# Anatomy and Biomechanics of the Elbow Joint

Stefan Fornalski, MD
Ranjan Gupta, MD
Thay Q. Lee, PhD
*Orthopaedic Biomechanics Laboratory VA Healthcare System*
*Long Beach, California*
*University of California*
*Irvine, California*

## ■ ABSTRACT

The elbow joint is a complex structure that provides an important function as the mechanical link in the upper extremity between the hand, wrist and the shoulder. The elbow's functions include positioning the hand in space for fine movements, powerful grasping and serving as a fulcrum for the forearm. Loss of elbow function can severely affect activities of daily living. It is important to recognize the unique anatomy of the elbow, including the bony geometry, articulation, and soft tissue structures. The biomechanics of the elbow joint can be divided into kinematics, stabilizing structures in elbow stability, and force transmission through the elbow joint. The passive and active stabilizers provide biomechanical stability in the elbow joint. The passive stabilizers include the bony articular geometry and the soft tissue stabilizers. The active stabilizers are the muscles that provide joint compressive forces and function. Knowledge of both the anatomy and biomechanics is essential for proper treatment of elbow disorders.
**Keywords:** elbow joint, elbow anatomy, elbow biomechanics, elbow stability, elbow ligaments, review

## ■ INTRODUCTION

The elbow is a critical element for a functional upper extremity. The upper extremity consists of a linked system between the shoulder, elbow, wrist, and hand. The primary functions of the elbow are to position the hand in space, act as a fulcrum for the forearm, and allow for powerful grasping and fine motions of the hand and

wrist. Loss of elbow function can cause significant disability and affect activities of daily living, work-related tasks, and recreational activities. A proper understanding of the elbow joint will aid the clinician in surgical and nonsurgical management. The first section discusses the normal anatomy of the elbow joint in terms of passive and active stabilizers. These include bony geometry, articulation, and soft tissue structures. The second section discusses elbow biomechanics, including kinematics, elbow stability, and force transmission through the elbow.

## ■ ANATOMY OF THE ELBOW

### Passive Stabilizers

***Osteology.*** The distal humerus comprises two condyles forming the articular surfaces of the capitellum laterally and trochlea medially. The more prominent medial epicondyle is an attachment point for the ulnar collateral ligament and flexor–pronator group. The less prominent lateral epicondyle is an attachment point for the lateral collateral ligament and extensor–supinator group. Anteriorly, the coronoid and radial fossa accommodate the coronoid process of the ulna and radial head, respectively, during flexion. Posteriorly, the olecranon fossa accommodates the olecranon process of the ulna during extension (Fig. 1).[1]

The proximal radius includes the cylindrical shaped radial head, which articulates with both the radial notch of the ulna and capitellum of the humerus. The radial neck at its most distal aspect has the radial tuberosity, which is the insertion of the biceps tendon (Fig. 1).[1]

The bony geometry of the proximal ulna provides the elbow articulation with an inherent stability, especially in full extension. The beaked greater sigmoid notch (also known as the incisura semilunaris) articulates with the trochlea of the humerus, and comprises the olecranon (site of triceps attachment) and coronoid process (site of brachialis attachment). On the lateral coronoid process, the radial notch (semilunar notch) articulates with the radial head. The crista supinatoris tuberosity is on the lateral aspect of the proximal ulna and serves as the

Corresponding author: Thay Q. Lee, PhD, Orthopaedic Biomechanics Laboratory, VA Long Beach Healthcare System (09/151), 5901 East 7th Street, Long Beach, California, 90822. E-mail: tqlee@med.va.gov or tqlee@uci.edu.
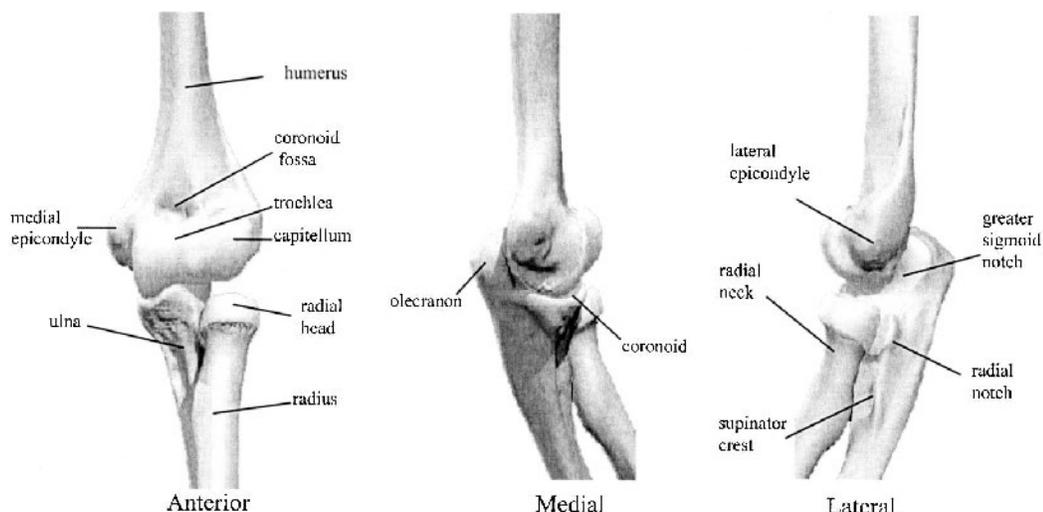
**FIGURE 1.** Bony landmarks of anterior, medial, and lateral distal humerus and proximal ulna and radius.

attachment for the lateral ulnar collateral ligament. On the medial aspect of the proximal ulna, the anterior portion of the medial collateral ligament attaches to the coronoid process (Fig. 1).

