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Original Article

# The articular surfaces of the proximal segment of ulna: Morphometry and morphomechanics based on digital image analysis and concepts of fractal geometry

Ahmed Al-Imam[a,b,*], Ashok Sahai[c], Shams Al-Nuaimi[d], Mustafa Ismail[d]

[a] Department of Anatomy and Cellular Biology, College of Medicine, University of Baghdad, Iraq
[b] Department of Postgraduate Medicine, School of Life and Medical Sciences, University of Hertfordshire, United Kingdom
[c] Dayalbagh Educational Institution, Deemed University, Dayalbagh, Agra, 282 005, UP, India
[d] College of Medicine, University of Baghdad, Iraq

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A B S T R A C T

*Introduction:* The elbow joint is a compound joint made of articulations in between the humerus, ulna and the radius. The coupling areas (joints) are of prime importance from the kinetic-biomechanical perspective and of potential inter-ethnic significance. These articulations can be affected by several pathologies that may require medical and surgical interference. This experimental analysis aims to infer data in relation to the morphometry of the proximal segment of the ulna and its articular surfaces represented by the greater sigmoid notch (trochlear notch) and lesser sigmoid notch (radial notch).
*Methods:* A sample of fifty ulnae (n = 50, 27 right and 23 left) was studied in connection with; the surface area of the sigmoid notches (SA), weight of ulna, and the volume of proximal portion of ulna (including the olecranon process and reaching inferiorly to the lowest margin of the radial notch), the length of ulna (L). Longitudinal dimensional parameters were also studied including; the straight distance between the highest point (tip) of the olecranon and that of the coronoid process (OCD), and the mid-olecranon thickness in mediolateral (T1) and anteroposterior orientation (T2).
*Results:* It has been inferred that there were no significant differences in between right versus left ulnae and in relation to the majority of morphometric parameters with an exception for OCD (22.47 vs 20.75, *p-value* = 0.002). There was a positive correlation in between all the parameters, although the strongest associations were observed in between OCD, the area of the trochlear notch, and the weight of ulna.
*Discussion:* A precise conclusion was reached in relation to morphometry, volumetry and the pertinent biomechanics of the proximal segment of the ulna. Key findings are of value to biomedical engineers, medical professionals including orthopaedic surgeons and rheumatologists, evolutionary biologist, and physical anthropologist. Data from this study can be used to (reverse) engineer the perfect implant for the elbow joint.


## 1. Introduction

The elbow joint in humans is a synovial hinge joint between the distal end of the humerus and the proximal end of both radius and ulna. Many standard anatomy textbooks, including Gray's anatomy, describe this joint as a uniaxial articulation permitting movement on the transverse axis.[1,2] However, according to Kapanji, it is considered biaxial allowing two axes of motion (biaxial) for flexion-extension and pronation-supination (pivotal rotation).[1,2] Hence, the elbow is also described as trochoginglymus joint.[3] To be more specific, the elbow joint is a compound joint which is made of three discrete articulations; the humeroulnar joint (humero-trochlear), humeroradial joint (radio-capitellar), and the proximal (superior) radioulnar joint.[1,2,3] The Humeroradial joint is a shallow ball-and-socket hinge type of synovial joint, and it is made by the articulation of capitulum of the humerus against the superior articular facet of the head of the radius.[1,4] The trochlear notch of ulna has four quadrants with a rounded bony ridge extending from the tip of the coronoid process to the tip of the olecranon process dividing the notch into medial and lateral compartments, in addition to a non-articular indentation which

* Corresponding author at: House 18/5, Al-Akhtal Street, District 318, Al-Adhamyia, 10053, Baghdad, Iraq.
*E-mail address:* a.m.al-imam@herts.ac.uk (A. Al-Imam).

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partly divides the notch into an upper (proximal) and a lower (distal) portion.[3]

Numerous pathologies can affect the proximal segment of ulna including fractures, subluxations, dislocations, tumorous conditions, heterotopic ossification, osteophyte formation and arthritic changes.[5,6] Most of these conditions eventually require surgical manipulation and correction including potential resection of the proximal segment of the ulna, implantation of an engineered prosthesis, and joint arthroplasty.[1,2,5–7] All these procedures require high accuracy for the restoration of the joint morphometry, kinematic, and biomechanics. Precision can be achieved via (reverse) engineering aiming to mimic the original dimensions of the ulna, humeroulnar joint and the proximal radioulnar joint. On the other hand, the insertion of an improper implant of the proximal ulna may result in several changes including either shortening or lengthening of the ulna, which can alter the kinematics-biomechanics of upper limb at the level of the elbow and the wrist. Therefore, an improper implant can result in limitation of joint mobility, premature stress concentration and wearing, and an early-onset osteoarthritic changes of the relevant articulations.[1,2,4,8,9] The collateral ligaments and the annular ligament (ANL) provide good support for the elbow joint thus preventing potential subluxation and dislocation which tends to occur due to the shallowness of the cup-like surface of the head of the radius.[1,2,4] Without the annular ligament, the bicipital tendon tends to pull the radial head out of its articulation with the capitulum at the distal end of the humerus.[1,8] Interestingly, during the fetal period, the growth of the ANL occurs independently from the functional joint demand.[10]

