Biomechanics of the Elbow

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Introduction

The elbow joint is composed of three articulations that share a common joint capsule: the ulnotrochlear joint, the radiocapitellar joint, and the proximal radioulnar joint. Together, these articulations are described as a "trochoginglymoid" joint as they allow two degrees of freedom: elbow flexion and extension and forearm pronation and supination. The elbow thus complements the sphere of motion provided by the shoulder, allowing the hand to be positioned in a wide variety of locations in space. Elbow stiffness and instability can thus lead to substantial functional loss that can threaten a patient's function. The ulnotrochlear joint also provides a fulcrum against which the forearm acts a lever. In this capacity, pressures generated in the elbow can exceed three-times body weight.

The flexion/extension motion of the elbow has been described as a "sloppy hinge" because the axis of rotation moves up to 3–4° and 2.5 mm when ranging from a fully extended to a fully flexed position. This is due to obliquity in the trochlear groove and corresponding sigmoid notch [1]. The flexion-extension axis of the joint does not lie within any cardinal plane of the body as it is 3–8° internally rotated relative to the humeral epicondyles and is in 4–8° of valgus relative to the long axis of the humerus. The valgus obliquity of the flexion-extension axis, combined with obliquity in the humeral and ulnar shafts contributes to the "carrying angle" of the elbow, which is 10–15° in men and 15–20° in women [1, 2]. The combination of internal rotation and valgus in the flexion/extension axis ensures that objects carried in the hand with the elbow extended and the shoulder adducted do not strike the ipsilateral leg and that with flexion the hand naturally comes towards the mouth.

A number of landmarks can be used fluoroscopically to locate the flexion-extension axis of the elbow. On a perfect lateral view of the elbow, this axis should lies at (a) the center of a best-fit circle placed upon the capitellum [1, 3], (b) the center of a best-fit circle placed upon the trochlea [4], and (c) the intersection between the axis of center the radial shaft and the anterior humeral cortical line [5]. The native varus-valgus laxity of the joint has been incorporated into the design of total elbow arthroplasty articulations to create "semi-constrained" implants, which have decreased rates of aseptic loosening [1, 3]. However, apart from the extremes of flexion and extension, the flexion and extension motion of

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the elbow can basically be considered a simple hinge, allowing the placement of hinged external fixators without significant alteration of joint kinematics [4, 6, 7]. Clinically, accurate location of the axis of rotation is challenging and requires an anatomic reduction and repeated cyclic motion with observation of the articular surfaces for gapping during hinged fixator placement. This must be performed very accurately since malalignments as small as 5° increases energy expenditures for flexion and extension by 3.7-fold [7].

The pronation/supination motion of the elbow takes place through a longitudinal axis that passes through the convexity of the radial head at the proximal radioulnar joint. Although forearm rotation has traditionally been conceptualized as radial rotation around a stable ulna, this axis of rotation is oblique to the axis of the ulna [1, 2]. Thus, some axial ulnar rotation occurs with forearm rotation. In cadaveric studies, up to 6° of ulnar rotation occurs with forearm rotation even with an intact capsule, intact ligaments, and intact articular surfaces [8].

Normal elbow joint range of motion is from 0° of extension to 150° of flexion and from 75° of pronation to 85° of supination. The elbow joint capacity reaches a maximum of 25 mL at 80° [9], which has been suggested as the reason why joint contractures usually center at this position [10]. Classically it has been suggested that only 30° of extension and 130° of flexion are necessary for activities of daily living [11]. Extension loss is often well tolerated because patients can move closer to objects that cannot be reached as a result of an extension loss, while flexion loss is poorly tolerated because it interferes with feeding and head hygiene. Historically, it was suggested that supination loss is more poorly tolerated than pronation loss because pronation loss can be compensated for with shoulder abduction. However, with the advent of keyboards, many patients value pronation over supination as shoulder abduction over an extended period of time rapidly leads to rotator cuff fatigue and pain. A recent study has demonstrated that contemporary tasks such as using a computer mouse or keyboard may require a functional range of motion greater than that reported previously [12].

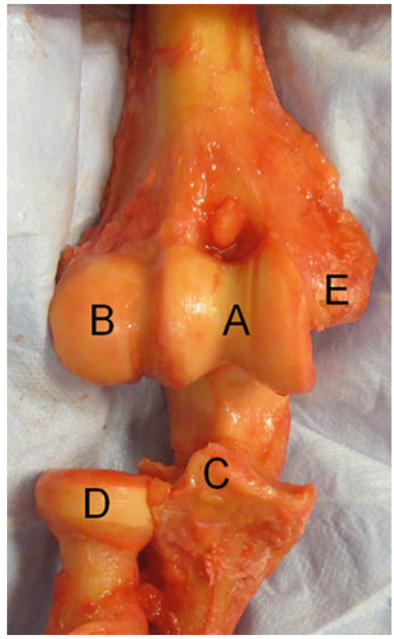

Fig. 2.1 This clinical photograph with all soft tissues removed from the elbow demonstrates the osseous congruity of the articulation. (*A*) Trochea. (*B*) Capitellum. (*C*) Coronoid. (*D*) Radial head. (*E*) Medial Epicondyle

The articular surfaces of the elbow are among the most highly congruent of any joint within the body and thus significantly contribute to elbow stability. In particular, between the coronoid, sigmoid notch, and olecranon, the proximal ulna provides a 180° arc of articular cartilage that articulates with a 320° of articular cartilage on the trochlea of the distal humerus during flexion and extension motion. The trochlea also has a sulcus that provides a guiding groove for a matching ridge within the sigmoid notch (Fig. 2.1). Numerous cadaveric studies have been conducted to determine the relative contributions of the articular surfaces as compared to the medial and lateral collateral ligaments to elbow stability [5, 13–20]. Regardless of these cadaveric studies, clinically it is known both that (1) in the absence of a periarticular fracture, most elbow dislocations can be treated successfully nonoperatively without recurrence of instability [21, 22] and that (2) in a majority of elbow dislocations both the medial and lateral collateral ligament complexes are completely torn. In many of these cases the entire extensor musculature is avulsed from the humerus as well [23]. Thus, intact articular congruity is sufficient for clinical stability in most cases. These findings are bolstered by a cadaveric study showing that elbow resistance to displacement, torsion, and axial forces in both flexion and extension has an inverse linear relationship to proximal ulnar excision [13].

Muscular forces interact with articular conformity to maintain elbow stability. Coactivation of the agonist–antagonist group (biceps, brachialis, and triceps) acts to center joint forces within the available articular arc of the ulnotrochlear joint [24, 25], while activation of the wrist extensors acts to center the radial head on the capitellum [15, 26]. Both the ulnohumeral and radiocapitellar joints are stabilized via a concavity-compression mechanism. After instability secondary to trauma, elbow rehabilitation regimens have thus focused upon supine active range of motion focusing on coactivation [27]. Electromyographic studies have shown that the anconeus is active during almost all elbow motions, which has led some authors to suggest that this muscle may also serve a role as a dynamic stabilizer [2]. The triceps has more than twice the cross-sectional area of any other muscle crossing the elbow joint and is larger than the biceps and brachialis combined. Of the flexors, the brachioradialis has a larger moment arm than the biceps, which is also larger than the brachialis. Generally, as muscle moment arms increase both muscle force and joint reaction force increase. Thus, those muscles with insertions closest to the articulation have larger moment arms and can produce the largest joint compression forces and thus make the largest dynamic contributions to stability. Moment is affected by joint position. In flexion, the overall potential flexor moment is equal to the potential extensor moment, while in extension the potential extensor moment exceeds the potential flexor moment. This may contribute to a greater propensity for elbow instability in extension as compared to flexion [2]. Muscle moment arms are also affected by humeral length, with potential triceps force production reduced by 20 % with one cm of humeral shortening, 40 % with two cm of humeral shortening, and 60 % with three cm of humeral shortening [28].