The medial and lateral cutaneous nerves at the elbow lie superficial to the deep fascia and therefore can be protected by the surgeon's use of full-thickness skin flaps.[2–4]

*Articulation.* The elbow joint is highly congruous and is made up of the articulation between the radius, ulna, and humerus bones. The ulnohumeral joint is a hinge (ginglymus) joint with motion of flexion and extension. The proximal radioulnar and radiohumeral joints are pivoting joints (trochoid) allowing rotation.[1,5]

The trochlea of the distal humerus is a pulley-shaped surface that is larger medially than laterally, and it ar-

ticulates with the sigmoid notch of the proximal ulna. Laterally, the capitellum articulates with the radial head. The trochleocapitellar groove between the trochlea and capitellum is a point of articulation for the rim of the radial head.[1] Both the capitellum and sigmoid notch are covered with hyaline cartilage.[6] In relation to the humeral shaft, these articular surfaces are oriented 30° anterior, in 5° internal rotation, and in 6° of valgus angulation (Fig. 2).[1,7]

The proximal radius has a cylindrical head with hyaline cartilage covering both the depression for articulation with the capitellum and also at the outside circumference of the radial head. Approximately 240° of the radial head has hyaline (articular) cartilage, with the anterolateral third devoid of hyaline cartilage. The head and shaft form an approximate 15° angle to the shaft.[1]
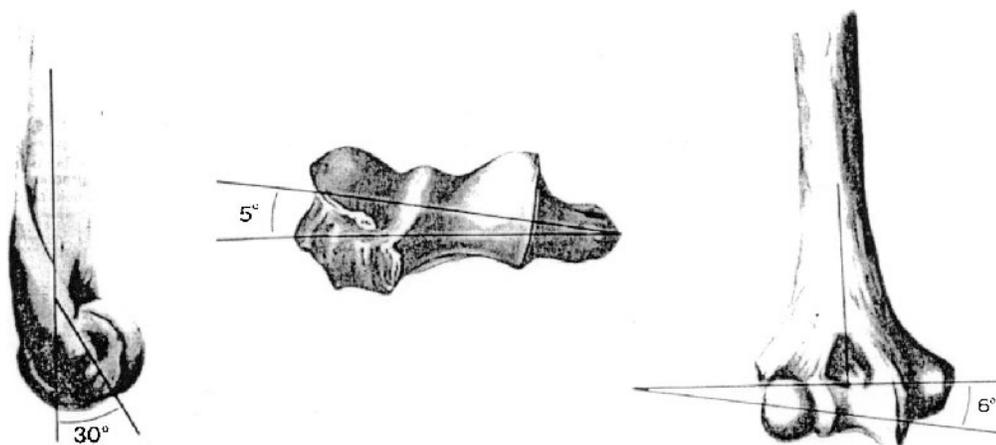


**FIGURE 2.** A, Lateral view shows 30° anterior rotation of the distal humeral condyles. B, Axial view shows 5° to 7° internal rotation of the distal humerus articular surface. C, Anterior view shows 6° to 8° degrees of valgus tilt at the distal humerus. Reprinted with permission.[1]
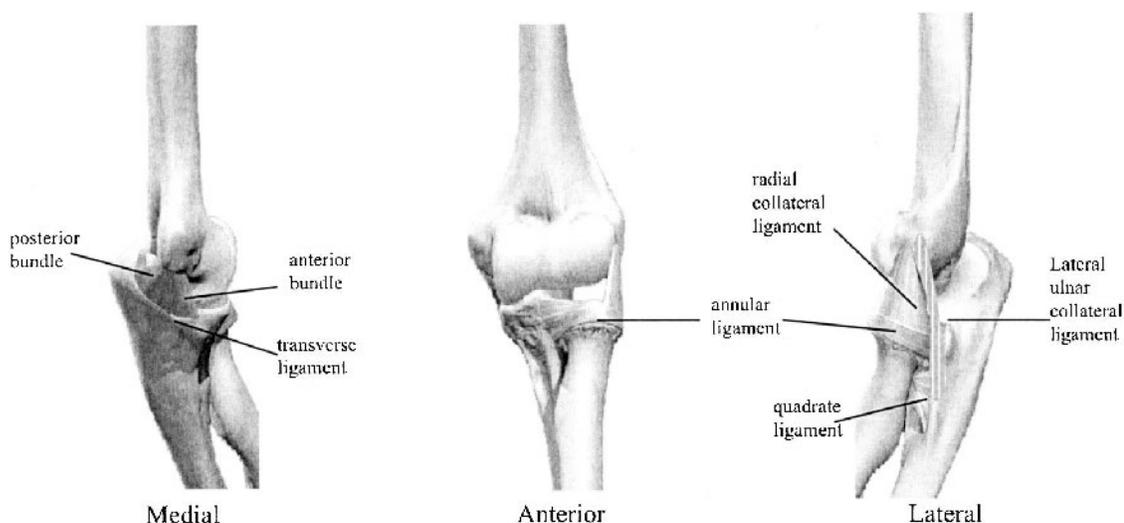
**FIGURE 3.** A, Medial elbow view shows the components of the medial collateral ligament complex. B, Anterior view. C, Lateral view shows the radial collateral ligament complex.

The proximal ulna consists of the coronoid and olecranon process (Fig. 1). These make up the saddle-shaped, ellipsoid articular surface of the sigmoid notch. The midportion of the sigmoid notch is usually devoid of articular cartilage where it is covered by fatty tissue.[8] The greater sigmoid notch has an arc of approximately 190°.[9] The greater sigmoid notch opens 30° posterior to the long axis of the ulna. This angle complements the 30° anterior angle of the distal humerus and articular surface.[1] The lesser sigmoid notch has an arc of approximately 70° and articulates with radial head at the lateral coronoid.[10]

The carrying angle of the elbow is formed by the longitudinal axis between the humerus and ulna when the elbow is in full extension. In females, the average valgus angle is 13° to 16°, whereas in males, it is 11° to 14°.[1] The joint capsule normally has a thin anterior portion. The anterior capsule becomes taut in extension and lax in flexion. The normal volume capacity of the joint is 30 ml,[11] with the greatest capacity occurring at approximately 80° flexion.[1,12]