## 2. Materials and methods

This study has been approved by the ethical committee and the institutional review board (IRB) of the College of Medicine at the University of Baghdad. Procedures and experimentation were conducted in compliance with the ethical standards imposed by the Declaration of Helsinki. Identities and affiliations of deceased individuals were adequately concealed. The morphometric and volumetric analyses included in this study represent an experimental cross-sectional study of dry osseous specimens (ulnae) of adult individuals of the Middle Eastern ethnicity from Iraq. This study was planned to be complimentary for prior research efforts by Al-Imam and Sahai in connection with the morphometry of the superior articular surface of the head of the radius.[11]

The primary aim of this analysis is to reach a goal, based on inferential models of data science, in relation to the morphometry of the proximal segment of the ulna. The main findings should be respondent to the research questions with regard to the morphometry of the articular surfaces, including the trochlear notch (greater sigmoid notch) and the radial notch (lesser sigmoid notch), and the volumetry of the bony segment of ulna bearing those surfaces. The greater sigmoid notch (trochlear notch) has been divided into four discrete areas (SA 1–4). SA1 represents the proximal medial area (PM), SA2 represents the proximal lateral area (PL), while SA3 represents the distal medial area (DM), and SA4 represents the distal lateral area (DL).[3,12] An analogous research methodology for the calculation of areas and volumes was carried out by Al-Imam and co-workers earlier in 2017; their aim was to measure the surface area of the articular facets of the patella in connection with the patellofemoral articulation at the knee joint.[13]

Materials used included a digital Vernier calliper, an electronic balance for measuring the weight of ulnae, and a fast-setting elastic dust-free alginate cast impression material. This cast material (Fig. 1) was utilized for the calculation of the volume of the proximal segment of ulna bearing the articular surfaces of ulna which extends from the lowest margin for the radial notch to the high tip of the olecranon process.[14] The calculation of volume was double-checked with another volumetric method based on the Archimedes' principle of buoyancy and fluid displacement.[15,16] Other tools included a digital image analysis software (Digimizer Image Analysis Software) which was utilized for the calculation of the surface area of articular surfaces (Greater and lesser sigmoid notches) of the proximal segment of ulna (Fig. 2).[17]

All of the bone specimens belonged to adult individuals from the Iraqi population. They were of unknown age, gender, handedness, and patterns of cerebral dominance. Bony samples were fifty in total (n = 50) pertaining to both upper limbs (27 right, and 23 left). A standard digital Vernier was utilized to measure four longitudinal dimensional parameters. These parameters included the distance from the tip of the olecranon process to the tip of the coronoid process (OCD), the bony thickness in the mid-region of the olecranon process in between the highest point of the olecranon process and the coronoid process, and in mediolateral orientation (T1), and in

