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Optimizing the Management of Anterior Monteggia Fractures: A Biomechanical Evaluation of Treatment Options

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Abstract

Anterior Monteggia injuries are frequently complicated by persistent radial head instability and suboptimal outcomes. Using a cadaveric elbow motion simulator, we quantified the contributions of ligaments of the proximal radius on maintaining radial head stability, evaluated the effectiveness of ulnar overcorrection to create an apex dorsal angulation in stabilizing the radiocapitellar joint, and finally compared the stabilizing effect of annular ligament repair to three different reconstruction techniques. Our results showed increased anterior radial head translation with progressive soft tissue sectioning with the annular ligament as the primary stabilizer. Ulnar overcorrection and forearm pronation were shown to decrease anterior translation of the radial head. Finally, our results showed annular ligament repair restored stability closest to the intact state. These findings support the importance of safeguarding the annular ligament and repairing if feasible. Our findings also suggest pronation may be a useful method of postoperative immobilization for patients with anterior radiocapitellar instability.

Keywords

Monteggia, Radial Head, Subluxation, Dislocation, Instability, Anterior, Posterior, Angulation, Annular Ligament, Repair, Reconstruction, Overcorrection

Summary for Lay Audience

Monteggia injuries are fracture-dislocations of the forearm and elbow. The forearm is made up of two bones – the ulna and the radius. When the ulna breaks close to the elbow, it can often cause the radial bone to dislocate out of its joint, at the elbow. These injuries occur most commonly from a direct blow to the forearm while the elbow is extended, like during wresting or football activities or due to conditions like osteoporosis. Monteggia fractures occur most often in young males and elderly females.

There are different types of Monteggia fractures and they are grouped into their direction of ulnar fracture and radial head dislocation. This study focuses on type 1 Monteggia fractures, which are apex anterior ulnar fractures associated with an anterior dislocation of the radial head. Type 1 Monteggia fractures are the most common type occurring in children. While children may get away with nonoperative treatment, surgical management is crucial for the majority of Monteggia fractures in adults.

The overall purpose of this biomechanical investigation is to study the specific injuries which play a role in anterior Monteggia fractures leading to anterior radial head instability. We also evaluate surgical strategies to improve radial head stability including rebreaking the ulna and creating a posterior angulation, also known as overcorrection. We also evaluated four different annular ligament repair and reconstruction procedures. In order to investigate this, we employed a cadaver-based biomechanical testing protocol.

The results showed the annular ligament to be an important stabilizer of the radial head. We also found that overcorrection of the ulna as well as a pronated forearm position helped to stabilize the radial head. Finally, we found that the annular ligament repair was the best method to restore radial head stability.

Clinical implications of these findings suggest evaluating and keeping the annular ligament protected throughout treatment. It has also been shown that overcorrection can be a viable surgical option to increase stability. Finally, since pronation helped stabilize the radial head, this could be an optimal position of immobilization for the arm in patients with anterior Monteggia fractures.

Co-Authorship Statement

Chapter 1:
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Specimen Preparation: Kirk Vannitamby, Carlos Prada
Data Collection: Kirk Vannitamby, Cole Fleet
Data Analysis: Kirk Vannitamby, Cole Fleet
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This project would not have been possible without the generous support of many individuals, but first and foremost, I would like to thank my supervisors, Dr. Graham King and Dr. Jim Johnson.

Dedication

I would like to dedicate this work to my beautiful wife Neneh Vannitamby and our daughter Eden. Without the support of whom, none of this would be possible.

Table of Contents

List of Figures

Chapter 1

1 Introduction

The purpose of this thesis is to investigate treatment options for radial head instability in anterior Monteggia injuries using an in vitro biomechanical model.

This chapter reviews the relevant anatomy and biomechanics of the elbow. An overview of Monteggia fracture-dislocations with a focus on their patterns, proposed mechanisms of injury, management and outcomes are also presented. The rationale, objectives and hypotheses of this thesis are then summarized.

1.1 Elbow and Forearm Anatomy

1.1.1 Bony Anatomy

The elbow joint is a confluence of the distal humerus, the radial head and the proximal ulna. Within the elbow there are three main articulations which include: the radiocapitellar, the ulnohumeral and the proximal radioulnar joints (Figure 1-1). These three joints allow the elbow to perform flexion-extension and pronation-supination movements.

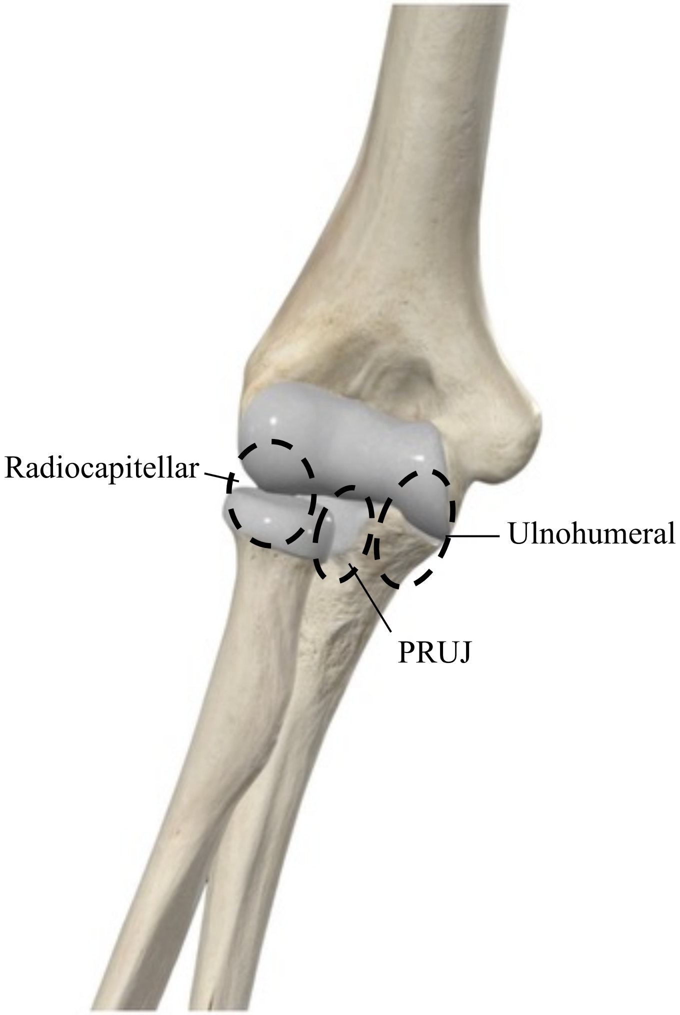

Figure 1-1: Elbow Joint Articulations.[1]

The elbow joint consists of three articulations: the radiocapitellar joint, the proximal radioulnar joint (PRUJ) and the ulnohumeral joint.

The distal humerus articulates with the radial head laterally through the capitellum and medially with the ulna through the trochlea (Figure 1-2). Laterally, the humerus contains a prominence termed the lateral epicondyle which serves at the origin of the lateral collateral ligament (LCL) and the supinator-extensor muscles (Figure 1-3). Medially, a prominence of the humerus called the medial epicondyle serves as the origin of the medial collateral ligament (MCL) and the flexor-pronator muscle group. To accommodate for flexion-extension through the elbow joint, the humerus has crypts known as fossa both anteriorly and posteriorly, respectively. Anteriorly the distal humerus contains two fossae: the radial fossa and the coronoid fossa. Posteriorly, it contains the olecranon fossa.

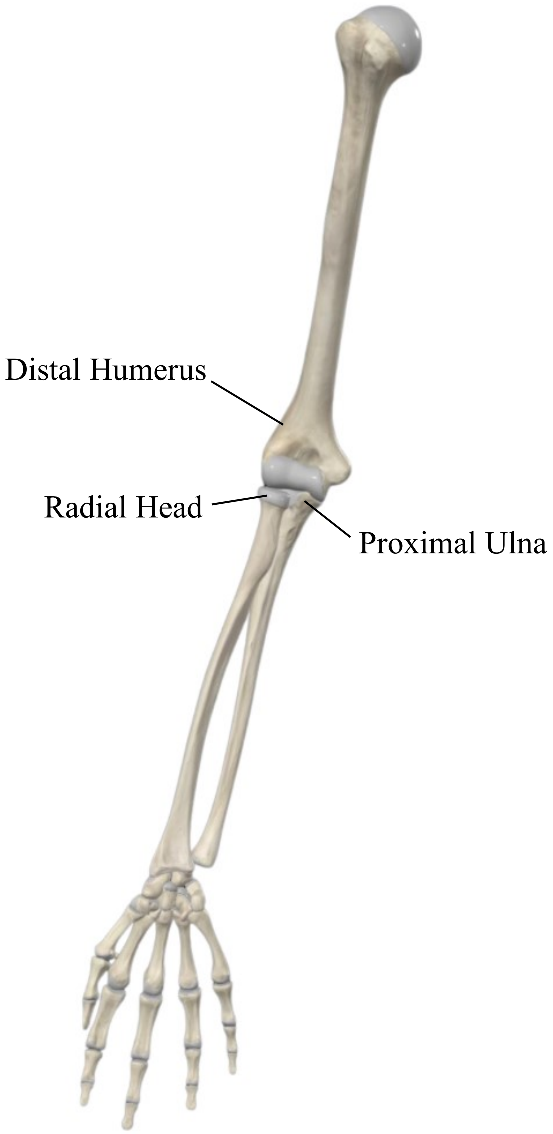

Figure 1-2: Bony Anatomy of the Elbow Joint.[1]

The elbow is comprised of three articulations formed by the distal humerus, the radial head, and the proximal ulna.

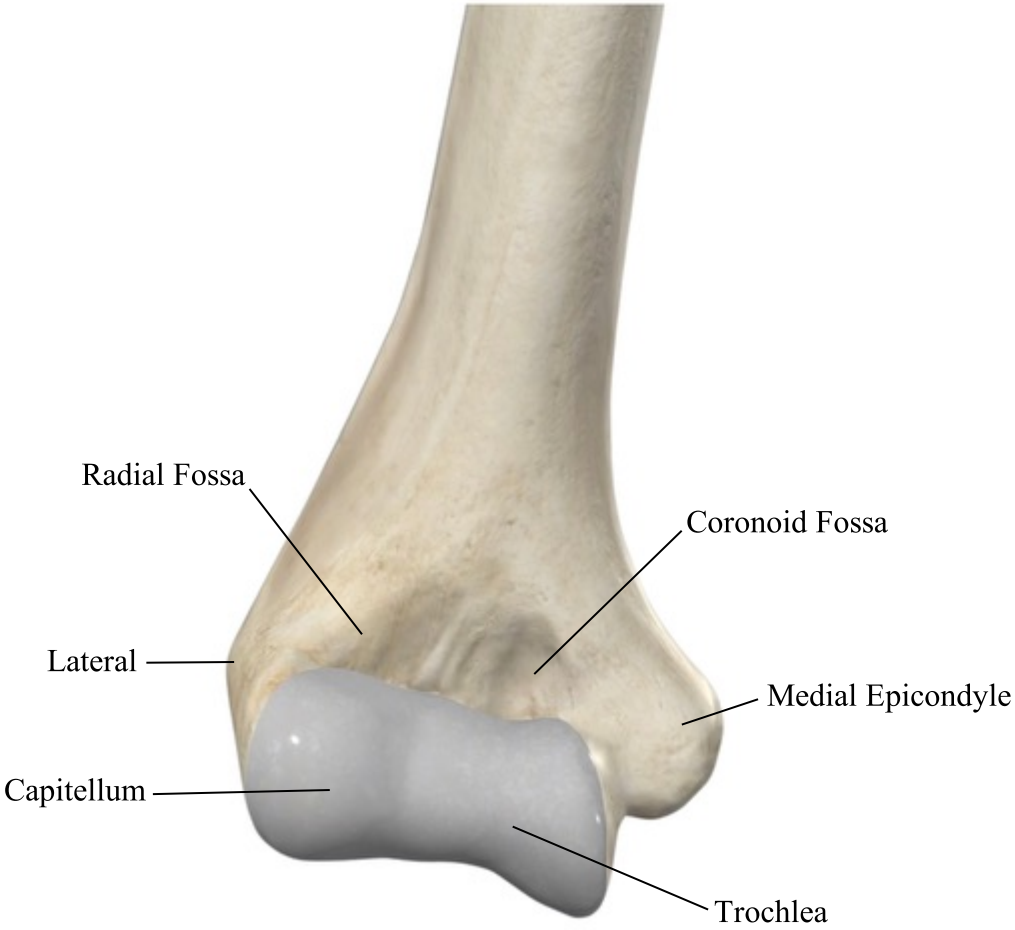

Figure 1-3: Bony Anatomy of the Distal Humerus.[1]

The distal humerus features an articular surface composed of the capitellum and trochlea. Additionally, the flexor-pronator and supinator-extensor muscle groups originate from the medial and lateral epicondyles, respectively. Furthermore, the radial and coronoid fossae can be found on the anterior surface of the distal humerus.

The proximal radius articulates with the distal humerus and allows for pronation and supination. Proximally, the radius is comprised of the radial head, radial neck, and radial tuberosity (Figure 1-4). The radial head is an elliptical concave surface that articulates with the convex shape of the capitellum of the humerus forming the radiocapitellar joint. The radial tuberosity serves as an insertion point of the biceps tendon.

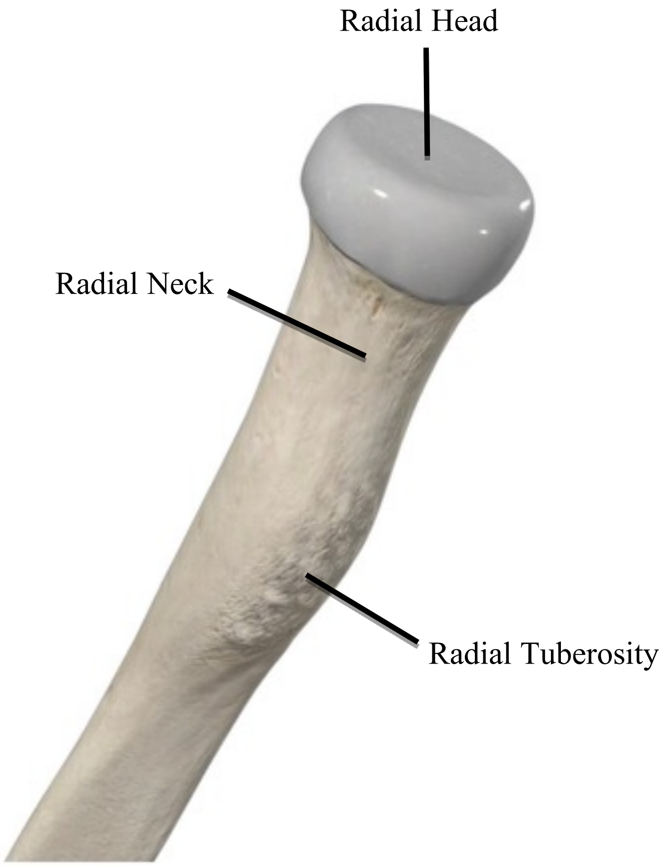

Figure 1-4: Bony Anatomy of the Proximal Radius.[1]

The radial head articulates with the capitellum and the lesser sigmoid notch. The biceps brachii tendon inserts at the radial tuberosity.

The proximal ulna articulates with both the proximal radius as well as the distal humerus. Proximally, the ulna is comprised of the greater sigmoid notch, the lesser sigmoid notch, the olecranon process and the coronoid process (Figure 1-5). The ulna articulates with the trochlea of the distal humerus through the greater sigmoid notch which is a concave surface between the coronoid process and the olecranon. This is known as the ulnohumeral joint. The lesser sigmoid notch, located just lateral to the coronoid process, articulates with the rim of the radial head forming the proximal radioulnar joint (PRUJ). Extension maneuvers are performed with the help of the triceps muscle with inserts into the olecranon process. Flexion maneuvers are performed with the help of the brachialis muscle which inserts itself to a prominence on the anterior ulna known as the coronoid process.

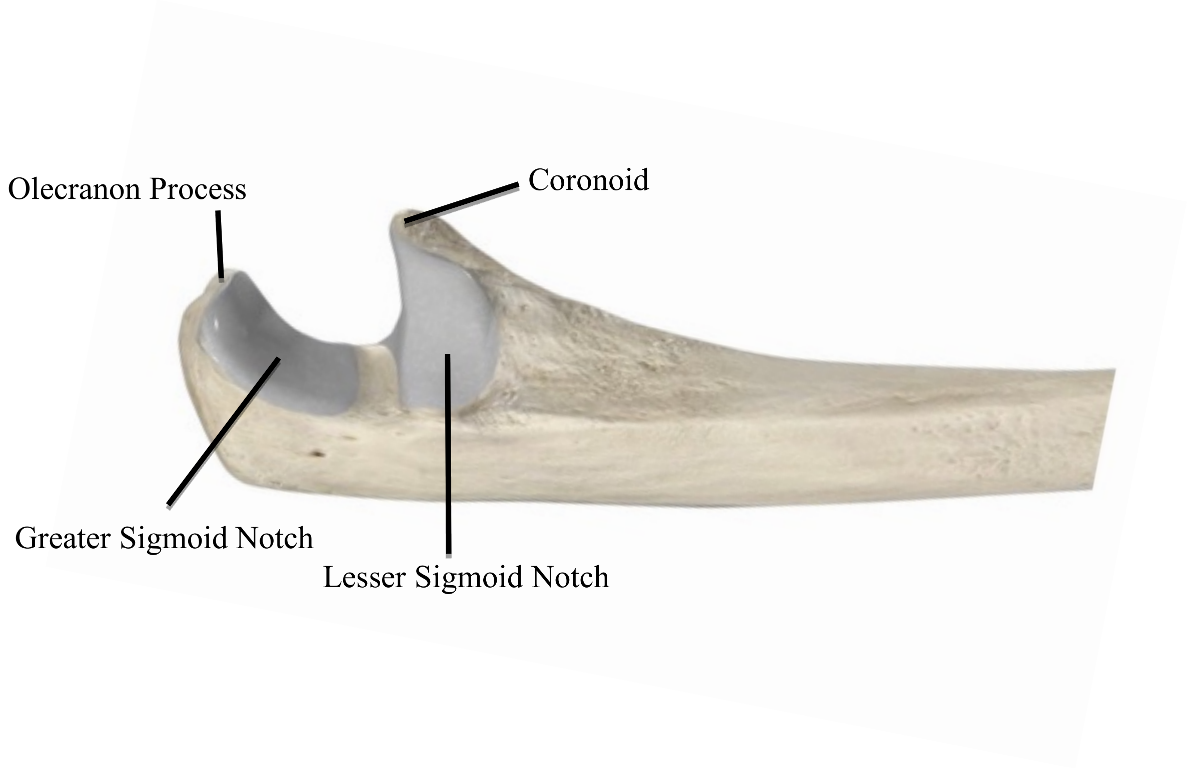

Figure 1-5: Bony Anatomy of the Proximal Ulna.[1]

The greater sigmoid notch articulates with the trochlea. The lesser sigmoid notch articulates with the radial head. The coronoid and olecranon processes are also depicted here.

The radius and ulna make up the bones of the forearm (Figure 1-6). Their main articulations include both the proximal radioulnar joint (PRUJ) as well as the distal radioulnar joint (DRUJ).

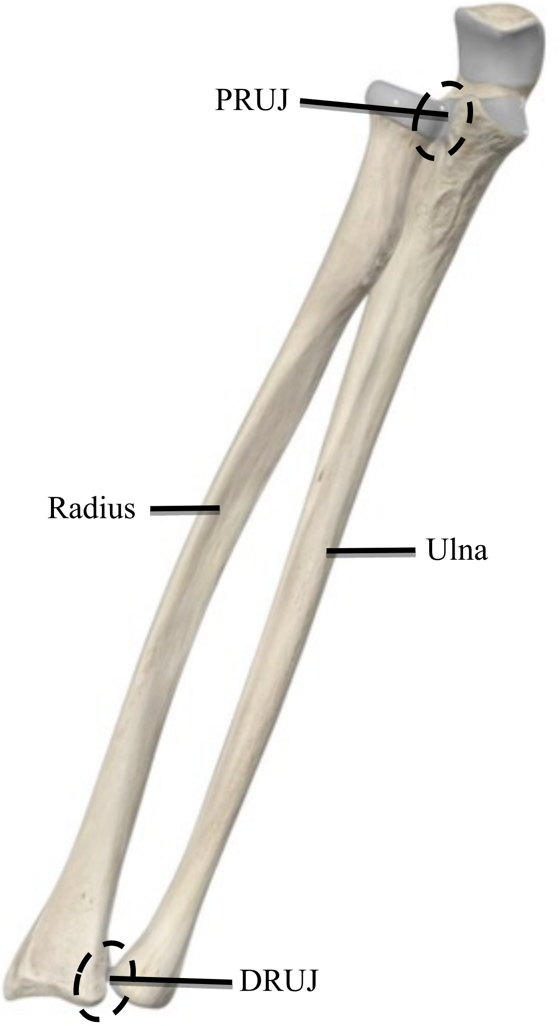

Figure 1-6: Articulations between the Radius and Ulna.[1]

Proximally, the radius and the ulna articulate at the PRUJ. Distally the radius and ulna articulate at the DRUJ.

