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REVIEW ARTICLE

The Anatomy and Biomechanics of the Elbow

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Abstract:

A sound knowledge of the elbow anatomy and biomechanics is critical to understanding the pathology of various elbow disorders and instigating appropriate management. The elbow joint is a trochoginglymoid joint: that is, it has flexion-extension [ginglymoid] motion at the ulnohumeral and radiocapitellar articulations and pronation and supination [trochoid] motion at the proximal radioulnar joint. Stability of the elbow joint is achieved through static and dynamic components. The aim of this article is to concisely describe the anatomy and biomechanics of the elbow joint relevant to the practice of trauma and orthopaedic surgeons.

Keywords: Anatomy, Elbow, Biomechanics, Radiocapitellar, Ulnohumeral, Trauma.

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1. INTRODUCTION

A mobile and stable elbow joint is important for daily work and recreational and sporting activities. Acting as the fulcrum of the forearm lever, the elbow has an important role in positioning the hand for its various functions. Elbow flexion, coupled with supination, is used to bring the hand to the body and face to eat, dress and perform personal hygiene, as well as to pull or carry objects. Elbow extension coupled with pronation is used to reach, throw and push [3, 4]. Loss of elbow function can significantly impair an individual's ability to perform even simple daily activities.

Static and dynamic constraints provide stability to the elbow joint. The ulnohumeral articulation, the anterior bundle of the medial collateral ligament [AMCL] and the lateral ulnar collateral ligament [LUCL] are primary static stabilisers whilst the radiocapitellar articulation, the common flexor, the common extensor tendons and the capsule are secondary stabilisers. Muscles crossing the elbow joint that provide joint compressive forces provide Dynamic stability.

In a normal elbow, there is a good balance between mobility and stability. The interplay between the articular geometry and soft tissue structures around the elbow maintains this balance. A clear understanding of these concepts is important for advising various treatment options appropriately and in performing surgical procedures in the trauma and elective settings and in designing implants and developing techniques for elbow arthroplasty.

In this article, anatomy of the elbow joint will be discussed in terms of osteology, capsuloligamentous structures, and muscles. Biomechanics section will concisely explain the concepts around motion and stability.

2. ELBOW ANATOMY

2.1. Osteology

The components of the highly congruent articular surface of the elbow joint include the rochlea and capitellum of the distal humerus proximally and the upper end of the ulna and radial head distally. There are three articulations in the elbow joint complex, including the ulnohumeral, radiohumeral and proximal radioulnar joints. Together they make the elbow a trochoginglymoid joint that possesses two degrees of freedom of motion *i.e* flexion-extension [ginglymoid] motion at both the ulnohumeral and radiocapitellar articulations and pronation and supination [trochoid] motion at the proximal radioulnar joint [1, 2].

The congruent bony articular components possess specific features and orientation that play a significant role in elbow stability as static stabilizers.

The articular surface of the distal humerus is formed by two condyles. Medially the spool-shaped trochlea that articulates with the greater sigmoid notch of the proximal ulna and laterally the hemispherically shaped capetellum that articulates with the articular surface of the radial head [2, 6].

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The medial ridge of the trochlea is larger than the lateral ridge, which causes a mean of 5 to 7 degrees of valgus tilt at the ulnohumeral joint. The articular surface of the humerus is rotated anteriorly about 30 degrees in reference to the long axis of the humerus. The distal humeral articulation is also externally rotated about 3 to 5 degrees in reference to the plane of the posterior surface of the medial and lateral columns [1, 7, 8].

The proximal ulna forms a highly congruous joint with the humeral trochlea, forming one of the primary static stabilizers of the elbow joint. The saddle shaped, ellipsoid articular surface of the greater sigmoid fossa is made up of the coronoid process distally and the olecranon process proximally. The greater sigmoid notch has an arc of curvature of approximately 185-190 degrees [1, 9]. The sagittal ridge of the greater sigmoid notch runs longitudinally and articulates with the apex of the trochlea. The concavities that are medial and lateral to the sagittal ridge complement the convex medial and lateral faces of the trochlea [2]. The articular surface is thin, measuring 2 to 3 mm. The articular cartilage is usually discontinuous at the center of the greater sigmoid fossa. Hence the contact area consists of the anterior coronoid and posterior olecranon surfaces. This must be borne in mind when performing arthroscopic examination of the elbow as this can be misinterpreted as an articular cartilage defect. In addition, olecranon osteotomy should be directed through this portion to avoid unnecessary articular cartilage damage [1, 7].