*Ligaments.* The ligamentous complexes stabilizing the elbow joint are medial and lateral capsular thickenings that form the medial and lateral collateral ligaments. The triangular medial (ulnar) collateral ligament comprises three components, including the anterior bundle, posterior bundle, and transverse segment (Fig. 3). The anterior bundle is the significant component of the medial collateral ligament complex. The posterior bundle (Bardinet ligament) is a posterior capsular thickening and is best defined at 90° flexion.[1,13] The transverse ligament (ligament of Cooper) contributes little to elbow stability.[1] The medial collateral ligament originates from the broad anteroinferior medial epicondylar surface.[14] The anterior

bundle attaches inferior to the axis of rotation and inserts to the sublime tubercle at the medial coronoid process. The posterior bundle attaches inferior and posterior to the axis of rotation and attaches to the medial mar-
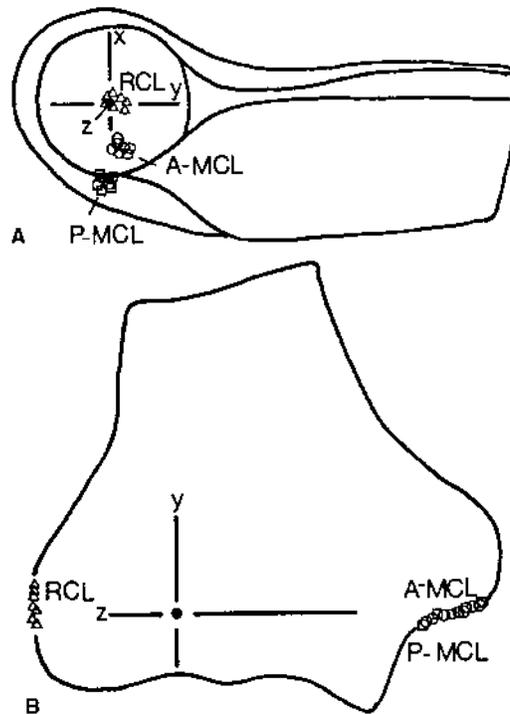


**FIGURE 4.** A, Lateral view. B, Anterior view of the distal humerus, demonstrating the locus of both medial (A-MCL and P-MCL) and lateral (radial, RCL) ligament complexes with respect to their origin and the axis of rotation of the distal humerus. Only the lateral (radial, RCL) complex lies in the axis of rotation. Reprinted with permission.[15]

**TABLE 1.** *Origin, insertion nerve supply, and action of muscles crossing the elbow joint*

| Muscle | Origin | Insertion | Nerve supply | Action |
|---|---|---|---|---|
| **Posterior** | | | | |
| Triceps brachii | | Aponeurosis from long and lateral heads blend and insert into olecranon | Radial nerve, C7–C8 | Elbow extension |
| Long head | Infraglenoid tuberosity of scapula | | | |
| Lateral head | Humerus above spiral groove | | | |
| Medial head | Humerus below spiral groove | Aponeurosis and olecranon | | |
| Anconeus | Posterior lateral epicondyle | Dorsolateral proximal ulna | Motor branch to medial head of triceps, C7–C8 | Elbow extension, abduction, and stabilization |
| Extensor carpi ulnaris | Lateral epicondyle and aponeurosis from subcutaneous border of ulna | Fifth metacarpal | PIN, C6–C7 | Wrist extension and ulnar deviation |
| Extensor digitorum communis | Anterolateral epicondyle | Extensor mechanism of each finger | PIN, C7–C8 | Metacarpal phalangeal joint extension |
| **Lateral** | | | | |
| Extensor carpi radialis brevis | Inferolateral lateral epicondyle | Third metacarpal | PIN, C6–C7 | Wrist extension |
| Extensor carpi radialis longus | Lateral supracondylar ridge | Second metacarpal | Radial nerve, C6–C7 | Wrist extension |
| Brachioradialis | Lateral supracondylar ridge | Radial styloid | Radial nerve, C5–C6 | Elbow flexion with forearm in neutral rotation |
| Supinator | Anterolateral lateral epicondyle, lateral collateral ligament, supinator crest of ulna | Proximal and middle third of radius | PIN, C5–C6 | Forearm supination |
| **Medial** | | | | |
| Flexor digitorum superficialis | Medial epicondyle, ulnar collateral ligament, medial coronoid and proximal two-thirds of radius | Middle phalanges of fingers | Median nerve, C7–C8 | Flexion of PIP joints |
| Flexor digitorum profundus | Medial olecranon and proximal three-fourths of ulna | Distal phalanges of fingers | Median nerve (index and middle fingers), ulnar nerve (ring and little fingers), C8–T1 | Flexion of DIP joints |
| **Anterior** | | | | |
| Biceps brachii | | Tendon into bicipital tuberosity of radius | Musculocutaneous nerve, C5–C6 | Elbow flexion, supination of flexed |
| Long head | Supraglenoid tubercle of scapula | | | |
| Short head | Coracoid process of scapula | Eponeurosis into forearm fascia and ulna | | |
| Pronator teres | Anterosuperior medial epicondyle, coronoid process of ulna | Pronator tuberosity of radius | Median nerve, C6–C7 | Forearm pronation, weak elbow flexion |
| Humeral head | | | | |
| Ulnar head | | | | |
| Flexor carpi radialis | Anteroinferior aspect of medial epicondyle | Second and thrid metacarpals | Median nerve, C6–C7 | Wrist flexion and weak forearm pronation |
| Palmaris longus | Medial epicondyle | Palmar aponeurosis | Median nerve, C7, C8, T1 | Wrist flexion |
| Flexor carpi ulnaris | Medial epicondyle | Pisiform and fifth metacarpal | Ulnar nerve, C7–C8, T1 | Wrist flexion and ulnar deviation |
| Humeral head | Medial olecranon, proximal two-thirds of ulna and aponeurosis from subcutaneous border of ulna | | | |
| Ulnar head | | | | |