The proximal ulnar diaphysis shape is complex. The proximal diaphysis contains a bow oriented in the sagittal plane called the proximal ulnar dorsal angulation (PUDA), which is an apex dorsal bow in the ulna averaging about 5.7 degrees, which is on average 47 mm from the tip of the olecranon (Figure 1-7)[2] Coronally, the proximal ulna has a varus bow averaging about 17.7 degrees which is on average 85mm from the tip of the olecranon.[3] The middle and distal sections of the ulna are relatively straight.

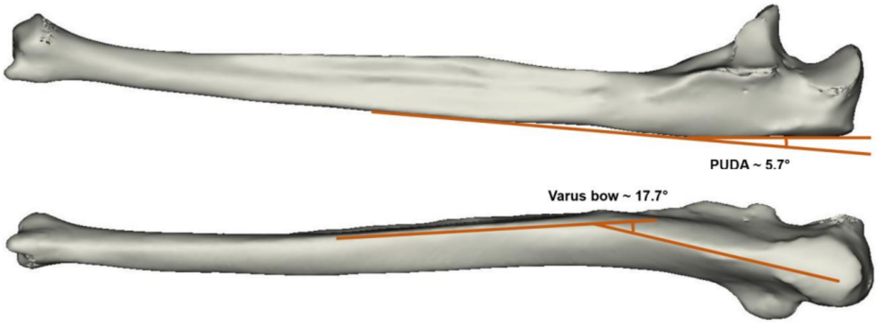

Figure 1-7: Coronal and Sagittal Orientations of the Proximal Ulna.[4]

The top image shows a saggital view of the Ulna. The proximal ulna has a dorsal angulation, PUDA. Two tangent lines are drawn, one long the dorsal surface of the ulnar shaft and the other along the dorsal surface of the olecranon. The bottom image displays a coronal view of the ulna showing it's varus bow. To measure and determine the apex of this bow, once again two tangential lines are drawn one in line with the longitudinal axis of the ulnar shaft and the other in line with the longitudinal axis of the olecranon.[5]

The radius on the other hand, has complexities of its own. There is an apex dorsal bow averaging 4.7 degrees which is on average 11.7 cm from the radial head, coupled with a varus bow of 10.3 degrees in the middle third of the radius (Figure 1-8).[6] Proximally, the radial neck is 15 degrees angulated opposite the radial tuberosity in relation to the overall radial shaft (Figure 1-9).[7]

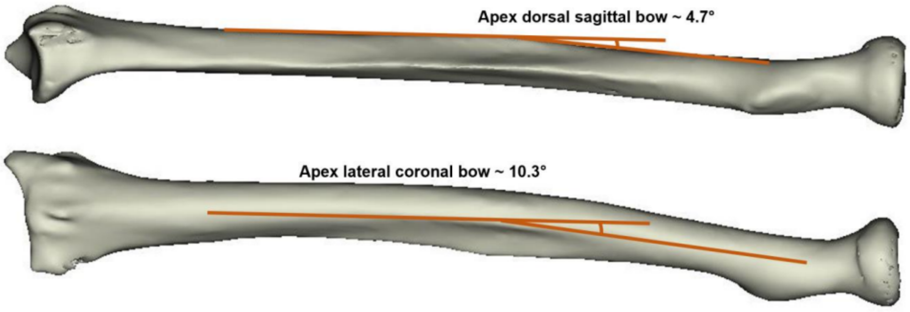

Figure 1-8: Coronal and Sagittal Orientations of the Radial Shaft.[4]

The top image shows the saggital plane in which the radial shaft has an apex dorsal bow. The image below, shows the coronal plane, in which the radial shaft has an apex lateral bow.[6]

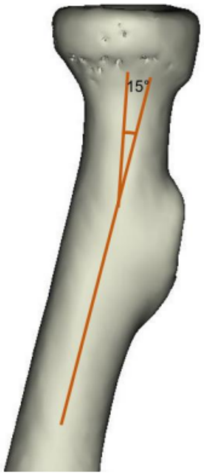

Figure 1-9: Coronal Orientation of the Proximal Radius.[4]

The radial neck angulates about 15° from the radial shaft in the coronal plane.[7]

1.1.2 Musculature

Muscles of the arm and forearm can be divided into two main categories: anterior and posterior compartments. Muscles of the anterior compartment of the arm and forearm function primarily in elbow flexion, forearm pronation, wrist flexion, and finger flexion (Figure 1-10). Elbow flexion is carried out through the biceps brachii, brachialis and brachioradialis. The biceps brachii inserts into the bicipital tuberosity of the proximal radius, the brachialis inserts on the coronoid process as well as the tuberosity of the ulna and the brachioradialis inserts onto the distal radius superior to the radial styloid process. The flexor-pronator muscle group originates from the medial epicondyle. The pronator teres (PT) is the main pronator of the forearm which is also a weak contributor to elbow flexion. The flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), and the flexor digitorum superficialis (FDS) are the other muscles that originate from the medial epicondyle and contribute to wrist and finger flexion.

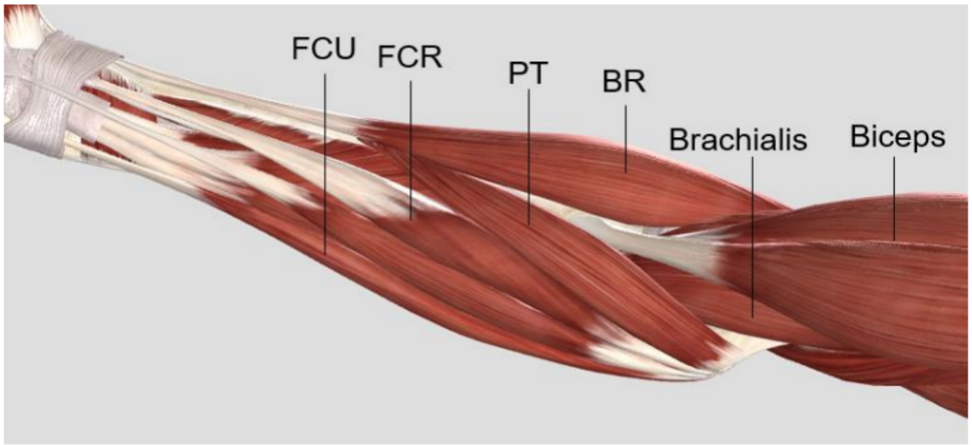

Figure 1-10: Anterior Forearm Compartment Musculature.[1]

Shown are the muscles located in the anterior compartment of the forearm. BR: brachioradialis, PT: pronator teres, FCR: flexor carpi radialis, FCU: flexor carpi ulnaris

Muscles of the posterior compartment of the arm and forearm function primarily in elbow extension, forearm supination, wrist extension and finger extension (Figure 1-11). The main extensor of the elbow is the triceps brachii. Another muscle that contributes to elbow extension is the anconeus. From the lateral epicondyle originates the extensor-supinator muscle group. The extensor carpi ulnaris (ECU) and the extensor digitorum communis (EDC) are primary contributors to wrist and finger extension. Also originating from the lateral epicondyle is the supinator muscle which in collaboration with the biceps brachii are the main supinators of the forearm (

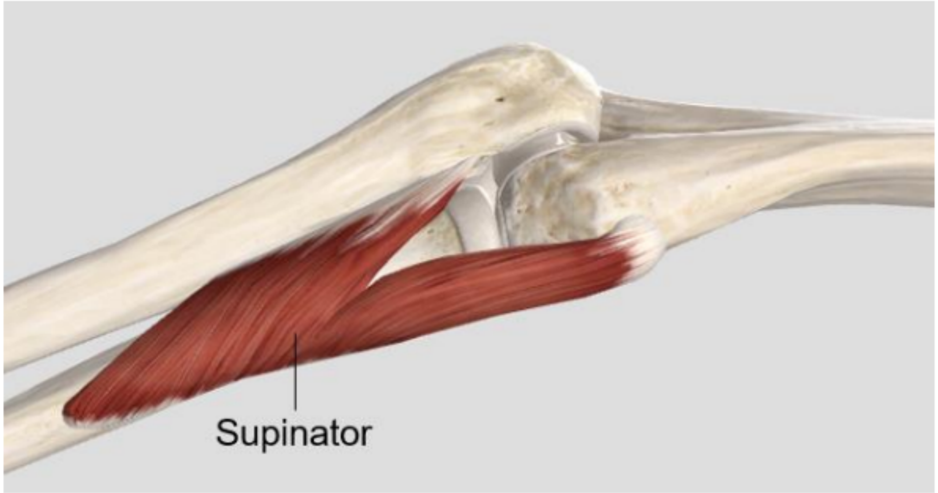

Figure 1-12).

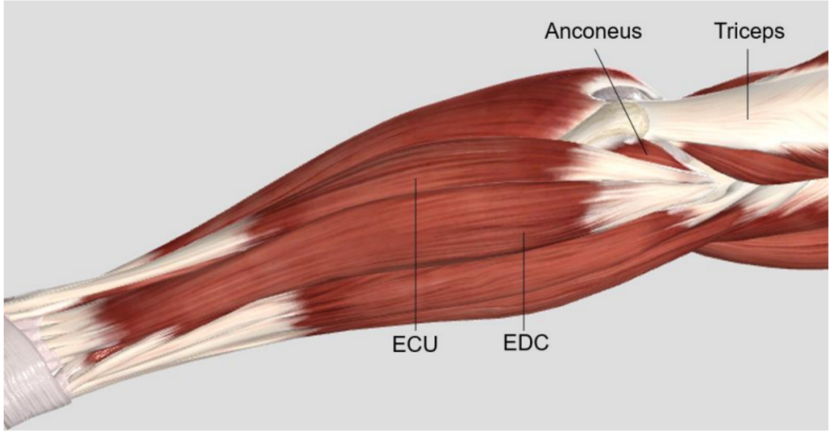

Figure 1-11: Posterior Forearm Compartment Musculature.[1]

Shown are the muscles located in the posterior compartment of the forearm. EDC: extensor digitorum communis, ECU: extensor carpi ulnaris.

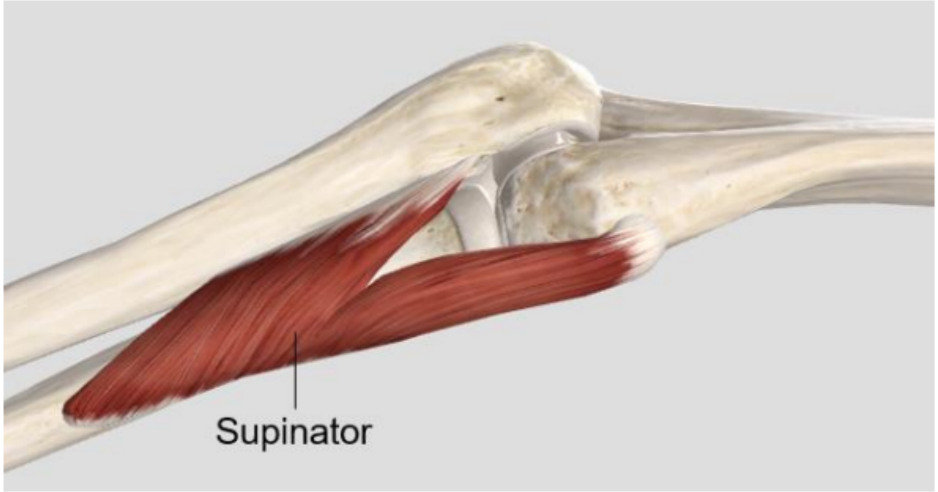

Figure 1-12: The Supinator Muscle.[1]

Shown is the supinator muscle, located deep within the posterior compartment of the forearm.

Another group of muscles are termed the mobile wad. This is composed of the brachioradialis (BR), the extensor carpi radialis longus (ECRL), and extensor carpi radialis brevis (ECRB) (Figure 1-13). The brachioradialis is a flexor of the elbow joint, whereas the ECRL and ECRB extend the wrist.

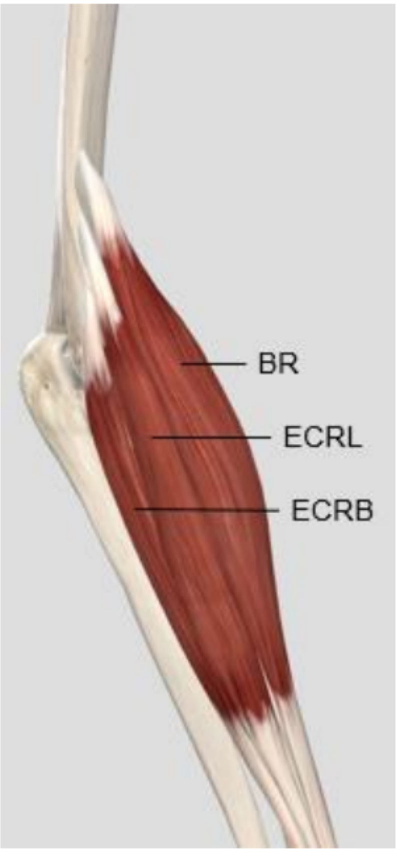

Figure 1-13: Mobile Wad Musculature.[1]

Shown are the muscles of the mobile wad compartment of the forearm. BR: brachioradialis, ECRL: extensor carpi radialis longus, ECRB: extensor carpi radialis brevis.

1.1.3 Capsular and Ligamentous

The elbow joint is surrounded by a capsule that completely encompasses all three articulations and simultaneously acts as a static stabilizer of the elbow joint. The anterior segment of the capsule is attached proximally to the anterior aspect of the distal humerus just proximal to the coronoid and radial fossa where its distal attachment is to the coronoid process and annular ligament (Figure 1-14). The posterior segment of the capsule is attached proximally to the posterior aspect of the distal humerus just proximal to the olecranon fossa and its distal attachment is to the medial and lateral articular margins of the sigmoid notch (Figure 1-14). The medial and lateral portions of the capsule are thickened forming the collateral ligaments of the elbow joint.

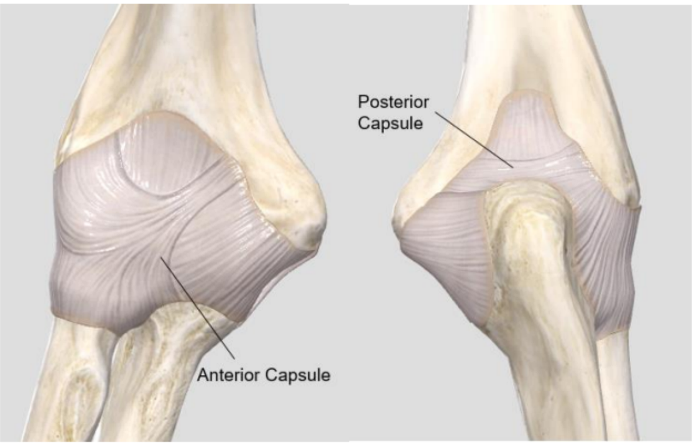

Figure 1-14: Capsular Anatomy of the Elbow Joint.[1]

Left figure shows the anterior capsule covering the elbow joint articulations. Right figure shows the posterior capsule covering the elbow joint articulations.

The lateral collateral ligament (LCL) is composed of the radial collateral ligament (RCL), the annular ligament, and the lateral ulnar collateral ligament (LUCL) (Figure 1-15).[8] The RCL originates from the lateral epicondyle and inserts into the annular ligament. The annular ligament originates and inserts onto the anterior and posterior margins of the lesser sigmoid notch. The LUCL originates from the lateral epicondyle and inserts into the crista supinatoris of the ulna. There is a thickening of the fibrous capsule of the elbow joint that lies just distal to the annular ligament, this is called the quadrate ligament. It extends from the lateral side of the ulna just distal to the PRUJ to the neck of the radius just distal to the articular margin (Figure 1-16).[9,10] Other portions of the LCL have been described including the accessory lateral collateral ligament and the oblique cord [9,11,12], however, these structures are variably present, and their role is less well defined. The LCL is the main stabilizer against varus and posterolateral rotatory instability (PLRI) of the elbow.

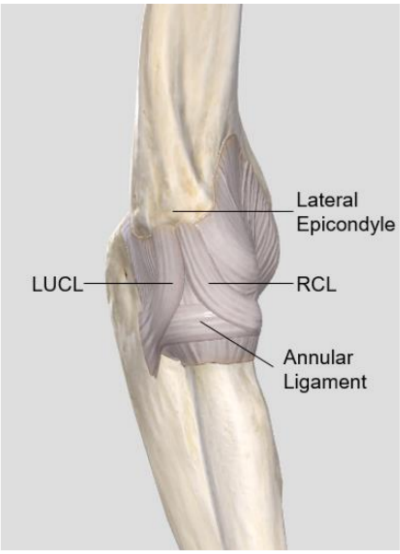

Figure 1-15: Lateral Collateral Ligament (LCL) of the Elbow.[1]

Shown are the main components of the LCL. RCL: radial collateral ligament, LUCL: lateral ulnar collateral ligament.

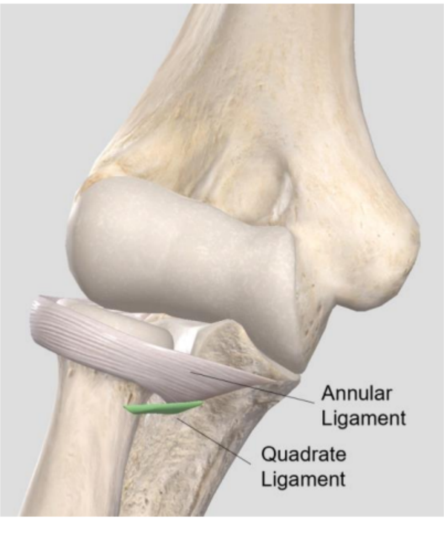

Figure 1-16: Anatomy of the Quadrate Ligament.[1]

Shown is the Quadrate ligament, distal to the annular ligament.

Three main components comprise the medial collateral ligament (MCL). These include the anterior bundle, the posterior bundle and the transverse segment (Figure 1-17)^{8}. The anterior bundle of the MCL gets its origin from the anteroinferior surface of the medial epicondyle and inserts on the sublime tubercle of the coronoid. The anterior bundle is also the most discrete and strongest portion of the MCL. The posterior bundle is a thickening of the medial capsule and inserts along the mid portion of the medial margin of the greater sigmoid notch. Finally, the transverse segment is oriented horizontally between the coronoid and the tip of the electron. The MCL is the main constraint against valgus instability of the elbow.

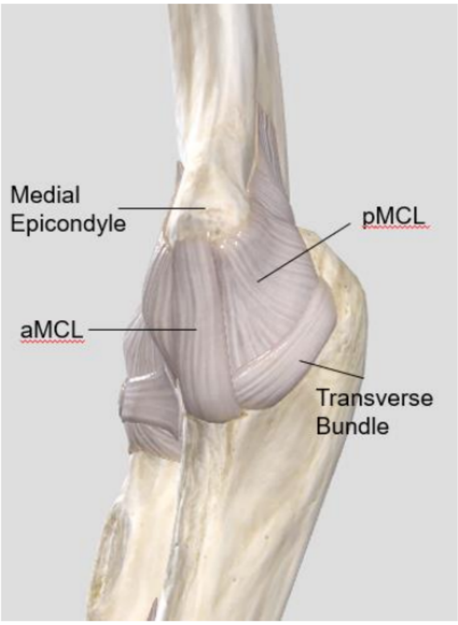

Figure 1-17: Medial Collateral Ligament (MCL) of the Elbow.[1]

Shown are the components of the MCL. aMCL: anterior bundle of the MCL, pMCL: posterior bundle of the MCL.