**Fig. 1.** Cast Material for Calculation of Volume.

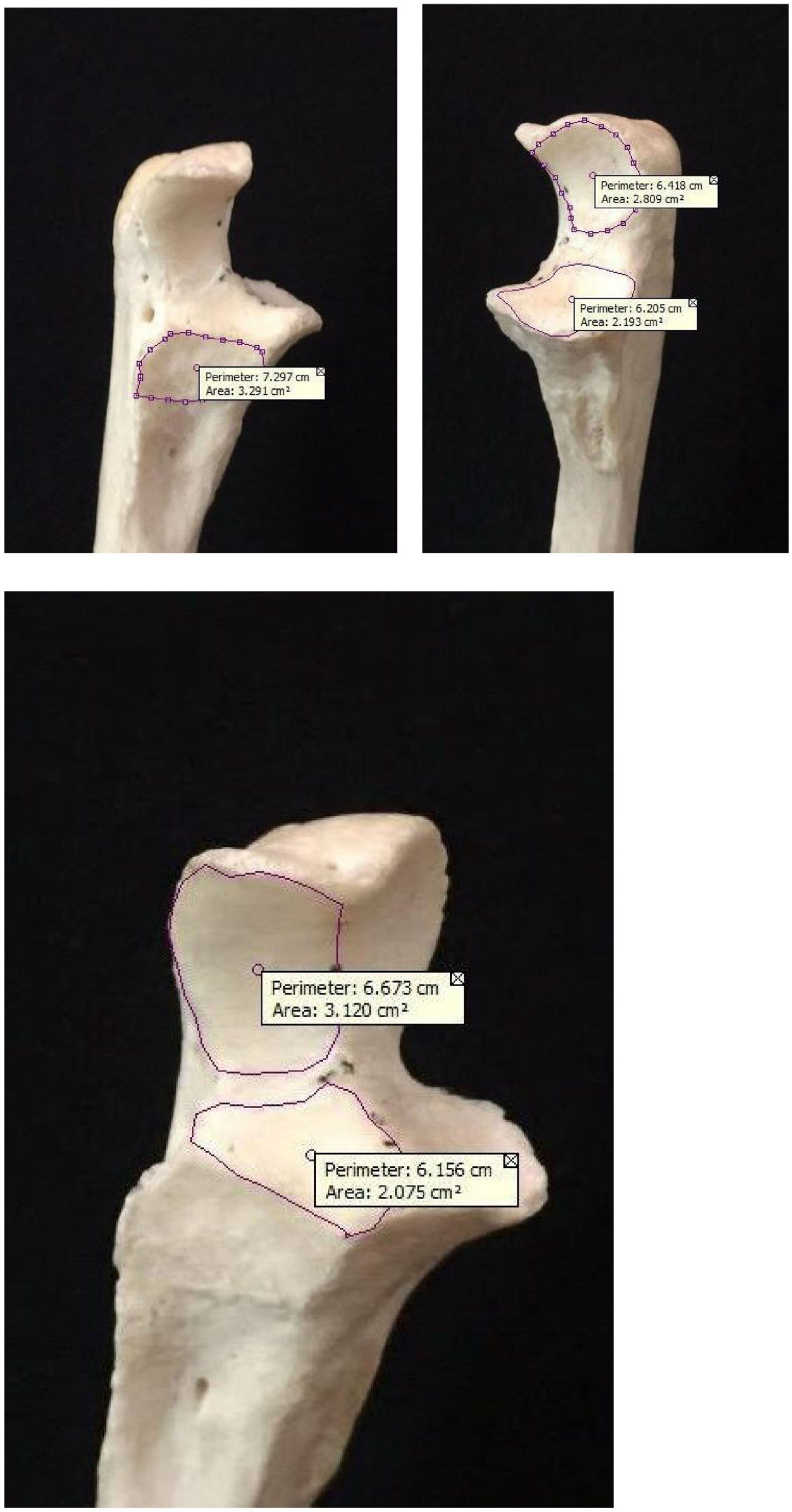


**Fig. 2.** The Articular Surfaces of Proximal Ulna: Trochlear Notch and Radial Notch.

anterior-posterior direction (T2). The fourth measurement represented the length of the ulna from the tip of the olecranon process to the tip of the styloid process of ulna (L1).

The adopted units of measurements were in millimetres (mm) for longitudinal parameters, square centimetres (cm2) for the articular surface area, cubic centimetres (cc) for volume, and in gram (gm) for weight. All measurements were approximated to the nearest percentile of a unit. The measurements were taken while each bony specimen was firmly fixed vertically on a robust stable platform. Further, to prevent man-made errors and biases, two researchers had made independent measurements for all of the observed parameters. In case of significant discrepancies in relation to the measured parameters, a third reading was taken to resolve the numerical disparity. The final measures for each parameter represent the average numerical value of these measurements.

The statistical analyses were both descriptive and inferential. These were carried out via Microsoft Excel 2016 and the Statistical Package for Social Sciences (SPSS v.20). The implemented inferential statistical tests included Student's t-test, F-test, the Analysis of Variance and Covariance (ANOVA), Chi-Square test, and Linear Regression. An alpha value of 0.05 and a confidence interval of 95% (95% CI) were adopted as the cut-off margin for the purpose of testing the statistical significance. The level-of-evidence of this study is estimated to be of level-4 in accordance with categorization scheme approved by the Oxford Center for Evidence-Based Medicine.[18] Additionally, a systematic review of prior research attempts was carried out on medical and paramedical databases of literature including PubMed/Medline, the Cochrane Library, Embase, EBSCO, CINAHL, ResearchGate, Academia, Google Scholar,

