Three-dimensional morphological variation and sexual dimorphism in the humerus of dromedary camels *(Camelus dromedarius)* from El Oued region: a geometric morphometric analysis

Mohamed Amine FARES[1,a,✉]

[1]University of Souk Ahras, Institute of Agriculture and Veterinary Sciences Taoura, Laboratory of Sciences and Technics of the Livings, Department of Veterinary Sciences, Souk Ahras, Algeria.

[a]ORCID: 0000-0003-4721-018X

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✉**Corresponding author**
m.fares@univ-soukahras.dz

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ABSTRACT

This study investigates the three-dimensional morphological variation and allometric relationships in the humerus of dromedary camels *(Camelus dromedarius)* from the El Oued region, with a focus on sex-based differences. The aim is to analyze the morphological diversity and sexual dimorphism in the humeri of dromedary camels using advanced geometric morphometric techniques. This includes discerning patterns of variation and covariation, particularly related to sexual dimorphism and size-related shape changes. A sample of 59 humeri (29 males and 30 females) was collected. High-resolution three-dimensional scans were used to capture detailed shapes, followed by Procrustes superimposition and Principal Component Analysis to analyze the data. The analysis revealed significant sexual dimorphism, with male camels having more robust and thicker humeri compared to the more slender and delicate humeri of female camels. The allometric analysis showed notable size-related shape changes, especially in the deltoid tuberosity and distal epiphysis regions. The study underscores the presence of sexual dimorphism and its impact on the functional morphology of camelid skeletal structures. The findings provide valuable comprehension into the adaptation pressures and functional demands shaping these bones, demonstrating the utility of geometric morphometrics as a powerful tool in skeletal morphology studies. This research sets a new standard for future studies by integrating high-resolution three-dimensional scanning with sophisticated morphometric analyses.

Introduction

The dromedary camel (*Camelus dromedarius*) is a keystone species in arid and semi-arid regions, particularly the Saharan desert, where it plays a crucial role in the socio-economic and cultural lives of nomadic and pastoralist communities. These animals are renowned for their remarkable adaptations to extreme environments, including their ability to survive long periods without water, as well as, their unique physiological and anatomical traits (1, 8). However, despite their importance, the detailed anatomical studies of their skeletal structures, particularly in the context of sexual dimorphism and regional morphological variations, remains underexplored.

The humerus, a primary bone of the forelimb, is integral to the locomotion and load-bearing functions of dromedaries. Understanding the morphological variations in the humerus is essential for clarity into the biomechanics, adaptations, and veterinary care of these animals. Prior studies on camelid bones have largely focused on the scapula and other bones (3), revealing significant sexual dimorphism and allometric patterns. However, comprehensive studies on the humerus, especially in relation to sex-based differences and allometric relationships, are limited.

To address these gaps, geometricmorphometrics provides a powerful analytical framework for examining bone morphology. This analytical framework enables the precise quantification and comparison of complex shapes (4, 13, 15, 34). By employing geometric morphometric techniques, this study aims to elucidate the extent of sexual dimorphism and allometric relationships in the humerus of dromedary camels from the El Oued region.

Sexual dimorphism, defined as the systematic difference in form between individuals of different sex within the same species, is a well-documented phenomenon in many vertebrates, including mammals (26). In camelids, males and females often exhibit distinct morphological traits, likely due to differences in their roles and physical demands. Males typically engage in more physically demanding activities, such as territorial defense and mating competition, which may contribute to the development of more robust skeletal structures (25). In contrast, females may exhibit morphological adaptations associated with offspring care and foraging strategies.

Beyond sexual dimorphism, allometric relationships play a crucial role in shaping skeletal morphology, influencing both structural integrity and functional adaptations. That is allometry describes how variations in body size correlate with changes in shape, ensuring optimal biomechanical performance across different growth stages and ecological demands, the study of the relationship between size and shape, is another critical aspect of morphological research. Allometric patterns can provide insights into how size-related shape changes influence function and performance in skeletal elements (9, 10, 17). In this context, understanding the allometric relationships in the humerus of dromedaries can reveal how size variations impact bone morphology and, consequently, the biomechanical and functional capabilities of these animals.

Building on the advancements in geometric morphometrics, recent innovations in imaging and computational techniques have further refined the ability to analyze skeletal structures with greater precision. High-resolution 3D imaging, for instance, allows for the detailed reconstruction of bone surfaces, enabling more comprehensive assessments of shape variations (31). Such technologies have opened new avenues for studying the subtle morphological differences that may arise due to environmental pressures or genetic factors. In dromedary camels, these advanced methods can uncover previously unrecognized patterns of variation and adaptation, providing deeper insights into their evolutionary biology (21).

