Introduction

The overhead throwing motion is created by a complex series of coordinated movements involving different motor groups and the articulations of the upper extremity as well as the kinetic chain. The necessary kinematics of throwing place significant stresses across the joints of the upper extremity, which can lead to potential overload and injury. The shoulder and elbow are most susceptible to injury during throwing. Even though, this text is centered upon the medial collateral ligament (MCL) injury to the elbow, one must be aware of the biomechanics of the entire upper extremity in throwers in order to understand the cause and prevention of such injuries.

Recent technologic advances in motion analysis have given researchers a better understanding of the anatomic, biomechanical, and physiologic demands placed on the shoulder and elbow during throwing. Clearly, changes in kinetics and kinematics during throwing can have a significant effect upon the anatomy and lead to serious, even career ending injury. For these reasons, it is imperative to have a comprehensive and sport-specific knowledge of muscle recruitment sequences in order to understand potential causes of anatomic failure and subsequent injury. In addition, this fundamental knowledge can lead to the development of better rehabilitation programs to prevent these injuries.

Of all overhead athletes, baseball pitchers are at greatest risk of acute and chronic upper extremity pathology, particularly injury to the MCL and medial elbow. While some other athletes may be at risk, such as javelin throwers, tennis servers, and even football throwers, pitchers carry the highest risk and have the highest incidence. Epidemiologic studies of injury patterns in baseball players have shown that there are a higher percentage of upper extremity injuries in Division I college players (58%) [1]. In Major League Baseball, approximately 30% of player days on the disabled list were the result of shoulder (and elbow) injury. Pitchers comprised the majority of disability days at 48%, compared to 20% for outfielders. Most of the injuries pitchers sustained were the result of repetitive overuse of shoulder or elbow [2]. The purpose of this chapter is to define the biomechanics in the overhead athlete with a special emphasis upon the biomechanics of the elbow.

Biomechanics of Throwing

As a framework for the understanding of the biomechanics of the throwing shoulder, the pitching cycle is now broken down into six distinct phases, each with its own changes in muscle and joint activity at the shoulder and elbow. During this activity, the thrower must create potential energy generated
from the lower extremities and transmitted upward through the pelvis to the trunk and ultimately to the smaller segments of the upper extremity, thereby creating the kinetic energy delivered to the ball in a purposeful manner. This is known as “The Kinetic Chain Theory” of throwing.

**Six Phases of the Baseball Pitch**

In order to understand the biomechanics of throwing, one must be aware of the six phases of pitching and the effect of the kinetic chain. The throwing motion of the overhead pitch has been divided into 6 segments or phases from wind-up to follow-through [3, 4].

*Phase I* This initial stage is called the windup phase. During this phase the pitcher balances on the trailing push-off leg, while the stride leg reaches its maximum hip flexion. The arm is in slight abduction and internal rotation. The elbow is flexed and forearm pronated.

*Phase II* This stage is known as the early cocking phase, during which the ball is removed from the glove, the hands separate and the shoulder abducts and externally rotates. As this occurs, the ground reactive forces manifest in the lower body segments and these forces are then directed through the hip and pelvis of the push-off leg creating forward movement of the body to generate the kinetic energy in the direction of the throw. As this push-off force increases so does the velocity of the throw. During this phase there is increased activation in virtually all muscle groups of the shoulder girdle except the upper and lower trapezius with the highest degree of activation being observed in the upper trapezius (64% MVIC, multispectral visible imaging camera) and supraspinatus (51% MVIC) (Fig. 2.1; [5]). The elbow remains flexed between 80–90°.

![Baseball Pitch: EMG Data](image)

**Fig. 2.1** Electromyographic analysis of the upper extremity musculature during overhead throwing. *EMG* electromyography, *MVIC* multispectral visible imaging camera
Phase III The late cocking phase is characterized by maximal shoulder abduction and external rotation. The elbow is flexed 90–120° and forearm pronation is increased to 90°. During this phase, the greatest activation is noted in the subscapularis (124% MVIC) and serratus anterior (104% MVIC) [6].