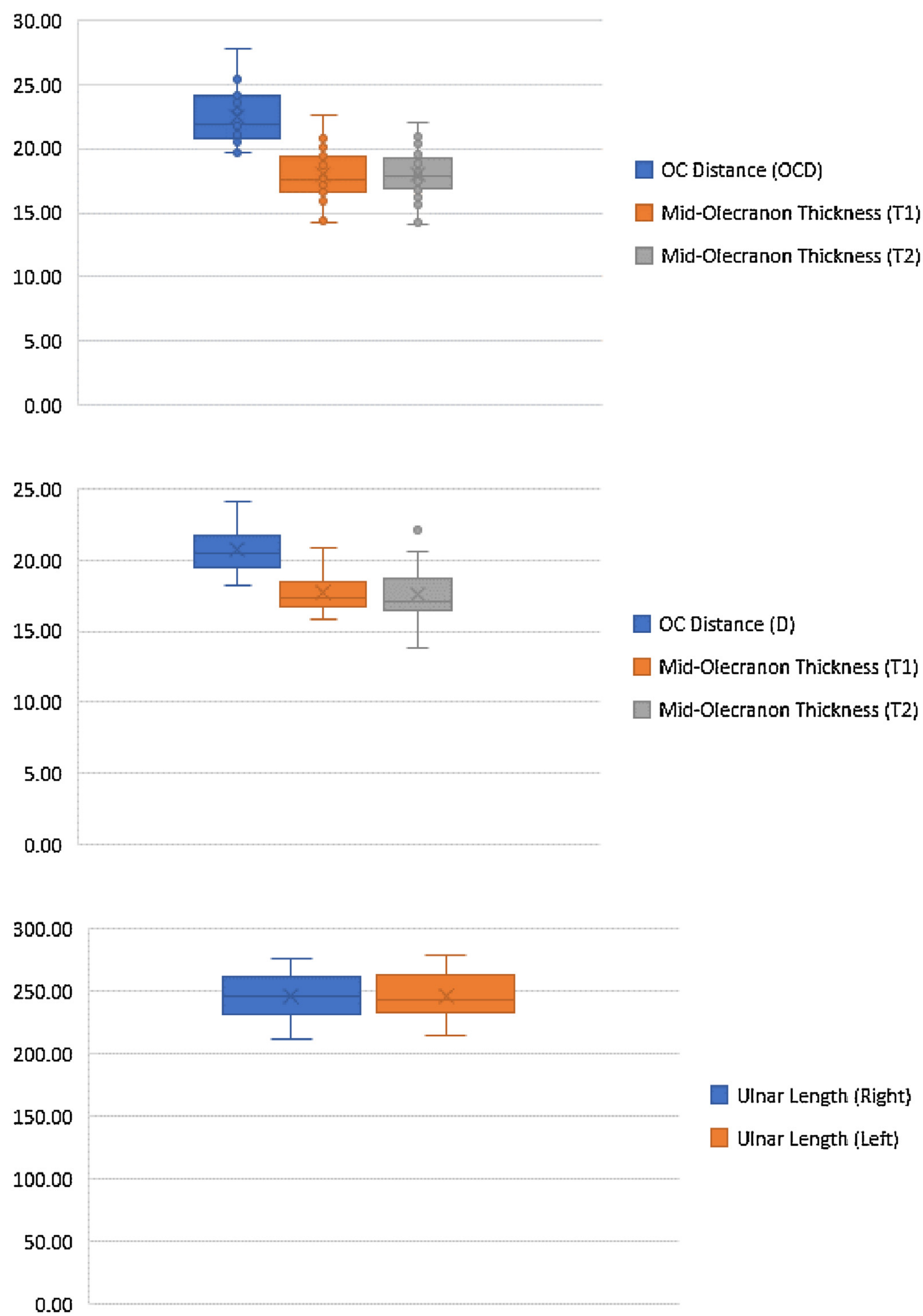


**Fig. 3.** Boxplot Presentation of Longitudinal Parameters: Right Ulnae (above) and Left Ulnae (middle), and Ulnar Length (below).

Semantic Scholar, and Sci-Hub, and the Iraqi Virtual Science Library.

## 3. Results

In relation to the morphometric parameters of the right ulnae (Figs. 3–5), the mean values were calculated to be 22.25 +/− 2.03 (OCD), 17.97 +/− 2.09 (T1), 18.02 +/− 1.97 (T2), 246.50 +/− 18.44 (L), 33.23 +/− 9.32 (weight), 6.41 +/− 2.96 (volume), 1.63 +/− 0.41 (SA1), 1.75 +/− 0.39 (SA2), 1.60 +/− 0.36 (SA3), 1.27 +/− 0.25 (SA4), 1.21 +/− 1.21 (SA5). In case of the left ulnae, the mean values were calculated to be20.75 +/− 1.68 (OCD), 17.71 +/− 1.37 (T1), 17.61 +/ − 1.86 (T2), 245.89 +/− 16.59 (L), 29.96 +/− 7.69 (weight), 6.76 +/ − 2.81 (volume), 1.59 +/− 0.43 (SA1), 1.67 +/− 0.33 (SA2), 1.64 +/ − 0.41 (SA3), 1.16 +/− 0.33 (SA4), 1.24 +/− 0.37 (SA5). ANOVA test had confirmed the existence of a significant difference in between OCD, T1, and T2 (*p-value* < 0.001) for each of right and left ulnae. Further, there were no statistically significant differences in between right and left ulnae in connection with T1 (p = 0.597), T2 (p = 0.453), L (p = 0.903), while there was a significant difference in relation to OCD and in favour of right ulnae (22.47 vs 20.75, p = 0.002). The significant difference could be related to the handedness of an individual and the underlying patterns of cerebral dominance [11,19–21]. Additionally, linear regression confirmed the existence of a positive correlation for each of right and left ulnae in between OCD versus T1 ($R^2$ score = 0.467 for right ulnae, and $R^2$ = 0.580 for left ulnae), OCD versus T2 (0.359, 0.632), OCD versus L (0.518, 0.519), T1 versus T2 (0.581, 0.678), T1 versus L (0.495, 0.396), and T2 versus L (0.432, 0.378). The correlation in between T1 versus T2 was the strongest.

In relation to the volume and weight, there were no significant differences in between right and left ulnae (p = 0.179, p = 0.670). There was also a positive correlation in between weight and volume for right ulnae ($R^2$ = 0.563) and left ulnae (0.466). In relation to the area calculation (SA), there were no significant differences in between right and left ulnae for each of SA1, 2, 3, 4, and 5 (p = 0.729, 0.443, 0.718, 0.197, 0.730).

ANOVA test also confirmed the existence of significant differences among all five areas (SA1-5) at a *p-value* < 0.001. Further, in relation to each of the right and left ulnae, there were no significant differences in the surface area with an exception for; SA1 vs SA 4, SA1 vs SA5, SA2 vs SA4, SA2 vs SA5, SA3 vs SA4, and SA3 vs SA5. On the other hand, there were additional significant differences in relation to right ulnae for SA1 vs SA2 (0.031), and SA2 vs SA3 (0.006). However, no significant differences were detected in connection with these same areas for the left ulna. Perhaps, this can also be attributed to handedness and the patterns of lateralization of brain functions for which future studies are