Classically, 40 % of axial loads across the elbow are transferred across the ulnohumeral joint and 60 % across the radiohumeral joint. However, load transfer is sensitive to a variety of factors. Changes in varus and valgus positioning of the elbow can lead to large changes in joint loading force. In valgus, 93 % of axial loads are transferred across the radius [29]. In addition, flexion and extension alter loading, with the radiocapitellar joint being more loaded in full extension [30]. This is due to the fact that in this position the muscles passing across the ulnotrochlear joint have the shortest moment arms [24]. The integrity of the interosseous membrane, in particular the central band [31], also alters load transfer, particular with the elbow in varus [29]. Finally, forearm rotational position alters load transfer, with pronation loading the ulnotrochlear joint and supination loading the radiocapitellar joint [29]. Loss of elbow stability can lead to malalignment and overload of one side of the joint, which can lead to accelerated radiocapitellar or ulnotrochlear degenerative changes.

While abundant cadaveric biomechanical studies have been conducted in attempt to understand the contributors to elbow stability [5, 13–20], these experiments are difficult to perform and their findings can be difficult to generalize to biokinematics in the live patient. First, in addition to displacement, instability can occur with rotation in three planes of each of the three bones. Second, cadaveric studies provide incomplete simulation of the contributions from the dynamic stabilizers. Third, while early experiments were performed using mechanical testing equipment, later experiments with electromagnetic tracking equipment have in several cases arrived at very different conclusions [32]. Fourth, forearm rotational position also alters laxity and joint reaction forces, with varus/valgus laxity in general increased in forearm pronation [33, 34], although the medial soft tissues are stressed more in pronation and the lateral soft tissues are stressed more in supination [5, 20, 25, 27, 35]. Finally, the relative contributions of each structure depend upon the deforming force applied, with many early studies applying nonphysiologic forces. As a result, even relatively elementary aspects of elbow biomechanics remain controversial.

Lateral Elbow Stability

As described by O'Driscoll and colleagues, the most common mechanism for dislocation of the elbow is rotation of the forearm on the humerus into valgus, extension, and external rotation as the forearm supinates off the humerus [36]. As this motion progresses tissue damage progresses from lateral to medial. The lateral collateral ligament complex first tears [37], then the anterior and posterior capsules tear, and finally the ulnar collateral ligament tears [36]. Depending upon the position of the arm and the energy of the trauma during the injury as well as the patient's anatomy, the radial head and coronoid may also be fractured [38–40]. In 66 % of cases there are concomitant tears of the common extensors and in 50 % of cases there are concomitant tears of the anterior band of the ulnar collateral ligament [37]. Dislocation of the elbow without tearing the ulnar collateral ligament is theoretically possible with rotation around an intact ulnar collateral ligament although clinical dislocation without tearing of the ulnar collateral ligament is uncommon [36]. Finally, recent video evidence has suggested valgus may be more common than varus as a mechanism of injury [41].

The articular surfaces provide the majority of the stability to varus stress, supplying 55 % of stability in extension and 75 % in flexion [2]. Among the soft tissues, the lateral collateral ligament complex is the primary stabilizer of the ulnohumeral joint to varus stress [5, 8, 16, 35], with fascial bands within the extensor musculature (in particular the extensor carpi ulnaris, which has the best mechanical advantage) also playing a role resisting varus stress [5]. Clinically, residual lateral instability of the elbow is poorly tolerated because shoulder abduction places a varus stress across the elbow and thus many activities of daily living subject the elbow to varus stress (Fig. 2.2). By the same logic, an external fixation device applied to the lateral elbow for residual instability after instability repair protects the lateral collateral ligament complex by acting as a tension band, while offering relatively less protection to a medial repair or reconstruction [6].

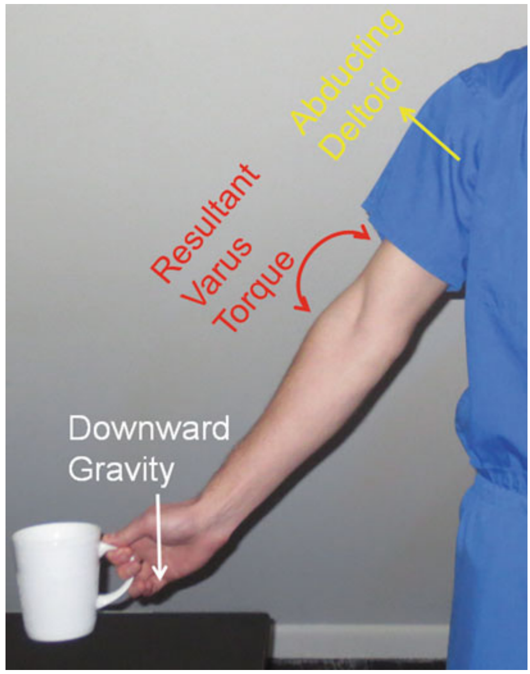

Fig. 2.2 This clinical photograph demonstrates how activities of daily living subject the elbow to varus stress. In this image, a subject is picking a coffee cup up off of a table. The deltoid (*straight yellow arrow*) pulls through the arm as a lever against gravity on the cup (*straight white arrow*) to create a varus stress across the elbow (*curved red arrow*)

Lateral Collateral Ligament Complex

The lateral collateral ligament complex is classically thought to be composed of three portions: the lateral ulnar collateral ligament, the radial collateral ligament, and the annular ligament (Fig. 2.3) [5, 16, 42]. These structures are anatomically discrete from one another and from the overlying extensor musculature to a variable degree [5, 43]. Both the lateral ulnar collateral ligament and the radial collateral ligament arise anterior to the lateral epicondyle, with the radial collateral ligament becoming confluent with the fibers of the annular ligament while the lateral ulnar collateral ligament continues to the supinator ridge of the ulna (Fig. 2.4). The lateral collateral ligament complex was classically described to arise from the axis of rotation of the elbow, with the lateral ulnar collateral ligament being

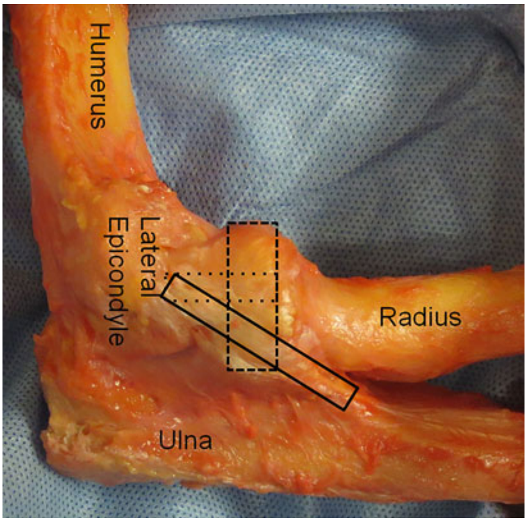

Fig. 2.3 This clinical photograph of a cadaveric dissection in which all structures aside from the humerus, radius, ulna, joint capsule, and ligaments have been removed demonstrates the lateral collateral ligament complex, including the lateral ulnar collateral ligament (*solid box*), annular ligament (*dashed box*), and radial collateral ligament (*dotted box*)