In the coronal plane, the articular surface of the ulna is in 5-7 degrees valgus with reference to the axis of the shaft. This contributes in part to the carrying angle of the elbow, which is formed by the longitudinal axis between the humerus and ulna when the elbow is in full extension. This angle is 11-14 degrees in males and 13-16 degrees in females [10]. In sagittal plane, the articular surface of the greater sigmoid notch is oriented about 30 degrees posterior to the long axis of the ulna. This complements the 30 degrees anterior rotation of the distal humeral articular surface thus making the elbow stable in extension [10]. Osseous stability is further enhanced in extension when the tip of the olecranon rotates into the olecranon fossa. In flexion, osseous stability is enhanced when the coronoid process locks into the coronoid fossa of the distal humerus and the radial head are contained in the radial fossa of the distal humerus [2]. The lesser sigmoid notch, which is present at the lateral aspect of the coronoid process, articulates with the radial head. It has an arc of curvature of about 70 degrees.

Being an important secondary static stabilizer, the cylindrical shaped radial head articulates with the capitellum of humuerus and lesser sigmoid notch of ulna to make the radiocapellar and proximal radioulnar joints respectively. Hyaline cartilage covers the concave proximal articular surface and an arc of approximately 240 degrees of the rim. The remaining 120 degrees of this arc can be used for placing hardware during reduction and fixation of displaced radial head fractures. The radial head and neck make an angle of approximately 15 degrees with the long axis of radius. This allows the forearm to undergo an arc of rotation [pronation-supination] of about 180 degrees while maintaining a precise and constant orientation with the capitellum. The slightest abnormality or alteration of this angle markedly alters forearm rotation [1]. At the distal end of the radial neck is the radial tuberosity, which is the insertion site for the biceps brachii tendon.

2.2. Capsuloligamentous Anatomy

The medial and lateral collateral ligaments and the elbow joint capsule are the passive soft tissue stabilizers of the elbow joint. An understanding of their role in elbow pathoanatomy and kinematics has improved in recent years. Together with the joint capsule, these structures form the principle soft tissue stabilizers of the elbow joint.

3. MEDIAL COLLATERAL LIGAMENT

The medial collateral ligament [MCL] originates from the anteroinferior aspect of the medial epicondyle. The MCL complex consists of three components: the anterior bundle, the posterior bundle and the transverse segment. The anterior bundle is further subdivided into anterior, central and posterior bands [2, 11 - 14]. The anterior element of the medial collateral ligament originates at the site of the axis of rotation for the elbow. This bundle is taut throughout the arc of motion; the anterior fibers are most taut in extension and the posterior bundles become tightened in flexion. The anterior bundle is the essential component of medial collateral ligament and is a primary static stabilizer of the elbow. Hence a precise restoration of the humeral origin of the ligament must be attained with ligamentous reconstruction procedures. The role of the anterior portion of the medial collateral ligament has been linked to the anterior cruciate ligament at the knee [1]. There is an average increase of 18% in length of the anterior bundle from full extension to 120 degrees of flexion [7, 13, 15]. The posterior bundle originates posterior to the sagittal axis of rotation. Hence a cam effect is present and the posterior bundle is taut only in flexion. This structure is now recognized to be contracted in those with elbow contractures limiting flexion and may need to be surgically released [1]. The transverse ligament runs between the coronoid and the tip of the olecranon and often cannot be separated from the capsule. It is believed that the transverse ligament does not contribute significantly to joint stability [2, 13].

4. LATERAL COLLATERAL LIGAMENT

The Lateral Collateral Ligament (LCL) complex consists of the lateral ulnar collateral ligament, the radial collateral ligament, the annular ligament and the accessory collateral ligament. It originates from the lateral epicondyle near the axis of rotation of the elbow therefore it is uniformly taut throughout the flexion and extension movement. The Lateral Ulnar Collateral Ligament (LUCL) inserts at the tubercle of the supinator crest of the ulna. It is one of the primary static elbow constraints and provides varus and posterolateral stability. Because of its insertion distal to the posterior attachment of the annular ligament, it maintains the varus stability of the elbow after the radial head has been excised. Deficiency of the LUCL results in posterolateral instability of the elbow [16]. This most frequently occurs after elbow dislocation or from release and inadequate reconstruction after surgical procedures involving this structure [1]. The radial collateral ligament inserts into the annular ligament and stabilizes the radial head [17]. The annular ligament originates and inserts on the anterior and posterior margins of the lesser sigmoid notch. It maintains the radial head in contact with the ulna. The anterior insertion becomes taut during supination and the posterior insertion during pronation because the radial head is not a spherical structure [7, 18 - 20]. The accessory collateral ligament has attachments at the annular ligament and the supinator crest. It functions to stabilize the annular ligament during varus stress at the elbow [2, 5, 21].

