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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

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ABSTRACT

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. Background

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

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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.

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