Applying these advanced analytical techniques in a geographically distinct population provides valuable insights into how regional factors influence skeletal morphology. Given this, the El Oued region, known for its distinct environmental conditions and traditional camel breeding practices, provides a unique context for studying the morphological variations in dromedaries. Camels in this region are adapted to specific ecological niches, which may influence their skeletal morphology (11). By focusing on a sample of humeri from this region, this study aims to provide a detailed analysis of sex-based morphological differences and allometric relationships, contributing to the broader understanding of camelid anatomy.

Building on the morphological analysis of dromedary humeri, This study has three primary objectives; the first is to document the three-dimensional morphological variation in the humerus of male and female dromedaries, the second is to analyze the allometric relationships between bone size and shape, and the third is to compare the findings with existing literature on camelid skeletal morphology. By addressing these objectives, this research aims to fill the existing gaps in our knowledge of dromedary humerus morphology and provide valuable insights for veterinary anatomists, biologists, and biomechanists. To accomplish this, geometric morphometric techniques are employed to investigate the three-dimensional morphological variation and allometric relationships in the humerus of dromedary camels from the El Oued region. The findings are expected to enhance our understanding of sexual dimorphism and size-related shape changes in camelid skeletal structures, contributing to improved veterinary care and deeper insights into the adaptations of these remarkable animals.

Materials and Methods

Sample Collection: Fifty nine adult dromedary camels (*Camelus dromedarius*) from the El Oued region (Figure 1) were selected for this study, comprising twenty nine males and thirty females. The animals were sourced from a regional slaughterhouse, ensuring ethical considerations were met, and permissions were obtained from the relevant authorities.

Following post-mortem examination, the humeri were carefully extracted and cleaned of soft tissues in preparation for detailed analysis. To remove residual soft tissues, the bones were subjected to a boiling method, in which they were immersed in hot water at approximately 80–90°C for several hours until all remaining soft tissues detached. Subsequently, the bones were manually cleaned to eliminate any residual tissues. No chemical bleaching agents were applied to preserve the natural bone structure and surface integrity.

To ensure that the sample accurately represented typical adult morphology and was free of skeletal abnormalities, the age and health status of the camels were documented.

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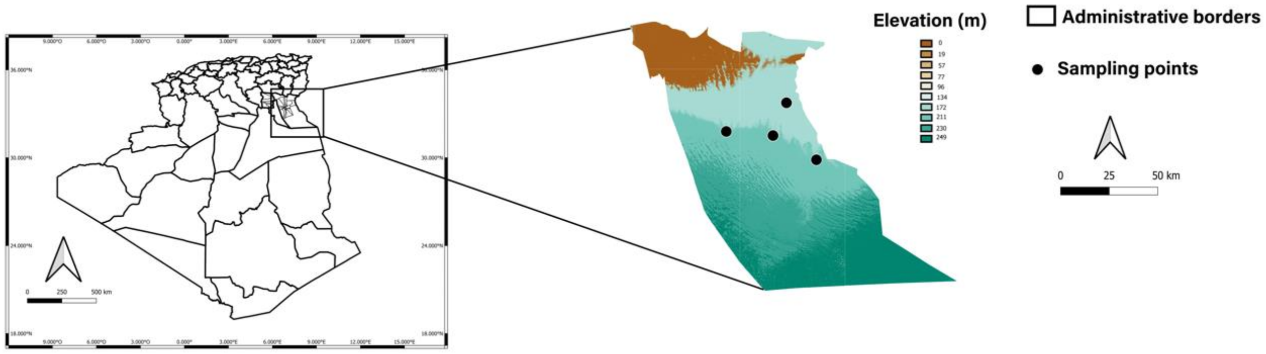

Figure 1. Study area: A digital elevation map of the El Oued region in southeast Algeria, showing sampling points.

Photogrammetry and 3D Modeling: High-resolution three-dimensional models of the humeri were created using photogrammetry. To ensure high image quality and precision, each humerus was photographed from approximately 80 to 120 different angles using a Canon EOS 90D DSLR camera equipped with an EF 50mm f/1.8 STM lens. The photographs were then processed using Meshroom software (Version 2023.3.0) (5) to generate 3D models of the bones. Subsequently, the generated models were refined and optimized using MeshLab software (Version 5.15.2).

Landmark Generation and Pseudolandmarks: In 3D Slicer (version 5.4.0), the PseudoLM Generator module in the GeoMorph extension was used to generate pseudo-landmarks on the humeri. A source landmark template was established using this plug-in, with a spacing tolerance of 3%. The 'Original Geometry' option was selected to derive a sampling pattern based on the model's geometry. The initial number of sampled points in the template was set to 15, and a template mesh was generated using the 'Generate Template' function. Subsequently, a 'Project points to surface' operation was performed, followed by enforcing a spatial sampling rate to exclude samples with a point-to-point distance lower than the defined threshold (Figure 2)(2, 7, 33).