5. CAPSULE

The capsule of the elbow is attached to the articular margins of the joint and its fibers are connected to the annular ligament. The anterior capsule extends proximally above the coronoid and radial fossae, distally to the edge of the coronoid process, and laterally to the annular ligament. The posterior capsule attaches proximally above the olecranon fossa, distally along the medial and lateral articular margins of the greater sigmoid notch, and laterally becomes continuous with the annular ligament. The capsule becomes taut anteriorly when the elbow is extended and posteriorly when the elbow is flexed [2]. Its maximum distension is with the elbow at 70°-80° of flexion where the capacity is about 25-30ml [22, 23]. The contribution of the capsule as a passive stabilizer is a controversial point; some studies have suggested no change in the joint laxity after complete capsulotomy whilst others have reported that the anterior capsule contributes about 15% of the resistance to varus-valgus stress when the elbow is in full extension [1, 7].

5.1. Muscles

The musculotendinous units which cross the elbow joint provide dynamic stability to the elbow. They can be divided into four main groups: Posteriorly, elbow extensors; anteriorly, the elbow flexors; laterally, the wrist and hand extensors and forearm supinator; and medially, the wrist and hand flexors and forearm pronator. Only a few muscles crossing the elbow have an action on moving the elbow joint itself. These include brachialis and biceps brachii that are the primary elbow flexors. The triceps is the principal elbow extensor. Although anconeus likely plays a minor role in elbow extension, it is thought to act as a dynamic constraint to varus and posterolateral rotatory instability. Pronation is provided by the pronator teres and pronator quadratus. The biceps brachii performs the majority of forearm supination, with assistance from the supinator muscle. Each muscle that crosses the elbow applies a compressive load to the joint when contracted thus producing a dynamic stabilization and protecting the static ligamentous constraints [7, 25 - 27]

6. BIOMECHANICS AND KINEMATICS OF THE EBLOW JOINT

The elbow is described as trochoginglymoid joint; that is, it possesses two degrees of freedom: flexion-extension and forearm pronation and supination.

6.1. Flexion and Extension

The normal arc of elbow flexion is 0 [full extension] to 145 degrees. However, there is considerable variation between individualS: hyperlax individuals may hyperextend by 10 degrees or more and bodybuilders may flex only up to 130 degrees due to their muscle bulk [1]. Morrey *et al*. demonstrated that most activities of daily living could be performed with an arc of 30 to 130 degrees of flexion [28]. The elbow joint is considered as a hinge joint due to the congruity of its bony articulations and soft tissue constraints. However, three-dimensional studies using electromagnetic tracking technology have shown a potential varus-valgus and axial laxity of about 3 to 4 degrees during elbow flexion [4, 30 - 33]. In 1909, a study by Fischer showed the instant center of rotation of elbow flexion was an area 2 to 3 mm in diameter at the center of the trochlea. Other authors have found variations of up to 8 degrees in the position of screw axis from person to person [4, 34]. The axis of rotation is 3 to 8 degrees internally rotated relative to the plane of the epicondyles and it is 4 to 8 degrees valgus to the long axis of the humerus. Recognition of these facts inspired the development and clinical use of less constrained but coupled elbow joint replacement implants [35, 36]. From a practical point of view, the deviation of the center of joint rotation is minimal, thus the ulnohumeral joint could be assumed to move as a uniaxial articulation except at the extremes of flexion and extension. Hence elbow flexion may be considered primarily a spinning motion. A line extending from the center of capitellum to the anteroinferior aspect of the medial epicondyle may represent the axis of rotation [1, 4].

6.2. Pronation and Supination

The normal range of forearm supination averages about 85 degrees. This is approximately 5 to 10 degrees more than the mean normal range of pronation, which averages about 80 degrees. Morrey *et al*. reported that most activities of daily living can be accomplished with 100 degrees of forearm rotation [50 degrees of pronation and 50 degrees of supination] [28]. Although the loss of pronation can be compensated to some extent by shoulder abduction, there are no effective mechanisms to compensate for supination [2, 37]. The longitudinal axis of the forearm rotation runs from the center of radial head and capitellum proximally to the base of the styloid process of the distal ulna distally. Therefore it is oblique to the longitudinal axes of both the radius and the ulna and rotation is independent of elbow position [38, 39]. Moore *et al*. showed that the axis of rotation shifts slightly ulnar and volar in supination and radial and dorsal during pronation [40]. The radius has been shown to move proximally by 1 to 2 mm with pronation. This may increase the joint reaction force at the radiocapitellar articulation thus increasing valgus elbow stability [41, 42].