Phase IV Acceleration is marked by generation of a forward-directed force resulting in internal rotation and adduction of the humerus coupled with rapid elbow extension. The greatest activity is again noted in the subscapularis (152% MVIC) and serratus anterior (147% MVIC). There is also a large increase in the recruitment of the latissimus dorsi (from 32 to 110% MVIC). Stage 4 terminates with ball release and lasts 40–50 msec. During this brief amount of time, the elbow accelerates as much as 5000°/s² [7]. The medial elbow structures experience a tremendous valgus stress during the late cocking and early acceleration phases. Valgus forces as high as 64 Nm are observed at the elbow during late cocking/early acceleration [8].

Phase V Deceleration begins at ball release and with all muscle groups about the shoulder maximally contracting to decelerate arm rotation. Shoulder abduction is maintained at approximately 100° while the elbow reaches terminal extension at 20° short of full extension. Eccentric biceps and triceps contraction assists in slowing down elbow extension. Forceful deceleration of the upper extremity occurs at a rate of nearly 500,000°/s² over the short time of 50 ms [9].

Phase VI The final stage is follow-through. This phase involves dissipation of all excess kinetic energy as the elbow reaches full extension and the throwing motion is complete.

The Kinetic Chain Theory

The kinetic chain is defined as a rapid, coordinated progression of muscle activation and force development from the legs (distal segments) to the arm during initiation of unilateral arm throwing. Muscle activation is first seen in segments from the contralateral foot stabilizing structures and progressing through the lower legs to the pelvis and trunk and ultimately to the rapidly accelerating upper extremity. This progression captures the kinetic energy and transfers it effectively up the chain to the smaller upper extremity segments, as the shoulder is not able to generate very much force by itself. The main function of the shoulder is to harness the forces from below and to direct these forces to the arm. The forces of the kinetic chain within the upper extremity then propagate from proximal to distal resulting in a high-velocity ball release.

When looking specifically at the elbow and its interplay with the kinetic chain, two main interactions are found. First, the forearm muscle groups have been noted to assist in fine-tuning ball release. Hirashima et al. [10] analyzed pitching motions and found proximal-to-distal muscle activation, peak torque development, and force development from the trunk to the elbow. In this study of the trunk and arm muscles, the muscle activation sequencing and peak intensity proceeded from the contralateral internal and external obliques and rectus abdominis muscles to the scapular stabilizers, deltoid, and rotator cuff. Force development also proceeded in this pattern. The study showed that muscle activation around the elbow did not appear to continue in this force development sequence but rather occurred in conjunction as a way for the upper extremity to fine-tune and control the pitch. These forearm muscle activations have been called voluntary focal movements.

The second interaction between the kinetic chain and elbow is to create positions and motions that align elbow articulation to minimize the loads dissipated to the supporting ligaments. Internal rotation of the shoulder with the elbow near full extension and forearm pronated places significantly less stress on the medial elbow. This is seen clinically as elbow injuries during pitching have been associated with mechanics in which the elbow is positioned below the shoulder during the acceleration phase.

Without adequate proximal muscle activation, the distal extremity (i.e., elbow) will experience
an increased load and significant stress to generate an equivalent throwing force. Clearly, core conditioning is a critical factor in creating the appropriate timing necessary for the efficient transfer of forces up this chain, as well as in injury prevention.

**Anatomy and Biomechanics of the Elbow**

The medial ulnar collateral ligament (UCL) of the elbow is a frequent site of serious injury in the athlete performing overhead throwing motions, particularly the competitive baseball pitcher. The stability of the elbow stems from an intricate balance of osseous, ligamentous, and muscular forces. Injury to the UCL is rarely found in isolation, and therefore a keen understanding of the complex anatomy and the common injuries encountered along the medial elbow are paramount.