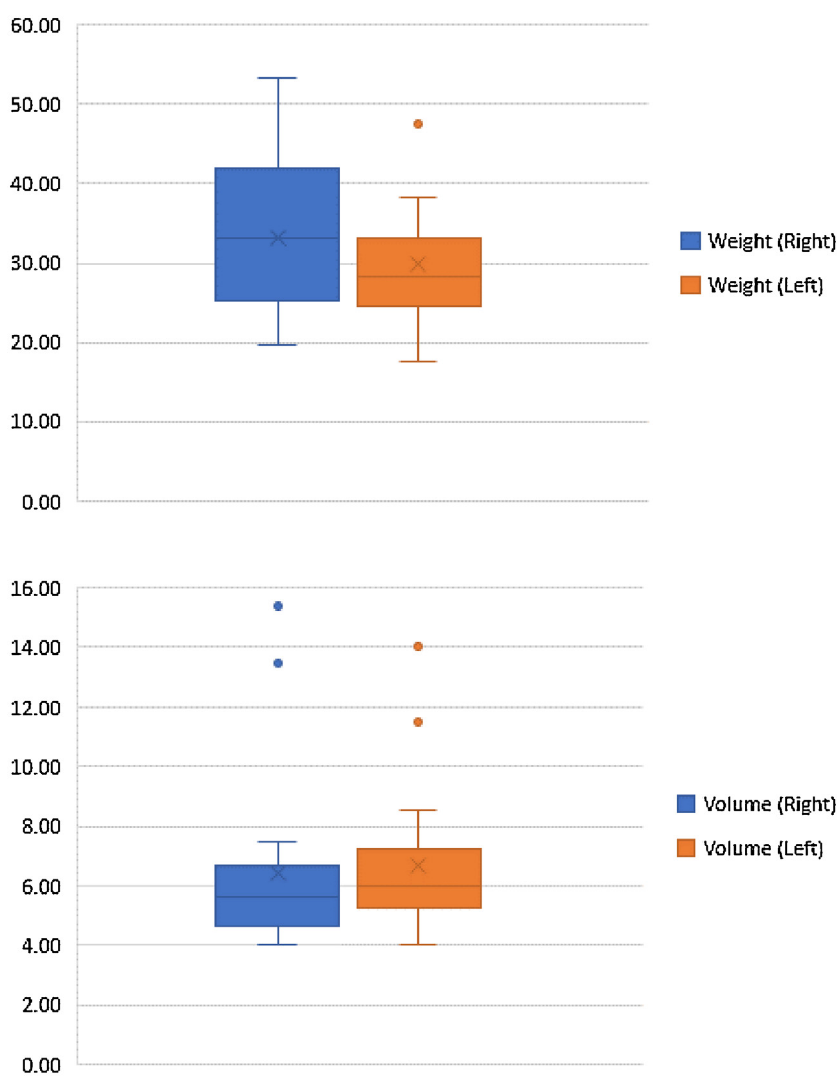


**Fig. 4.** Boxplot Presentation of Proximal Segment of Ulnar Weight (above), and Volume (below).

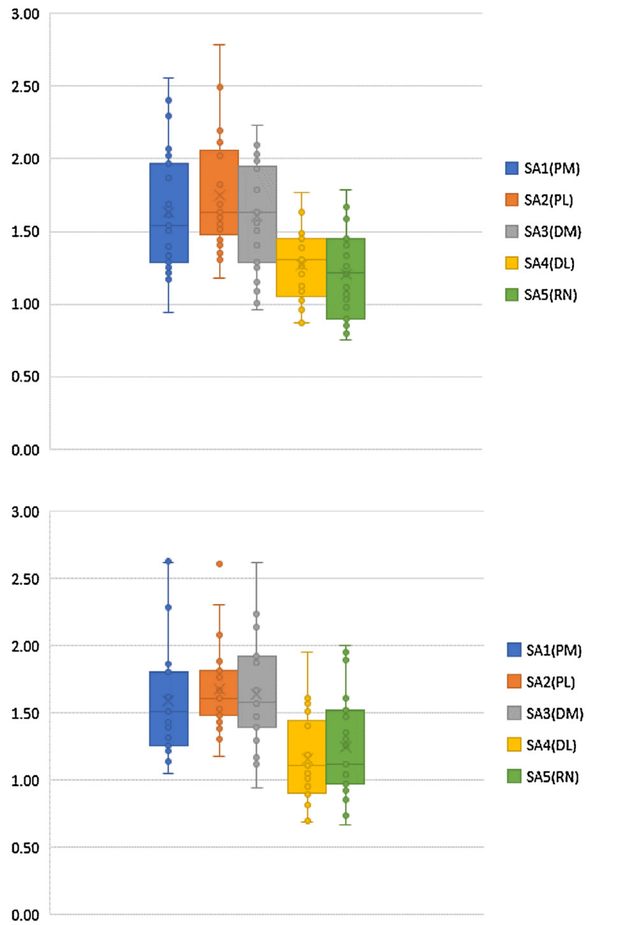


**Fig. 5.** Boxplot Presentation of Individual Surface Areas (SA): Right Ulnae (above), and Left Ulnae (below).

required both in-vivo and in-vitro. Accordingly, it can be inferred that the proximal lateral articular area is significantly larger than the proximal medial area of the trochlear notch and the radial notch, while the proximal medial area is considerably larger than the distal lateral region of the trochlear notch and the radial notch. Hence, the radial notch (lesser sigmoid notch) represent the smallest area.

Summative analyses (medial trochlear, lateral trochlear, total trochlear and radial) of surface areas (Figs. 6 and 7) confirmed the absence of any significant differences in the corresponding regions of right versus left ulnae. On the other hand and in relation to the right ulnae, there were significant differences in between; medial vs lateral trochlear area (3.23 vs 3.02, $p = 0.018$), and total trochlear vs radial area (6.25 vs 1.21, $p < 0.001$). It was also the same case for the left ulnae (0.005, <0.001 respectively). It can be inferred that the medial trochlear area is significantly larger than the lateral area, while the lateral area is larger than that of the radial notch.