PIN, posterior interosseous nerve; PIP, proximal interphalangeal; DIP, distal interphalangeal.
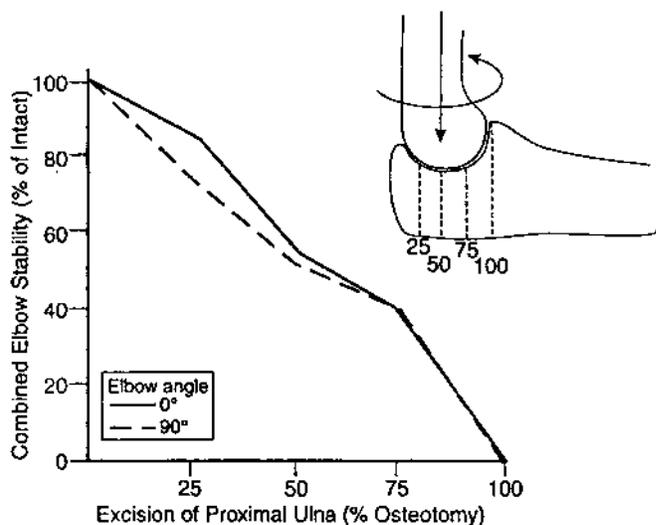
gin of the trochlear notch and is tight in flexion. The transverse ligament is limited to the ulna.[1,14] The anterior bundle width averages 4 to 5 mm, whereas the posterior bundle width averages 5 to 6 mm.[15] The lateral (radial) collateral ligament complex consists of the radial collateral ligament, annular ligament, lateral ulnar collateral ligament, and accessory lateral collateral ligament (Fig. 3).[1] The radial collateral ligament originates from the lateral epicondyle and inserts to the annular ligament. It also serves as a partial origin for the supinator muscle. The average dimensions of the ligament are 20 mm in length and 8 mm in width. The origin of the ligament is close to the axis of rotation and is therefore uniformly taut throughout flexion-extension movement (Fig. 4).[1,15] The annular ligament maintains contact between the radial head and ulna at the lesser sigmoid notch. It originates and inserts on the anterior and posterior margins of the lesser sigmoid notch. The anterior insertion becomes taut during supination and the posterior origin becomes taut in pronation.[1] The lateral ulnar collateral ligament originates at the lateral epicondyle and inserts at the tubercle of the supinator crest of the ulna. It functions as the primary lateral stabilizer of the ulnohumeral joint, and deficiency of this ligament results in posterolateral rotatory instability.[16] The accessory lateral collateral ligament blends with fibers of the annular ligament and inserts to the tubercle of the supinator crest. It functions to stabilize the annular ligament during varus stress at the elbow.[1,13] The oblique ligament is a small structure comprising the fascia overlying the deep head of the supinator between the radius and ulna, and is believed to have limited functional importance.[1] The quadrate ligament is a thin fibrous layer between the annular ligament and ulna and is a stabilizer
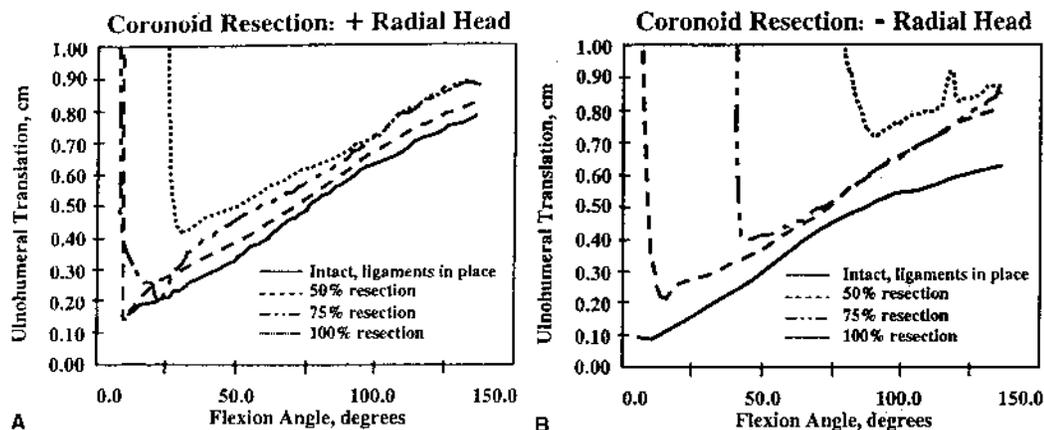


**FIGURE 6.** A, Increasing ulnohumeral instability with successive coronoid resection and the protective role of the radial head until almost full extension. B, After radial head resection, ulnohumeral stability occurs with less coronoid resection and in less extension. Reprinted with permission.[1]

**DEGREES FLEXION**
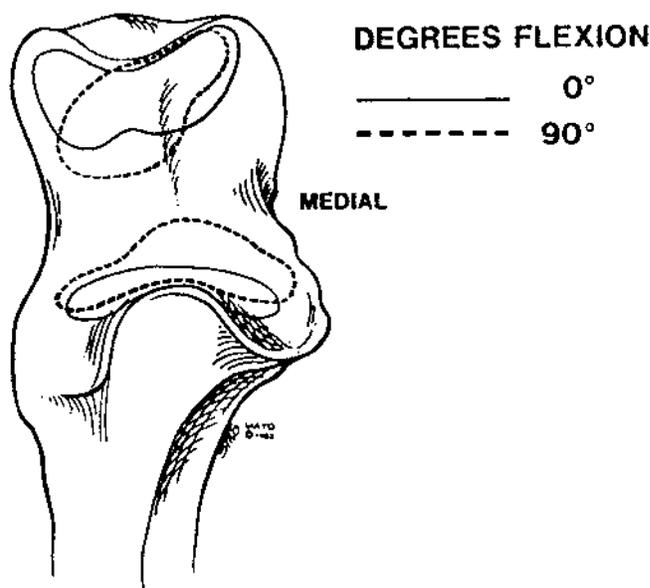—————— 0°
- - - - - - 90°

MEDIAL

FIGURE 7. Four separate areas of contact in the sigmoid fossa. Contact moves toward the center of the sigmoid during flexion. Reprinted with permission.[1]

of the proximal radioulnar joint during pronosupination (Fig. 3).[1]

### Active Stabilizers

*Muscles.* The muscles crossing the elbow joint can be divided into four main groups. Posteriorly, the elbow extensors cross the elbow joint, and are innervated by the radial nerve. Laterally, the wrist and finger extensors and the supinator are found and innervated by the radial nerve. Medially, the flexor–pronator group, including the flexor carpi radialis, flexor carpi ulnaris, palmaris longus, and pronator teres, crosses the joint, and are innervated by the medial and ulnar nerves. Anteriorly, the elbow flexors cross the joint, and are innervated by the musculocutaneous nerve.[1] The extensor muscles, including the brachioradialis, extensor carpi radialis brevis, and longus muscles, originate at the lateral epicondyle. This

group has been termed by Henry[1,13] as the *mobile wad of three* (Table 1).