6.3. Interplay Between Osteoarticular and Capsuloligamentous Stabilizers in Elbow Stability

The elbow joint is one of the most stable joints due to its highly congruent articulation and soft tissue constraints that contribute almost equally to elbow stability. The three primary static constraints include the ulnohumeral articulation, the anterior bundle of the Medial Collateral Ligament (MCL) and the Lateral Collateral Ligament (LCL) complex whilst secondary constraints include the radiocapitellar articulation, the common flexor and the common extensor tendon and the capsule. The muscles crossing elbow joint are the dynamic stabilizers.

The relative contribution of each stabilizing structure has been shown by sequentially eliminating each component and recording the resultant effect of varus and valgus loads on elbow stability at different degrees of elbow flexion [4]. Morrey and An [43] showed that in full extension, varus stress is resisted primarily by joint articulation [55%] and anterior capsule (32%) with only a small (14%) contribution from radial collateral ligament. At 90 degrees flexion, joint articulation contributes 75% to varus stability. Valgus stability is equally divided among the medial collateral ligament, anterior capsule and bony articulation in full extension; whereas, at 90° of flexion the contribution of the anterior capsule is assumed by the medial collateral ligament which provides approximately 55% of the stabilizing contribution to valgus stress. In extension, the anterior capsule provides 85% resistance to distraction whilst at 90 degrees flexion, the main contribution to resistance against distraction comes from medial collateral ligament (78%). However, a later study by Morrey *et al*. [4, 44] produced more accurate data by using electromagnetic tracking devices and identified that this experimental model resulted in overestimation of the role of the radial head in resisting valgus load. It showed that the radial head does not resist valgus stresses in the presence of an intact medial collateral ligament. If the medial collateral ligament is released or compromised, however, the radial head does play an important role in resisting valgus stresses. Damage to both structures results in gross abduction laxity and elbow subluxation. This study defines the Medial Collateral Ligament (MCL) as the primary constraint of the elbow joint to valgus stress and the radial head as a secondary constraint [44]. The role of the medial collateral ligament and the radial head in elbow stability has been likened to that of anterior cruciate ligament and meniscus in knee stability [1].

Studies have also shown the important role of forearm rotation in elbow stability. In the presence of medial collateral ligament deficiency, elbow is more stable when placed in supination whilst lateral collateral ligament deficient elbow is more stable in pronation [15]. Moreover, a cadaveric study by Beingessner *et al*. showed that, in the presence of coronoid fracture, the elbow is more stable in supination than in pronation [45]. These facts are important to recognise optimal positioning and rehabilitation of elbow after osseous and ligamentous injuries and reconstruction.

6.4. Forces Across the Elbow Joint

Using pressure sensitive transducers, Halls and Travill reported the distribution of stress was 57% across the radiocapellar and 43% across the ulnohumeral articulation [45]. The greatest amount of forces pass across the elbow articulation at 0-30 degrees of flexion and in pronation [1, 41]. With the elbow in greater degrees of flexion, the moment arm of the flexors increases so a greater strength of flexion is generated. As a result the contact forces across the elbow are less in flexion than in full extension.

The line of action of both flexors and extensors of the elbow generates a posteriorly directed force component. Hence, the tendency toward posterior displacement of the joint after severe ligament and articular injury and the frequently observed loss of fixation following distal humerus fractures [1].

An *et al*. has shown that if the line of action of the contact pressure is in the middle of the articulation, the stress is almost equally distributed throughout the articular surface. On the other hand, when the force is directed towards the margin of the articulation, the weight-bearing surface becomes smaller, the contact stresses become higher and the stress distribution becomes uneven [4]. This may lead to pain and arthritic changes in a chronically unstable, incongruous elbow joint.

7. DISCUSSION AND CONCLUSION

An understanding of the clinical anatomy and biomechanics of the elbow joint complex is crucial for the comprehensive understanding of pathology affecting the elbow and their successful management. The future design and development of arthroplasty components designed to recreate normal elbow kinematics will depend on a thorough understanding of these principles. It remains to be seen in the coming years whether newer products in the market for both fracture fixation and for partial or total joint replacement techniques are able to recreate normal kinematics and tolerate normal load bearing forces across the elbow joint.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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