The radius and ulna are connected by a fibrous structure located deep within the forearm called the interosseous membrane (IOM) (Figure 1-18). This consists of three portions: the proximal membranous portion, the middle ligamentous complex (also known as the central band) and the distal portion. The proximal oblique cord and the dorsal oblique cord comprise the proximal portion of the membrane.[13,14,15] The proximal oblique cord originates from the anterior lateral aspect of the coronoid process and inserts just distally to the radial tuberosity.[13] The dorsal oblique cord originates from the junction of the proximal third and distal two-thirds of the ulna and inserts into the interosseous crest of the radius.[13] The central band and the accessory band comprise the middle portion of the IOM.[13,16] The central band is one of the most important functional components of the IOM and is oriented obliquely from proximal-radial to distal-ulnar. Its radial origin lies at approximately 60% of the length of the radius from the styloid.[17] The ulnar insertion is at approximately the junction of the middle two-thirds and the distal third of the ulna.[17] The distal portion is comprised of the distal oblique bundle (DOB).[13] This originates from the ulna at approximately the level of the pronator quadratus and inserts along the inferior rim of the sigmoid notch and the DRUJ capsule.[13,17] The IOM functions in multiple facets such as transferring load from the radius to the ulna as well as elbow and DRUJ stability.[18,19] At the wrist, most of the axial load is transmitted through the radius. In a neutral rotation, 82% of the axial load is transmitted through the radiocarpal joint and 18% is transmitted through the ulnocarpal joint.[20] The IOM is able to shift the load from the radius to the ulna such that at the elbow 70% of the axial load is borne by the radiocapitellar joint and 30% by the ulnohumeral joint with the forearm in neutral rotation.[21]

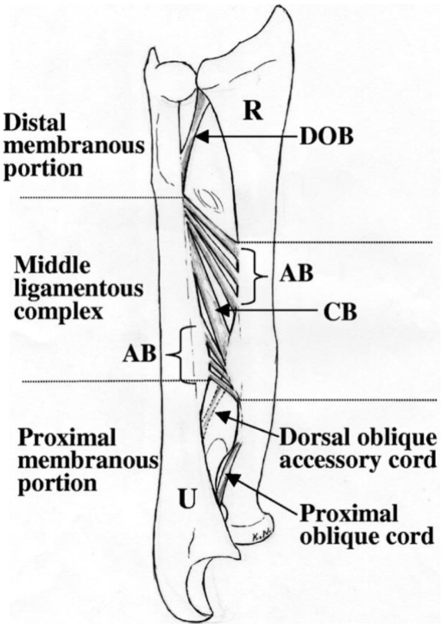

Figure 1-18: Interosseous Membrane (IOM) Anatomy.[4]

Shown are components of the proximal, middle and distal portions of the IOM. R: radius, U: ulna, AB: accessory band, CB: central band, DOB: distal oblique bundle.[13]

1.2 Biomechanics of the Elbow and Forearm

1.2.1 Kinematics

The elbow is a trochoginglymoid joint, with two degrees of freedom, with one being flexion-extension (Figure 1-19) and the other pronation-supination (Figure 1-20). The axis of flexion-extension of the elbow passes through the center of the arcs of the capitellum and trochlea. Variability in the flexion axis with the active and passive range of motion and forearm rotation has been previously shown in past studies.[22,23] On average, the flexion axis ranges from 30 to 80 internal rotation relative to the transepicondylar axis and from 4o to 8o of valgus relative to the long axis of the humerus (Figure 21).[24]

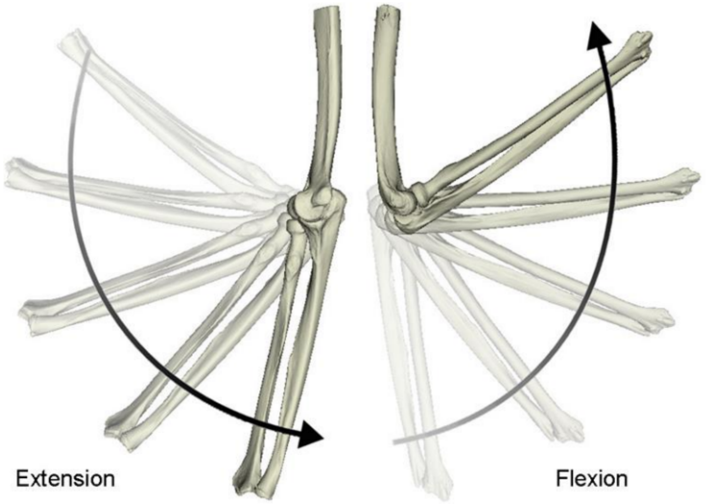

Figure 1-19: Flexion-Extension of the Elbow.[4]

The image on the left depicts the medial view of an elbow moving through a flexion-extension arc. The image on the right depicts the lateral view of an elbow moving through a flexion-extension arc.[25]

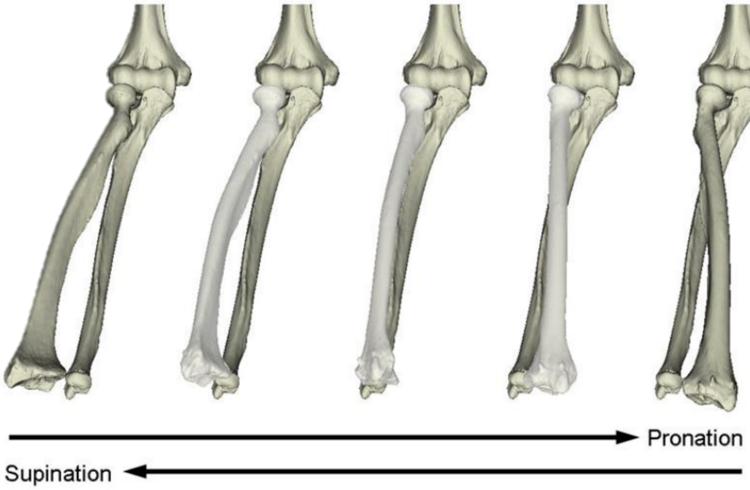

Figure 1-20: Pronation-Supination of the Forearm.[4]

Shown is the view anteriorly of a right elbow moving through the supination-pronation arc of forearm rotation.[25]

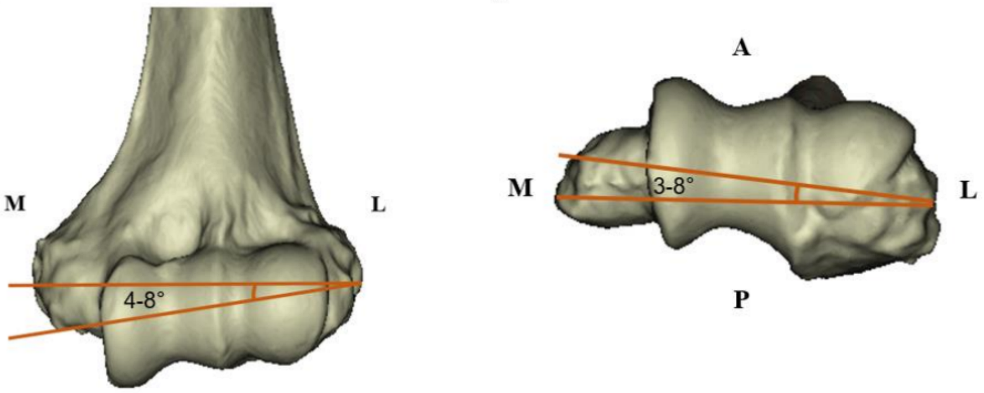

Figure 1-21: Flexion-Extension Axis of the Elbow Joint.[4]

Shown on the left: the coronal view of the distal humerus with the flexion-extension axis in 4-8° of valgus. Shown on the right: the axial view of the distal humerus with the flexion-extension axis in 3-8° of internal rotation. M: medial side, L: lateral side, A: anterior side and P: posterior side.

Pronation-supination is created by the radiocapitellar and proximal radioulnar joints. Forearm rotation occurs from the center of the radial head to the center of the distal ulna independent of elbow position.[26,27]

1.2.2 Stability

Elbow stability is created by both osseoussoft tissue structures, and muscle loading. Primary static stabilizers are the ulnohumeral articulation and the medial and lateral collateral ligaments.[19,28,29] Secondary static stabilizers are the radial head, joint capsule, flexor-pronator origin and extensor-supinator muscle origins.[19,28,29] Dynamic stability is provided by the muscles crossing the elbow joint, including the biceps brachii, brachialis, brachioradialis, triceps, and anconeus.[19,28,29,30]

The osseous and ligamentous structures contributing to radial head stability within the radiocapitellar articulation and the PRUJ have not been fully explored. However, important roles in radial head stability have been attributed to the annular ligament, interosseous membrane and quadrate ligament. [9,10,31–33] Spinner and Kaplan demonstrated that anterior radial head subluxation with an intact ulna, would only occur with sectioning of the annular ligament, posterior border of the quadrate ligament and proximal third of IOM.[9] A subsequent cadaveric biomechanical study by Anderson et. al focusing on radial head stability after sequential sectioning of the annular ligament, proximal IOM, central band and distal IOM, showed significant radial head instability only after sectioning of the central band.[32] Additionally, it was found that the order in which the soft tissues were sectioned, i.e. proximal to distal versus distal to proximal, had no significant effect on radial head stability. Another biomechanical investigation found significant radial head instability after sectioning of the anterior joint capsule, annular ligament, quadrate ligament as well as the proximal half of the IOM.[33] However, this study was significantly limited by the fact that the cadaveric specimens were dissected free of all muscles and tendon, meaning the effects of these structures on radial head stability were not accounted for. The importance of the soft tissue stabilizers of the radial head requires further investigation as their roles remain controversial.

1.3 Monteggia Injuries

1.3.1 Classification

In 1814, Giovanni Monteggia first recognized and reported a fracture of the proximal third of the ulna, along with an anterior dislocation of the radial head (Figure 1-22).[34] This particular type of fracture was later elaborated on by Louis Bado who categorized Monteggia fractures into four distinct types. This classification was based on the location of the ulnar fracture, the direction of radial head subluxation, and whether there was a concurrent fracture of the proximal radius (Figure 1-23).[35]

Figure 1-22: Radiograph of Monteggia Fracture-Dislocation.

Lateral radiograph showing proximal ulna fracture and an anterior radial head dislocation.

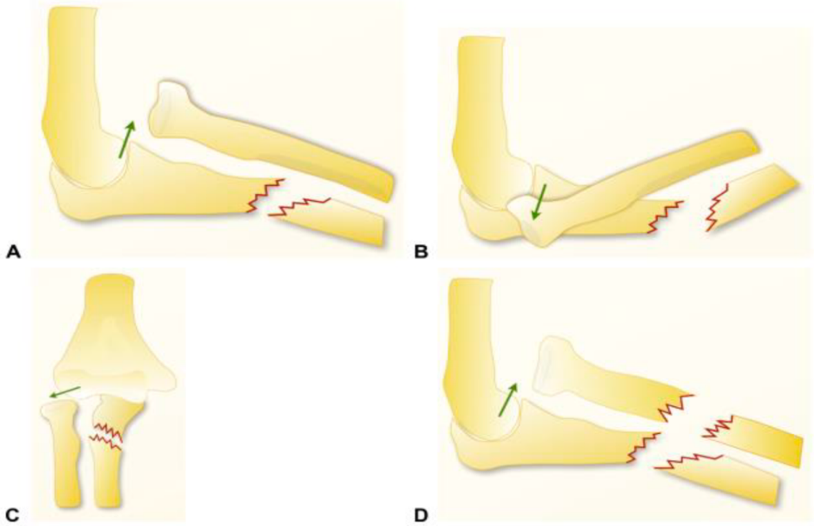

Figure 1-23: Bado Classification of Monteggia Injuries.[4]

A) illustrates a type I Monteggia with an apex anterior ulna fracture and an anterior radial head dislocation. B) illustrates a type II Monteggia with an apex posterior ulna fracture and a posterior radial head dislocation. C) illustrates a type III Monteggia with metaphyseal ulna fracture and an anterolateral radial head dislocation. D) illustrates a type IV Monteggia with proximal radial shaft fracture at the same level as the ulnar shaft fracture and an anterior radial head dislocation.[34]

Type I Monteggia injuries are characterized by an apex anterior fracture at the proximal or middle third of the ulna along with an anterior dislocation of the radial head. Type II injuries are defined by an apex posterior fracture at the proximal or middle third of the ulna accompanied by posterior or posterolateral dislocation of the radial head. Type III injuries are identified by a fracture at the ulnar metaphysis with an anterolateral dislocation of the radial head. Lastly, Type IV injuries involve a fracture of the proximal radial shaft occurring simultaneously at the same level as the ulnar shaft fracture and an anterior dislocation of the radial head.

Type I injuries are typically seen most frequently in children, while type II injuries occur more commonly in adults.[36] According to a comprehensive study conducted by Ramski and his team across multiple centers, the most frequent fracture location was the upper third of the ulna, followed by the middle third.[37] In addition, the average angle of ulnar deviation was found to be 19.6 ±14.4° for all directions, based on radiographic evidence.[37]

1.3.2 Proposed Mechanisms of Type 1 Monteggia Injuries

In 1940, Speed and Boyd suggested that Monteggia fractures occur due to a forceful impact directly on the forearm, leading to an ulnar fracture at the point of collision driving the radial head anteriorly.[38] However, other scholars contested this hypothesis, citing several reasons, including the infrequency of severe bruises or open wounds at the impact site, which one would anticipate if a direct blow was the cause.[39] Additionally, they argued that a direct impact should lead to more comminuted fractures (Figure 1-24).

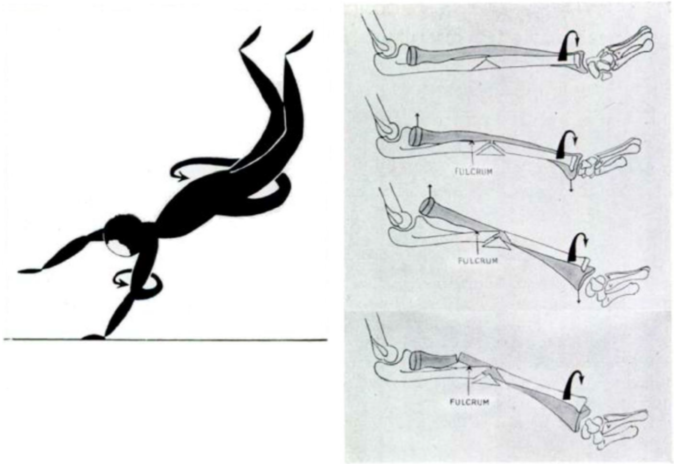

Figure 1-24: Evan's Proposed Theory of Monteggia Injuries[4].

With a fall on an outstretched hand, the hand becomes relatively fixed to the ground, but the rest of the body continues to rotate resulting in a hyperpronation force. This results in an ulnar fracture which forms a fulcrum that can lever the radial head out of the joint or result in proximal radial shaft fracture.[40]

The radiocapitellar joint, shielded by the sturdy anterior capsule, supinator, and brachialis muscles, is unlikely to be affected by a direct blow strong enough to result in an ulnar fracture and radial head dislocation simultaneously. In 1949, Evans proposed that type I Monteggia lesions are due to hyperpronation force.[40] He theorized that when a patient stumbles and lands on an outstretched hand, the forearm is already pronated, and upon impact, the hand stabilizes against the ground and the rest of the body continues its rotational movement, resulting in relative hyperpronation of the forearm. This rotational force through pronation coupled with the axial load from the fall causes an apex anterior fracture at the ulna that forms a fulcrum levering the radius out of joint or resulting in fracture (Figure 1-24)

To validate his theory, Evans conducted experiments using 18 cadavers. He stripped all the soft tissues from the elbow and forearm, except the joint capsule, ligaments, and the interosseous membrane. The humeral shaft was clamped, and the forearm was slowly pronated, resulting in a fracture of the ulna's middle third and an anterior dislocation of the radial head (recreating type I Monteggia) in 12 instances. The remaining specimens exhibited both-bone forearm fracture, isolated anterior radial head dislocation, and elbow dislocation in three, two, and one case respectively.

In 1967, Bado lent further support to the hyperpronation theory with clinical and radiographic evidence.[35] He reasoned that children presenting with type I Monteggia injuries often have a pronated forearm, suggesting a pronation force as the root cause. Additionally, he suggested that the ease with which supination and slight traction often reduce these injuries is therapeutic evidence of a pronation force being the responsible factor.

In 1971, Tompkins critiqued Evans's proposed mechanism, arguing that Evans's experiments did not take into account the role of the surrounding muscles, and his concept of body rotation around a fixed hand was not adequately reflected in his experimental model.[41] Tompkins also disputed Bado's argument about the position of the bicipital tuberosity on radiographs being proof of the pronation theory.[41] In reviewing radiographs of patients with type 1 Monteggia injuries, he found the bicipital tuberosity to be posteriorly oriented with the forearm in neutral rotation and laterally in full pronation. He also found the forearm to be in neutral or supination in the majority of cases. So instead, Tompkins proposed an alternative method, that the radial head might have been pulled out of the joint, with the biceps muscle contraction being the only possible traction force in that direction.[41] Tompkins suggested that during a fall on an outstretched hand, the anterior dislocation of the radial head could be attributed to a violent reflex contraction of the biceps, and the forearm might be in any rotational position. The subsequent longitudinal compressive force on the ulna, coupled with the intact interosseous membrane's pull and the simultaneous contraction of the brachialis, results in an ulna fracture and anterior angulation (Figure 1-25). Tompkins's theory was backed by the observation that the radial head is easily reduced once the biceps relaxes and the elbow flexes beyond 90 degrees.

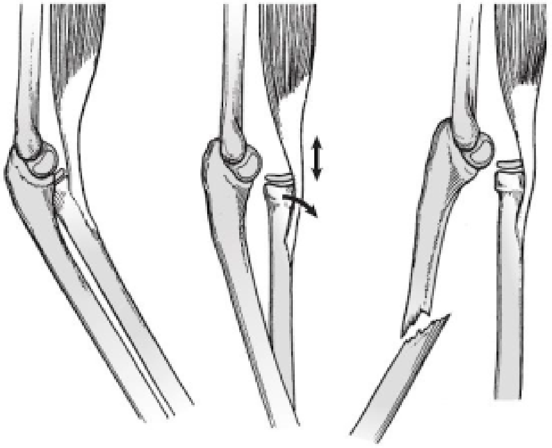

Figure 1-25: Tompkins' Proposed Theory of Monteggia Injuries.[4]

During a fall, biceps contraction results in dislocation of the radial head. The longitudinal compressive force on the ulna then results in the ulnar fracture.[42]

The precise mechanism underlying Bado type 1 Monteggia injuries remains unclear, and further studies are necessary to shed light on this complex orthopedic condition. Despite advancements in medical research and imaging techniques, the exact sequence of events leading to this specific type of forearm fracture-dislocation remains a subject of ongoing investigation. As such, a deeper understanding of the underlying mechanisms is crucial for improving diagnostic accuracy and optimizing treatment strategies for patients with Bado type 1 Monteggia injuries.

1.3.3 Management and Outcome of Monteggia Injuries

Monteggia fractures are inherently unstable and require immediate orthopaedic intervention.[43] Overall, children usually have better outcomes than adults, which is thought to be due to factors such as the remodeling ability of small angular deformities, shorter healing time, and less osseous instability of Monteggia fractures in children.[44] Depending on the severity of the fracture, closed reduction and casting is usually successful in children, however recurrent radial head dislocation is not uncommon even with an adequate initial reduction. Persistent radial head subluxation despite anatomic reduction of the ulna is postulated to be due to disruption of soft tissues such as the annular ligament and activation of the biceps.[4,33,41] On the other hand, operative management is crucial for the majority of Monteggia fractures in adults, who are more prone to persistent angulation and shortening with a closed reduction.[44]

While adequate results have been reported with the majority of the pediatric population, the outcomes in adults remain variable and are associated with high rates of complications.[36,45–49] When first describing these injuries, Monteggia observed that the ulna fracture was inherently linked to the radial head dislocation and that both required simultaneous attention.[34] Currently, the treatment of choice in adults is operative, specifically, open reduction of the ulnar shaft to achieve anatomical reconstruction.[50] Open reduction of the ulna is also required following a failed closed reduction in pediatric patients. Generally, this approach leads to satisfactory reduction of the radial head, however, in cases where the radial head remains dissociated or there is soft tissue interposition blocking the reduction, open reduction of the radial head through the lateral approach with or without annular ligament repair or reconstruction is recommended.[50]

Monteggia fractures can vary considerably in injury patterns, involving pathologies such as radial head fractures, coronoid fractures, and ulnohumeral instability[43] As such, they can be difficult to diagnose clinically and if proper management is not initiated, debilitating complications can often be the result.[51,44] In fact, approximately 25-50% of these injuries are initially missed and management of chronic Monteggia fractures prove to be much more challenging.[52,53] Indeed, high rates of complications were found in past follow-up studies with residual radial head dislocation being the most common complication.[51] Past research has shown that the revision surgery rate is nearly 20% with the most common causes being hardware removal and proximal ulnar malunions.[43] The risk of heterotopic ossification and displacement are higher with severe soft tissue trauma and fracture comminution.[43]

1.3.4 Biomechanical Studies of Monteggia Repair and Reconstruction

Several techniques of annular ligament reconstructions have been described to manage recurrent or persistent radiocapitellar instability after Monteggia injuries. Bell Tawse et al. proposed using a strip from the central portion of the triceps brachii tendon, leaving the tendon strip attached to the ulna and passing the tendon from posterior to anterior around the radial neck before fixing it to the proximal ulna through a drill hole.[54] Other authors, such as Lloyd-Roberts et al. also used the triceps tendon for annular ligament reconstructions, however with modifications, such as using the lateral bundle of the triceps tendon.[55] Lloyd-Roberts et al. described a separate technique using the palmaris longus tendon to stabilize the proximal radius.