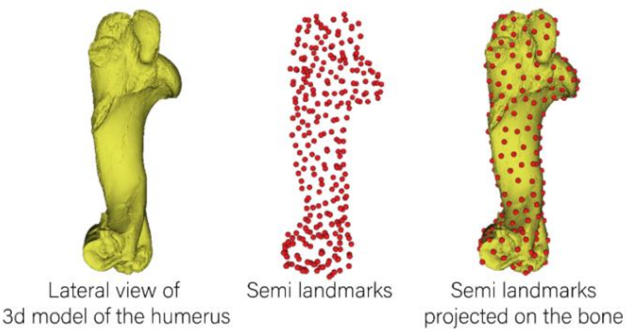

Figure 2. Lateral view of 3D humerus model showing semi-landmarks projection on the bone surface.

Landmark Transfer and Semi-landmarks: The ALPACA (Aligning Landmarks for Procrustes and Canonical Analyses) algorithm (24) tool was used for the efficient transfer of landmarks from the draft pseudo-landmark template to the target 3D models. A batch processing approach was implemented to apply the draft pseudo-landmark across all samples using the "Single Template (ALPACA)" option. The identical mesh model served as both the source and the target, with the draft pseudo-landmark prepared for each specific sample acting as the source landmark. The process was finalized with the execution of the 'Run-auto landmarking' function, resulting in the recording of 285 semi-landmark sets (28), each documented separately for all samples (Figure 3).

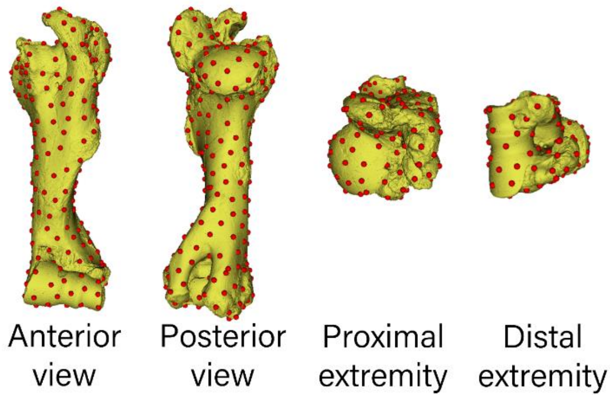

Figure 3. Projection of 285 landmarks of the humerus bone.

Shape Analysis: The semi-landmark coordinates were analyzed using Generalized Procrustes Analysis (GPA) (6, 31). GPA aligns the shapes by eliminating differences in position, orientation, and scale, thereby standardizing them for comparative analysis. This process involves translating, rotating, and scaling the landmark configurations to a common reference, enabling the assessment of true shape differences without the influence of confounding factors.

