Discussion

The present study provided new quantitative insight into variation in vertebral morphology and morphometry in *Ursus arctos*, demonstrating clear sexual dimorphism, significant connections to body weight and age, and occasional numerical variation within an otherwise consistent vertebral formula. The presented data support the understanding of the evolutionary and functional background of the ursid axial skeleton. Across most vertebral levels, males exhibited larger vertebral width, length and height than females, particularly in thoracic vertebra T7 and lumbar vertebra L5. Among the measured parameters, width showed the most consistent differences between sexes and the strongest correlation (positive) with body weight. Vertebral height followed similar pattern, whereas length exhibited greater variability, especially in thoracic region. This suggests that not all dimensions of the vertebra scale uniformly with body size.

Evolutionary and functional perspective

The comparative anatomical and evolutionary analyses across representatives of the Ursidae have frequently shown the strong connection between skeletal toughness and bears' ecological strategies (Davis, 1964; Swenson *et al.*, 2021). Unlike cursorial carnivores such as canids, ursids are plantigrade, supporting the great body mass while maintaining the capacity to walk long distances, dig, stand bipedally, climb (in some species), and perform short bursts of forceful movement (Swenson *et al.*, 2021; Belyaev *et al.*, 2024). This wide range of behavioral demands shapes the mechanical role of the vertebral column as both a load-bearing and flexible system.

The results from the present study suggest that heavier and adult bears have significantly wider, longer, and higher vertebrae, reflecting structural reinforcement of the axial skeleton with increasing body mass. This pattern confirms the wider carnivoran functional analyses, which demonstrate that axial robustness is related to increased trunk loading and lower mobility requirements (Belyaev *et al.*, 2024). It could be interpreted that the increased size of the vertebra in bears enhances resistance to compressive and bending forces that are generated during locomotion, support of visceral weight, and powerful muscular actions, specifically in the thoracolumbar region, which serves as a major anchoring site for the epaxial musculature.

Comparative anatomical studies in humans and large mammals also support these functional interpretations. The structural reinforcement of the *columna vertebralis* with increasing body size and locomotion load is a broadly established principle in mammalian evolution, in which vertebral geometry reflects the axial stability requirements and the locomotor constraints (Sheng *et al.*, 2009). Detailed comparative study of the cervical vertebrae in pigs, calves, and humans has shown that differences in the dimensions of the vertebrae closely correlate to body size, weight-bearing demands, and overall biomechanical characteristics (Sheng *et al.*, 2016). These observations comply with the size-dependent reinforcement observed by us in *Ursus arctos*, strengthening the interpretation that vertebral enlargement with increasing body mass represents a functional adaptation that supports trunk stabilization, protective neural canal architecture, and resistance to mechanical stress.

The cervical vertebrae, which also showed significant differences between the males and the females, are responsible for supporting the heavy skull and allowing the powerful neck movements in bears. Well-developed cervical musculature associated with feeding strategy, social interactions, and behavioral ecology was established in other ursids (Endo *et al.*, 2001; Spătaru & Spătaru, 2007). For example, the polar and malayan bears exhibit strong muscular and osteological adaptations that support the head and neck, strengthening the concept that cervical robustness is a conserved and specific functional requirement of the family Ursidae. Our results suggest that similar principles apply in *Ursus arctos*, where neck musculature and loading likely contribute to vertebral dimensional adaptations.

The pronounced sexual dimorphism observed in some specific segments, such as T7 and L5, is noteworthy. Male brown bears show increased overall body weight and muscular development compared to females (Swenson *et al.*, 2021). These differences appear to be mirrored in the vertebral architecture. The reinforcement of the thoracic vertebrae is likely related to the stabilization of the robust shoulder girdle and forelimb loading, giving the functional significance of the forequarters in bears for locomotion, digging, and climbing. The enlargement of the lumbar vertebrae in males may reflect the requirements for trunk stabilization and transmission of forces to the pelvic limb, supporting the idea that sexual dimorphism in skeletal morphology is closely associated with functional demands and the overall size-dependent correlations in ursids.

The variation in the numbers observed in one female bear (T15/L5 instead of T14/L6, with a constant thoracolumbar total) represents an interesting finding from an anatomical perspective. The comparable transitional or supernumerary vertebrae were observed and documented in many mammals, including carnivores, and are considered a part of the vertebral developmental plasticity rather than necessarily pathological (Covasa, 2024). In an evolutionary perspective, this variation correlates to the dynamic developmental regulation of vertebral patterning and supports the idea that regional boundaries within the mammalian *columna vertebralis*, although generally conserved, could occasionally shift without weakening function. The maintenance of a consistent thoracolumbar total suggests that regional identity may be more rigidly controlled than the precise distribution between thoracic and lumbar elements.

The results presented in this study support an evolutionary interpretation in which the brown bear spine is perfectly balanced between stability, load-bearing capacity, and functional flexibility. The enlargement of the vertebrae related to sex, weight, and adult maturity likely reflects adaptive structural reinforcement as a response to biomechanical demands and life-history characteristics. These characteristics are consistent with the widely documented evolutionary interpretation for Ursidae, in which the skeletal system has evolved not just focused on high-speed locomotion but also on strength, endurance, and multifunctionality (Davis, 1964; Swenson *et al.*, 2021; Belyaev *et al.*, 2024).

Veterinary and clinical relevance

The present observations have important clinical relevance, beyond evolutionary implications. There are several documented clinical cases that confirm that bears can develop degenerative and pathological spinal conditions, including spondyloarthropathy and intervertebral disc disease (Hadžiomerović *et al.*, 2019; Wagner *et al.*, 2005). An example is a lumbar stenosis in a captive polar bear, described by Morrison *et al.* (2017 and successfully treated by laminectomy. This shows that the axial skeleton of ursids is subject to clinically significant pathologies comparable to those observed in domestic mammals and humans.

Comparative morphometric research in domestic mammals provided clinical parallels and gave us greater space for interpretation of the established results. For example, in cats, detailed quantitative analyses done by Richter *et al.* (2024 have demonstrated that regional variation in *canalis vertebralis* and intervertebral disc dimensions is closely associated with susceptibility to neurological compression syndromes and spinal diseases. Such studies underline that the morphometric differences might have significant clinical implications, particularly in species with considerable body mass, as bears. By analogy, the dimensional differences noted and documented in the present study may influence the regional vulnerability to some degenerative or compressive spinal pathology in *Ursus arctos*, showing the clinical relevance and importance of the precise vertebral morphometry.

We could note that clinicians who manage bear spinal pathologies should consider the sex and body mass as relevant anatomical predictors, due to the demonstrated sexual dimorphism and documented size-related variation in vertebral structure. The presence of occasional vertebral fusion and ossification in several individuals in our study, which led to their exclusion from the measurements, also supports the likelihood of age-related degenerative changes in the spine of the brown bear. A greater understanding of the vertebral morphology would aid in enhancing radiological interpretations, surgical planning, and preventive care in captive bears.

Conclusion

To our knowledge, the presented study provides the first detailed morphometric analysis of the cervical, thoracic, and lumbar vertebrae of the brown bear with explicit evaluation of the sex, the weight, and the age. Vertebral width was the most robust parameter, while height and length showed similar but less pronounced pattern and greater variability. The established observations support the strong evolutionary and functional connection between vertebral morphology, support of body mass, behavioral ecology, and axial biomechanics in *Ursus arctos*. At the same time, they provide a valuable anatomical foundation for veterinary practitioners treating spinal pathologies in bears, underscoring the dual importance of anatomical research in both evolutionary biology and wildlife medicine.

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