In relation to the summative analyses (proximal trochlear, distal trochlear, total trochlear, and radial) of surface areas, there were also no significant differences between right versus left ulnae, while there were significant differences in between the proximal and distal area of the trochlear notch for each of right and left ulnae ($p < 0.001$) and in favour of the proximal area of the notch. It can be inferred that proximal area is significantly larger than the distal, while the medial area was larger than the lateral, while the surface area of the radial notch is the smallest of all. Additionally, there was a positive linear correlation in between the proximal and distal area for right ulnae ($R2 = 0.669$) and left ulnae ($R2 = 640$).

Finally, there was a positive relationship between all other parameters and for each of right and left ulnae including weight versus OCD, volume vs OCD, area of the trochlear notch vs OCD, and the area of lesser sigmoid area vs OCD. The strongest of these correlations were for weight versus OCD ($R2 = 0.660$), and trochlear notch area versus OCD (0.638). These associations were even higher for right ulnae. Similarly, there were positive relationships in between weight versus length, volume versus length (L), area of sigmoid notches versus the length of ulna, and area of sigmoid notches versus volume. The most substantial correlation of these correlations existed in-between the area of trochlear notch versus ulnar length, weight versus length, and area of trochlear notch versus volume.

To re-encapsulate, it can be concluded that most of the morphometric parameters of the proximal segment of ulna were positively correlated with each other, and for specific parameters (OCD, trochlear notch area, and weight of ulna). The correlation was even stronger with specimens of right ulnae. It was also confirmed that there were no significant differences for all the morphometric parameters in between right and left ulnae with an exception OCD distance and in favour of the right ulnae.

## 4. Discussion

Could some of the significant differences between the left and right ulnae be explained based on the difference in patterns of handedness among the individuals to whom these specimens belong?.[11],[19–21] Future efforts should be directed to resolving this particular disparity in morphometry in between right and left ulnae. Experimental models should be deployed in-vivo and in-vitro and among populations of different age, gender, nationality, ethnicity, and patterns of handedness. A particular morphometric study for embryos, newborns, infants and pre-school children will be precious to (dis)prove whether this difference is due to different patterns of handedness and cerebral dominance or as a result of a differential embryological growth.[20–22]

From a biomechanical perspective, the force distribution between the humeroradial and humeroulnar articulating surfaces was studied by Halls and Travill. They observed that the radius and ulna were responsible for transmitting forces proximally to the humerus at a ratio of 57:43 respectively.[23] Five decades later, Shin and colleague inferred that the proportion of the articular surface area of the radial head to the coronoid process was 1:1.51 (cadavers) and 1:1.46 (in-vivo, based on computerized tomography).[24] In 2016, Malone and co-authors discovered that the articulating surface areas of the proximal and distal radioulnar joints as well as the whole bone volumes, were significantly different although they were strongly correlated.[25] It was also found that the constraint of the humeroulnar joint appeared linearly proportional to the area of remaining articulation, and the proximal portion of the olecranon has a more significant effect on the humeroulnar restriction.[26],[27]

Several pathologies, including fractures, can affect the proximal segment of the ulna. Management of fractures and dislocations of the elbow demands a sound knowledge of the anatomical structures responsible for the stability of the elbow. The improved surgical techniques and designed implants altogether with the proper understanding of dedicated ligament repair, have led to a superior outcome of medical interference.[28] For instance, in relation to the fractures of the proximal segment of the ulna, it was found that double plating represents a useful modality for fixation because it can decrease the chance of soft tissue complications.[29] Another example is in case of the coronoid process fractures, for which there is no universally accepted approach for the coronoid process fixation, although Yang and co-workers opine that an anterior surgical procedure for the fixation together with minimal