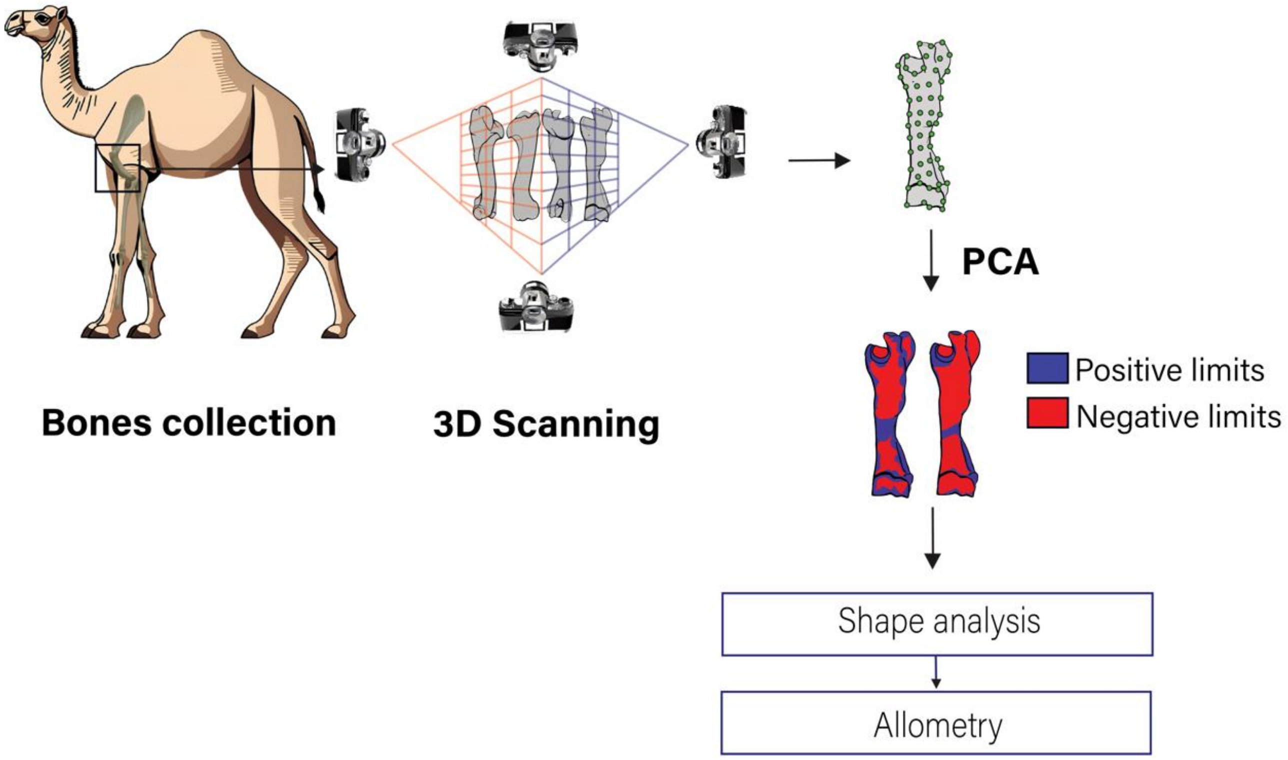

Figure 4. Workflow illustration of the methodology from bones sampling to data analysis and results extraction.

Principal Component Analysis: Principal Component Analysis (PCA) was performed on the aligned landmark coordinates to identify the primary axes of shape variation among the humeri. PCA reduces the dimensionality of the data by transforming it into principal components, which are orthogonal linear combinations of the original variables that capture the maximum variance in the dataset (12, 13). The principal components were subsequently analyzed to determine the extent of morphological variation and to identify shape differences between male and female humeri. Additionally, 3D changes were obtained from Slicer (version 5.4.0), and Procrustes distances were calculated for all samples.

Allometric Analysis: To investigate the relationship between shape and size, an allometric analysis was performed using centroid size as a proxy for humerus size. Centroid size is a measure of the geometric size of an object, is calculated as the square root of the sum of squared distances of each landmark from the centroid (5, 17). The shape variables (principal component scores) were regressed against the centroid size using R Studio (version 4.3.2) statistics programs, enabling the evaluation of how size influences shape variation. Multivariate regression analysis was used to investigate whether allometry existed in the dromedary humerus and to assess the statistical significance of the results (9). The overall workflow is presented in (Figure 4).

Statistical Analysis: To assess the statistical significance of shape and size differences between male and female humeri, Procrustes ANOVA was conducted to evaluate the variation in shape associated with group membership (sex) by partitioning the total shape variation into components attributable to sex (13, 17). The centroid size differences between sexes were analyzed using one-way ANOVA to determine whether size variation was statistically significant. One-way ANOVA was performed using R Studio (version 4.3.2), with a significance threshold set at $P < 0.05$.

Results

The humerus of the dromedary camel exhibits a robust and elongated structure, reflecting its adaptation to weight-bearing and locomotion. The proximal end is distinguished by a well-developed humeral head, which articulates with the scapula to form the shoulder joint. The greater and lesser tubercles are prominent, serving as attachment sites for key shoulder muscles. Additionally, The deltoid tuberosity, located along the cranial aspect of the shaft, is notably pronounced, indicating strong muscular attachment, particularly for the deltoid and brachialis muscles.

The humeral shaft displays a gentle curvature, contributing to biomechanical efficiency in load distribution during movement. The distal end is characterized by a distinct trochlea and capitulum, which articulate with the radius and ulna to facilitate forelimb flexion and extension. Furthermore, medial and lateral epicondyles are well-defined (Figure 5).

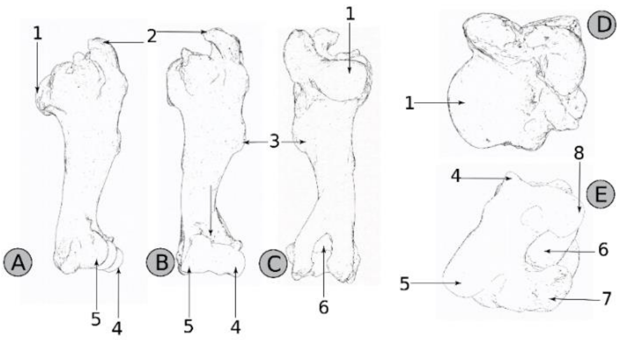

Figure 5. Left humerus of the camel (a) lateral view, (b) cranial view, (c) caudal view, (d) proximal view, (e) distal view; 1: The head, 2: Major tuberosity, 3: Deltoid tuberosity, 4: Capitulum, 5:Trochlea, 6: Olecranon fossa, 7: Lateral epicondyle, 8: Medial epicondyle.