The use of interference screws in annular ligament reconstructions has also been described by Seel & Peterson who suggested that having two points of fixation in the proximal ulna would provide greater radial head stability.[56] They proposed placing two interference screws at the level of origin of the annular ligament for reconstruction with triceps tendon. The authors concluded that this technique allowed for treatment of radial head dislocation in any direction.[56]

More recently, techniques by Itadera et al. and others have approached the elbow laterally and reconstructed the annular ligament using a palmaris longus tendon autograft, which was folded double and passed around the radial neck through a bony tunnel created in the ulna beneath the supinator crest and just distal to the radial notch.[57] Use of the superficial head of the brachialis muscle for annular ligament reconstruction has also been proposed by Nwoko et al., who suggested that its location of insertion near the anterior attachment of the annular ligament at the sigmoid notch, its proximity to the radial head, as well as its availability as a graft made it the superior choice of tendon to use.[58]

Most recently, another modified Bell Tawse technique was proposed by Marinello et al. by completely detaching a lateral triceps tendon strip from the ulnar insertion and fixing the annular ligament graft with suture anchors in full forearm supination to reduce the radio-capitellar joint, despite instability in this position.[59] The authors reasoned that supination allowed the radial head to be closer to the sigmoid notch of the proximal ulna, therefore allowing for an improved reduction of the radial head after annular ligament reconstruction.[59] Additionally, they suggested that incorporating the remnant part of the native annular ligament would reinforce the construct.[59]

Only a handful of biomechanical studies have delved into the impact of Monteggia fracture alignment on functionality and stability. A study by Sandman et al. scrutinized the implications of ulnar misalignment, elbow positioning, forearm rotation, and the integrity of the annular ligament on subluxation of the radial head.[60] The team examined ulnar angulation in increments of 5°, ranging from an extension of 10° to a flexion of 10°. Their study considered four elbow positions (full extension, 45°, 90°, full flexion) and three forearm positions (neutral, pronation, supination).[60] They noted an increase in anterior radial head subluxation with progressive ulnar extension misalignment, progressive elbow flexion, and a damaged annular ligament.[60] The maximum average displacement of the radial head observed was 61%, which occurred when the elbow was fully flexed, the ulna was misaligned by 10° of extension, and the annular ligament was ruptured.[60] While they didn't explicitly probe the influence of biceps contraction on radial head stability, they theorized that the effect of elbow flexion on anterior radial head subluxation may be tied to biceps tension.[60] It is worth noting that the applied load on the biceps and brachialis wasn't physiologically accurate as they used a 50:50 ratio, despite studies indicating that load distribution between these muscles changes throughout the elbow's range of motion, with the brachialis being the dominant force during elbow flexion[61–63]. Moreover, they didn't take into account the role of other elbow flexors such as the brachioradialis. Badre et al. proposed to rectify this by applying physiologic loads to the elbow. They demonstrated that progressive ulnar extension angulation resulted in an incremental increase in anterior radial head translation in the setting of anterior Monteggia injuries.[51] They also showed that biceps muscle tension has a significant effect on radial head instability in anterior Monteggia injuries.[4]

The annular ligament, quadrate ligament and interosseous membrane have been suggested to play a vital role in radial head stability. Spinner & Kaplan showed that with an intact ulna, anterior dislocation of the radial head was only possible after sectioning of the annular ligament, quadrate ligament and proximal IOM.[9] Additionally, Anderson et al. found that significant radial head instability occurred only after sectioning of the annular ligament, quadrate ligament proximal IOM and central IOM.[32] The authors from this study were also able to conclude that the order in which the soft tissues were sectioned did not significantly affect radial head stability in the setting of pure radial head dislocations.[32] However, these studies had a limitation in that they dissected the cadaveric specimen free of all muscles and tendons, thereby overlooking the influence of these structures on radial head stability.

In a study noted above, Badre et al. maintained the surrounding musculature. They found that, in agreement with Anderson et al., there was significant anterior radial head translation after sectioning of the annular ligament, quadrate ligament, proximal IOM and central IOM.[51] Interestingly, Badre et al. studied these effects in the setting of anterior Monteggia injuries. However, they. conceded that neither the sequence of soft tissue sectioning nor the effect of forearm rotation on radial head stability was evaluated.

1.4 Experimental Biomechanical Techniques for the Elbow

In-vivo elbow joint motion can be studied via experimental motion simulation. Despite lack of perfect elbow joint analogs as methods of joint simulation, motion simulation allows for isolation and control of the specimens and their environments, thus creating more analyzable systems.[25] Prior to application in patients, surgical procedures and implants can be examined and augmented by using simulators, ultimately allowing for optimized and advanced medical care. Additionally, safety and practicality issues often lead to complications when performing many in-vivo studies.

Generally, four principal upper extremity positions can be simulated in flexion-extension, including vertical or gravity-dependent, horizontal, varus and valgus positions.[25] These four positions cover a broad range of externally applied forces during normal elbow use.

In the past, in-vitro joint simulators succeeded in mimicking kinematics and loading for various motions. Most in-vitro systems have simulated forces in the major muscle groups crossing the elbow joint in either static positions or with the arm passively flexed.

Elbow motion can be simulated either in-silico, that is virtually using computer models, or in-vitro, meaning physically using cadaveric specimens by using specialized equipment to achieve motion and recording its characteristics. Each method presents itself with its own advantages and challenges.

On one hand, in-silico models can be inexpensive and readily reusable while also allowing virtual models to control and adjust every variable the model is designed to account for – making them applicable and valuable for a variety of studies. However, in-silico models need to account for various assumptions and simplifications of anatomical functions and properties to successfully execute the simulations.[64] Such assumptions need to be incorporated in order to compensate for incomplete knowledge of involved tissues, such as ligament versus tendon properties to model mechanical properties.[65–67] Overall, the function of the elbow involves a complex interaction among a variety of structures whose incompletely defined mechanical properties could potentially compound modelling errors.[64]

Human tissue mechanical properties, including their complex interactions, is a clear advantage for in-vitro simulations as the tissues can be left to function as they normally would in-vivo. Using cadaveric specimens from the human population also ensures the incorporation of wide variations in osseous anatomy, ligament and tendon properties that occur among individuals.[68] Additionally, certain studies require real tissue examinations, such as the evaluation of in-vitro surgical repairs to account for normal variations in outcomes caused by the practical aspects of surgery.[64] The hands-on nature of surgical repairs allows for proper evaluation of surgical performance. Additionally, in-vitro simulation appears to be the optimal choice when investigating measurements of motion or internal forces.

Elbow joint function can be simulated with either passive or active motion simulators. Passive motion can be used for in-vitro tests with or without simulated muscle forces, while active motion must produce flexion-extension and/or forearm rotation representative of in-vivo motion.[25]

With passive motion simulators, the forearm is manually moved through a range of motion, while dependent variables such as kinematics or joint forces are measured.[25] Ultimately, passive motion simulations can have implications for post-trauma and post-surgical rehabilitation protocols allowing patients to employ passive motion to regain elbow function.[25]

Several studies have previously reported using passive simulators to investigate elbow joint function. Morrey et al. simulated muscle forces with static weights applied to the brachialis, biceps, and triceps muscle tendons, which were 5% of the maximum potential force for those muscles and less than the physiologic forces needed to move the joint.[69] These forces were originally only intended to stabilize the joint to improve joint congruity and likely more physiologically accurate kinematics in-vitro.[69] Elbow flexion was produced manually, and a humeral mount allowed for axial rotation of the humerus to model varus and valgus gravity loaded flexion.[69] Several subsequent studies have since used this simulator first introduced by Morrey et al.[69]

While passive motion with simulated muscle loads allows for a balanced static system of loads producing muscle loading, in-vivo active motion is a dynamic unbalanced system of loads that generates the flexion-extension moment about the elbow flexion axis.[25] Overall, in-vivo motion cannot be completely and physiologically accurately modeled by in-vitro passive motion.[25]

Active in-vitro motion simulators must produce flexion-extension that is representative of in-vivo motion, meaning the flexion-extension moment must be developed from forces crossing the elbow joint.[25] Past in-vitro studies have shown that balanced loading of the triceps, biceps, and brachialis significantly stabilize the intact elbow, while simulated muscle loading has also been demonstrated to have a stabilizing effect on the intact elbow, which is more evident following transection of primary stabilizers, such as the MCL or LCL.[70–72]

One major area of concern that needs to be addressed when designing active simulators involves employing muscle forces consistent with muscle effort during in-vivo motion. This can be achieved by obtaining in-vivo muscle activation data via the use of electromyography (EMG) and muscle cross-sectional area, which produces a measure of load (muscle effort) during motions that can directly be applied in in-vitro investigations.[73]

In the past, active motion simulators fell into one of two categories: Load-control versus position-control devices.[25] The type of actuators used to load the muscles to produce joint motion determined the category of the active simulator. Actuators can produce either a desired and controlled load or position, however, not both. Pistons or rotary actuators driven by pneumatic, hydraulic, or electromechanical solenoids are defined as load-control actuators, while stepper or servo motors are position-control actuators producing rotary (angular) output.[25]

The major muscle groups involved in elbow flexion include the brachialis, biceps, and triceps, of which the brachialis muscle was considered the prime mover for flexion. Its movement was previously position-controlled using Proportional Integral Derivative (PID) algorithm simulating active elbow flexion in the vertical position and was particularly well-suited for gravity-dependent vertical flexion.[71] A stabilizing effect was maintained by tensing the agonist flexors (i.e. biceps, brachialis, brachioradialis), requiring little control for the antagonist (i.e. triceps).[71] One main drawback, however, included the inability to perform horizontal, varus or valgus elbow flexion, however this issue has been addressed by using feedback algorithms in more modern simulators.[71] Other previously reported simulators also simulated active muscle loads by achieving active flexion with the help of actuators.[73]

1.5 Thesis Rationale

The outcomes of Monteggia injuries show wide variability, particularly among adults, and often yield suboptimal results. Persistent and recurrent subluxation and dislocation of the radial head leads to a poor outcome, even in the setting of an anatomical reduction of the ulna.[36,74] Consequently, individuals afflicted by this condition often experience pain, stiffness, weakness, and functional limitations. While various surgical approaches have been proposed to address chronic Monteggia injuries, they have exhibited subpar long-term results, frequently accompanied by a high incidence of complications, without a universally accepted optimal reconstruction method. A deeper comprehension of the biomechanical aspects of Monteggia injuries is necessary to identify the factors contributing to radial head instability in these cases. This knowledge can then be leveraged to refine surgical techniques and rehabilitation protocols with the aim of improving patient outcomes.

1.6 Objectives and Hypotheses

The overall purpose of this biomechanical investigation is to study the ligament injuries which play a role in the stability of anterior Monteggia injuries. We will also evaluate strategies to improve stability when treating these injuries including over-reduction of the ulna with an apex dorsal angulation as well as annular ligament repair and reconstruction procedures. Moreover, we aim to investigate the role of soft tissues around the elbow, including the annular ligament, quadrate ligament and the interosseous membrane, in the stability of the Monteggia injuries. It is proposed to employ cadaver-based biomechanical testing protocols to optimize the management of anterior Monteggia fractures.

The specific objectives are:

1. To determine the contribution of soft tissue stabilizers of the proximal radius using sequential sectioning of the:
    - a) central interosseous membrane
    - b) proximal interosseous membrane
    - c) annular and quadrate ligaments
2. To determine the contribution of overcorrection of the ulna on radial head stability in anterior Monteggia fractures.
3. To determine the efficacy of four different types of annular ligament reconstruction/repairs in restoring stability of the radial head.

Hypotheses:

1. Sectioning the annular ligament leads to increased anterior translation of the radial head in relation to the capitellum.
2. Overcorrecting the ulna decreases anterior radial head translation in the setting of anterior Monteggia fractures.
3. Repairing the annular ligament decreases anterior radial head translation in the setting of anterior Monteggia fractures.
4. The anatomic annular ligament reconstruction produces optimal stability.

1.7 Thesis Overview

This thesis examines the biomechanics of radial head stability in anterior Monteggia injuries.

Chapter 2 presents an in vitro cadaver-based study which explores the contributions of soft tissue stabilizers of the proximal radius

Chapter 3 presents an in vitro cadaver-based study which investigates the effects of overcorrection of ulnar angulation on radial head stability in anterior Monteggia fractures.

Chapter 4 presents an in-vitro cadaver-based study which investigates the impact of four different annular ligament reconstructions on restoring radial head stability in anterior Monteggia fractures.

Chapter 5 provides a final overview and discussion of the findings and potential future directions of the work.

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Chapter 2

2 Determining the Contribution of Soft Tissue Stabilizers of the Proximal Radius on Radial Head Stability

Persistent radial head instability continues to be a challenge in treating Monteggia injuries even after anatomic restoration of the ulnar fracture.[1–4] *This chapter assesses the contribution of soft tissue stabilizers of the forearm and proximal radius using sequential sectioning of the central interosseous membrane, proximal interosseous membrane and the annular and quadrate ligaments in anterior Monteggia fractures.*

2.1 Introduction

(The background in this section was also provided in Chapter 1 but is summarized here as this chapter forms the basis of a manuscript for submission for publication).

Monteggia fractures represent a unique and complex category of forearm injuries, named after Giovanni Battista Monteggia, an Italian surgeon who first described them in the 19th century. They are characterized by a fracture of the ulna, often near the elbow, coupled with a dislocation of the radial head at the elbow joint.[5] This distinctive combination of a break and dislocation typically occurs due to direct trauma or a fall onto an outstretched hand.[6,7] The importance of Monteggia fractures lies in their potential to cause long-term functional impairment if not correctly diagnosed and treated, which involves both managing the ulnar fracture and ensuring the radial head is appropriately reduced and stabilized.

Persistent radial head instability following anatomical reduction of the ulna in anterior Monteggia injuries can present a significant clinical challenge. This condition can occur despite achieving an appropriate alignment of the ulna, pointing to the complexity of the injury and the integral role that soft tissue structures play in maintaining the stability of the joint. A common cause of persistent instability is the disruption of the annular ligament, which is critical for stabilizing the radial head.[8–10] When this ligament is damaged, it can lead to continual subluxation or dislocation of the radial head, even after the ulna has been anatomically reduced. Other potential contributing factors include injury to the interosseous membrane, damage to the joint capsule, or the presence of intra-articular fragments.[8,10] These issues underscore the importance of a comprehensive approach to the management of Monteggia injuries, which not only aims for anatomical reduction of the ulna but also addresses associated soft tissue injuries.

Research suggests that the annular ligament, quadrate ligament, and interosseous membrane (IOM) are vital for radial head stability. Spinner & Kaplan and Anderson et al. found that significant radial head instability occurred only after sectioning these structures, with the sequence of sectioning having no substantial impact on stability.[11,12] However, these studies did not account for the role of muscles and tendons, presenting a significant limitation. More recently, Badre et al. performed a sequential sectioning study of the annular ligament, the quadrate ligament and finally the proximal interosseous membrane on radial head stability in the context of anterior Monteggia fractures, a focus not previously seen in biomechanical studies. However, they did not evaluate the effect of soft tissue sectioning sequence or forearm rotation on radial head stability.[13]

In light of the foregoing, the objective of this study was to investigate the contribution of soft tissue stabilizers of the proximal radius in anterior Monteggia injuries. These variables were assessed in supination, neutral and pronation, as well as reversing the sequence of sectioning performed by Badre et al.[13] We hypothesized that sectioning the annular ligament last would lead to the most marked increased anterior translation of the radial head in relation to the capitellum.

2.2 Materials and Methods

2.2.1 Specimen Preparation and Experimental Setup

Testing was conducted on eleven (11) fresh-frozen right upper extremity cadavers, with an average age of 70±18 years. Prior to testing, computed tomography (CT) scans were obtained to exclude any pre-existing degenerative articular pathology or skeletal deformity. Specimens were stored at -20°C and thawed at room temperature (approximately 22°C) for at least 18 hours before testing. To prepare for testing, soft tissues were removed around the upper humerus to facilitate mounting in the testing system.

Each cadaveric limb was securely affixed to a validated elbow simulator using a humeral clamp, as described in previous studies[14–16] (Figure 2-1). The elbow joint was set at a 90° angle of flexion on the simulator, with the hand firmly secured using a floor-mounted clasp. This hand clasp was adjustable to allow for testing in neutral forearm rotation as well as at both 45° of supination and pronation relative to the neutral orientation.

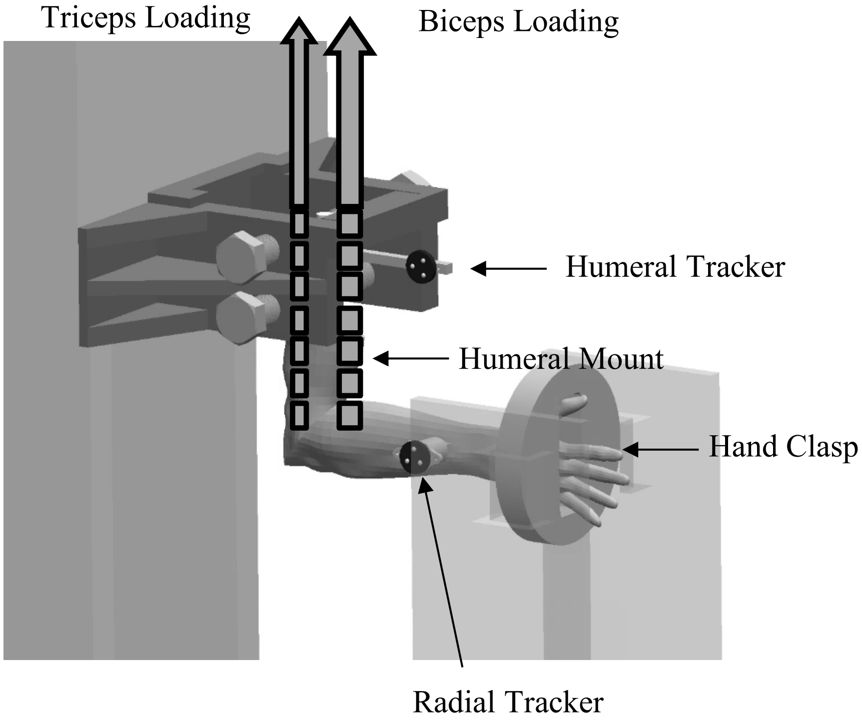

Figure 2-1: Biomechanical elbow simulator.

A right cadaveric elbow mounted onto the biomechanical simulator in 90° of flexion in neutral orientation. Cadaver is shown with angulation attached to ulna in 0° angulation.

To mimic activity of the musculature, loading was applied to the biceps and triceps. The distal tendons were sutured using #5 Ethibond (Ethicon, Johnson & Johnson, New Brunswick, NJ) in a continuous locking pattern, and connected to high-strength braided lines that followed physiological muscle pathways and were linked to computer-controlled pneumatic actuators.

2.2.2 Testing Protocol

Isometric muscle loading was utilized with a specific 2:1 ratio between the biceps and triceps, respectively. The biceps were responsible for applying a forward-directed muscle force to the proximal radius, while the triceps countered this force to keep the elbow consistently flexed at 90°. We incrementally increased the biceps load in 10N increments until reaching a maximum load of 150N. This load was chosen based on preliminary investigations, which indicated that it was adequate for detecting variations in radial head (RH) stability across the various test conditions assessed. This procedure was repeated for each test state with the arm positioned in neutral, supination, and pronation.

2.2.3 Experimental Variables

Each cadaver was first evaluated in its native state with all relevant soft tissue structures intact (intact condition). Dissection was then carried out through an anterior Henry approach to gain access to the anterior forearm and elbow. The anterior joint capsule was then sectioned transversely to gain access to the elbow joint. Soft tissue sectioning was then carried out in three phases. We moved from distal to proximal, sectioning the central IOM, proximal IOM and finally the annular and quadrate ligaments. In stage 1, the central portion of the IOM was sectioned. The central band originates at approximately 60% of the length of the radius measured from the radial styloid and inserts approximately at the junction of the middle and distal thirds of the ulna.[17] It is oriented obliquely from proximal-radial to distal-ulnar which differentiates this portion of the IOM from the proximal IOM. In stage 2, the proximal portion of the IOM was sectioned. The proximal IOM is comprised of the proximal and dorsal oblique cords.[18–20] The proximal oblique cord originates from the anterolateral aspect of the coronoid process and inserts just distal to the radial tuberosity. The dorsal oblique cord originates from the junction of the proximal third and distal two-thirds of the ulna and inserts into the interosseous crest of the radius. In stage 3, the annular ligament and the quadrate ligament, if present, were sectioned. Figure 2-2 displays the various stages of soft tissue sectioning.