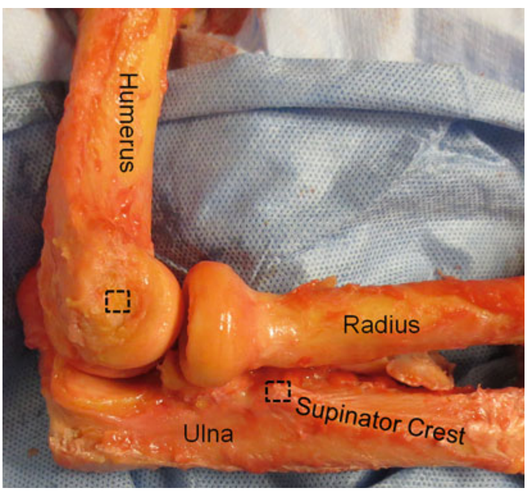

Fig. 2.4 This clinical photograph with the lateral collateral ligament complex removed demonstrates the attachment sites for the lateral ulnar collateral ligament (*dashed boxes*)

isometric (Fig. 2.5) [2, 42, 44]. However, this remains controversial as both a computer modeling study [45] and a cadaveric study [46] have suggested that the radial collateral ligament is isometric while the lateral ulnar collateral ligament

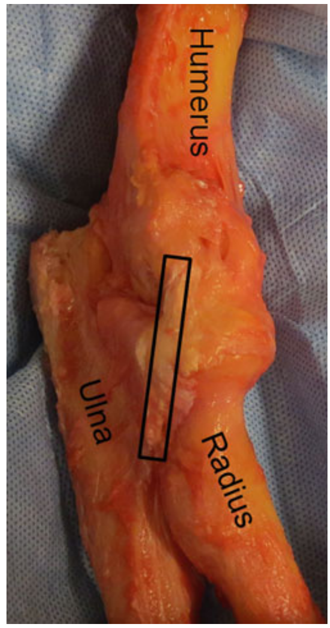

Fig. 2.5 This clinical photograph demonstrates that, in extension, the lateral ulnar collateral ligament (*solid box*) can be seen to be nearly isometric

is taut in flexion and loose in extension. The isometric point laterally has been identified 2 mm proximal to the center of the capitellum [45].

Elbow instability is thought to occur in stages such that isolated tears of the lateral collateral ligament complex are possible, leading to a subluxation phenomenon called posterolateral rotatory instability (Fig. 2.6) [47, 48]. Posterolateral rotatory instability is a combination of external rotation/supination of the forearm on the humerus, axial loading, valgus angulation, and posterior displacement of the forearm on the humerus. Clinically, a tear in the lateral ulnar collateral ligament is thought to be the defining pathology to allow this subluxation [44, 48]. However, the Y-shaped configuration of the lateral ulnar collateral ligament and the radial collateral ligament may be structurally self-reinforcing therefore injury of only the lateral ulnar collateral ligament may not lead to gross instability. Cadaver studies have shown that isolated sectioning of either the lateral ulnar collateral ligament or radial collateral ligament is not sufficient to produce posterolateral rotatory instability and requires sectioning of both structures to create instability [18, 49].

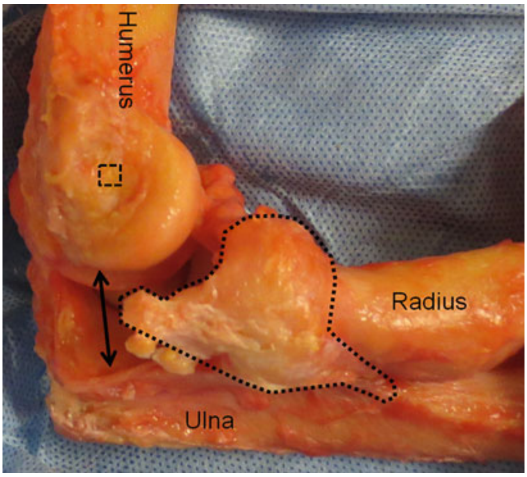

Fig. 2.6 This clinical photograph demonstrates that after release of the lateral collateral ligament complex (*outlined in dots*) from the humeral attachment (*outlined with a dashed box*) the ulnotrochlear joint gaps (*black double-sided arrow*) with a rotatory stress

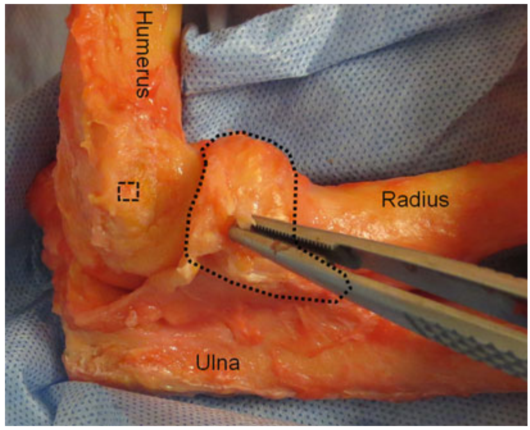

Fig. 2.7 This clinical photograph demonstrates release of the humeral attachment (*dashed box*) of lateral collateral ligament complex (*outlined in dots* and *gripped by the forceps*), which is the most common anatomic location for ligament tears

Nevertheless, the relative importance of each portion of the lateral collateral ligament complex remains controversial. Olsen and colleagues found that sectioning of the annular ligament while leaving the lateral ulnar collateral ligament intact increased varus opening from 2–3° to 6–11°, suggesting that the lateral ulnar collateral ligament may not be the primary stabilizer and that the annular ligament, which was traditionally thought to be of relatively little importance for stability, may be functionally important [50]. In a sequential sectioning study, Olsen and colleagues found that the radial collateral ligament was the primary stabilizer and that the lateral ulnar collateral ligament was an accessory, while the annular ligament played essentially no role in stabilizing the lateral elbow [8]. Consequently, all components of the lateral complex probably play a role in lateral sided stability and repair of each component will likely maximize stability.

Anatomically, the lateral soft tissues most commonly tear from the humeral origin resulting in tears of both the radial collateral ligament and lateral ulnar collateral ligament. Thus, the preceding debate regarding which portions of the ligament are most important for stability may not be clinically important as both are commonly injured as a unit (Fig. 2.7) [5, 16, 23, 35, 37]. In acute repairs, most surgeons attempt to gather tissue from both from the radial collateral ligament and lateral ulnar collateral ligament [39, 40]. In chronic instability, reconstruction of just the lateral ulnar collateral ligament leads to excellent functional outcomes and reliable restoration of stability [16, 39, 40, 48]. One cadaveric study demonstrated that reconstruction of the lateral ulnar collateral ligament provides equivalent stability to reconstruction of both the lateral ulnar collateral ligament and radial collateral ligament [17]. Thus, regardless of the controversy in cadaveric studies, the lateral ulnar collateral ligament appears to be the most critical part of the lateral collateral ligament complex to reconstruct.