**Osseous Anatomy**

The osseous anatomy of the elbow allows for flexion-extension and pronation-supination through the ulnohumeral and radiocapitellar articulations, respectively. The bony architecture of the proximal ulna and distal humerus provide approximately 50% of the overall stability of the elbow. With the elbow in 0–30° of extension the olecranon is the primary stabilizer to varus stress. The innate resistance to varus stress of the highly congruous, interlocking ulnohumeral articulation is further increased by the normal valgus carrying angle of 11–16° with the arm fully extended. In contrast, the radiocapitellar joint acts as a secondary stabilizer to valgus load. The remaining stability of the elbow is afforded by the radial collateral ligament complex, the UCL complex, and the anterior joint capsule.

In the young athletic elbow, it is important to have a full understanding of the secondary ossification centers that form the distal humerus, proximal ulna, and radius. These apophyses of the elbow appear and fuse at predictable ages and are listed in Table 2.1. These growth centers do not contribute to the overall length of the arm, but are important attachment sites for muscle groups and stabilizing ligaments.

**Table 2.1 Elbow ossification centers**

<table>
<thead>
<tr>
<th>Site</th>
<th>Age at appearance of epiphysis/apophysis</th>
<th>Age at closure of epiphysis/apophysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capitellum</td>
<td>18 months</td>
<td>14 years</td>
</tr>
<tr>
<td>Radial head</td>
<td>5 years</td>
<td>16 years</td>
</tr>
<tr>
<td>Medial epicondyle</td>
<td>5 years</td>
<td>15 years</td>
</tr>
<tr>
<td>Trochlea</td>
<td>8 years</td>
<td>14 years</td>
</tr>
<tr>
<td>Olecranon</td>
<td>10 years</td>
<td>14 years</td>
</tr>
<tr>
<td>Lateral epicondyle</td>
<td>12 years</td>
<td>16 years</td>
</tr>
</tbody>
</table>

**Ligamentous Anatomy: Medial Elbow**

The UCL complex consists of three ligaments: the anterior oblique (AOL), posterior oblique (POL), and the transverse ligaments. The origin of the AOL and POL is from the anteroinferior surface of the medial epicondyle.

The AOL, consisting of parallel fibers running from its origin and inserting on the medial coronoid process, is functionally the most important due to its strength in resisting valgus stress. The AOL is 4–5 mm wide and is functionally further subdivided into anterior bands (AB) and posterior bands (PB) that provide reciprocal functions in resisting a valgus force through the range of motion. The AB is the primary restraint to valgus stress up to 90° of flexion and becomes secondary with further flexion. The PB becomes functionally more important between 60° and full flexion of the elbow. As a corollary, the PB has increased utility in the overhead athlete, as it is the primary restraint to valgus force with higher degrees of flexion. When both bands of the UCL are completely sectioned, elbow laxity is greatest at 70° of flexion.

The POL is a fan-shaped thickening of the capsule that originates from the medial epicondyle and inserts onto the medial margin of the semilunar notch. The POL is 5–8 mm wide at its midportion, is thinner than the AOL and forms the floor of the cubital tunnel. It plays a secondary stabilizing role with the elbow in flexion beyond...
90° and therefore vulnerable to valgus stress only when the anterior bundle is completely detached.

The transverse ligament, also known as Cooper’s ligament or the oblique ligament, connects the inferior medial coronoid process with the olecranon. This ligament does not cross the elbow joint and is generally believed to confer no stability against a valgus force.

**Musculotendinous Anatomy**

Any muscle that crosses the elbow joint does create a joint reactive force, thereby stabilizing the joint through dynamic articular compression. Morrey et al. have shown the stability conferred to the elbow by the triceps, biceps, and brachialis through an elbow model in which the medial UCL and radial head were resected [11]. In addition to these three muscles and pertinent to the overhead thrower, the flexor-pronator muscles provide further support to valgus stress across the medial elbow. Originating from the medial epicondyle, the flexor-pronator group (from proximal to distal) includes the pronator teres, flexor carpi radialis (FCR), palmaris longus, flexor digitorum superficialis, and flexor carpi ulnaris (FCU). The FCU and portions of the flexor digitorum superficialis lie directly over the anterior bundle of the medial UCL and therefore have an enhanced role in dynamic stabilization. As a corollary, electromyographic studies have shown maximal activity for the flexor-pronator muscle group during the acceleration phase of throwing.