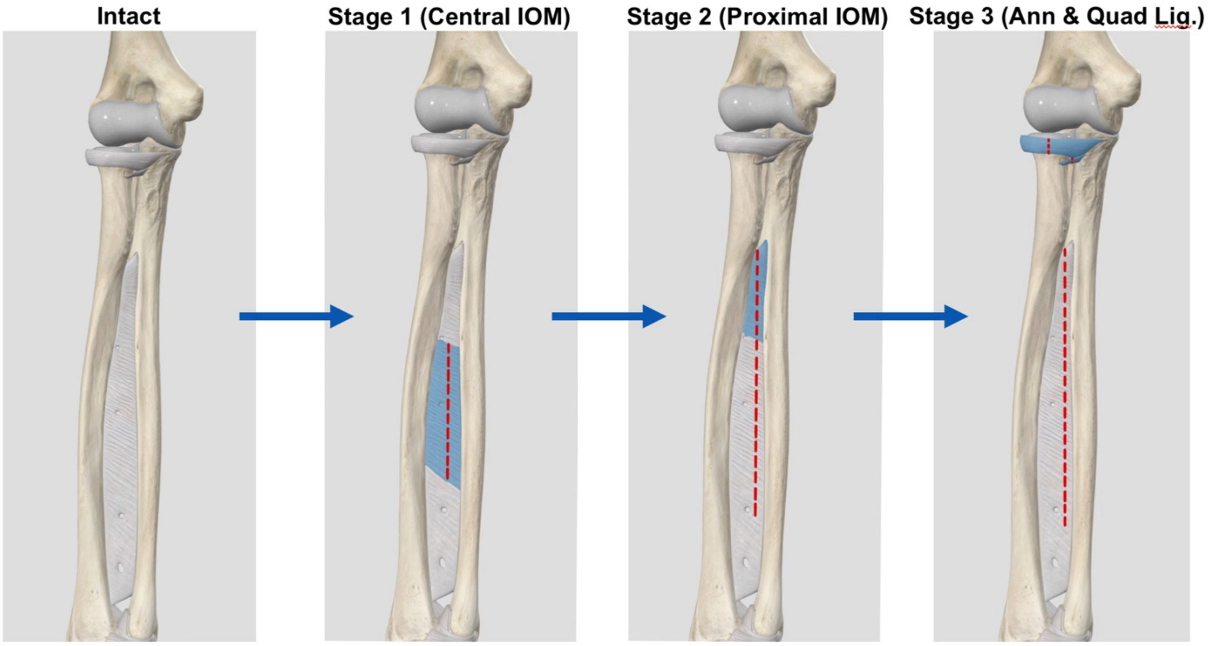

Figure 2-2: All stages of soft tissue sectioning.[21]

All soft tissue conditions evaluated in this study are illustrated here, including the progressive soft tissue sectioning of the central interosseous membrane, proximal interosseous membrane, annular ligament, and quadrate ligament.

2.2.4 Outcome Variables and Statistical Analysis

The primary focus of this study was centered on assessing the stability of the radiocapitellar joint. To measure this stability, we employed a modified version of the radiocapitellar ratio (RCR), originally introduced by Rouleau et al.[22] Our modification aimed to express anterior subluxation in three dimensions, as opposed to the original two-dimensional representation.

To track the position and orientation of the radius relative to the humerus, we utilized an optical tracking system (Optotrak Certus; Northern Digital, Waterloo, ON, Canada). Following testing, bony landmarks were digitized on both the humerus and radius. A trace of the capitellum allowed us to determine the center and diameter of the capitellum through a sphere-fitting algorithm. A plane was fitted to the rim of the radial head (RH) using data obtained from tracing this landmark. Subsequently, a vector normal to this plane was determined and positioned at the center of the RH, determined by the centroid of anterior, posterior, lateral, and medial points digitized on the RH's rim.

We established a distal humeral coordinate system by digitizing points on both the medial and lateral epicondyles, along with tracing the humeral shaft. Next, we projected the RH vector and the center of the capitellum into the sagittal plane of the humeral coordinate system to prevent any medial or lateral subluxation from affecting the RCR value. We measured the length of the perpendicular bisector from the RH vector to the center of the capitellum, treating it as a positive value if the vector passed anteriorly relative to the capitellum center and negative if it passed posteriorly. The RCR was then calculated by dividing this length by the diameter of the capitellum. Consequently, an RCR value of 100% indicated complete anterior dislocation of the RH relative to the capitellum, while 0% indicated a centered joint (Figure 2-3).

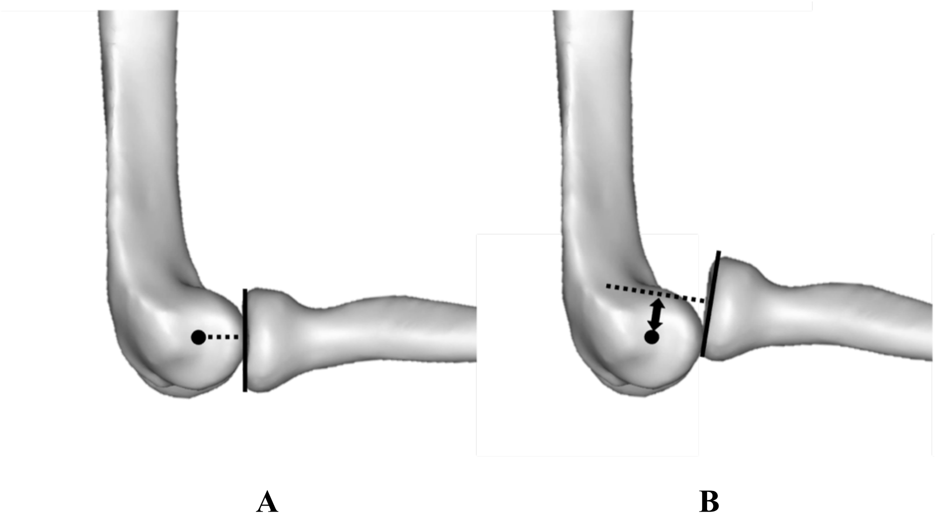

Figure 2-3: Illustration of the radiocapitellar ratio.

(A) *Reduced joint corresponding to a RCR of 0%.* ***(B)*** *Anterior subluxation radial head with the RCR determined by the distance indicated by the black line.*

For statistical analysis, a three-way repeated measures analysis of variance was conducted using SPSS software (IBM, Armonk, NY, USA). The three independent variables in this analysis were the stage of soft tissue sectioning, forearm orientation, and biceps force. To account for multiple comparisons, we applied a Bonferroni correction, setting the threshold for statistical significance to $P \leq 0.05$.

2.3 Results

The stage of soft tissue sectioning and the magnitude of the biceps force were shown to have a significant effect on the RCR (P<0.001). Forearm rotation was not shown to significantly affect the RCR (P=0.250), although when combined with the stage of sectioning did influence the RCR (P=0.009).

2.3.1 Soft Tissue Sectioning

The mean RCR for all stages of soft tissue sectioning are shown in Figure 2-4 for each forearm rotation evaluated. The RCR was observed to increase with progressive soft tissue sectioning in all forearm positions. Stage 3 soft tissue sectioning resulted in the greatest RCR in neutral (79±35%), pronation (66±37%), and supination (77±30%) positions and was significantly greater than all other soft tissue sectioning conditions for all forearm positions (P<0.001). Stage 2 soft tissue sectioning resulted in the second greatest RCR (neutral: 12±8%, pronation: 8±9%, and supination: 9±8%), followed by stage 1 soft tissue sectioning (neutral: 4±7%, pronation: 2±8%, and supination: 3±7%) and the intact (neutral: 3±7%, pronation: 2±7%, and supination: 1±8%) soft tissue conditions respectively. The mean RCR during stage 2 of soft tissue sectioning was significantly greater than that during stage 1 soft tissue sectioning for neutral (P=0.021) and pronation (P=0.018) positions but not for supination (P=0.069). It should be noted however that the magnitude of the differences in the mean RCR values between the intact and soft tissue sectioning stages 1 and 2 were far less than those observed between stage 3 soft tissue sectioning and all other testing conditions. The difference between mean RCR values for stage 1 soft tissue sectioning and the intact soft tissue condition were not statistically significant for any forearm position (P≥0.208).

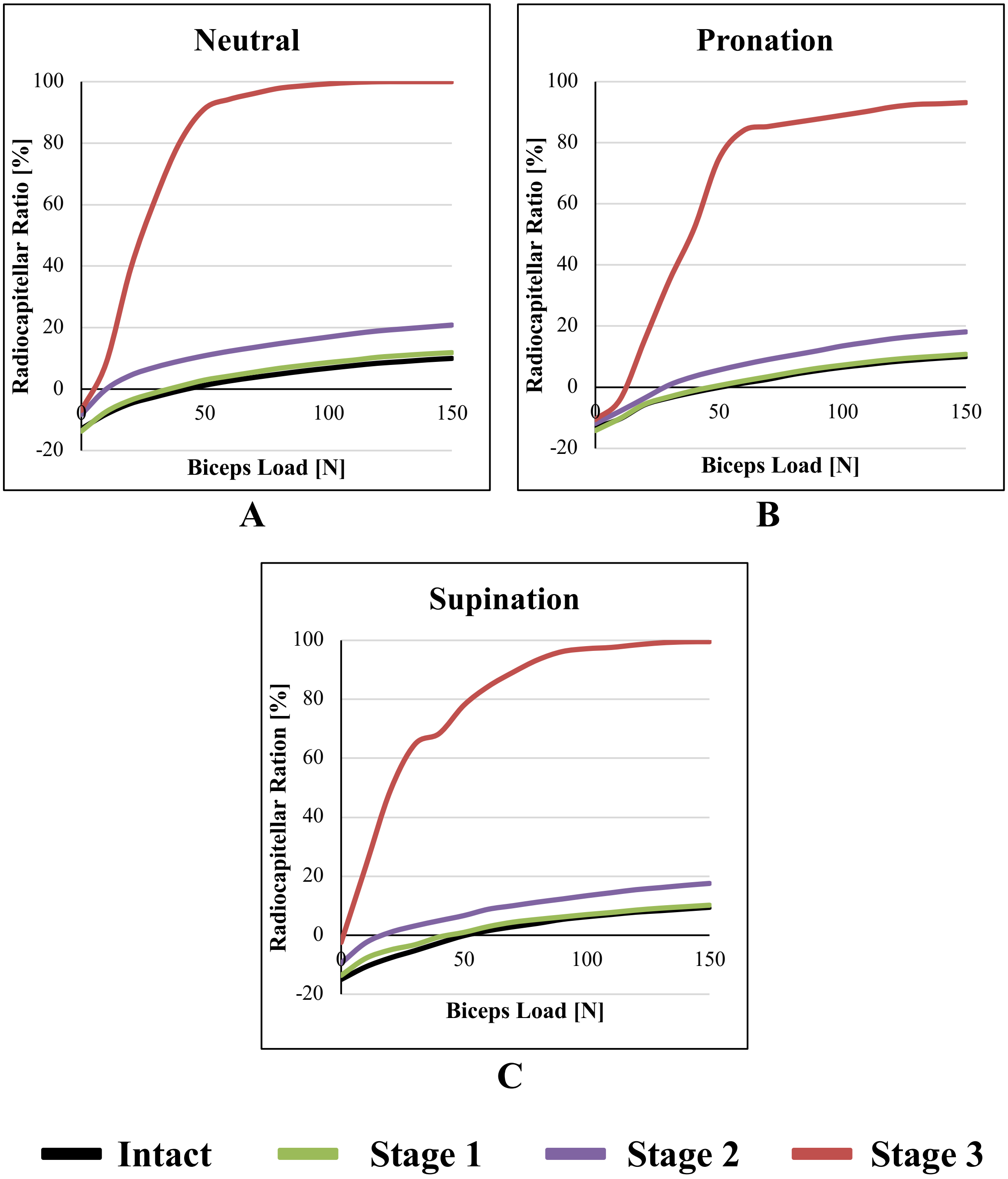

Figure 2-4: Radiocapitellar ratio comparing soft tissue sectioning stages.

The mean radiocapitellar ratio is compared between the intact and all soft tissue sectioning stages for(A) neutral, (B) pronation, and (C) supination forearm positions. The standard deviation range for each condition was: intact=13-22%, stage 1=12-22%, stage 2 =10-19%, and stage 3=0-39%).

2.3.2 Forearm Rotation

Figure 2-5 displays the mean RCR trends for forearm rotation across the full range of biceps loading for each soft tissue sectioning stage. No statistically significant differences in the mean RCR were observed between the intact, and stages 1 and 2 of soft tissue sectioning for neutral, pronation, and supination positions ($P \geq 0.214$). However, after stage 3 soft tissue sectioning, pronation was observed to significantly reduce the mean RCR compared to both neutral ($P=0.002$) and supination ($P=0.011$). No statistically significant differences were observed in the mean RCR between neutral and supination positions during stage 3 of soft tissue sectioning ($P=1.000$).

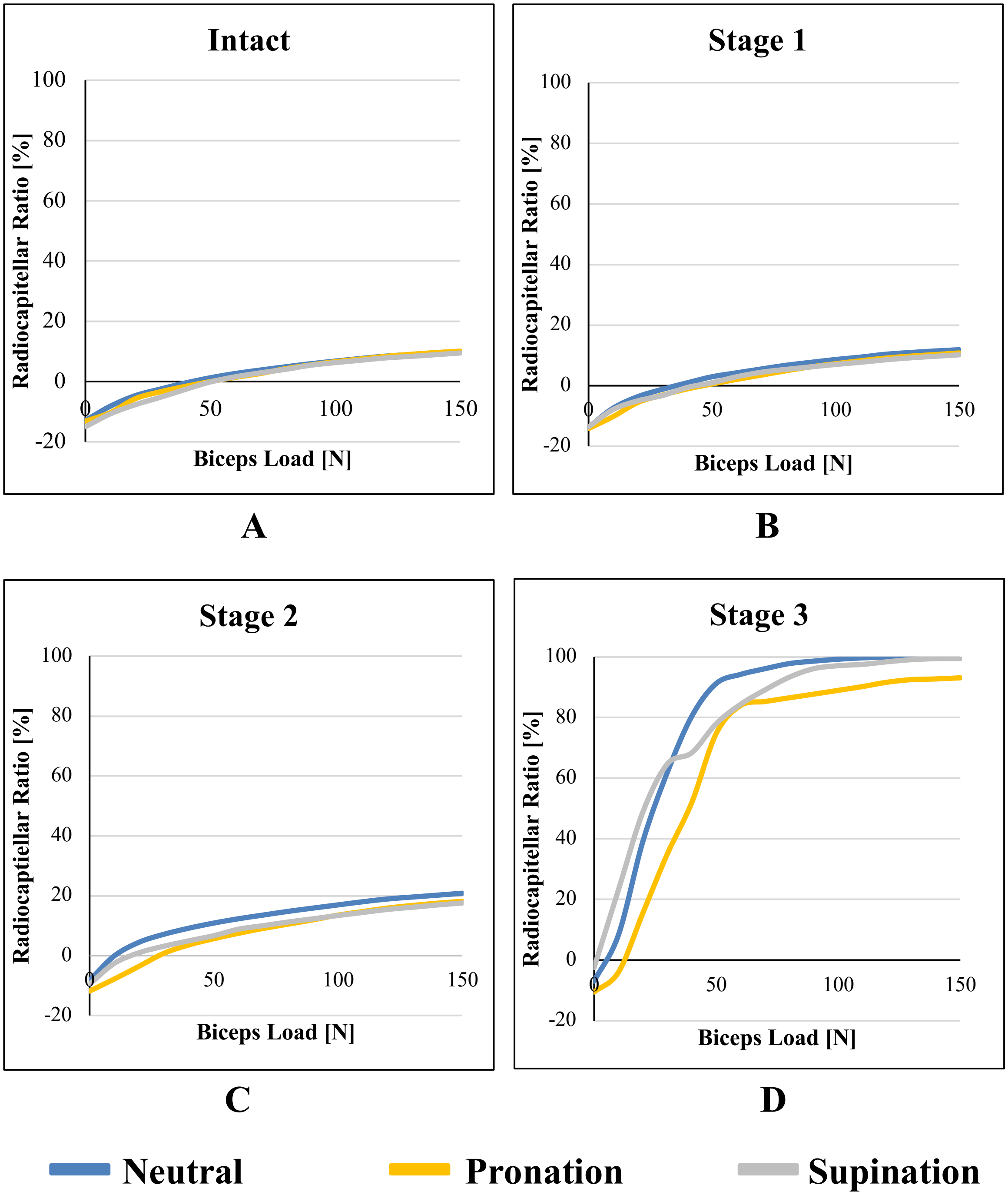

Figure 2-5: Radiocapitellar ratio comparing forearm positions in each sectioning stage.

Comparison of the mean radiocapitellar ratio between neutral, pronation, and supination forearm positions for all soft tissue conditions. The standard deviation range for each condition was: neutral=0-39%, pronation=10-37%, and supination=2-39%.

2.4 Discussion

This biomechanical investigation assessed the contributions of soft tissue stabilizers of the proximal radius. Our findings demonstrate that while sectioning the central and proximal IOM had some minor effects on stability, it was only after sequential sectioning of the annular and quadrate ligaments that a major and statistically significant change in anterior translation of the radial head was observed. This study also shows significantly increased radial head stability with forearm pronation in comparison to supinated and neutral forearm positions.

Evaluating the effects of progressive soft tissue sectioning in Monteggia injuries our study demonstrated no significant radial head translation with sectioning of the central and proximal IOM when compared to the intact state. A significant increase in anterior radial head translation was seen, however, once the annular and quadrate ligaments were sectioned, which remains consistent with previous anatomic and biomechanical studies showing worsening radial head subluxation with compromise to the annular ligament in the setting of Monteggia injuries.[11,23] In contrast, Badre et al did not find a significant radial head translation with sectioning of the annular ligament alone, however, did show statistically significant anterior radial head translation after additional sectioning of the proximal and central IOM.[10] Badre et al did, however, explain that this was likely due to limited sample size. This seemed to agree with past studies showing significant contributions of the proximal and central IOM to the instability patterns displayed in pure radial head dislocations.[8,12] An important limitation of these past studies, however, remains that these cadaveric specimens were dissected of all muscles, tendons and skin and moreover, they did not examine radial head stability during physiologic loading conditions. It is also worth noting that our study reversed the order in which sectioning took place relative to that employed by Badre et al. Sectioning in Badre's study took place from proximal to distal with annular and quadrate sectioned first, then proximal IOM and finally central IOM. We performed our sectioning in the reverse order from distal to proximal, sectioning central IOM first, then proximal IOM and finally annular and quadrate ligaments. Although trends suggest increased anterior translation of the radial head with progressive sectioning of the central and proximal IOM, in our study, this failed to show statistical significance. It wasn't until sectioning of the annular and quadrate ligaments took place, that anterior translation of the radial head was statistically significant to that of the intact state, suggesting the annular ligament as the primary stabilizer of the radial head to anterior translation.

This study also showed significantly increased radial head stability in pronation compared to supinated and neutral forearm positions. Current teachings suggest supination is a more stable position for the radiocapitellar joint postulating that since biceps activation leads to increased anterior translation of the radial head, supination would place the biceps under less tension, aiding in reduction.[24] We believe that contrary to current doctrines, placing the biceps in a pronated position may aid in stabilizing the radial head by altering the direction of pull of the biceps from a direct anterior line of force as seen in supination to a more torsional vector as the radial tuberosity rotates medially when the forearm is held in pronation. Furthermore, in line with how pronation tends to increase ulnar variance, the additional axial force through the radiocapitellar joint associated with a pronated forearm position might help to add stability to the joint.[25] It is important to note that while the effect of forearm rotation was statistically significant, the magnitude of the difference between the three forearm rotations was small. This suggests that relative to the soft tissue status, and the magnitude of biceps activation, forearm rotation is likely clinically less important. Future studies are needed to determine if positioning the forearm in supination in an effort to reduce biceps activation is more important than the favorable biomechanical effect of forearm pronation as observed in the current study.

The present study does possess certain limitations. In our biomechanical cadaver-based model investigating anterior Monteggia injuries, it is important to note that these injuries typically occur in individuals younger than the mean age of the cadavers. The diminished soft tissue flexibility in older specimens might lead to an underestimation of the clinically apparent radial head movement. Another limitation would include inadequate replication of soft tissue properties as aging and post-mortem changes can alter the properties of soft tissues in cadavers, potentially reducing the relevance of the findings to live human tissues. Furthermore, the controlled environment of the sectioning protocol and the testing set-up employed herein cannot exactly replicate the dynamics of real-life trauma that often involve multiple forces and the biceps muscle activation which occurs after the surgical treatment of these injuries.

The results of this biomechanical investigation have several clinical implications. In agreement with previous studies, the annular ligament proves to be the primary stabilizer of the radial head to anterior translation. Given these results it would seem logical to suggest that protecting the annular ligament intraoperatively when performing surgical approaches to the elbow where possible and repairing it when sectioned or injured should be considered. Finally, our study showed pronation of the forearm reduced instability during static testing. This could have implications on the rehabilitation process and possibly suggest pronation as an optimal position for immobilization in anterior Monteggia injuries. Further studies are needed to better understand the importance of forearm rotation in the management of Monteggia fracture-dislocations.

2.5 Conclusion

This biomechanical investigation demonstrates that increasing soft tissue disruption results in progressive anterior instability of the radial head. In cases of Monteggia injuries with persistent radial head instability after an anatomical reduction of the ulna has been achieved, injury to the annular ligament should be suspected. This study also shows radial head stability was significantly increased with forearm positioned in pronation as compared to supination or neutral.