### ■ BIOMECHANICS OF THE ELBOW

### Elbow Stability and Stabilizing Structures

The elbow joint is a highly congruous and stable joint. The passive and active stabilizers provide biomechanical stability in the elbow joint. The passive stability results from both the highly congruent articulation between the humerus and ulna and the soft tissue constraints. The active stability is caused by joint compressive forces provided by the muscles.

*Passive Bony Stabilizers.* The ulnohumeral joint is a highly congruous joint and is a dominant factor as a passive bony stabilizer. The contribution of articular geometry of the radial head to elbow stability has been

FIGURE 8. Length variation of the anterior medial collateral ligament (A-MCL) and lateral collateral ligament complex (RCL) and the effect of orientation with respect to the axis of rotation. Reprinted with permission.[1]
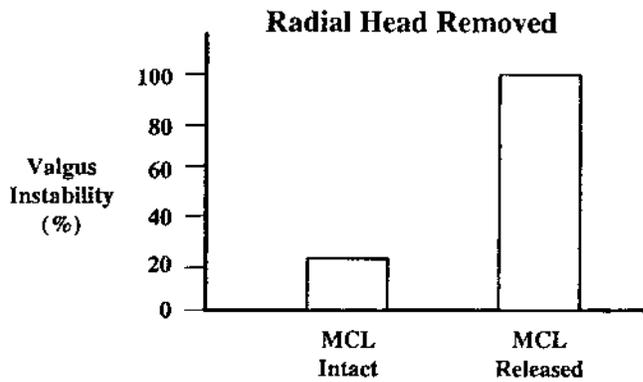
**Radial Head Removed**
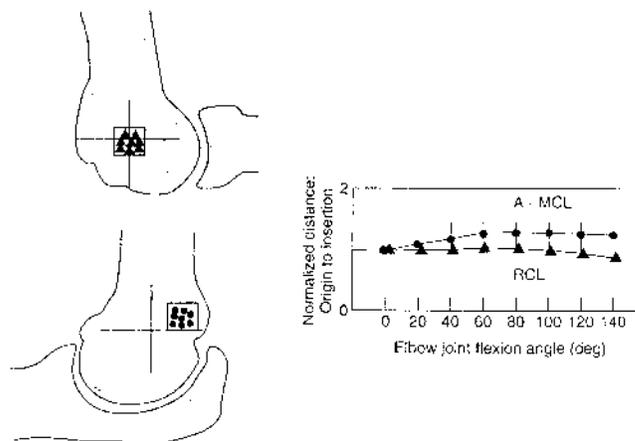
**FIGURE 9.** The stabilizing role of the radial head to valgus stress. The radial head mainly functions in this role once the medial collateral ligament is released (MCL), showing the radial head to function as a secondary stabilizer to valgus stress. Reprinted with permission.[1]

evaluated with successive removal of parts of the proximal ulna.[17] A linear decreasing relationship in stability was seen with successive removal of the olecranon, in both flexion and extension positions (Fig. 5). In extension and flexion, 75% to 85% of valgus stress was found to be resisted by the proximal half of the sigmoid notch. The distal half of the sigmoid notch (coronoid) resisted 60% of varus stress in flexion and 67% in extension.[17] The elbow becomes more unstable as successive portions of the coronoid are removed. With radial head resection, this instability occurs earlier with less coronoid resection (Fig. 6).[1]

The contact areas in the elbow joint vary with the type of applied stress. In a laboratory study, contact areas of the elbow have been shown to occur at four facets in the sigmoid fossa, two at the coronoid and two at the olecranon (Fig. 7).[1] With varus and valgus loads, the contact changes medially and laterally, respectively. Morrey et al.[18] have experimentally shown a varus–valgus pivot point just lateral to the middle of the lateral face of the trochlea.

As previously described, the carrying angle is formed by the longitudinal axis between the humerus and ulna in full extension. In females, the average valgus angle is 13° to 16°, whereas in males, it is 11° to 14°.[1] The carrying angle orientation changes from a valgus orientation in extension to varus orientation in flexion.[19] For simplicity, one may assume that the ulnohumeral joint is a pure hinge joint, and that the axis of rotation coincides with the trochlea so that the change in carrying angle with flexion is caused by anatomic variations of the articulation.[20]

***Passive Soft Tissue Stabilizers.*** Passive soft tissue stabilizers include the medial and lateral collateral ligament