Principal Component Analysis (PCA): The application of PCA to the humerus bones identified two primary components, PC1 and PC2, which account for substantial portions of the shape variance within the dataset. Specifically, PC1 explains 19.6% of the total variance, while PC2 accounts for 11.9%. The PCA scatterplot visually illustrates the distribution of the samples across these principal components, effectively highlighting the morphological diversity among the specimens (Figure 6).

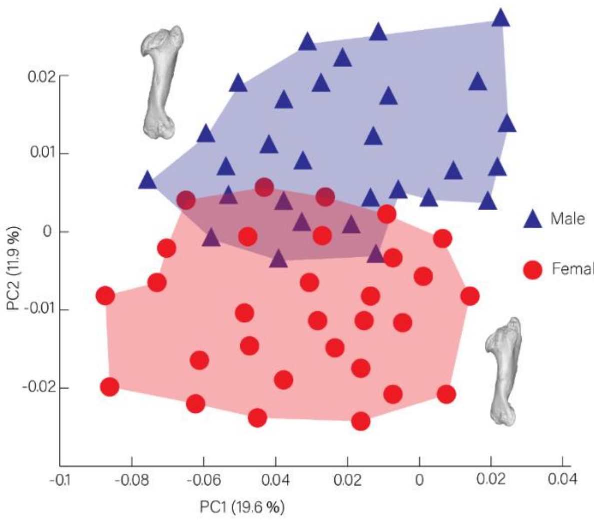

Figure 6. Principal component analysis (PCA) scatterplot of 3D geometric morphometrics of male and female humeri in dromedaries, including convex hulls delineating each sex (males in blue triangles, females in red circles).

Positive and Negative Values of PC1: The results of the principal component analysis (PCA) revealed significant morphological variations in the humeri of dromedary camels along the first principal component (PC1), highlighting pronounced sexual dimorphism. The lateral view demonstrated that the positive limits (blue) of PC1 were associated with a more robust humeral head, major tuberosity, and deltoid tuberosity, whereas the negative limits (red) corresponded to less prominent structures. The cranial view showed a more bulbous and extended head, along with more pronounced capitulum and trochlea in the blue regions, compared to flatter structures in the red regions. Similarly, in the caudal view, the olecranon fossa appeared deeper and more defined in blue, while shallower in red, with both lateral and medial epicondyles exhibiting similar size variations. The proximal view reinforced these observations, with larger and more robust head and major tuberosity in the blue regions. Finally, the distal view highlighted more prominent capitulum, trochlea, and epicondyles in the blue regions, contrasting with flatter and less distinct structures in the red regions, male camels exhibited more robust and structurally prominent humeri (blue regions), whereas female camels displayed more slender and delicate humeri (red regions), particularly in the head, major tuberosity, deltoid tuberosity, capitulum, trochlea, olecranon fossa, and epicondyles (Figure 7).

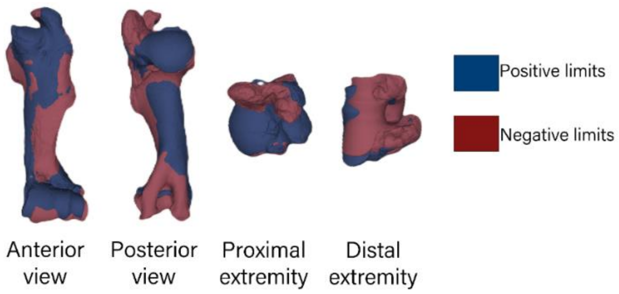

Figure 7. Distribution of principal component 1 (PC 1) values with negative (red) and positivie (blue) limits.