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Chapter 3

3 Determining the Contribution of Apex Posterior Overcorrection of the Ulna on Radial Head Stability in Anterior Monteggia Fractures

Monteggia fractures account for 1-2% of all forearm fractures.[1] *Despite anatomic restoration of the ulnar fracture, radial head anterior instability may persist, leading to poor outcomes. This chapter examines the effect of apex posterior ulnar overcorrection on radial head stability in anterior Monteggia fractures.*

3.1 Introduction

(The background in this section was also provided in Chapter 1, but is summarized here as this chapter forms the basis of a manuscript for submission for publication).

(This work has been presented at the American Shoulder and Elbow Society in Scottsdale, AZ. It has been submitted for publication to the Journal of Pediatric Orthopaedics)

Monteggia fractures, first described in 1814 by Giovanni Monteggia, represent 1-2% of all forearm fractures.[2] Bado et al [3] classified these forearm fractures into four types based on the direction of radial head (RH) dislocation. This investigation focused on Type 1 Monteggia injuries, which represents an apex anterior fracture of the proximal or middle one third of the ulna and anterior displacement of the RH. Type 1 Monteggia injuries are the most common type in the pediatric population, accounting for about 70% of all Monteggia fractures.[1]

Monteggia injuries can be difficult to diagnose clinically and if proper management is not initiated, debilitating complications can often result. In fact, approximately 25-50% of these injuries are initially missed and management of chronic Monteggia fractures prove to be much more challenging.[1,4] Indeed, high rates of complications were found in previous follow-up studies with residual RH dislocation being the most common.[5–7]

A limited number of biomechanical studies have investigated the impact of Monteggia fractures and alignment on function and stability. Sandman et al[8] studied how ulnar misalignment, elbow and forearm positions, and annular ligament integrity affected RH subluxation. They reported that anterior RH subluxation increased with apex anterior ulnar misalignment, elbow flexion, and annular ligament damage. Badre et al[9] confirmed that progressive apex anterior ulnar angulation in anterior Monteggia injuries results in an incremental increase in anterior RH translation. However, the influence of apex posterior overcorrection of the ulna on RH stability is unknown. Therefore, it was the objective of this study to evaluate the effect of posterior ulnar angulation and forearm position on anterior RH stability in simulated anterior Monteggia fractures. It was hypothesized that increasing apex posterior angulation of the ulna as well as a supinated forearm position would decrease anterior RH translation.

3.2 Materials and Methods

3.2.1 Specimen Preparation and Experimental Setup

Nine (9) fresh-frozen cadaveric right upper extremities (mean age: 73 ± 18 years) were resected at the mid-humerus. Computed tomography (CT) scans were obtained prior to testing to rule out pre-existing degenerative articular pathology or skeletal deformity. Specimens were stored at -20°C and thawed at room temperature (~22°C) for a minimum of 18 hours prior to testing. For testing preparation, the upper humerus was first denuded to allow mounting in the testing system. Each cadaver was fixed to a validated elbow simulator using a humeral clamp[10–12] (Figure 3-1). The elbow was positioned on the simulator in 90° of flexion using a floor-mounted clasp to fix the hand. This hand clasp could be rotated to allow for testing in neutral forearm rotation and both 45° of supination and pronation relative to the neutral orientation. The distal tendons of biceps and triceps were sutured using #5 Ethibond (Ethicon, Johnson&Johnson, New Brunswick, NJ) in a running locking fashion and were connected to high strength braided lines which were routed along physiological muscle lines and attached to computer controlled pneumatic actuators.

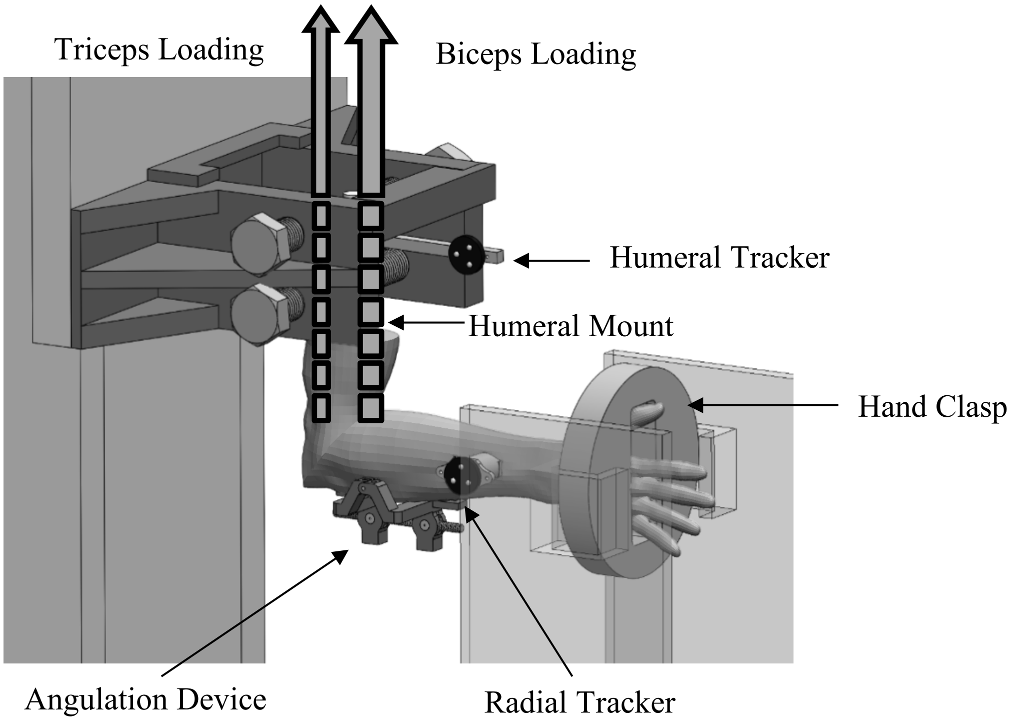

Figure 3-1: Biomechanical Elbow Simulator.

Biomechanical elbow simulator with a mounted right cadaveric elbow in 90° of flexion in neutral orientation. Cadaver is shown with angulation device attached to ulna in 0° angulation.

3.2.2 Testing Protocol

Isometric muscle loading was employed using a 2:1 ratio between the biceps and triceps respectively. The biceps served to apply an anteriorly directed muscle force on the proximal radius while the triceps provided a compensatory load in the aforementioned ratio to maintain the elbow at 90° of flexion. Stepwise incremental loading was performed in 10N increments up to a maximum biceps load of 150N, as pilot studies demonstrated that this load was sufficient to observe changes in RH stability between the different test states evaluated.

3.2.3 Experimental Variables

Each cadaver was first evaluated in its native state with all relevant soft tissue structures intact and the testing protocol was completed for all forearm orientations. An anterior Monteggia fracture and associated soft-tissue disruption was simulated. To model the fracture, several steps were taken. First, the length of the ulna was measured and a mark was created on bone between the proximal and middle thirds. This mark corresponded to the location where the Monteggia fracture would be simulated. The anterior joint capsule was then sectioned transversely to gain access to the elbow joint. This was followed by the sectioning of the proximal and central interosseous membrane, along with the annular and quadrate ligaments to de-stabilize the radiocapitellar joint. A custom angulation device was then affixed to the ulna using four, self-tapping, 3.5mm cortical screws (Figure 3-2). This device was secured to the posterior surface of the ulna so the middle of the device was aligned with the previously marked location on the ulna. The purpose of this device was to simulate apex posterior angulation of the ulna. The location of the device's center of rotation was determined by the mean anterior-posterior (AP) thickness at the point between the proximal and middle one-third of all ulnae used in this study. This distance was obtained by analyzing the CT scans of all cadavers to be employed in this study prior to testing using visualization software (Mimics, version 21.0, Materialise, Belgium). The center of rotation of the device was designed at this location to prevent impingement between the anterior cortex of the proximal and distal ulnar segments during testing, effectively creating an opening wedge osteotomy at the point between the middle and proximal thirds of the ulna. A threaded rod was used to connect both proximal and distal ends of this device together, thus controlling the angulation of the ulna. The distance between two points engraved into the side of the device was measured throughout testing using a digital calliper and was used with a trigonometric formula to determine the relative angle between proximal and distal ulnar segments. Lastly, a Monteggia fracture was simulated by performing an ulnar transverse osteotomy using a micro sagittal saw at the point between the proximal and middle one-thirds of the ulna. The osteotomy was performed after the angulation device had been fixed to the ulna to prevent malalignment of the proximal and distal ulnar segments. Each cadaver was tested in 0°, 10 °, 20° and 30° of posterior ulnar angulation in a randomized fashion.

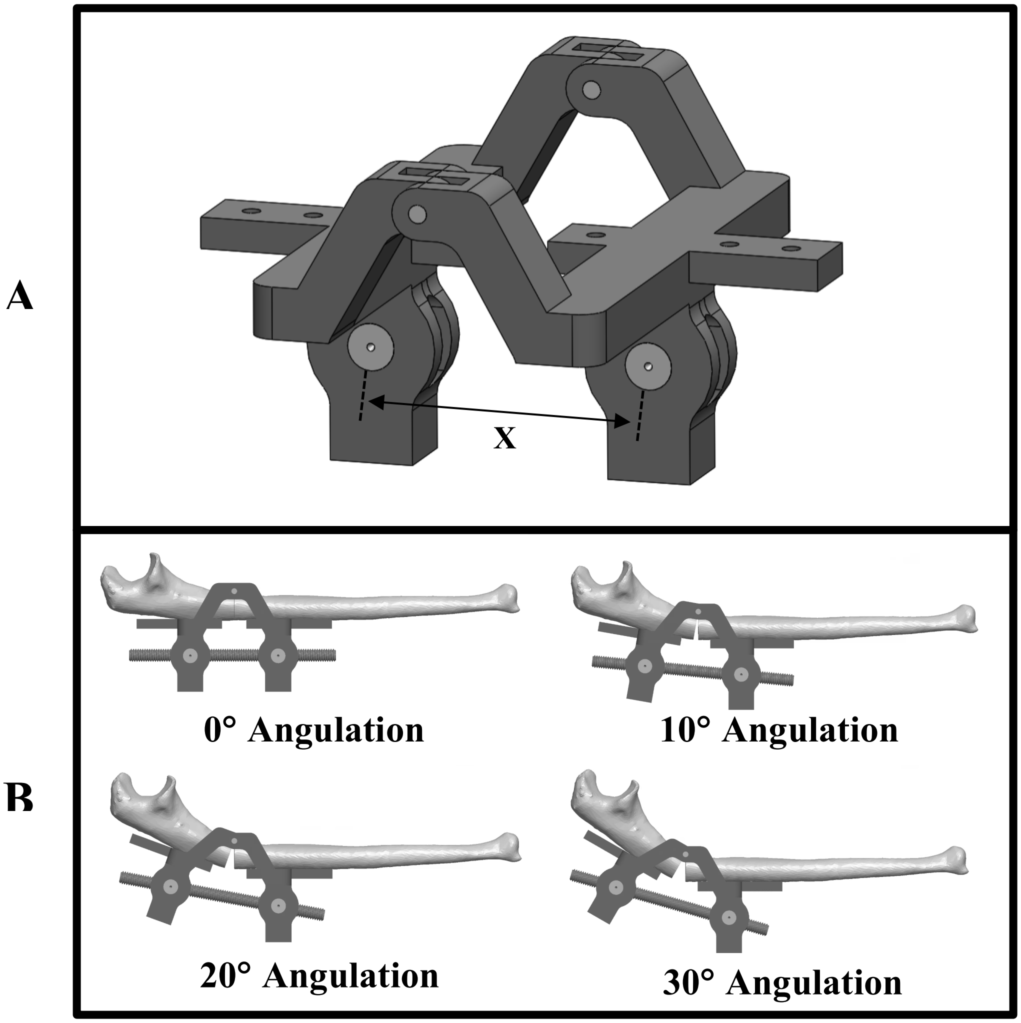

Figure 3-2: Ulnar angulation device.

(A) *The custom device used to control the posterior angulation of the ulna is illustrated. 'X' corresponds to the distance used to determine the angulation between the two parts of the device.* ***(B)*** *The device mounted onto the ulna is shown for all four posterior angulations evaluated.*

3.2.4 Outcome Variables and Statistical Analysis

The primary outcome for this study was anterior radiocapitellar joint stability. To quantify this, the radiocapitellar ratio (RCR) as originally described in Rouleau et al[13] was modified for the purpose of expressing anterior subluxation in three-dimensions opposed to two-dimensions. The position and orientation of the radius relative to the humerus was tracked using an optical tracking system (Optotrak Certus; Northern Digital, Waterloo, ON, Canada). Bony landmarks on the humerus and radius were digitized after testing. A trace of the capitellum was performed and used to determine the center and diameter of the capitellum through a sphere-fitting algorithm. A plane was then fit to the rim of the RH using the data obtained from a trace of this landmark. A vector normal to this plane was calculated and positioned at the centre of the RH, which was determined by the centroid of the anterior, posterior, lateral, and medial points digitized on the rim of the RH. A distal humeral coordinate system was then established using the digitized points of both medial and lateral epicondyles, in addition to a trace of the humeral shaft. The RH vector and center of the capitellum were then projected into the sagittal plane of the humeral coordinate system, as this prevented any medial or lateral subluxation of the RH to influence the value of the RCR. The length of the perpendicular bisector from the RH vector to the centre of the capitellum was then determined (Figure 3-3). The length of this line was taken as a positive value if the vector passed anteriorly relative to the capitellum center, and negative if the vector passed posteriorly relative to the capitellum center. The length of the perpendicular bisector was then divided by the diameter of the capitellum to determine the RCR. Therefore, an RCR value of 100% corresponded to complete anterior dislocation of the RH relative to the capitellum, while 0% corresponded to a centered joint.

Statistical analysis was conducted using a three-way repeated measures analysis of variance using SPSS software (IBM, Armonk, NY, USA). The 3 independent variables for this analysis were the state of the ulna, biceps force, and forearm orientation. A Bonferroni correction was applied to account for multiple comparisons, while statistical significance was set at $P \leq 0.05$.

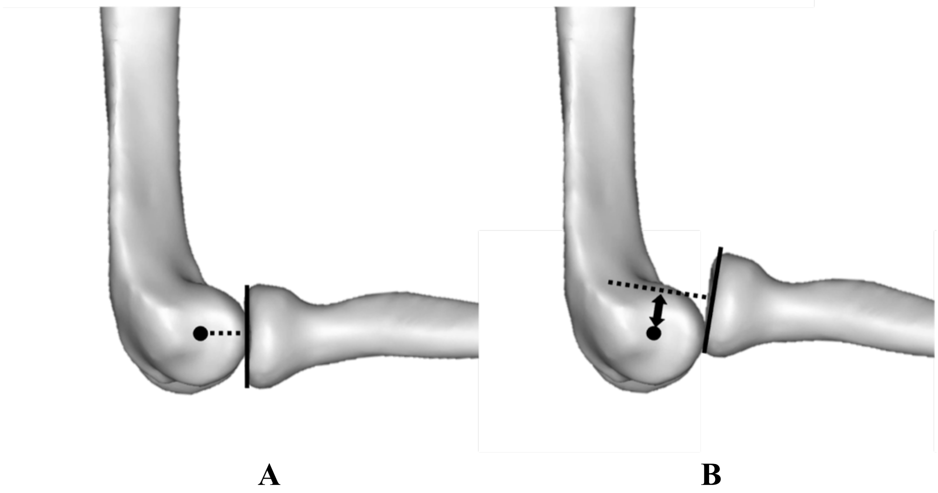

Figure 3-3: Illustration of the radiocapitellar ratio.

(A) *Reduced radiocapitellar joint corresponding to a RCR of 0%.* ***(B)*** *An anteriorly subluxated radial head with the RCR determined by the distance indicated by the black line.*

3.3 Results

The RCR for neutral, pronation, and supination for all test states are shown in Figure 3-4. Increasing posterior angulation and forearm position were both shown to exhibit statistically significant effects on the RCR ($P \leq 0.001$).

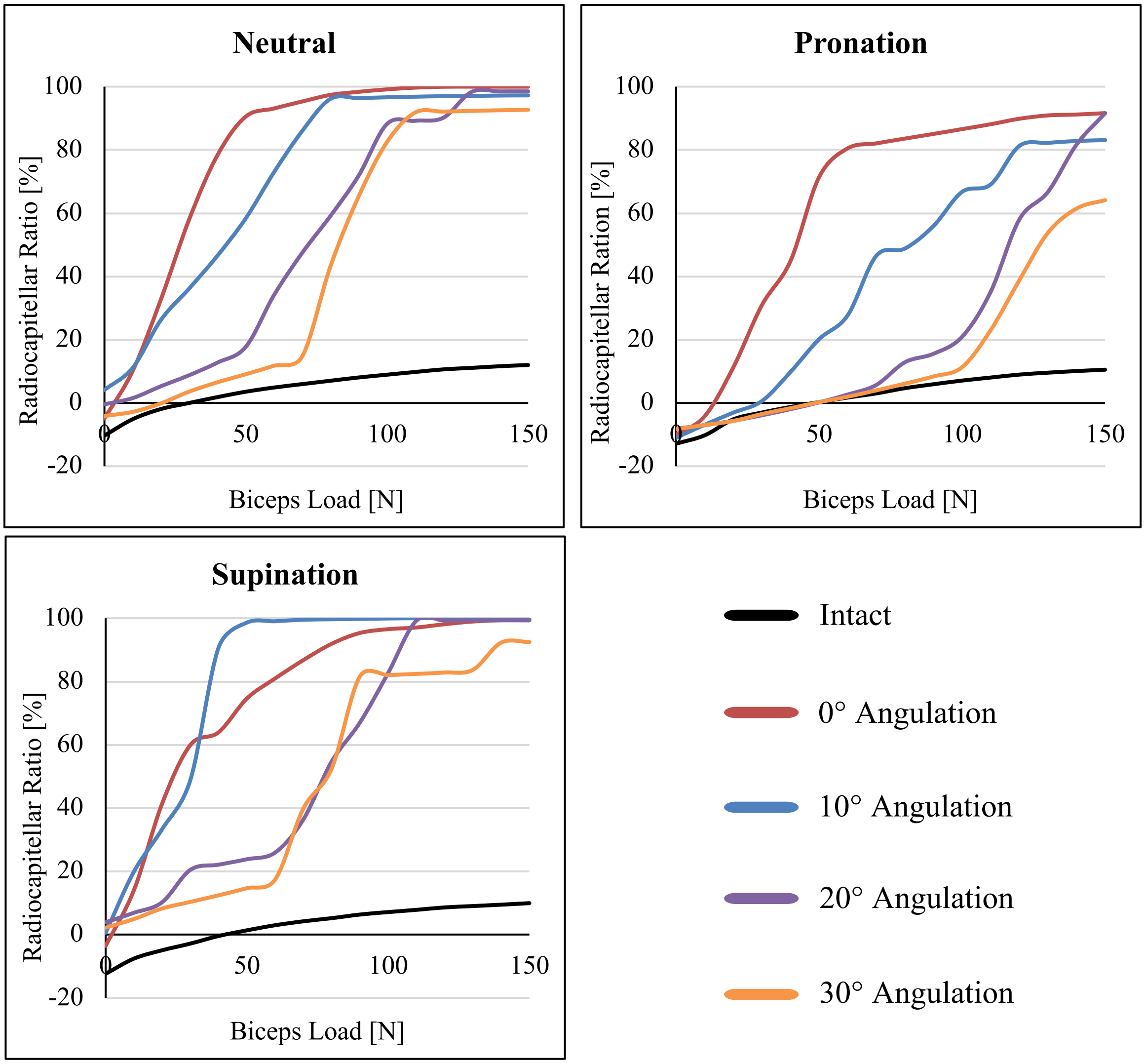

Figure 3-4: Radiocapitellar Ratio comparing posterior angulations in each forearm position.

Comparison of the mean radiocapitellar ratio (RCR) between the intact, 0°, 10°, 20°, and 30° posterior ulnar angulation test states for neutral, pronation, and supination forearm orientations. The standard deviation range for each condition was as follows: intact=7%, 0°=32-36%, 10°=34-35%, 20°=34-40%, and 30°=25-42%.

For all forearm rotations evaluated, the intact soft tissue condition exhibited the lowest RCR when averaged across all bicep loads (neutral: 5±7%; pronation: 2±7%; supination:

3±7%). Increasing posterior angulation of the Monteggia fracture was observed to reduce the RCR for all forearm rotations. In the presence of a simulated Monteggia fracture, the lowest average RCR was obtained with 30° of posterior ulnar angulation (neutral: 43±42%; pronation: 15±25%; supination: 47±37%), followed by 20° (neutral: 51±40%; pronation: 23±34%; supination: 53±38%), 10° (neutral: 70±34%; pronation: 41±35%; supination: 81±34%), and 0° (neutral: 78±35%; pronation: 63±36%; supination: 75±32%) respectively. The RCR for all posterior angulations when tested in neutral, pronation, or supination were significantly greater than the RCR of the corresponding intact soft tissue condition, except in pronation with 30° of posterior angulation ($P=0.101$).