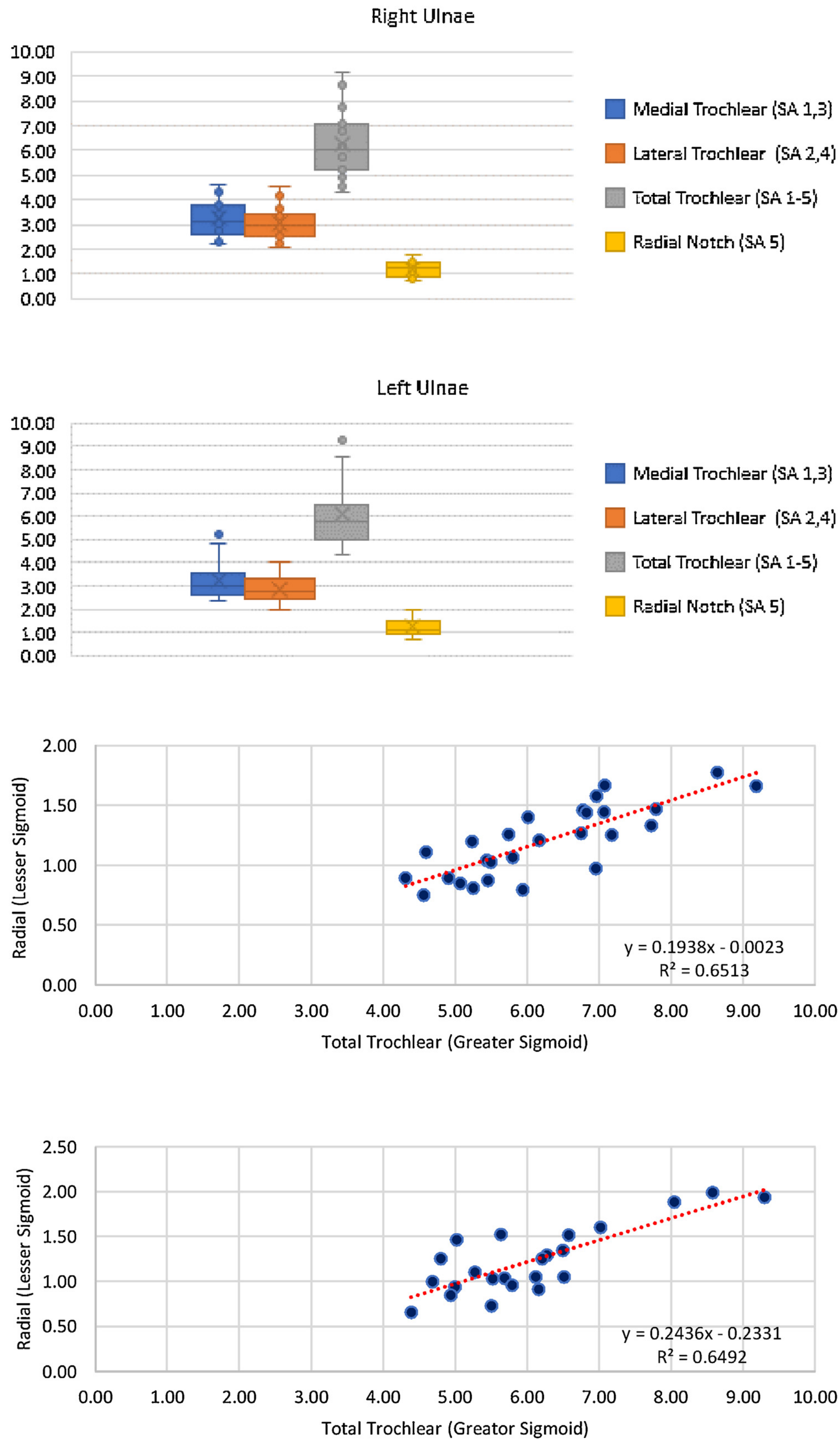


**Fig. 6.** Summative Surface Area (Medial, Lateral, and Radial) of Sigmoid Notches: Boxplot Presentation (1st and 2nd graph), and Linear Regression (3rd and 4th graph).

surgical dissection is perhaps the best.[30] Another study by Bellatto and colleagues has shown that the reconstruction of the coronoid process via the use of an osteochondral graft was necessary.[31]

Goodfellow and Bullough are considered to be the first who documented the location of contact areas of the elbow joint.[32] Nearly a decade later, a parallel study was carried out by Walker.[33]