Positive and Negative Values of PC2: The results of the second principal component (PC2) analysis revealed significant morphological variations in the humeri of dromedary camels, indicating distinct shape differences. The lateral view demonstrated that the positive limits (blue) of PC2 were associated with a more expanded and pronounced humeral head, major tuberosity, and deltoid tuberosity, whereas the negative limits (red) corresponded to more compact and less prominent structures. The cranial view showed a more bulbous and expanded head, along with more pronounced capitulum and trochlea in the blue regions, compared to flatter structures in the red

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regions. From the caudal view, the olecranon fossa appeared deeper and more defined in blue, while shallower in red, with both lateral and medial epicondyles exhibiting similar size variations. The proximal view reinforced these observations, with a larger and more robust humeral head and major tuberosity in the blue regions. Finally, the distal view highlighted more prominent capitulum, trochlea, and epicondyles in the blue regions, contrasting with flatter and less distinct structures in the red regions. Overall, the positive side of PC2 (blue regions) was associated with more expanded, pronounced, and robust humeral structures, whereas the negative side (red regions) corresponded to more compact, less pronounced, and delicate structures, particularly in the head, major tuberosity, deltoid tuberosity, capitulum, trochlea, olecranon fossa, and epicondyles (Figure 8).

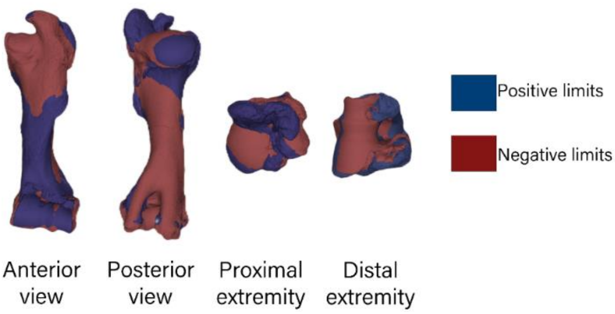

Figure 8. Distribution of principal component 2 (PC2) values with negative (red) and positive (blue) limits.

PCA Scatterplot Analysis: The Principal Component Analysis (PCA) scatterplot visually represents the shape variation within the humerus bones of the camel sample set, comprising twenty nine males and thirty females. This analysis elucidates the primary axes of morphological variation, with PC1 accounting for 19.6% of the total variance and PC2 capturing an additional 11.9% (Figure 6).

The PCA scatterplot, accompanied by convex hulls to encapsulate the variation within each group, demonstrates a notable separation of specimens along the PC1 axis. This separation suggests that PC1 is the predominant factor influencing shape variation in the humerus bones, likely capturing the major morphological differences between male and female specimens. The distinct clustering along this axis indicates significant sexual dimorphism in the shape of the camel humerus.

In contrast, there is some degree of overlap observed along the PC2 axis. This overlap implies that while PC2 captures shape variation, it represents secondary morphological differences that are less pronounced than those captured by PC1. The additional variation encapsulated by PC2 may be attributed to factors such as age-related changes, individual variation within sexes, or environmental influences on bone morphology.

The convex hulls drawn around the male and female groups highlight the dispersion and extent of morphological variation within each sex. These convex hulls serve as a visual boundary, illustrating the range of shape variations present in the sample set. The overlap between the convex hulls of males and females along PC2 further supports the presence of shared morphological traits between the sexes, despite the overall sexual dimorphism captured by PC1 (Figure 6).

Clusters of specimens with similar morphological traits are evident within the scatterplot. These clusters may correspond to subpopulations or distinct age groups within the sample set. Analyzing these clusters in greater detail could provide insights into the functional implications of the observed shape variations. For instance, variations in the robustness or gracility of the humerus bones could be related to differences in locomotor behavior or biomechanical loading patterns.

Interpretation of Morphological Variations: The observed morphological variations in the humerus bones provide valuable insights into the functional adaptations of camels. The humerus with positive PC1 values, characterized by its increased width and robustness, likely reflects adaptations for handling greater loads and accommodating substantial muscular attachments. This is particularly relevant for camels living in harsh desert environments, where such adaptations are crucial for effective locomotion and survival.

In contrast, the narrower and more gracile humerus associated with negative PC1 values may signify adaptations for less strenuous locomotion or represent different age or sex groups within the camel population. This variation highlights the diverse functional demands placed on the humerus depending on the camel's role and environment.

The variations captured by PC2 provide additional insights into the functional adaptations of the humerus. The elongated and slender humerus associated with positive PC2 values may suggest adaptations aimed at enhancing speed and agility, which could be advantageous in certain environmental or behavioral contexts. Conversely, the shorter and more robust humerus linked to negative PC2 values likely indicates adaptations for strength and endurance, potentially reflecting different functional or environmental pressures.

Procrustes ANOVA and Centroid Size Analysis: The results of the Procrustes ANOVA indicated no statistically significant shape differences between male and female camel humeri. Sex explained only 0.06% of the total shape variation ($R^2 = 0.0006$, $P = 0.97$), suggesting that humeral

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morphology is highly conserved between sexes. The observed variation appears to be primarily attributable to individual differences rather than sex-specific traits. These findings imply that sexual dimorphism in humeral shape is either negligible or undetectable given the current dataset and sample size.