Coronoid

The coronoid is a critical elbow stabilizer, acting as a buttress against axial loading, rotation, and posterior displacement of the ulna. The coronoid also serves to lengthen the articular surface of the sigmoid notch, improving flexion/extension range of motion. The coronoid is also relatively exposed to shear stress and is thus at risk for fracture. Up to 60 % of the anteromedial facet portion of the coronoid is unsupported by metaphyseal bone placing it at risk for fracture especially during varus posteromedial rotatory dislocations [38]. In one series of operatively treated elbow dislocations, 63 % patients had a coronoid fracture [37].

While all authors agree that the coronoid is an important stabilizer for the elbow, coronoid fracture height varies and the exact height necessitating operative fixation is controversial. One study suggested that loss of as little as 25 % of the coronoid can lead to subluxation of the ulnotrochear joint in midflexion in the absence of the radial head [2]. Another biomechanical study demonstrated that fracture of 40 % of the coronoid increased both varus laxity and internal rotation stress [51]. Still another study found that radial head excision and removal of 30 % of the coronoid could lead to a dislocation even with the medial and lateral ligamentous complexes intact [52]. With an intact radial head, the same study found that 50–70 % coronoid excision was necessary to create a dislocation [52]. Based upon these studies, the threshold that a coronoid surgical repair is indicated remains controversial. The threshold is likely 40–50 % based upon the biomechanical data for fractures in isolation, although it may be as small as 10–15 % depending upon the concomitant injuries and how effectively they can be addressed [38, 52]. As a result, coronoid fracture fixation is a critical portion of the surgical treatment of elbow instability and should be considered as a necessary component of most repairs to maximize stability [38–40]. In cases of instability with coronoid bone loss, several coronoid reconstruction techniques have been described including radial head autograft, olecranon autograft, iliac crest autograft, coronoid allograft, and prosthetic reconstruction emphasizing the importance of restoring the coronoid to achieve stability [51].

Radial Head and Capitellum

The radial head provides lateral stability through three mechanisms: (1) by acting as a buttress, (2) through the concavity compression mechanism, and (3) by tensioning the lateral ulnar collateral ligament. The radial head is commonly fractured in the setting of elbow instability and in general should be repaired or reconstruction in most cases to maximize stability. Radial head resection increases laxity in multiple directions [52]. In one series of operatively treated elbow dislocations, 58 % of patients had a concomitant radial head fracture [37].

Multiple biomechanical analyses have demonstrated the importance of the radial head in elbow stability. In a cadaveric study, Hotchkiss and colleagues demonstrated that the radial head contributes up to 30 % of stability to valgus torque/displacement in the setting of an intact ulnar collateral ligament [53]. Subsequent cadaveric studies have demonstrated that isolated radial head excision doubles the valgus laxity of the elbow [52] and increases rotatory laxity by up to 145 % [54]. The radial head is particularly important in association with a coronoid fracture—in one cadaveric study when both were absent subluxation occurred even with completely intact ligaments and radial head replacement alone could stabilize the elbow [54]. The mechanism of posterolateral rotatory instability has been suggested to require pathologic external forearm rotation. The radial head serves as a block to excess external rotation, as the anterior radial head must sufficiently externally rotate to clear the distal capitellum to result in posterolateral rotatory instability [55]. Thus even small radial head defects can play an important role in stability if they are inopportunely placed [55]. The capitellum likely plays a similarly important role—in one study after excision of the capitellum -valgus laxity increased 3.1° with active elbow flexion in pronation [56]. Nevertheless, other data supports no change in varus/valgus displacement after capitellar excision in the setting of intact ligaments [57].

In addition to stabilizing the elbow to varus and external rotation, the radial head may also act to tension the lateral collateral ligament complex, as, after excision of the radial head and sectioning of the lateral collateral ligament complex, restoration of both structures is necessary to completely restore elbow laxity [58].

Because the radial head acts as a physical block to dislocation, multiple studies have shown that monoblock radial head replacements provide significantly more stability than bipolar components [15, 59]. In a cadaver study of surgically fixated terrible triad injuries comparing monoblock and bipolar components, 16-fold more force was required to dislocate a monoblock component than a bipolar component [59]. A second, similar study showed that this effect was amplified by the status of the lateral collateral ligament complex and common extensor because the bipolar radial head not only allows posterior translation but it then tilts so that continued force on the radial head now resolves to contain a dislocating shear force vector [60]. Anatomic restoration of radial head height is critical both to restore stability and to avoid altered ulnotrochlear kinematics and accelerated capitellar chondrosis [61]. With excessive radial length the ulna tracks in varus and external rotation, while with inadequate length the ulna tracks in valgus and internal rotation [61]. Even fractures that only involve a portion of the radial head may be plagued by similar issues—in a cadaver study Shukla and colleagues demonstrated that fractures that involved only 30 % of the surface area of the radial head reduced subluxation force by 80 %, even if the fragment was retained but depressed 2 mm or retained but angulated 30°, presumably due to loss of the concavity-compression mechanism [26].

Medial Elbow Stability

The ulnar collateral ligament has three distinct sections: the anterior band, the posterior band, and the transverse band (Fig. 2.8) [19, 42, 62]. The anterior band of the ulnar collateral ligament has been described as isometric in some studies [19, 42, 46] and anisometric in others (Fig. 2.9) [63]. The posterior band is taut from 60 to 120° of flexion and can limit flexion in the stiff elbow and require release [19, 64]. In flexion, the anterior band of the ulnar collateral ligament serves as the primary stabilizer of the elbow to valgus stress (Fig. 2.10) [19, 23, 50, 53, 62, 64], with the radial head serving as a secondary stabilizer [32]. In full extension the anterior capsule and osseous congruity provide valgus stability to the elbow [53],

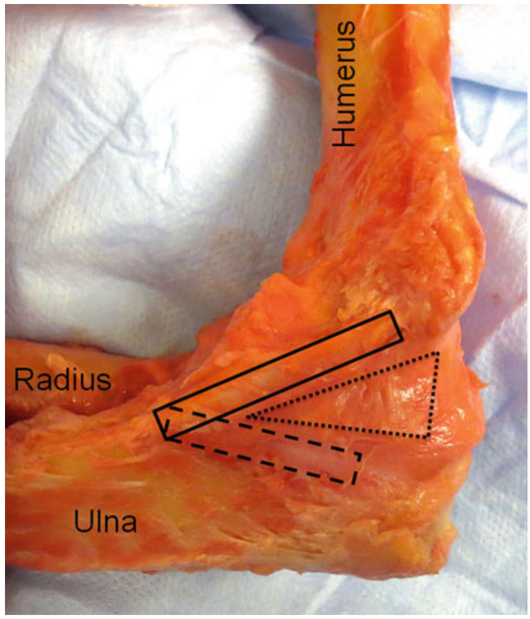

Fig. 2.8 This clinical photograph of demonstrates the ulnar collateral ligament, including the anterior band (*solid box*), posterior band (*dotted box*), and transverse band (*dashed box*)