Figure 3-5 compares the RCR for the different forearm rotations as a function of biceps load. The mean RCR was similar across all forearm positions in the intact soft tissue condition. For all posterior angulations, the RCR was significantly less in pronation compared to both neutral and supination ($P\leq0.046$). However, similar trends in the RCR were observed between neutral and supination for all posterior angulations ($P\leq0.210$).

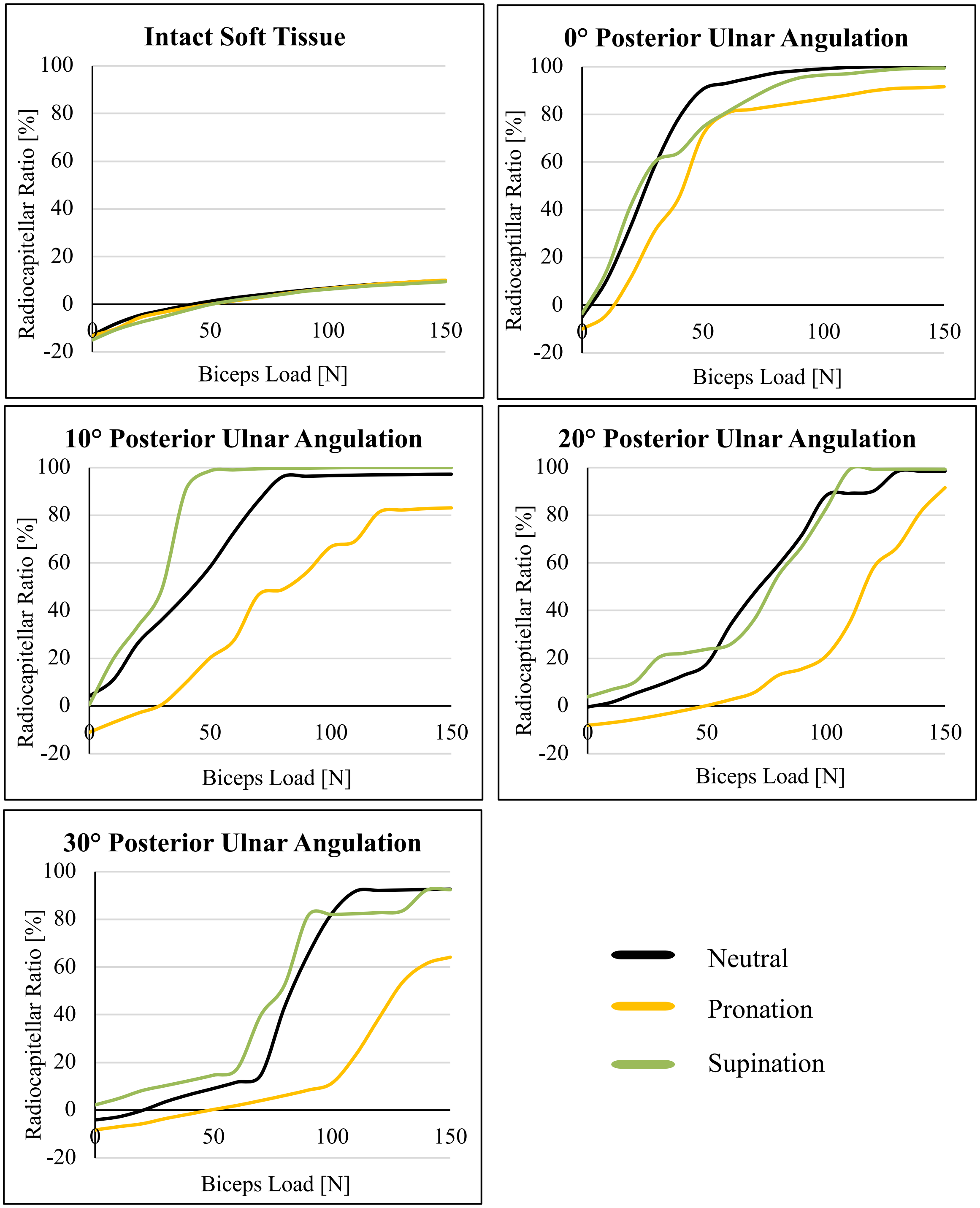

Figure 3-5: Comparison of radiocapitellar ratio between forearm positions.

Radiocapitellar ratio (RCR) at 90 degrees of elbow flexion in neutral, supination, and pronation for all posterior ulnar angulations evaluated. The standard deviation range for each orientation was: neutral=7-42%, pronation=7-36%, supination=7-38%.

3.4 Discussion

In this biomechanical study, we assessed the effect that posterior ulnar angulation and forearm rotation position have on anterior RH stability in an anterior Monteggia injury model. Our findings showed that posterior overcorrection of the ulna in anterior Monteggia injuries can improve anterior radiocapitellar joint stability, although not to that of the native state. This finding suggests that anatomical reduction of the ulna is insufficient in achieving premorbid radiocapitellar joint stability. Another key finding was that RCR was significantly reduced in pronation compared to both neutral and supination positions for all posterior angulations evaluated.

A limited number of biomechanical studies have investigated the impact of Monteggia fractures and alignment on functionality and stability. Sandman et al[8] studied how ulnar misalignment, different arm positions, and annular ligament integrity affected RH stability. They reported that anterior RH subluxation increased with anterior ulnar misalignment, elbow flexion, and annular ligament damage. In agreement with Sandman et al, Badre et al[9] confirmed that progressive anterior ulnar angulation in anterior Monteggia injuries increases anterior RH translation. In our study, we demonstrated that apex posterior overcorrection of the ulna decreased the RCR when compared to the soft tissue sectioned elbow with an anatomic reduction (0°). Furthermore, no level of posterior ulnar overcorrection was successful in restoring the stability to that of the intact state. This suggests that biceps activation should be avoided in the postoperative period. Soft tissue repair or reconstruction may need to be considered in the setting of persistent radiocapitellar joint instability after posterior overcorrection has been attempted. We postulate that the overcorrection of the ulnar fracture results in a relative shortening of the ulna allowing for greater axial force through the radiocapitellar joint and hence enhances RH stability by increasing concavity compression through the radiocapitellar joint.

Interestingly, we also found forearm pronation to exhibit greater RH stability in all posterior ulnar angulations evaluated compared to neutral and supination positions. Current teachings suggest supination offers a more stable position for the radiocapitellar joint postulating that since biceps activation leads to increased anterior translation of the RH, supination would place the biceps under less tension, aiding in keeping the RH in joint.[14]

Our findings suggest that if similar loads are applied to the biceps, forearm pronation enhances the radiocapitellar joint stability. It is possible that by changing the muscle line of action of the biceps from a direct anterior line of force as occurs in supination, to a more torsional vector as the radial tuberosity rotates medially in pronation, could allow for a greater stability of the RH. Additionally, similar to how pronation tends to increase ulnar variance, the additional axial force through the radiocapitellar joint associated with forearm pronation might help to add stability to the joint.

This cadaveric biomechanical study of anterior Monteggia injuries does have some limitations. Cadaveric testing does not replicate the complex in-vivo physiological environment, including factors such as muscle forces, tissue healing, and patient variability. It is important to note that not all Monteggia fractures will behave like the ones we have simulated in our study. Furthermore, these cadavers came from older individuals and might not accurately reflect the bone quality and mechanical response of younger, healthier populations. In terms of overcorrection of the ulna, it is essential to note that translation of these results into clinical practice can be challenging and also the different ulna fracture patterns may challenge the accurate achievement of overcorrection when needed. The degree of overcorrection that can successfully restore RH stability may vary from patient to patient, thereby necessitating careful individualized considerations. Additionally, the effect of ulnar posterior angulation on the proximal and distal radioulnar joint mechanics was not investigated. It is almost inevitable that an overcorrection of the ulna would impact both joints however this remains poorly understood and merits future investigation.

The findings of this study could have several clinical implications. This study confirmed the clinical observation that anterior RH translation in Monteggia injuries can be reduced by overcorrection of the ulna creating an apex posterior angulation. However, this does not completely restore premorbid radiocapitellar stability, thus supporting the role for soft tissue repair or reconstruction in the setting of persistent RH instability, even after overcorrection of the ulna. Additional studies are needed to determine if early passive and/or active ROM can be performed safely when these strategies are implemented. Finally, our study showed pronation of the forearm improved stability during static testing.

This could have implications on the rehabilitation process and possibly suggest pronation as an optimal position for immobilization in anterior Monteggia injuries; further studies are needed to confirm this hypothesis.

3.5 Conclusion

This biomechanical investigation demonstrates that progressive posterior angulation of the ulna in anterior Monteggia injuries results in an incremental increase in anterior stability of the radial head. This study also shows that pronation significantly improves stability of the radial head in comparison with neutral and supinated forearm positions.

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Chapter 4

4 Determine the Efficacy of Four Different Types of Annular Ligament Repair-Reconstructions in Restoring Stability of the Radial Head

Persistent or recurrent instability of the radial head is not uncommon in anterior Monteggia injuries despite anatomic restoration of the ulnar fracture.[1] *Persistent radial head instability is due to the pull of the biceps muscle commonly associated with rupture of the annular ligament and other soft tissue stabilizers of the proximal radius.*[2] *Currently, the optimal method to stabilize the proximal radius and reconstruct the annular ligament is unknown. The purpose of this biomechanical study was to compare annular ligament repair with three different annular ligament reconstructions in restoring radial head stability.*

4.1 Introduction

(The background in this section was also provided in Chapter 1, but is summarized here as this chapter forms the basis of a manuscript for submission for publication).

(This work has been presented at the American Shoulder and Elbow Society in Scottsdale, AZ. It has been submitted for publication to the Journal of Shoulder and Elbow Surgery)

Monteggia fractures are complex orthopedic injuries characterized by a fracture of the proximal ulna along with dislocation of the radial head (RH)[3]. The outcomes of Monteggia injuries are quite variable and often suboptimal, particularly in the adult population[4,5]. Persistent and recurrent subluxation and dislocation of the RH can occur and lead to poor outcomes, even in the setting of an anatomical reduction of the ulna.[1,6,7] This results in pain, stiffness, weakness and functional disability.[1,7] Activation of the biceps pulls the RH anteriorly and contributes to persistent instability due to the disruption of the stabilizing structures of the proximal radius.[2] Radial head instability can also occur in isolated radial head dislocations; however these are much less common than Monteggia injuries.[8–10]

Given that in many cases of anterior Monteggia injuries there is an inability to repair the native annular ligament, various methods of annular ligament reconstruction have been developed to address persistent radiocapitellar instability. One technique reported by Bell Tawse involved the use of a triceps brachii tendon strip.[11] Lloyd-Roberts et al[12] modified this approach using the lateral triceps tendon bundle, in addition to proposing a separate technique utilizing the palmaris longus tendon for stabilization. Modern techniques, such as those proposed by Itadera et al[13], use a palmaris longus tendon autograft, passing it around the radial neck via a bony tunnel created in the ulna. Nwoko et al[14] recommended the use of the brachialis muscle's superficial head for reconstruction due to its optimal location and graft availability. Recently, Marinello et al[15] offered a modified Bell Tawse technique involving a completely detached lateral triceps tendon strip and suture anchors in full forearm supination to reduce the radio-capitellar joint. They also proposed incorporating remnants of the native annular ligament for added reinforcement.

Although various surgical procedures have been proposed for the reconstruction of chronic Monteggia injuries, poor long-term outcomes with high complication rates have been reported, with no commonly agreed upon reconstruction technique for optimal treatment. In light of the foregoing, the aim of this study was to compare an annular ligament repair with three different annular ligament reconstructions in their ability to restore native RH stability in an anterior Monteggia fracture cadaveric model. The three reconstructions evaluated in this study included: 1) a Bell Tawse reconstruction, 2) a free tendon graft reconstruction described by Itadera et al., and 3) a new, more proximally located, free tendon graft reconstruction termed the anatomic reconstruction. We hypothesized that repairing the annular ligament would be most effective in restoring normal anterior RH stability and that the anatomic reconstruction would restore optimal stability.

4.2 Materials and Methods

4.2.1 Specimen Preparation

Eight fresh-frozen cadaveric right upper extremities (mean age: 73 ± 18 years) were obtained for the biomechanical evaluation. All cadavers were scanned using computer tomography (CT) to ensure there were no signs of articular pathology or skeletal deformity. Prior to testing, each cadaver was resected at the mid-diaphysis and thawed at room temperature (~22°C) for a minimum of 18 hours. Using a Henry approach, the distal tendons of the biceps and triceps were tagged using #5 Ethibond (Ethicon, Johnson & Johnson, New Brunswick, NJ) in a running locking fashion and were connected to high strength braided line. Optical tracking markers were rigidly fixed to the radius and humerus to quantify the position and orientation of each bone throughout testing.

4.2.2 Experimental Setup and Loading Protocol

A previously validated elbow simulator was used to conduct all biomechanical testing (Figure 4-1).[16–18] For each cadaver, the humerus was fixed to the simulator using two threaded clamps while a floor mount was used to position the elbow in 90 degrees of flexion and the forearm in neutral rotation by clamping the hand in a locked position. The braided line sutured to the biceps and triceps were routed along physiological muscle lines to computer controlled pneumatic actuators. Static muscle loading was applied to the biceps and triceps using a 2:1 ratio in 10N increments, up to a maximum biceps load of 150N. A maximum load of 150N was determined from several pilot studies which showed this load to be sufficient in capturing the different changes in RH translation between all test states. Antagonistic loading of the triceps was used to prevent flexion of the elbow during testing.

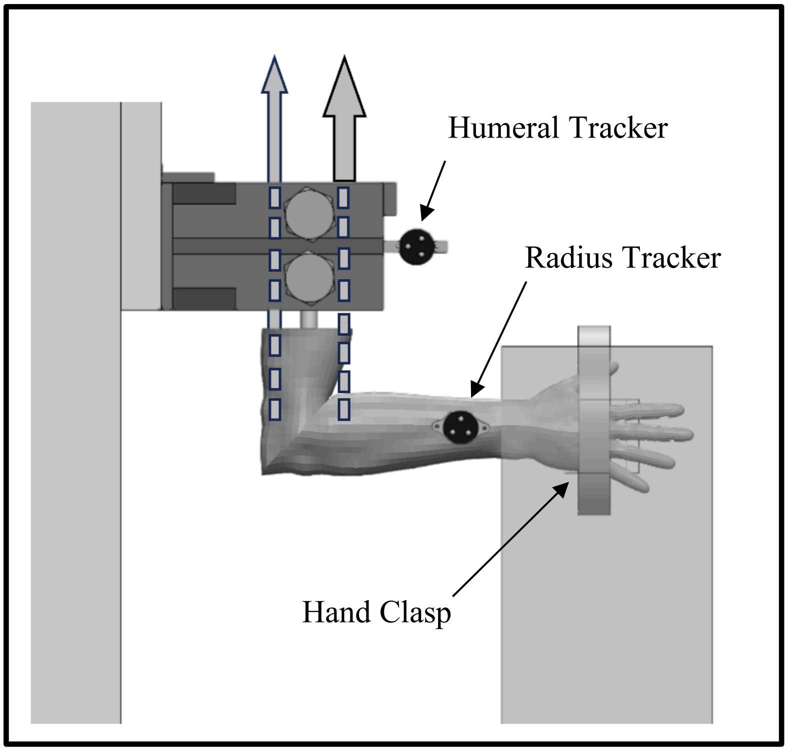

Figure 4-1: Biomechanical elbow simulator.

Right cadaveric elbow mounted onto a biomechanical simulator in 90° of flexion in neutral rotation.

4.2.3 Repair and Reconstruction Protocols

The native state of each cadaver was first evaluated (intact). The anterior joint capsule was then sectioned horizontally to visualize the elbow. Soft tissue stabilizing structures of the proximal radius were then sectioned, including the proximal interosseous membrane (IOM), central IOM, annular ligament and quadrate ligament.

An annular ligament repair and three different annular ligament reconstructions were then evaluated in a randomized order (Figure 4-2). The annular ligament repair and all the reconstructions were performed using #5 Ethibond. For the Itadera reconstruction bone tunnels were drilled in the ulna beneath the supinator crest just distal to the radial notch from anterior to posterior. The exiting limb of the tunnel was drilled from lateral to medial at the same level of the anterior to posterior tunnel to allow passage of the graft from anterior to lateral and around the radius, allowing the graft to then be sutured onto itself. Flexor digitorum superficialis (FDS) of the long or ring fingers were used for tendon grafts. The anatomic reconstruction was prepared in a similar fashion to that of the Itadera reconstruction. However, bone tunnels were drilled proximal to that of the Itadera tunnels at the level of the proximal radioulnar joint, allowing for the graft to sit directly at the RH and once again be sutured onto itself. FDS of the long or ring fingers were used for tendon grafts. The final reconstruction evaluated was the Bell Tawse reconstruction, which utilized the strip of triceps fascia. To perform this procedure, the strip of triceps fascia was left attached to the ulna distally and then looped around the radial neck without bone tunnels and sutured to itself.

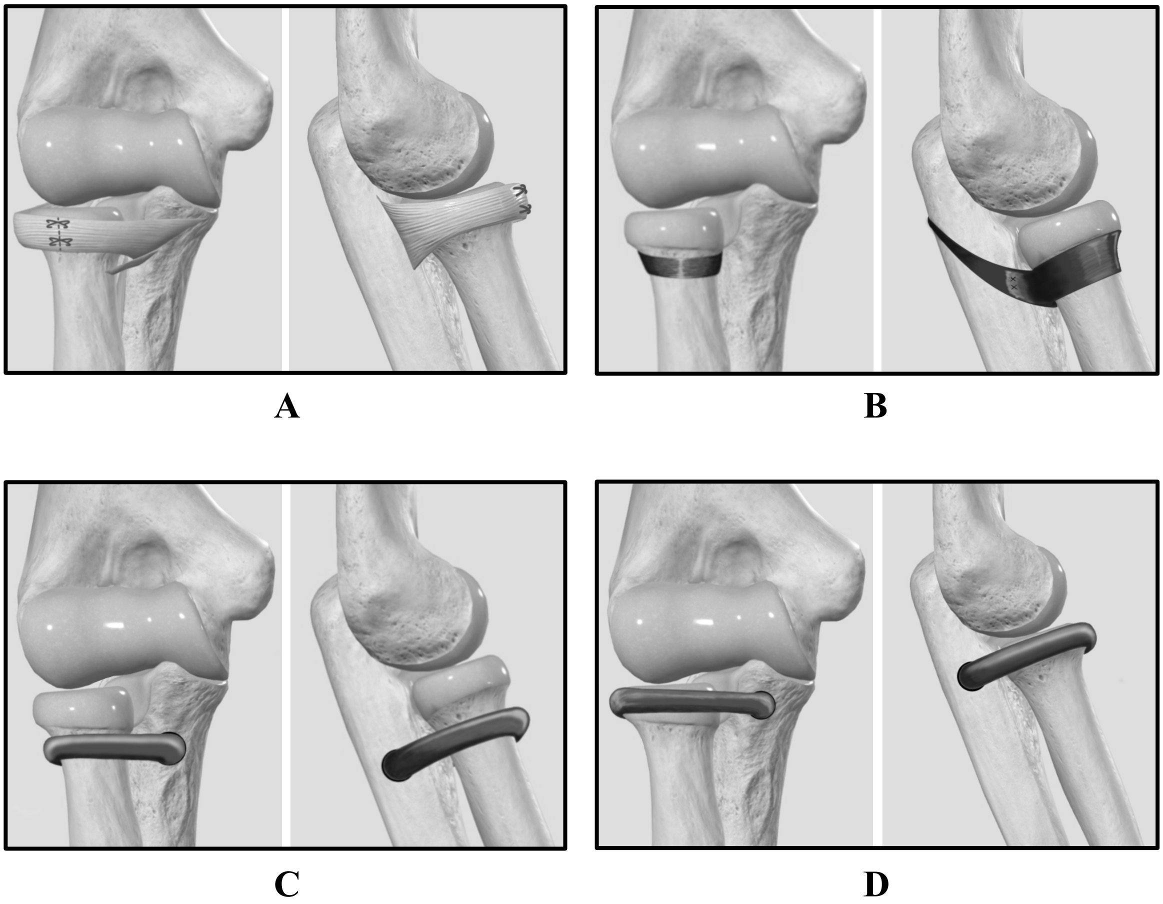

Figure 4-2: Graphic depictions of repair and reconstruction techniques.[19]

(A) *Annular ligament repair,* ***(B)*** *Bell Tawse annular ligament reconstruction,* ***(C)*** *Itadera annular ligament reconstruction, and* ***(D)*** *anatomic annular ligament reconstruction. All illustrations are shown from an anterior and lateral view.*

4.2.4 Kinematic Analysis and Outcome Variables

For all testing conditions, an optical tracking system (Optotrak Certus; Northern Digital, Waterloo, ON, Canada) was used to quantify the position and orientation of the radius relative to the humerus. After testing was completed, the humerus and radius were denuded of all soft tissue. Bony landmarks on both the humerus and radius were digitized using optical tracking markers and a stylus. The medial and lateral epicondyles of the humerus were digitized in addition to performing a trace of the humeral shaft to develop a distal humeral coordinate system. A trace of the capitellum was performed and was used in a sphere fitting algorithm to approximate the center and diameter of the capitellum. A trace of the RH rim was used to determine a plane, and vector orthogonal to this plane centered within the RH, which best fit the rim of the RH. The capitellum center and vector orthogonal to the rim of the RH were projected into the sagittal plane of the humerus coordinate system to prevent the influence of any medial or lateral translation of the RH when determining anterior RH subluxation (Figure 4-3).