Similarly, centroid size analysis also revealed no significant differences between male and female camel humeri. ANOVA results showed a P-value of 0.827 (F = 0.049), indicating that size variation between sexes is not statistically significant. Similar to shape, most of the size variation appears to be driven by individual differences rather than sex. These results suggest that sexual dimorphism in humeral size is minimal or undetectable with the available data.

Allometric Effects on Humeral Shape: Allometric analysis demonstrated a strong and statistically significant relationship between centroid size and humeral shape ($p < 0.001$). Size accounted for 71.7% of the total shape variation ($R^2 = 0.717$), highlighting its major role in determining humeral morphology. The F-statistic ($F = 119.11$) and Z-score ($Z = 7.27$) further reinforce the strength of this relationship. While size is a key factor in shaping humeral morphology, a remaining 28.3% of shape variation is unexplained, likely due to individual differences or other non-size-related influences.

By integrating the findings from PCA with an understanding of camel biomechanics and ecology, the study contributes valuable knowledge on the morphological diversity of camel humerus bones. This understanding not only elucidates the functional adaptations of camels but also establishes a framework for exploring the adaptation processes that have shaped their skeletal morphology. The integration of PCA results allows for a comprehensive analysis of shape variations and how these variations relate to the biomechanical demands placed on camels in their natural habitats. This holistic approach sheds light on the complex interplay between form and function in camel skeletal structures. Moreover, the study underscores the importance of considering both major and minor sources of shape variation to gain deeper insights into the evolutionary processes influencing camel morphology. By doing so, it enhances our understanding of how camels have adapted to their environments over time, offering valuable perspectives for further research in the field.

Discussion and Conclusion

This study presents a geometric morphometric analysis of camel humerus bones, utilizing Principal Component Analysis (PCA) to elucidate shape variations within the sample set. The PCA results reveal significant insights into the morphological diversity and functional adaptations of the camel humerus, enhancing our understanding of The PCA identified two principal components, PC1 and PC2, which collectively capture a substantial portion of the shape variance in the camel humeri. PC1, accounting for 19.6% of the variance, represents a primary axis of morphological variation, while PC2, explaining 11.9% of the variance, captures additional, less pronounced differences. This finding aligns with previous studies that have demonstrated the effectiveness of PCA in capturing major and minor shape variations in skeletal elements (2, 18, 31).

The positive values of PC1, characterized by a wider and more robust humerus with pronounced tuberosities and curvature, reflect adaptations associated with increased muscularity and load-bearing capacities. Such traits are consistent with the findings of (18), who observed similar morphological adaptations in the humeri of large terrestrial mammals. These characteristics are likely advantageous for camels, which are subject to significant biomechanical stresses in their arid habitats. A robust humeral structure may facilitate greater muscle attachment areas, thereby enhancing locomotor efficiency and load distribution (29).

In contrast, negative PC1 values correspond to a narrower and more gracile humerus, with smaller tuberosities and less pronounced curvature. This morphology suggests adaptations for reduced muscular demands or or may indicate a different demographic within the population. Similar variations have been observed in other species, where gracile bone structures are often associated with less demanding locomotor and functional requirements (22). These findings suggest that camels with such traits may be younger or possess different functional adaptations compared to their more robust counterparts.

PC2, which captures 11.9% of the variance, provides additional insights into the functional adaptations of the camel humerus. Positive PC2 values are associated with a more elongated and slender shaft, smaller tuberosities, and less pronounced curvature. This morphology could be indicative of adaptations for speed and agility, supporting findings from similar studies on limb bone morphology (20). The elongated, slender humerus may be advantageous for camels engaged in activities requiring rapid, agile movements, although such adaptations might be less critical in their primary desert habitat.

Conversely, negative PC2 values correspond to a humerus with a shorter, more robust shaft, larger tuberosities, and a more pronounced curvature. This morphology suggests adaptations for strength and endurance, likely reflecting different functional requirements. The robust humerus with larger tuberosities may be indicative of greater muscular attachments, enhancing the camel's capacity for sustained physical

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exertion (32). Such adaptations are consistent with observations in other large mammals, where robust bone structures are often linked to enhanced strength and load-bearing capabilities (20).

The PCA scatterplot demonstrates a clear separation of specimens along the PC1 axis, with some overlap observed along the PC2 axis. This separation indicates that PC1 predominantly captures the primary source of shape variation in the camel humerus, while PC2 reflects additional, less dominant variations. The clustering of specimens with similar morphological traits may represent different subpopulations or age groups within the sample set. This observation is in line with previous research that has utilized PCA to identify distinct morphological clusters within animal populations (16, 19).