**FIGURE 10.** A, Magnitude and orientation of forces at the distal humerus during flexion. B, Magnitude and orientation of forces at the distal humerus during extension. Reprinted with permission.[1]
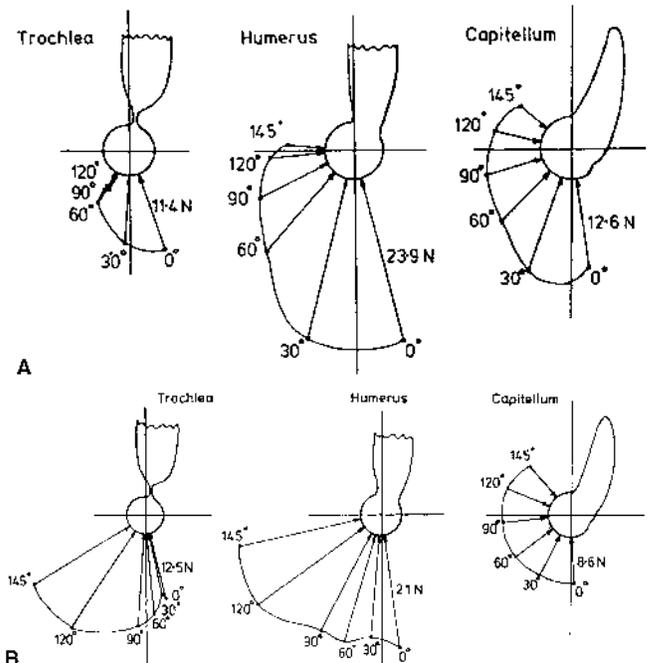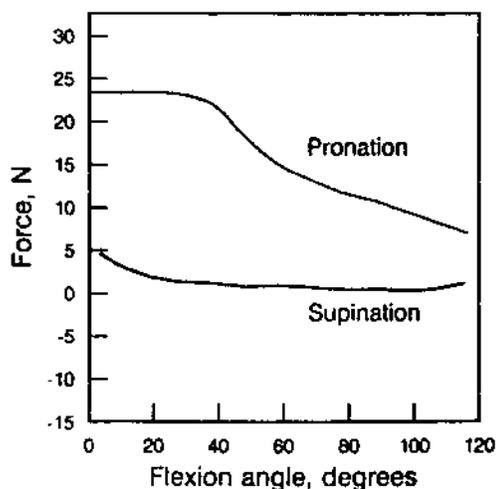
**FIGURE 11.** Greater force transmission across the radial head with pronation, suggesting proximal migration of radial head with pronation. Reprinted with permission.[1]

complexes and the anterior capsule. The lateral collateral ligament complex includes the lateral ulnar collateral ligament, which functions in stabilizing varus stress. Other components of the lateral collateral ligament complex include the radial collateral ligament, the annular ligament, and the accessory lateral collateral ligament.[1,21] The lateral and medial ligament complexes differ in their site of origin. The lateral collateral ligament originates from the lateral condyle at the point where the axis of rotation of the elbow passes through. This ligament has a fairly uniform tension throughout range of motion, because it originates at the axis of rotation (Fig. 8).[1] The medial collateral ligament consists of two main components, neither of which originates on the axis of rotation of the elbow. The anterior bundle of the medial complex has been further subdivided into an anterior band that is taut in extension and a posterior band that is taut in flexion. As the point of origin

of the different components of the medial complex do not occur at the axis of rotation, the different components are not uniformly taut during elbow flexion and extension (Fig. 8).[1]

***Interplay Between Passive Stabilizers.*** The contributions of elbow ligaments and articular components have been shown through materials testing by sequentially eliminating a component and determining the resultant instability.[1] The contributions of the articular geometry and ligaments to varus and valgus loads were studied by Morrey and An.[22] In 90° elbow flexion, the medial collateral ligament is the primary stabilizer to valgus stress, whereas in extension, the medial collateral ligament, anterior capsule, and bony fit (articulation) are fairly equally resistant to valgus stress.[22] The bony articulation provides much of the stability to varus stress with the elbow in both flexion and extension.[21] Eighty-five percent of the resistance of the joint to distraction is caused by the anterior capsule in extension, whereas only 8% of resistance is caused by the anterior capsule in 90° elbow flexion. With elbow flexion, 78% resistance to traction is provided by the medial collateral ligament complex.[1,21] Morrey et al.[19] showed that the primary restraint to valgus stress is the medial collateral ligament and the secondary stabilizer is the radial head. As can be seen in Figure 9, the removal of the radial head becomes significant if the medial collateral ligament is released.[23]

## Active Stabilizers

Muscles crossing the elbow joint and their function have been previously described (Table 1).[1,13] The line of pull and contraction of muscles across the elbow joint create forces within the joint at the humerus, radius, and ulna. These balanced forces likely function as dynamic stabilizers of the joint. During maximal isometric elbow flexion, forces acting on the humerus, coronoid, and radial head have been determined. The largest forces were seen
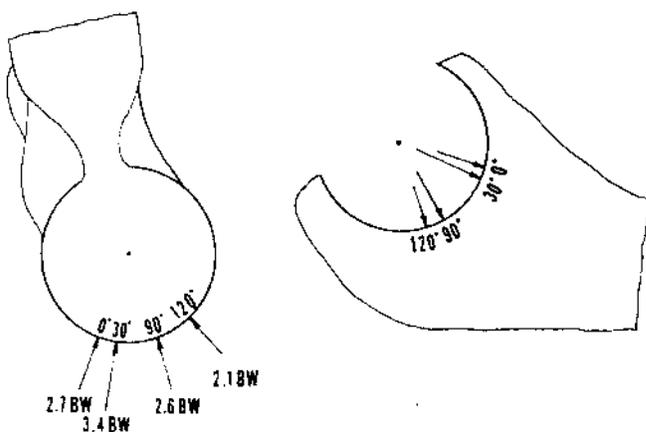


**FIGURE 12.** With heavy lifting, as much as three times the body weight may be transmitted across the elbow joint. Force vectors change with flexion angle. Reprinted with permission.[21]
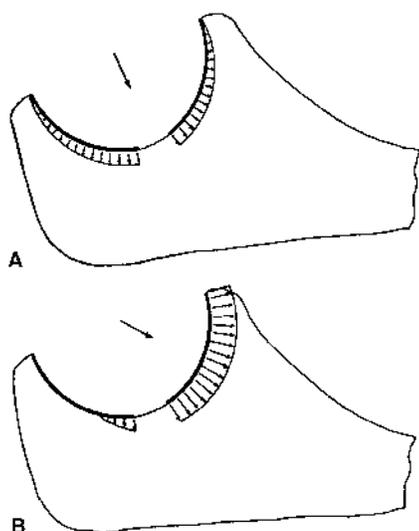
**FIGURE 13.** Contact pressure is dependent on the direction and magnitude of force. With the force directed at the center of the sigmoid notch, pressures are evenly distributed; with force applied toward the periphery of the articular surface, contact pressure increases and becomes asymmetric. Reprinted with permission.[1]

axially at the distal humerus near full extension, but decreasing forces were seen with increasing elbow flexion.[24]