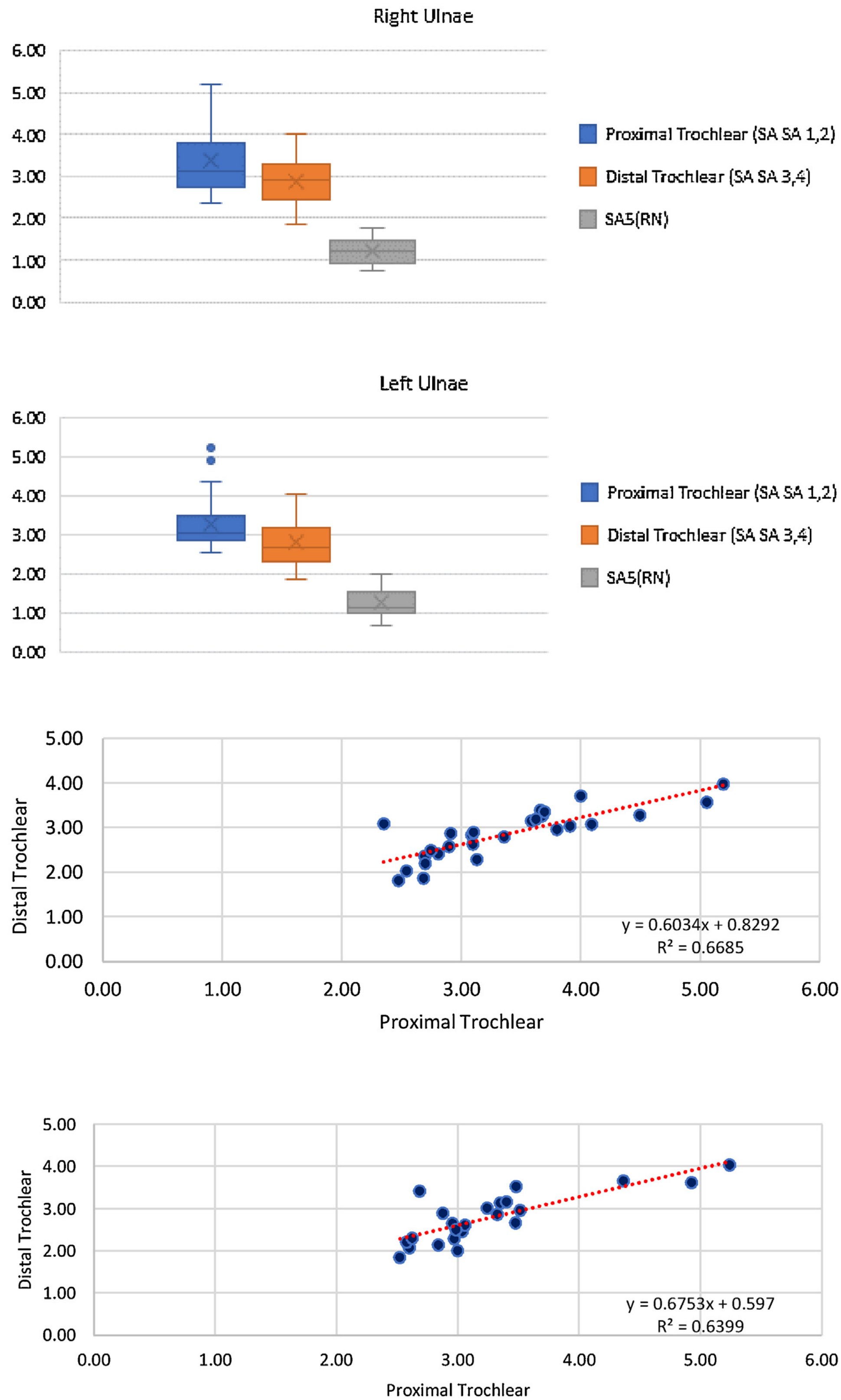


**Fig. 7.** Summative Surface Area (Proximal, Distal, and Radial) of Sigmoid Notches: Boxplot Presentation (1st and 2nd graph), and Linear Regression (3rd and 4th graph).

A more recent and venture was also attempted by Langohr and colleagues.[34] The contact areas, particularly of the humeroulnar joint, had a prime effect on the carrying angle of the elbow.[27,35,36] Prior studies have shown that the trochlear notch is deeper than necessary for an exact fit with the humerus (close-packed position).[37] Within the natural condition, the contact areas do not significantly differ owing to varus-valgus angulation. Conversely, in distal humeral hemiarthroplasty, the patterns of contact areas did change substantially. The medial ulnar contact is modified considerably by the varus-valgus angulation.[38]

In relation to physical Anthropology, the elbow joint of habitually arboreal extant apes were found to be more keeled than that of modern humans. In addition, extant (living) knuckle-walkers apes are characterized by joints that are distally expanded to provide a larger surface area of articulation while the loading force is being applied perpendicularly to the joint.[39] In an analogous fashion, Oreopithecus (an extinct hominin) was characterized by an evident keel of the greater sigmoid notch which resembles that of a chimpanzee or an orangutan. Further, The majority of the hominin fossils had a trochlear notch of an intermediate morphology in between Genus Homo and Gorilla, which may imply that the muscularity in case of hominin was less than that of the African apes but more than that of the modern humans.[39] From the perspective of comparative Anatomy, it was found that the morphology and morpho-mechanics of the proximal portion of the ulna were distinct in hounds and dogs when compared to humans.[40] Similarly, in Labradors dogs, it was concluded that an increment in the radiological opacity of the greater sigmoid notch was found to be in association with the fragmentation of the medial coronoid process.[41]

## 5. Conclusion

This study is the first of its kind to be conducted in Iraq. Innovative methods were implemented, based on digital image analysis and the concepts of fractal geometry, for the calculation of articular surface areas and volume of the proximal segment of the ulna. The articular surface area of the trochlear notch was inferred to be larger than that of the radial notch. In addition, the medial compartment of the greater sigmoid notch was found to be significantly larger than the lateral compartment. It seems that the articular surface area decline as an observer goes from medial to lateral and towards the radial notch.

Perhaps the most important conclusions based on statistical inference is the presence of a significant difference in relation to the OCD distance in between right and left ulnae. The explanation of this can be partially attributed to the status of handedness as an expression of the underlying cerebral dominance patterns as well as a potential distinct embryological growth of the right versus left upper limb. The morphometric and morpho-mechanic parameters of ulna can be exploited in connection with the disciplines of physical anthropology, comparative Anatomy, Evolutionary Biology, prosthesis and implants' design, biomedical and biomechanical applications, surgical reference values, orthopaedic and arthroscopic surgery, rheumatology and Regenerative Medicine, forensic sciences, and Anthropometrics.

## 6. Limitations

Limitations of this study can be described as multifactorial and can be attributed to the relatively small sample size, in addition to the imbalance of the number of the right and left ulnae. Further, the right and left ulnae did not belong to the same individual. Other limitations include the lack of data on age and gender of the deceased individuals. Those people were also of unknown weight, height, body mass index (BMI), health, and nutritional status. Similarly, they were of unknown patterns of handedness (right-handed, left-handed, or ambidextrous) which may reflect the underlying cerebral dominance and the patterns of lateralization of brain functions. Further, bones could have different bone densities which may result in weak correlations and hypothesis testing of the weight of ulna versus other parameters of interest including the volume of the proximal segment of the ulna and the olecranon process. Finally, the state of organic decay and the chemical processing of bones during the post-mortem period can have a detrimental effect on bone weight, density, volume, and potentially some anatomical osseous landmarks.

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This study was also entirely self-funded.

## Competing interests statement

The authors have nothing to be declared.

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