**Ulnar Nerve**

The ulnar nerve has an intimate anatomic relationship with the musculotendinous and ligamentous stabilizers along the medial elbow and is thereby prone to injury during repetitive overhead throwing activities. As the nerve courses distally within the brachium, it passes through the arcade of Struthers, which is located approximately 8 cm proximal to the medial epicondyle. Descending through the midportion of the arm, the nerve then traverses the medial intermuscular septum emerging from the anterior compartment into the posterior compartment. About the elbow, the nerve rests in the cubital tunnel which is bordered anteriorly by the medial epicondyle, posteriorly by the medial head of the triceps and superficially by Osborne’s ligament. The floor of the cubital tunnel is formed by the UCL complex. Sensory fibers within the peripheral nerve are at increased risk with UCL injury given their more superficial location in relation to the motor branches. Exiting the cubital tunnel the nerve then enters the forearm between the two heads of the FCU and finally rests on the flexor digitorum profundus.

Similar to all peripheral nerves, the ulnar nerve is susceptible to injury due to elongation, compression, and inflammation. Elongation occurs during moments of arm abduction, elbow flexion and wrist extension. A study evaluating the pressure within the ulnar nerve during various elbow and arm positions found a threefold increase in intraneural pressures with the elbow flexed at 90° and the wrist extended, which is a similar position to seen during the late cocking and early acceleration phases of throwing [12, 13]. In addition, superphysiologic elongation of the nerve may occur with a valgus stress to the elbow with an incompetent UCL causing traction neuritis. Narrowing of the cubital tunnel occurs during elbow flexion and is one of several sources of compression. Gelberman et al. demonstrated that the diameter of the cubital tunnel decreases by nearly half during elbow flexion [14]. Compression of the nerve can also occur due to loose bodies, synovitis, thickening of Osborne’s ligament, chronic inflammation and/or thickened UCL, or calcification of the UCL.

**Biomechanics of Medial Elbow Injury**

The significant valgus stress from overhead throwing activities creates tensile stresses that often predispose the UCL to injury. Kinematic testing has identified that the resultant valgus stress applied to the medial elbow during the acceleration phase is 64 N-m. Moreover, the static torque on the UCL during pitching has been
estimated to be 32 N-m. This force approaches the known ultimate tensile strength of the UCL of 33 N-m seen in cadaveric specimens [15]. This finding provides evidence for additive dynamic musculotendinous stabilization by the flexor-pronator group as well as a cause for attenuation and eventual collateral ligament failure. In addition, during the acceleration phase, the torque produced generates approximately 500 N of compressive force at the radiocapitellar joint and an estimated 300 N of medial shear force, contributing the valgus extension overload injuries.

In addition to isolated injuries to the UCL, the combination of large valgus loads with rapid elbow extension produces three phenomena: (1) tensile stress along the other medial compartment restraints (flexor-pronator mass, medial epicondyle apophysis, and ulnar nerve), (2) shear stress in the posterior compartment (posteromedial tip of the olecranon and trochlea/olecranon fossa), and (3) compression stress in the radiocapitellar joint. These phenomena have been termed “valgus extension overload syndrome” and form the basic pathophysiologic model behind the most common elbow injuries in the throwing athlete [16]. The syndrome is signified by olecranon tip osteophytes, loose bodies in the posterior or radiocapitellar compartment, and chondromalacia along the posteromedial trochlea. Associated findings include subtle laxity of the UCL, flexor-pronator tendinitis, ulnar neuritis, and medial epicondyle apophysitis in the skeletally immature. Those physicians who treat such injuries in overhead throwing athletes must retain a high degree of suspicion for underlying UCL laxity as the cause of many of these lesions.

References

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