Elbow joint compressive forces in both isometric flexion and extension have been reported.[25] Forces in the sagittal plane on the distal humerus in isometric flexion and extension are seen in Figures 10A and 10B.[25]
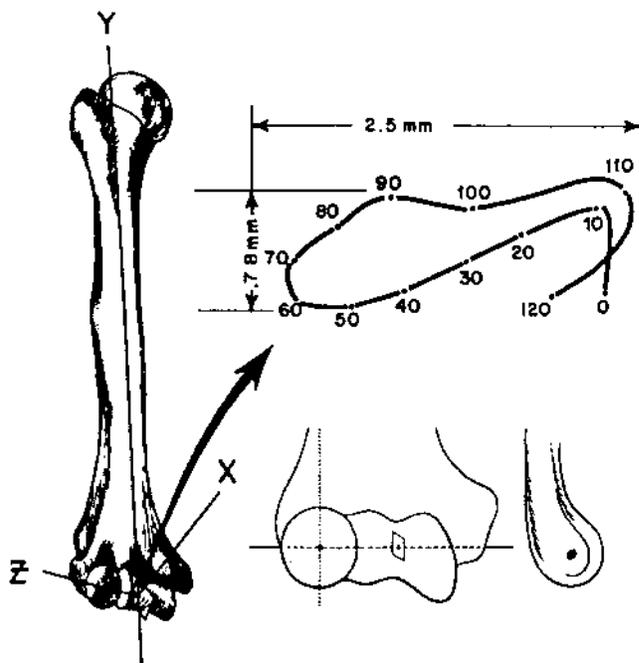
***Force Transmission Through the Elbow.*** Determining force distribution across the elbow is a difficult task. Investigators have used both experimental and analytical methods. Analytical models require knowledge of the muscles crossing the joint, the physiologic cross-sectional area, the moment arm, the line of pull, the muscle activity during motion, and the number of muscles involved. An et al.[26] found that of the muscles crossing the elbow joint, the brachialis and triceps muscles have the largest work capacity and contractile strength.

With extension and axial loading, the distribution of stress is 40% across the ulnohumeral joint and 60% across the radiohumeral joint.[1] Another cadaveric study has shown that only 12% of the axial load is transmitted across the proximal ulna with valgus alignment and 93% of the force is transmitted through the proximal ulna with varus alignment.[27]

Morrey et al.[28] measured force transmission through the radial head. A force transducer was placed at the radial neck as a flexion force was applied through the brachialis and biceps muscles. The extension forces were passive. Radial head forces were greatest from 0° to 30° flexion and always higher in pronation (Fig. 11).[28] An and Morrey[21] calculated the force in the ulnohumeral joint and found that the joint force in the ulnohumeral joint can range from one to three times body weight with strenuous lifting (Fig. 12). The direction of the resultant joint force changes with flexion angle, pointing more anteriorly with elbow extension and posteriorly with elbow flexion.



**FIGURE 14.** Anterior and lateral view of distal humerus showing the instant center of rotation of the elbow. Reprinted with permission.[1]
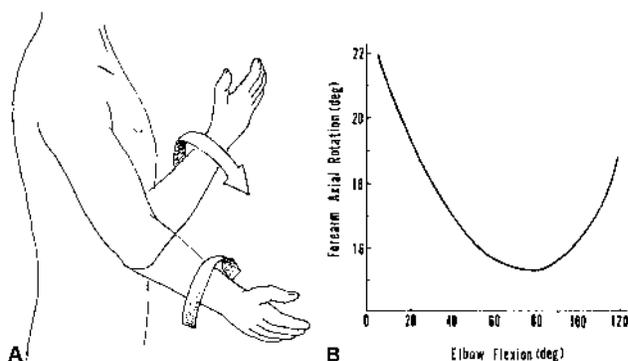
**FIGURE 15.** Axial rotation at the humeroulnar joint. Six-degree internal rotation occurs from extension to 80° elbow flexion; beyond 80° flexion, external rotation occurs. Reprinted with permission.[31]

The stress on the articular cartilage in the trochlear notch was evaluated by An et al.[29] As the joint surface is not a simple shape, a spring model was adopted to determine the contact pressures. The study showed that contact pressure depends on the direction and magnitude of the compressive force. When the force was oriented at the center of the articular surface, the contact stress was equally distributed throughout the articular surface. When the force was directed in an anterior or posterior direction towards the margin of the articulation, the weight-bearing surface was smaller, the contact stresses were higher, and the stress distribution was uneven (Fig. 13).[29]

Askew et al.[30] studied the isometric elbow strength in over 100 people. Elbow flexion, extension, pronation, and supination were measured with the elbow at 90° flexion in neutral rotation. The results showed men to be twice as strong as women and the dominant arm to be, on average, 6% stronger than the nondominant arm.

### Function

***Supination and Pronation.*** The primary motion of the forearm is supination and pronation, with the axis of rotation passing from the proximal radial head to the convex articular surface of the ulna at the distal radioulnar joint.[1] Morrey et al.[19] reported an average supination of 75° and average pronation of 70°. For most activities of daily living, most authors concur that 50° pronation and 50° supination are adequate.[19]

***Flexion and Extension.*** Fischer[1] in 1909 showed elbow flexion and extension to occur around an instant center of rotation involving an area of 2 to 3 mm in diameter at the trochlea (Fig. 14). More recently, An and Morrey[1] demonstrated that the orientation of the screw axis varies by as much as 8° from patient to patient. This inspired the development and use of semiconstrained elbow implants. For all practical purposes, the deviation of joint rotation is minimal, and elbow motion can be thought of as a uniaxial joint except at the extremes of flexion and extension.[1] With this simplification, the axis

of rotation can be thought of a line passing from the inferior medial epicondyle through the center of the lateral epicondyle.[1]

Elbow range of motion consists of flexion and extension from 0° (full extension) to 140° flexion. Morrey et al.[19] showed that most activities of daily living can be performed in the 30° to 130° range. The elbow is often mistakenly thought of as a simple hinge joint because of the congruous and stable ulnohumeral articulation. Studies have shown that in addition to flexion and extension, the ulnohumeral joint also has 6° axial rotation secondary to the obliquity of the trochlear groove (Fig. 15).[19,31]