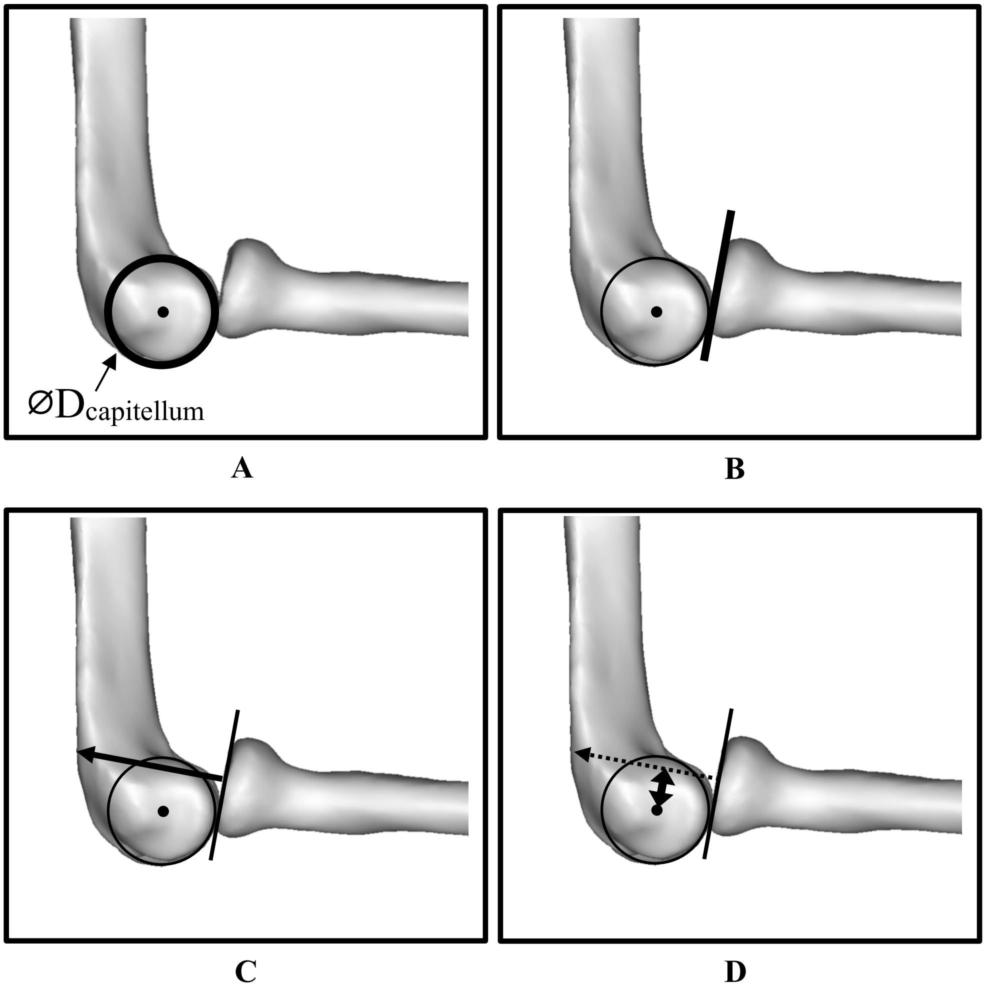

Figure 4-3: Illustration of the radiocapitellar ratio.

These illustrations show the process used to determine the radiocaptiellar ratio (RCR) for each testing condition. A sphere-fitting algorithm is used to determine the center and diameter of the capitellum ***(A)****. A best fit plane is fitted to the trace of the radial head rim* ***(B)*** *and is used to determine a vector passing through the center of the radial head* ***(C)****. The length of the perpendicular bisector between this vector and capitellum center* ***(D)*** *is divided by the diameter of the capitellum to determine the RCR.*

The length of the perpendicular bisector between the RH vector and the center of the capitellum was determined for each test state. If the RH vector passed anteriorly to the center of the capitellum, this length was taken as positive. The length of the perpendicular bisector was then divided by the diameter of the capitellum's best-fit sphere to give the radiocapitellar ratio (RCR). Positive RCR values corresponded to anterior RH subluxation while negative values corresponded to posterior RH subluxation. Furthermore, an RCR of 100% correlated to complete dislocation of the RH relative to the capitellum. This metric has previously been used to quantify anterior subluxation of the RH on two-dimensional radiographs.[20]

Based on the mean values of the RCR for each condition, a stability factor (SF) was also developed. This was determined using equation (1) below:

$$SF = \frac{100 - RCR}{100 - RCR_{Intact}} \qquad (1)$$

where RCR corresponds to the mean RCR of the condition of interest, while RCR_{Intact} corresponds to the mean RCR of the intact condition. This equation was used to provide a simple index measure which quantified the RH stability of each condition relative to the intact soft tissue condition. Values ranged between 0 and 1, with a value of 1 representing equivalent stability relative to the intact soft tissue state.

4.2.5 Statistical Analysis

A two-way repeated-measures analysis of variance was used to statistically compare the effect of the arm state and biceps loading magnitude on the RCR. This analysis was performed using validated software (SPSS, IBM, Armonk, NY, USA) with statistical significance set to $P \leq 0.05$.

4.3 Results

The RCR for all elbow states are shown in Figure 4-4 over the full range of biceps loading. The intact soft tissue state exhibited the greatest stability with a mean RCR of 5±7%. This was followed by the annular ligament repair (6±11%) and Itadera reconstruction (21±21%) respectively. Neither the repair nor Itadera reconstruction were significantly different compared to the intact soft tissue condition ($P=1.000$). The least stable conditions evaluated were the sectioned soft tissue state (78±34%), the Bell-Tawse reconstruction (69±40%), and the anatomic reconstruction (60±35%) respectively. All three reconstructions exhibited significantly greater RCRs compared to both the intact ($P\leq0.001$) and the annular ligament repair conditions ($P\leq0.002$). The Itadera reconstruction exhibited a significantly lower RCR compared to the sectioned soft tissue state and Bell Tawse reconstruction ($P\leq0.005$) but was not significantly different compared to the anatomic reconstruction ($P=0.120$).

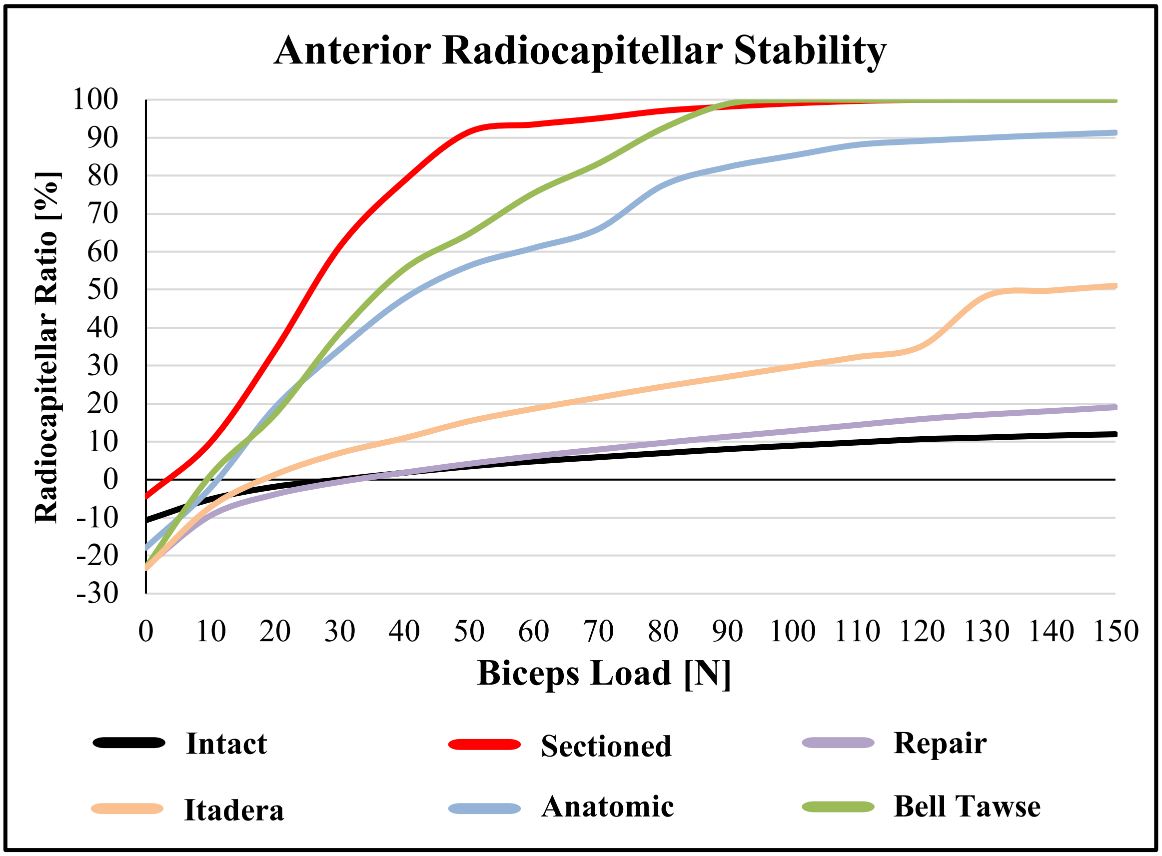

Figure 4-4: Radiocapitellar ratio comparing all states.

The mean radiocapitellar ratio is shown across the full biceps loading range for the intact and sectioned soft tissue states, annular ligament repair, and three annular ligament reconstructions. The standard deviation range for each state was as follows: intact=19-26%, sectioned=0-44%, repair=12-18%, Itadera=14-35%, anatomic=11-35%, and Bell Tawse=0-36%.

4.4 Discussion

Persistent or recurrent instability of the RH is not uncommon in anterior Monteggia fractures despite anatomic restoration of the ulnar fracture.[1,21,22] Persistent RH instability is due to the pull of the biceps muscle with rupture of the annular ligament and other soft tissue stabilizers of the proximal radius.[2] Currently, the optimal method to stabilize the proximal radius and reconstruct the annular ligament is unknown. A comparison of annular ligament repair with three different annular ligament reconstructions in restoring RH stability would aid in optimizing patient outcomes.

This biomechanical investigation demonstrated significant anterior RH translation with sectioning of the soft tissue stabilizers of the RH despite anatomic reduction of the ulna. This remains consistent with previous anatomic and biomechanical studies showing worsening RH subluxation with compromise to the annular ligament in the setting of Monteggia injuries.[23,24] In our study, the annular ligament repair was most effective at reducing the anterior RH instability observed with the sectioning of proximal soft tissue stabilizers and exhibited similar stability to that of the intact soft tissue condition with a SF of 0.98. This was most likely due to the strong repair of the sectioned annular ligament, accurately restoring the native anatomy. However, annular ligament repair is often not possible clinically as the structural integrity of this ligament is often compromised due to the injury. This requires an alternative approach to restoring RH stability using an annular ligament reconstruction. Bony corrections such as dorsal overcorrection of the ulna has also been described to help stabilize the RH, however the focus of this study was on soft tissue alternatives.[25–27]

The results from our study showed the Itadera technique to be most effective reconstruction tested in restoring RH stability, followed by the anatomic reconstruction and Bell Tawse respectively. We believe these trends occurred due to the ability of reconstruction to mimic the function of the native annular ligament. The anatomic reconstruction, although best replicating the position of the annular ligament had a tendency to subluxate either into the radiocapitellar joint or distal to the radial head. When this reconstruction subluxated off the radial head its tension decreased and allowed for greater anterior RH subluxation to occur. Thus, it was unable to reliably maintain its position around the RH, allowing for more instability of the RH in comparison with the Itadera reconstruction.[13] Conversely, the Itadera reconstruction, although its location is more distal to the native annular ligament, is able to reliably remain in its position without subluxating proximally or distally and so offered more consistent graft tensioning and hence stability of the proximal radius than the other reconstructions. Finally, although the Bell Tawse reconstruction also worked to stabilize the radius in a similar anatomical position as the Itadera reconstruction, we believe its poor performance can be attributed to the poor strength of the triceps fascia in comparison to the reconstructions using free tendon graft.[11,13] It is also important to note that the triceps facia tended to fail at its site of origin along the olecranon, whereas the tendon to tendon suture fixation in the reconstructions never failed during any of the trials.

Annular ligament repair and reconstruction also plays a crucial role in addressing isolated anterior and anteromedial dislocations of the radial head.[28,29] Dislocations of the radial head are usually associated with forearm fractures, however isolated radial head dislocations are rare injuries.[8–10] The annular ligament is a critical stabilizing structure for the radial head, and is torn during isolated radial head dislocations, leading to persistent pain, limited range of motion, and instability of the elbow joint.[30–32] Repair or reconstruction of the annular ligament is often necessary to restore stability and function to the affected joint.[29,33] Various techniques have been described, including repair of the damaged ligament or reconstruction when it cannot be adequately repaired.[11,13,28,29] This findings of this current biomechanical study likely also apply to the management of isolated radial head dislocations.

The results of this biomechanical investigation have several clinical implications. This study suggests that RH instability may persist even after anatomic restoration of the ulna in an anterior Monteggia fracture, emphasizing the importance of soft tissue stabilizers of the proximal radius and suggesting careful rehabilitation for the patient following reduction. Given our results we would recommend annular ligament repair as first line treatment. If repair is not possible, our data supports the use of a free tendon graft reconstruction of the annular ligament as described by Itadera.[13] Clinical studies are needed to confirm the efficacy of the Itadera reconstruction.

This in-vitro biomechanical study has certain limitations. These injuries typically occur in individuals younger than the mean age of the cadavers used in this biomechanical study. The diminished soft tissue flexibility in older specimens relative to children and adolescents might lead to an underestimation of the RH instability. Another limitation would include inadequate replication of soft tissue properties as aging and post-mortem changes can alter the properties of soft tissues in cadavers, potentially reducing the relevance of the findings to live human tissues. Finally, given the testing methodology, we were unable to test the efficacy of these repairs and reconstructions in different forearm rotations.

4.5 Conclusion

This biomechanical investigation demonstrates that anterior RH subluxation was observed with biceps activation when all radial soft tissues stabilizers were sectioned even with the ulna in the anatomical position. Our study demonstrated that the annular ligament repair most closely restored RH stability to that of the intact state while the Itadera technique was the most effective reconstruction.

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Chapter 5

5 Thesis Summary Conclusions

The outcomes of Monteggia fracture-dislocations show wide variability, and often yield suboptimal results. Persistent and recurrent subluxation and dislocation of the radial head leads to a poor outcome, even in the setting of an anatomical reduction of the ulna.[1,2] Consequently, individuals afflicted by this condition often experience pain, stiffness, weakness, and functional limitations. While various surgical techniques have been proposed to address both acute and chronic Monteggia injuries, they have exhibited unreliable long-term results, frequently accompanied by a high incidence of complications. There is currently no universally accepted optimal reconstruction method. The purpose of the in-vitro biomechanical investigations in this thesis were to study the ligament injuries which play a role in the stability of anterior Monteggia injuries as well as evaluate management strategies to improve stability when treating these injuries.

This thesis accomplishes the goals outlined in Chapter 1, which included:

1. To determine the contribution of soft tissue stabilizers of the proximal radius using sequential sectioning of the:
    a. central interosseous membrane (Chapter 2)
    b. proximal interosseous membrane (Chapter 2)
    c. annular and quadrate ligaments (Chapter 2)
2. To determine the contribution of overcorrection of the ulna on radial head stability in anterior Monteggia fractures. (Chapter 3)
3. To determine the efficacy of four different types of annular ligament reconstruction/repairs in restoring stability of the radial head. (Chapter 4)

The hypotheses and findings illustrated in Chapter 2, 3 and 4 are summarized in the following sections.

5.1 Summary of Chapter 2: Determining the Contributions of Soft Tissue Stabilizers of the Proximal Radius on Radial Head Stability

The objective of this chapter was to determine the contribution of the central IOM, proximal IOM and the annular and quadrate ligaments on their ability to stabilize the proximal radius. We hypothesized that sectioning the annular ligament would lead to increased anterior translation of the radial head in relation to the capitellum. Our findings indicate that increased disruption of soft tissue leads to greater instability of the anterior radial head, with the annular and quadrate ligaments identified as the primary stabilizers. Repairing or reconstructing the annular ligament is expected to enhance stability for patients with anterior Monteggia fractures and isolated radial head dislocations. Furthermore, these results suggest that forearm positioning can influence radial head stability in cases of significant soft tissue disruption. Pronation, as opposed to supination or a neutral position, may offer improved radial head stability when the annular and quadrate ligaments are compromised. This novel finding challenges dogma and emphasizes the importance of careful ligament management and forearm positioning postoperatively after the ulnar fracture is anatomically reduced and stabilized.

5.2 Summary of Chapter 3: The Contribution of Apex Posterior Overcorrection of the Ulna on Radial Head Stability in Anterior Monteggia Fractures

The objective of this chapter was to determine the contribution of apex posterior overcorrection of the ulna on radial head stability in anterior Monteggia fractures. We hypothesized that overcorrecting the ulna would decrease anterior radial head translation in the setting of anterior Monteggia fractures. Our results agreed with the hypothesis and showed that anterior radial head subluxation in Monteggia injuries can be decreased by overcorrection of the ulna creating an apex posterior angulation but did not return it to normal. This suggests that soft tissue repair or reconstruction may be a preferred option, rather than overcorrection of the ulna in the setting of persistent instability after an anatomic reduction of the ulna is achieved. Furthermore, we observed that pronation of the forearm reduced instability in comparison to supinated and neutral forearm positions, suggesting a possible optimal position of immobilization.

5.3 Summary of Chapter 4: Determining the Efficacy of Four Different Types of Annular Ligament Repair/Reconstructions in Restoring Stability of the Radial Head

The objective of this chapter was to determine the efficacy of four different types of annular ligament repairs/reconstructions in restoring stability of the radial head. We hypothesized that repairing the annular ligament would restore radial head stability in the setting of anterior Monteggia fractures and that an anatomic annular ligament reconstruction would also be effective. Our results showed that the annular ligament repair most closely restored radial head position to that of the intact state, however, did not restore stability to normal. Of the reconstructions, the Itadera reconstruction was the most effective at restoring radial head stability and should be considered over other proposed reconstructions when the annular ligament cannot be repaired. It should be noted that typically in anterior Monteggia lesions, the annular ligament is often not repairable so an effective method of reconstruction should be considered by surgeons. Our results suggest that careful rehabilitation will be important postoperatively as residual radial head instability can occur even with an anatomic reduction of the ulna and annular ligament reconstruction.

5.4 Future Work

The findings from this biomechanical investigation carry significant clinical implications. The results of this study would recommend that during surgical procedures, efforts should be made to safeguard the annular ligament, and when it is damaged or severed, repairing it should be a consideration. The research also reaffirms the clinical observation that reducing anterior radial head translation in Monteggia injuries can be achieved by overcorrecting the ulna with an excessive posterior angulation. Nevertheless, complete restoration of pre-injury radiocapitellar stability may not be attained through this means alone, highlighting the importance of soft tissue repair or reconstruction in cases of persistent radial head instability, even after ulna overcorrection. Furthermore, we do not know at this point if there are any detrimental biomechanical changes to the forearm induced by overcorrection such as loss of forearm rotation and/or increased radiocapitellar loading which may cause arthritis.

Further research is required to assess the safety and feasibility of early passive and/or active range of motion exercises when employing these strategies. Notably, this study underscores that radial head instability may persist even after achieving anatomical ulna restoration in anterior Monteggia fractures. This underscores the importance of proximal radius soft tissue stabilizers and calls for a cautious rehabilitation approach post-reduction.

The results of this study would recommend prioritizing annular ligament repair as the initial treatment option. In cases where repair is not feasible, data from this study support the use of a free tendon graft reconstruction of the annular ligament, as outlined by Itadera.[3] However, further clinical investigations are necessary to confirm the effectiveness of this reconstruction technique in patients.

Finally, our study reveals that forearm pronation enhances stability during static testing. This observation could influence the rehabilitation process, suggesting that pronation may be an optimal position for immobilization in anterior Monteggia injuries. Nevertheless, additional studies are essential to validate this hypothesis.

5.5 References

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