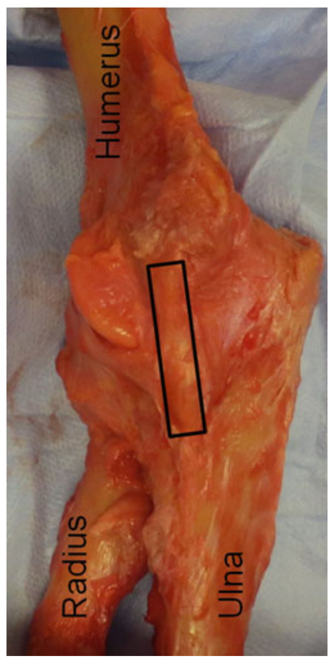

Fig. 2.9 This clinical photograph demonstrates that, in extension, the anterior band of the ulnar collateral ligament (*solid box*) is nearly isometric

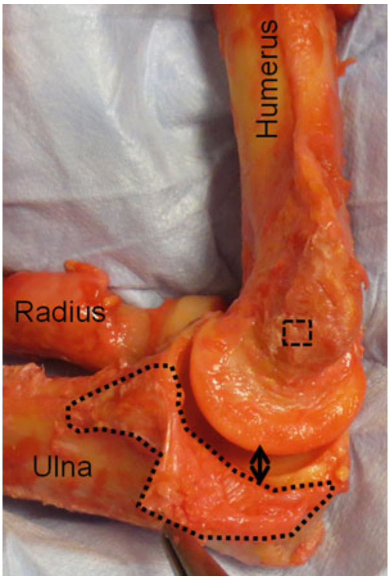

Fig. 2.10 This clinical photograph demonstrates that, after release of the ulnar collateral ligament (*outlined* in *dots* and *grasped by the forceps*) from the humeral attachment (*dashed box*), the ulnotrochlear joint gaps (*doubled-sided arrow*) to valgus stress

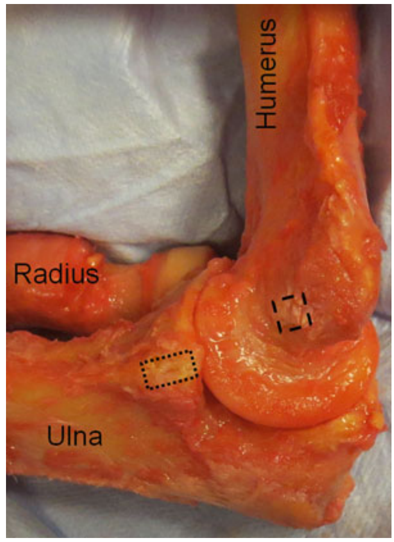

Fig. 2.11 This clinical photograph with the ulnar collateral ligament removed demonstrates the humeral (*dashed box*) and ulnar (*dotted box*) attachment sites for the ulnar collateral ligament

and thus clinically this ligament must be tested in flexion [20]. The anterior band of the ulnar collateral ligament takes origin from the anterior inferior aspect of the epicondyle proximally and inserts on the sublime tubercle of the ulna distally (Fig. 2.11). The anterior band of the ulnar collateral ligament has a long, thin insertion on the sublime tubercle and the portion immediately adjacent to the articular surface is most critical biomechanically [65].

While the anterior band of the ulnar collateral ligament is the primary valgus stabilizer, the radial head is a secondary valgus stabilizer and can even contribute up to 30 % of the stability with an intact anterior band of the medial collateral ligament [19, 23, 32, 50, 53, 62, 64]. Thus in injuries that affect both structures, the radial head becomes an important stabilizer that must be surgically addressed [32, 61]. If radiocapitellar column length is not restored, the ulnar collateral ligament may not heal at an anatomic length, potentially resulting in chronic valgus instability [32, 61]. However, unlike lateral instability, valgus instability of the elbow can be achieved equally with either monoblock or bipolar radial head arthroplasties [32, 34].

Most symptomatic valgus instability due to an incompetent ulnar collateral ligament is encountered in repetitive trauma in overhead athletes. The overhand pitching motion is one of the fastest human motions, with arm internal rotation velocities exceeding 7000°/s [66–70]. During the late cocking/early acceleration phase, the combination of the internal rotation torque placed on the humerus and the inertia of the forearm, hand, and ball exert a valgus stress on the elbow (Fig. 2.12). This valgus torque exceeds 64–120 Nm [66, 71, 72], which exceeds the 33 Nm capacity of the ulnar collateral ligament [46, 73–76]. As a result, ulnar collateral ligament tears have been frequently described in overhand pitchers, as well as javelin-throwers, quarterbacks, and other overhead athletes [77–82]. While the UCL tear was first documented by Waris in 1946 in javelin throwers [82], an operative reconstruction for this injury was not described until 1986 with Jobe's first cohort of 16 pitchers [79]. Pitchers with complete ulnar collateral ligament tears are frequently (42 %) unable to return to their pre-injury level with nonoperative treatment, but operative reconstruction has return to play rates in excess of 83 % in multiple series [77, 78, 80, 81, 83–87]. Because the valgus torque exerted on the elbow during

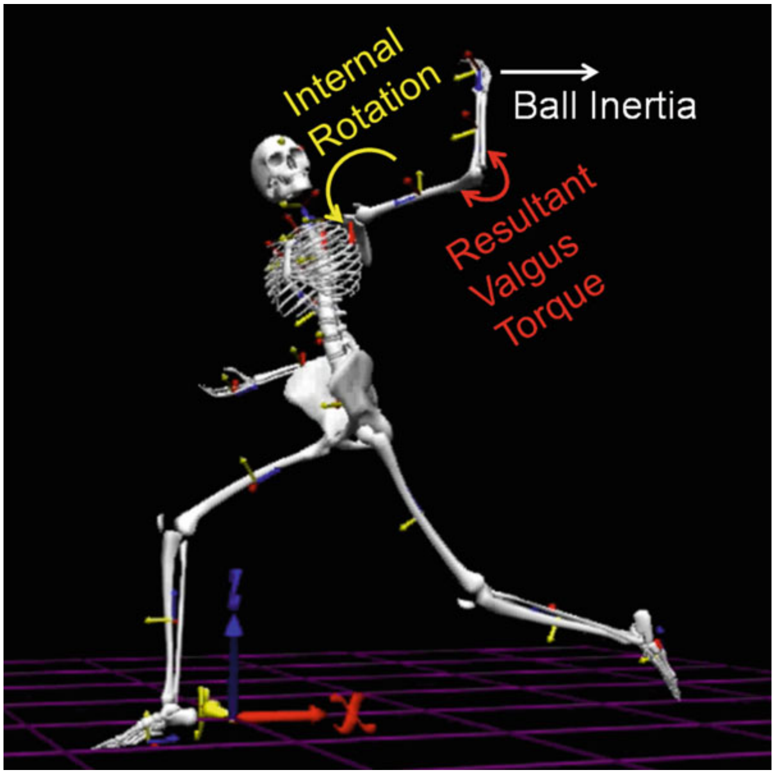

Fig. 2.12 This schematic of an overhand baseball pitcher demonstrates that during the acceleration phase rapid internal rotation of the humerus (*yellow curved arrow*), works against the inertia of the ball (*white arrow*), to create a valgus torque at the elbow (*red curved arrow*)

high velocity pitches exceeds the load-to-failure of the native ulnar collateral ligament, the flexor-pronator mass is known to act as an important dynamic stabilizer to valgus stress. However, with ulnar collateral ligament injuries, the flexor-pronator mass does not increase activity to compensate and stabilize the elbow, instead flexor-pronator activity is paradoxically decreased [88].