The presence of morphological clusters suggests that the camel population exhibits a range of adaptations corresponding to different ecological or functional contexts. These clusters could represent variations in age, sex, or environmental pressures, providing valuable insights into the functional dynamics of camel humeral morphology. Similar clustering patterns have been observed in other studies examining skeletal diversity and its relation to ecological factors (5, 30).

The observed morphological variations in the camel humerus offer valuable insights into the functional adaptations of camels. The robust humerus associated with positive PC1 values likely reflects adaptations for enhanced load-bearing and muscular attachments, crucial for coping with the biomechanical stresses of desert environments. These findings are consistent with the notion that skeletal adaptations in large mammals often correlate with their functional and environmental demands (27).

Conversely, the gracile humerus associated with negative PC1 values may indicate adaptations for less strenuous locomotion or or reflect different demographic characteristics. Such variations highlight the plasticity of camel skeletal morphology in response to varying functional and environmental pressures (21).

PC2 variations further elucidate the functional adaptations of the camel humerus. The elongated and slender humerus associated with positive PC2 values may reflect adaptations for speed and agility, whereas a robust humerus with larger tuberosities linked to negative PC2 values likely indicates adaptations for strength and endurance. These findings contribute to a broader understanding of how skeletal morphology is shaped by adaptation and functional demands (23).

The geometric morphometric analysis of camel humerus bones, facilitated by PCA, provides a comprehensive understanding of shape variations and their functional implications. The results underscore the importance of considering both major and minor sources of shape variation in elucidating the adaptive significance of skeletal morphology. Future research could further explore the relationship between humeral morphology and other ecological or physiological factors, offering deeper insights into the adaptation dynamics of camel anatomy (31).

The influence of environmental and genetic factors on camel humerus morphology cannot be understated. Recent studies have highlighted how environmental pressures, such as arid conditions and terrain variability, shape skeletal adaptations in camels (3). Genetic factors also play a crucial role, with specific genetic markers being associated with skeletal robustness and morphological traits (1, 14). By integrating these aspects, future research can provide a more holistic view of the determinants of camel humerus morphology, linking phenotypic variations to underlying genetic and environmental contexts.

The geometric morphometric analysis of camel humerus bones, facilitated by PCA, provides a comprehensive understanding of shape variations and their functional implications. The results underscore the importance of considering both major and minor sources of shape variation in elucidating the adaptive significance of skeletal morphology. Future research could further explore the relationship between humeral morphology and other ecological or physiological factors, offering deeper insights into the adaptation dynamics of camel anatomy (31).

One limitation of this study is the relatively small sample size, which, while sufficient for identifying general trends in humeral morphology, may not fully capture the complete range of variation within dromedary camels from the El Oued region. The inclusion of only 59 specimens from a single population restricts the ability to conduct more detailed subgroup analyses, such as age-related variations or potential regional differences. Additionally, the dataset may not be fully representative of the broader dromedary population, as factors such as genetic diversity, environmental influences, and biomechanical demands could contribute to variations in humeral morphology that were not captured in this study. Future research with a larger sample size, incorporating additional geographic locations and age groups, would enhance the robustness of statistical analyses and provide a more comprehensive understanding of sexual dimorphism and allometric patterns in camel humeri. Expanding the dataset would also allow for the application of more advanced morphometric techniques, improving the resolution of shape differences and further elucidating the functional and evolutionary significance of humeral morphology in dromedary camels.

This study provides significant insights into the three-dimensional morphological variation and sexual

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dimorphism in the humerus of dromedary camels (*Camelus dromedarius*) from the El Oued region. Using advanced geometric morphometric techniques, the research reveals substantial sexual dimorphism, with male camels displaying more robust and thicker humeri compared to the more slender and delicate humeri of female camels. The allometric analysis highlights notable size-related shape changes, particularly in the deltoid tuberosity and distal epiphysis regions. These findings underscore the functional adaptations and biomechanical demands placed on camelid skeletal structures, demonstrating the utility of geometric morphometrics in skeletal morphology studies. This research sets a new standard for future studies by integrating high-resolution 3D scanning with sophisticated morphometric analyses, contributing to a deeper understanding of the anatomical and functional diversity in dromedary camels.

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Ethical Statement

This study was conducted in accordance with the ethical standards for animal research. All procedures involving the handling and sampling of dromedary camels (*Camelus dromedarius*) were approved by the Committee of Ethics of the University of Souk Ahras in Algeria (Approval no: 2021/08704-180).

Conflict of Interest

The authors declared that there is no conflict of interest.

Data Availability Statement

The data supporting this study's findings are available from the corresponding author upon reasonable request.

Animal Welfare

The authors confirm that they have adhered to ARRIVE Guidelines to protect animals used for scientific purposes.

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