***Range of Motion.*** Normal elbow range of motion is from 0° to 150°, and forearm rotation averages 75° pronation and 85° supination. When the forearm muscles are removed from cadaver specimens, elbow flexion increases to 185°. The range of motion increases even further to 210°, after sectioning of the ligamentous structures.[1] Factors limiting extension likely include the impact of the olecranon process on the olecranon fossa, tension of the anterior bundle of the medial collateral ligament, and the flexor muscles.[1] Factors limiting flexion include the impact of the coronoid process against the coronoid fossa, the impact of the radial head against the radial fossa, and the tissue tension from the capsule and triceps muscle.[1] Pronation and supination motions are restricted more by the passive stretch of antagonistic muscles than by ligaments, although the quadrate ligament has been shown to provide static constraint to pronosupination motion.[1]

### ■ CONCLUSION

The elbow is a complex and critical link in the upper extremity, as a nonfunctional elbow is extremely limiting to the activities of daily living. An understanding of the anatomy and biomechanics is important for both the surgeon and researcher. This knowledge will help advance surgical treatments and acute fracture management, aid in the development of new elbow prostheses, and stimulate new areas of research.

## ■ REFERENCES

1. Morrey BF, ed. *The elbow and its disorders.* Philadelphia, PA: WB Saunders; 2000.

2. Chang CW, Oh SJ. Posterior antebrachial cutaneous neuropathy: case report. *Electromyogr Clin Neurophysiol.* 1990;30:3–5.

3. Leffert RD. Anterior submuscular transposition of the ulnar nerve by the Learmonth technique. *J Hand Surg (Am).* 1982;7:147–155.

4. Dowdy PA, Bain GI, King GJW, et al. The midline posterior elbow incision. An anatomic appraisal. *J Bone Joint Surg Br.* 1995;77:696–699.

5. Steindler A. *Kinesiology of the human body.* 5th ed. Springfield, IL: Charles C. Thomas; 1977.

6. Shiba R, Siu D, Sorbie C. Geometric analysis of the elbow joint. *J Ortho Research.* 1988;6:897.

7. Tanaka S, An KN, Morrey BF. Kinematics of ulnohumeral joint under varus–valgus stress. *J Musculoskel Res.* 1998; 2:45.

8. Tillman B. *A contribution to the function morphology of articular surfaces.* New York, NY; Thieme: 1978.

9. Sorbie C, Shiba R, Siu D, Saunders G, et al. The development of a surface arthroplasty for the elbow. *Clin Orthop.* 1986;208:100–103.

10. Weiss AP, Hasting H II. The anatomy of the proximal radioulnar joint. *J Shoulder Elbow Surg.* 1992;1:193–199.

11. O'Driscoll SW, Morrey BF, An KN. Intraarticular pressure and capacity of the elbow. *Arthroscopy.* 1990;6:100–103.

12. Fleisig GS, Andrews JR, Dillman CJ, et al. Kinetics of baseball pitching with implications about injury mechanism. *Am J Sports Med.* 1995;23:233–239.

13. Bain GI, Mehta JA. *Anatomy of the Elbow Joint and Surgical Approaches.* Philadelphia, PA: Springer; 2000:1–27.

14. O'Driscoll SW, Jaloszynski R, Morrey BF, et al. Origin of the medial ulnar collateral ligament. *J Hand Surg.* 1992; 17:164–168.

15. Morrey BF, An KN. Functional anatomy of the elbow ligaments. *Clin Orthop.* 1985;201:84–90.

16. Werner SL, Fleisig GS, Dillman CJ, et al. Biomechanics of the elbow during baseball pitching. *J Orthop Sports Phys Ther.* 1993;17:274–278.

17. An KN, Morrey BF, Chao EY. The effect of partial removal of proximal ulna on elbow constraint. *Clin Orthop.* 1986;209:270–279.

18. Stormont TJ, An KN, Morrey BF, et al. Elbow joint contact study: comparison of techniques. *J Biomech.* 1985;18:329–336.

19. Morrey BF, Askew LJ, An KN, et al. A biomechanical study of normal functional elbow motion. *J Bone Joint Surg Am.* 1981;63:872–877.

20. An KN, Morrey BF, Chao EY. Carrying angle of human elbow joint. *J Orthop Res.* 1984;1:369–378.

21. Peimer CA, ed. *Surgery of the hand and upper extremity.* New York, NY; McGraw-Hill: 1996.

22. Morrey BF, An KN. Articular and ligamentous contributions to stability of the elbow joint. *Am J Sports Med.* 1983;11:315–319.

23. Morrey BF, Tanaka S, An KN. Valgus stability of the elbow. *Clin Orthop.* 1991;265:187–195.

24. Amis AA, Miller JH. Design, development, and clinical trial of a modular elbow replacement incorporating cement-free fixation. *Eng Med.* 1984;13:175–179.

25. Amis AA, Dowson D, Wright V. Elbow joint force predictions for some strenuous isometric actions. *J Biomech.* 1980;13:765–775.

26. An KN, Hui FC, Morrey BF, et al. Muscles across the elbow joint: a biomechanical analysis. *J Biomech.* 1981; 14:659–669.

27. Markolf KL, Lamey D, Yang S, et al. Radioulnar load-sharing in the forearm: a study in cadavera. *J Bone Joint Surg Am.* 1998;80:879–888.

28. Morrey BF, An KN, Stormont TJ. Force transmission through the radial head. *J Bone Joint Surg Am.* 1988;70: 250–256.

29. An KN, Himeno S, Tsumura T, et al. Pressure distribution on the articular surfaces: Application to joint stability evaluation. *J Biomech.* 1990;23:1013–1020.

30. Askew LJ, An KN, Morrey BF, et al. Isometric elbow strength in normal individuals. *Clin Orthop.* 1987;222: 261–266.

31. Morrey BF, Chao EY. Passive motion of the elbow joint. *J Bone Joint Surg Am.* 1976;58:501–508.