Multiple studies have been conducted comparing varied ulnar collateral ligament reconstruction techniques and this remains an active area of research [63, 65, 89–96]. While these studies have differed in the which reconstruction technique offers to optimal biomechanical characteristics, all studies are in agreement that all current reconstruction techniques for the ulnar collateral ligament are biomechanically inferior the native ligament, which has led to the extended rehabilitation periods necessary after this procedure before overhead throwing can recommence.

Conclusion

Elbow stability is created by a combination of factors. The osseous congruency of the ulnotrochlear and radiocapitellar joints contributes to overall elbow stability. The dynamic muscular forces provided by the biceps, brachialis, triceps, and wrist extensors interacting to center joint forces within the available articular arc via a concavity-compression mechanism also contribute to stability. The lateral collateral ligament complex is torn with most elbow dislocations and is the primary stabilizer to varus stress. The radial head and coronoid also play a critical role in stability by providing an osseous buttress. The anterior band of the ulnar collateral ligament is the primary stabilizer to valgus stress, with the flexor-pronator mass also playing a valgus stabilizing role. While the ulnar collateral ligament is torn in nearly all elbow dislocations, it infrequently requires surgical treatment. However, the ulnar collateral ligament can be injured in overhead athletes, specifically pitchers, due to chronic valgus stress during the late cocking/early acceleration phase of pitching and often requires surgical treatment in this population for return to pre-injury level of play. Understanding the functional anatomy and biomechanics of elbow instability is critical to successful repair and reconstruction during surgical stabilization of the elbow.

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References

1. Morrey BF, Chao EY. Passive motion of the elbow joint. J Bone Joint Surg Am. 1976;58:501–8.
2. An K-N, Zobitz ME, Morrey BF. Biomechanics of the elbow. In: Morrey BF, editor. The elbow and its disorders. 4th ed. Amsterdam: Elsevier; 2009. p. 39–63.
3. Schlein AP. Semiconstrained total elbow arthroplasty. Clin Orthop Relat Res 1976; 222–9.
4. Deland JT, Garg A, Walker PS. Biomechanical basis for elbow hinge-distractor design. Clin Orthop Relat Res. 1987; 303–12.
5. Cohen MS, Hastings H. Rotatory instability of the elbow. The anatomy and role of the lateral stabilizers. J Bone Joint Surg Am. 1997;79:225–33.
6. Sekiya H, Neale PG, O'Driscoll SW, An KN, Morrey BF. An in vitro biomechanical study of a hinged external fixator applied to an unstable elbow. J Shoulder Elbow Surg. 2005;14:429–32.
7. Bigazzi P, Biondi M, Corvi A, Pfanner S, Checcucci G, Ceruso M. A new autocentering hinged external fixator of the elbow: a device that stabilizes the elbow axis without use of the articular pin. J Shoulder Elbow Surg. 2015;24:1197–205.
8. Olsen BS, Søjbjerg JO, Nielsen KK, Vaesel MT, Dalstra M, Sneppen O. Posterolateral elbow joint instability: the basic kinematics. J Shoulder Elbow Surg. 1998;7:19–29.
9. O'Driscoll SW, Morrey BF, An KN. Intraarticular pressure and capacity of the elbow. Arthroscopy. 1990;6:100–3.
10. Morrey BF. Post-traumatic contracture of the elbow. Operative treatment, including distraction arthroplasty. J Bone Joint Surg Am. 1990;72:601–18.
11. Morrey BF, Askew LJ, Chao EY. A biomechanical study of normal functional elbow motion. J Bone Joint Surg Am. 1981;63:872–7.
12. Sardelli M, Tashjian RZ, MacWilliams BA. Functional elbow range of motion for contemporary tasks. J Bone Joint Surg Am. 2011;93:471–7.
13. An KN, Morrey BF, Chao EY. The effect of partial removal of proximal ulna on elbow constraint. Clin Orthop Relat Res. 1986; 270–9.
14. Beuerlein MJ, Reid JT, Schemitsch EH, McKee MD. Effect of distal humeral varus deformity on strain in the lateral ulnar collateral ligament and ulnohumeral joint stability. J Bone Joint Surg Am. 2004;86-A:2235–42.
15. Chanlalit C, Shukla DR, Fitzsimmons JS, Thoreson AR, An K-N, O'Driscoll SW. Radiocapitellar stability: the effect of soft tissue integrity on bipolar versus monopolar radial head prostheses. J Shoulder Elbow Surg. 2011;20:219–25.
16. Cohen MS. Lateral collateral ligament instability of the elbow. Hand Clin. 2008;24:69–77.
17. Dargel J, Boomkamp E, Wegmann K, Eysel P, Müller LP, Hackl M. Reconstruction of the lateral ulnar collateral ligament of the elbow: a comparative biomechanical study. Knee Surg Sports Traumatol Arthrosc. 2015; doi: 10.1007/s00167-015-3627-3.
18. Dunning CE, Zarzour ZD, Patterson SD, Johnson JA, King GJ. Ligamentous stabilizers against posterolateral rotatory instability of the elbow. J Bone Joint Surg Am. 2001;83-A:1823–8.
19. Fuss FK. The ulnar collateral ligament of the human elbow joint. Anatomy, function and biomechanics. J Anat. 1991;175:203–12.
20. de Haan J, Schep NWL, Eygendaal D, Kleinrensink G-J, Tuinebreijer WE, den Hartog D. Stability of the elbow joint: relevant anatomy and clinical implications of in vitro biomechanical studies. Open Orthop J. 2011;5:168–76.
21. Eygendaal D, Verdegaal SH, Obermann WR, van Vugt AB, Pöll RG, Rozing PM. Posterolateral dislocation of the elbow joint. Relationship to medial instability. J Bone Joint Surg Am. 2000;82:555–60.
22. Josefsson PO, Gentz CF, Johnell O, Wendeberg B. Surgical versus non-surgical treatment of ligamentous injuries following dislocation of the elbow joint. A prospective randomized study. J Bone Joint Surg Am. 1987;69:605–8.
23. Josefsson PO, Johnell O, Wendeberg B. Ligamentous injuries in dislocations of the elbow joint. Clin Orthop Relat Res. 1987; 221–5.
24. An KN, Himeno S, Tsumura H, Kawai T, Chao EY. Pressure distribution on articular surfaces: application to joint stability evaluation. J Biomech. 1990;23:1013–20.
25. Seiber K, Gupta R, McGarry MH, Safran MR, Lee TQ. The role of the elbow musculature, forearm rotation, and elbow flexion in elbow stability: an in vitro study. J Shoulder Elbow Surg. 2009;18:260–8.
26. Shukla DR, Fitzsimmons JS, An K-N, O'Driscoll SW. Effect of radial head malunion on radiocapitellar stability. J Shoulder Elbow Surg. 2012;21:789–94.
27. Szekeres M, Chinchalkar SJ, King GJW. Optimizing elbow rehabilitation after instability. Hand Clin. 2008;24:27–38.
28. Hughes RE, Schneeberger AG, An KN, Morrey BF, O'Driscoll SW. Reduction of triceps muscle force

after shortening of the distal humerus: a computational model. J Shoulder Elbow Surg. 1997;6:444–8.
29. Markolf KL, Lamey D, Yang S, Meals R, Hotchkiss R. Radioulnar load-sharing in the forearm. A study in cadavera. J Bone Joint Surg Am. 1998;80:879–88.
30. Morrey BF, An KN, Stormont TJ. Force transmission through the radial head. J Bone Joint Surg Am. 1988;70:250–6.
31. Hotchkiss RN, An KN, Sowa DT, Basta S, Weiland AJ. An anatomic and mechanical study of the interosseous membrane of the forearm: pathomechanics of proximal migration of the radius. J Hand Surg Am. 1989;14:256–61.
32. Morrey BF, Tanaka S, An KN. Valgus stability of the elbow. A definition of primary and secondary constraints. Clin Orthop Relat Res. 1991; 187–95.
33. Pomianowski S, O'Driscoll SW, Neale PG, Park MJ, Morrey BF, An KN. The effect of forearm rotation on laxity and stability of the elbow. Clin Biomech (Bristol, Avon). 2001;16:401–7.
34. Pomianowski S, Morrey BF, Neale PG, Park MJ, O'Driscoll SW, An KN. Contribution of monoblock and bipolar radial head prostheses to valgus stability of the elbow. J Bone Joint Surg Am. 2001; 83-A:1829–34.
35. Safran MR, Baillargeon D. Soft-tissue stabilizers of the elbow. J Shoulder Elbow Surg. 2005;14:179S–85.
36. O'Driscoll SW, Morrey BF, Korinek S, An KN. Elbow subluxation and dislocation. A spectrum of instability. Clin Orthop Relat Res. 1992; 186–97.
37. McKee MD, Schemitsch EH, Sala MJ, O'Driscoll SW. The pathoanatomy of lateral ligamentous disruption in complex elbow instability. J Shoulder Elbow Surg. 2003;12:391–6.
38. Steinmann SP. Coronoid process fracture. J Am Acad Orthop Surg. 2008;16:519–29.
39. Tashjian RZ, Katarincic JA. Complex elbow instability. J Am Acad Orthop Surg. 2006;14:278–86.
40. Wyrick JD, Dailey SK, Gunzenhaeuser JM, Casstevens EC. Management of complex elbow dislocations: a mechanistic approach. J Am Acad Orthop Surg. 2015;23:297–306.
41. Schreiber JJ, Warren RF, Hotchkiss RN, Daluiski A. An online video investigation into the mechanism of elbow dislocation. J Hand Surg Am. 2013;38:488–94.
42. Morrey BF, An KN. Functional anatomy of the ligaments of the elbow. Clin Orthop Relat Res. 1985; 84–90.
43. Murthi AM, Keener JD, Armstrong AD, Getz CL. The recurrent unstable elbow: diagnosis and treatment. Instr Course Lect. 2011;60:215–26.
44. Anakwenze OA, Kancherla VK, Iyengar J, Ahmad CS, Levine WN. Posterolateral rotatory instability of the elbow. Am J Sports Med. 2014;42:485–91.
45. Moritomo H, Murase T, Arimitsu S, Oka K, Yoshikawa H, Sugamoto K. The in vivo isometric point of the lateral ligament of the elbow. J Bone Joint Surg Am. 2007;89:2011–7.
46. Regan WD, Korinek SL, Morrey BF, An KN. Biomechanical study of ligaments around the elbow joint. Clin Orthop Relat Res. 1991; 170–9.
47. O'Driscoll SW, Spinner RJ, McKee MD, et al. Tardy posterolateral rotatory instability of the elbow due to cubitus varus. J Bone Joint Surg Am. 2001; 83-A:1358–69.
48. O'Driscoll SW, Bell DF, Morrey BF. Posterolateral rotatory instability of the elbow. J Bone Joint Surg Am. 1991;73:440–6.
49. McAdams TR, Masters GW, Srivastava S. The effect of arthroscopic sectioning of the lateral ligament complex of the elbow on posterolateral rotatory stability. J Shoulder Elbow Surg. 2005;14:298–301.
50. Olsen BS, Henriksen MG, Sojbjerg JO, Helmig P, Sneppen O. Elbow joint instability: a kinematic model. J Shoulder Elbow Surg. 2009;3:143–50.
51. Gray AB, Alolabi B, Ferreira LM, Athwal GS, King GJW, Johnson JA. The effect of a coronoid prosthesis on restoring stability to the coronoid-deficient elbow: a biomechanical study. J Hand Surg Am. 2013;38:1753–61.
52. Schneeberger AG, Sadowski MM, Jacob HAC. Coronoid process and radial head as posterolateral rotatory stabilizers of the elbow. J Bone Joint Surg Am. 2004;86-A:975–82.
53. Hotchkiss RN, Weiland AJ. Valgus stability of the elbow. J Orthop Res. 1987;5:372–7.
54. Deutch SR, Jensen SL, Tyrdal S, Olsen BS. Elbow joint stability following experimental osteoligamentous injury and reconstruction. Journal of Shoulder and reconstruction. J Shoulder Elbow Surg. 2003;12(5):466–71. doi:10.1016/S1058-2746(03)00062-4.
55. Deutch SR, Jensen SL, Olsen BS. Elbow joint stability in relation to forced external rotation: an experimental study of the osseous constraint. J Shoulder Elbow Surg. 2003;12(3):287–92. doi:10.1016/S1058-2746(02)86814-8.
56. Sabo MT, Shannon HL, Deluce S, Lalone E, Ferreira LM, Johnson JA, King GJW. Capitellar excision and hemiarthroplasty affects elbow kinematics and stability. J Shoulder Elbow Surg. 2012;21:1024–1031.e4.
57. Root CG, Meyers K, Wright T, Hotchkiss R. Capitellum excision: mechanical implications and clinical consequences. J Orthop Res. 2014;32: 346–50.
58. Jensen SL, Olsen BS, Tyrdal S, Søjbjerg JO, Sneppen O. Elbow joint laxity after experimental radial head excision and lateral collateral ligament rupture: efficacy of prosthetic replacement and ligament repair. J Shoulder Elbow Surg. 2005;14:78–84.
59. Chanlalit C, Shukla DR, Fitzsimmons JS, An K-N, O'Driscoll SW. The biomechanical effect of prosthetic design on radiocapitellar stability in a terrible triad model. J Orthop Trauma. 2012;26:539–44.
60. Moon J-G, Berglund LJ, Zachary D, An K-N, O'Driscoll SW. Radiocapitellar joint stability with bipolar versus monopolar radial head prostheses. J Shoulder Elbow Surg. 2009;18:779–84.
61. Van Glabbeek F, Van Riet RP, Baumfeld JA, Neale PG, O'Driscoll SW, Morrey BF, An KN. Detrimental effects of overstuffing or understuffing with a radial head replacement in the medial collateral-ligament

deficient elbow. J Bone Joint Surg Am. 2004;86-A: 2629–35.
62. Schwab GH, Bennett JB, Woods GW, Tullos HS. Biomechanics of elbow instability: the role of the medial collateral ligament. Clin Orthop Relat Res. 1980; 42–52.
63. Armstrong AD, Dunning CE, Ferreira LM, Faber KJ, Johnson JA, King GJW. A biomechanical comparison of four reconstruction techniques for the medial collateral ligament-deficient elbow. J Shoulder Elbow Surg. 2005;14:207–15.
64. Søjbjerg JO, Ovesen J, Nielsen S. Experimental elbow instability after transection of the medial collateral ligament. Clin Orthop Relat Res. 1987; 186–90.
65. Hassan SE, Parks BG, Douoguih WA, Osbahr DC. Effect of distal ulnar collateral ligament tear pattern on contact forces and valgus stability in the posteromedial compartment of the elbow. Am J Sports Med. 2015;43:447. doi:10.1177/0363546514557239.
66. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. Am J Sports Med. 1995; 23:233–9.
67. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. Am J Sports Med. 2009;37:2043–8.
68. Anz AW, Bushnell BD, Griffin LP, Noonan TJ, Torry MR, Hawkins RJ. Correlation of torque and elbow injury in professional baseball pitchers. Am J Sports Med. 2010;38:1368–74.
69. Davis JT, Limpisvasti O, Fluhme D, Mohr KJ, Yocum LA, Elattrache NS, Jobe FW. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. Am J Sports Med. 2009;37:1484–91.
70. Dillman CJ, Fleisig GS, Andrews JR. Biomechanics of pitching with emphasis upon shoulder kinematics. J Orthop Sports Phys Ther. 1993;18:402–8.
71. Feltner ME, Dapena J. Three-dimensional interactions in a two-segment kinetic chain. Part 1; General model. Int J Sports Biomech. 1989;5:403–19.
72. Werner SL, Fleisig GS, Dillman CJ, Andrews JR. Biomechanics of the elbow during baseball pitching. J Orthop Sports Phys Ther. 1993;17:274–8.
73. Altchek DW, Hyman J, Williams R, Levinson M, Allen AA, Paletta Jr GA, Dines DM, Botts JD. Management of MCL injuries of the elbow in throwers. Tech Shoulder Elbow Surg. 2000;1:73–81.
74. Dodson CC, Altchek DW. Ulnar collateral ligament reconstruction revisited: the procedure I use and why. Sports Health. 2012;4:433–7.
75. Dodson CC, Thomas A, Dines JS, Nho SJ, Williams RJ, Altchek DW. Medial ulnar collateral ligament reconstruction of the elbow in throwing athletes. Am J Sports Med. 2006;34:1926–32.
76. Morrey BF, An KN. Articular and ligamentous contributions to the stability of the elbow joint. Am J Sports Med. 1983;11:315–9.
77. Bowers AL, Dines JS, Dines DM, Altchek DW. Elbow medial ulnar collateral ligament reconstruction: clinical relevance and the docking technique. J Shoulder Elbow Surg. 2010;19:110–7.
78. Conway JE, Jobe FW, Glousman RE, PINK M. Medial instability of the elbow in throwing athletes. Treatment by repair or reconstruction of the ulnar collateral ligament. J Bone Joint Surg Am. 1992;74:67–83.
79. Jobe FW, Stark H, Lombardo SJ. Reconstruction of the ulnar collateral ligament in athletes. J Bone Joint Surg Am. 1986;68:1158–63.
80. Savoie FH, Morgan C, Yaste J, Hurt J, Field L. Medial ulnar collateral ligament reconstruction using hamstring allograft in overhead throwing athletes. J Bone Joint Surg Am. 2013;95:1062–6.
81. Thompson WH, Jobe FW, Yocum LA, Pink MM. Ulnar collateral ligament reconstruction in athletes: muscle-splitting approach without transposition of the ulnar nerve. J Shoulder Elbow Surg. 2001;10:152–7.
82. Waris W. Elbow injuries of javelin-throwers. Acta Chir Scand. 1946;93:563–75.
83. Dodson CC, Craig EV, Cordasco FA, Dines DM, Dines JS, DiCarlo E, Brause BD, Warren RF. Propionibacterium acnes infection after shoulder arthroplasty: a diagnostic challenge. J Shoulder Elbow Surg. 2010;19:303–7.
84. Petty DH. Ulnar collateral ligament reconstruction in high school baseball players: clinical results and injury risk factors. Am J Sports Med. 2004; 32:1158–64.
85. Podesta L, Crow SA, Volkmer D, Bert T, Yocum LA. Treatment of partial ulnar collateral ligament tears in the elbow with platelet-rich plasma. Am J Sports Med. 2013;41:1689–94.
86. Rohrbough JT, Altchek DW, Hyman J, Williams RJ, Botts JD. Medial collateral ligament reconstruction of the elbow using the docking technique. Am J Sports Med. 2002;30:541–8.
87. Kodde IF, Rahusen FTG, Eygendaal D. Long-term results after ulnar collateral ligament reconstruction of the elbow in European athletes with interference screw technique and triceps fascia autograft. J Shoulder Elbow Surg. 2012;21:1656–63.
88. Glousman RE, Barron J, Jobe FW, Perry J, Pink M. An electromyographic analysis of the elbow in normal and injured pitchers with medial collateral ligament insufficiency. Am J Sports Med. 1992; 20:311–7.
89. Chronister JE, Morris RP, Andersen CR, Buford WL, Bennett JM, Mehlhoff TL. A biomechanical comparison of 2 hybrid techniques for elbow ulnar collateral ligament reconstruction. J Hand Surg. 2014;39:2033–40.
90. Ahmad CS, Lee TQ, ElAttrache NS. Biomechanical evaluation of a new ulnar collateral ligament reconstruction technique with interference screw fixation. Am J Sports Med. 2003;31:332–7.
91. Ciccotti MG, Siegler S, Kuri JA, Thinnes JH, Murphy DJ. Comparison of the biomechanical profile of the intact ulnar collateral ligament with the modified Jobe and the Docking reconstructed elbow: an in vitro study. Am J Sports Med. 2009;37:974–81.

92. Hurbanek JG, Anderson K, Crabtree S, Karnes GJ. Biomechanical comparison of the docking technique with and without humeral bioabsorbable interference screw fixation. Am J Sports Med. 2009;37:526–33.
93. McGraw MA, Kremchek TE, Hooks TR, Papangelou C. Biomechanical evaluation of the docking plus ulnar collateral ligament reconstruction technique compared with the docking technique. Am J Sports Med. 2013;41:313–20.
94. Morgan RJ, Starman JS, Habet NA, Peindl RD, Bankston LS, D'Alessandro DD, Connor PM, Fleischli JE. A biomechanical evaluation of ulnar collateral ligament reconstruction using a novel technique for ulnar-sided fixation. Am J Sports Med. 2010;38:1448–55.
95. Paletta GA, Klepps SJ, Difelice GS, Allen T, Brodt MD, Burns ME, Silva MJ, Wright RW. Biomechanical evaluation of 2 techniques for ulnar collateral ligament reconstruction of the elbow. Am J Sports Med. 2006;34:1599–603.
96. Ruland RT, Hogan CJ, Randall CJ, Richards A, Belkoff SM. Biomechanical comparison of ulnar collateral ligament reconstruction techniques. Am J Sports Med. 2008;36:1565–70.

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