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The Repair, Reconstruction and Replacement of the Coronoid Process

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Graduate Program in Medical Biophysics

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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THE REPAIR, RECONSTRUCTION AND REPLACEMENT OF THE CORONOID PROCESS

(Thesis format: Integrated-Article)

BASHAR ALOLABI

Graduate Program
in
Medial Biophysics

A thesis submitted in partial fulfilment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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ABSTRACT

The coronoid process is the most important articular stabilizer of the elbow. While most large coronoid fractures are treated surgically with open reduction and internal fixation, there is limited data on the most effective fixation method. The strengths of five different coronoid fixation methods were assessed using a materials testing machine. Plate fixation proved to be stronger than screw fixation; two screws, regardless of the orientation, were stronger than one; and suture fixation was unreliable. In the setting of an unfixable coronoid fracture, reconstruction of the coronoid using the tip of the olecranon has been described. However, this technique has not been evaluated biomechanically to verify its effectiveness. Using an elbow motion simulator, elbow kinematics were examined after a 40% coronoid deficiency and following reconstruction using the tip of the ipsilateral olecranon. The coronoid deficiency resulted in significant alterations in elbow kinematics, but these were restored after reconstruction. Nonetheless, when coronoid reconstruction is not possible, coronoid replacement may be required. Using the elbow simulator, the effects of coronoid replacement with a novel anatomic and extended tip prosthesis after a 40% coronoid deficiency were examined with the collateral ligaments both repaired and insufficient. When the collateral ligaments were repaired, both prostheses restored stability to the coronoid-deficient elbow. In the setting of ligament insufficiency, an extended prosthesis reduced elbow laxity relative to the anatomic prosthesis, yet was still less stable than the intact elbow with repaired ligaments.

Keywords: elbow, coronoid, fracture, fixation, reconstruction, prosthesis, replacement, biomechanics
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Sincerely,

Bashar Alolabi
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# LIST OF ABBREVIATIONS, SYMBOLS, AND NOMENCLATURE

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>°</td>
<td>Degree</td>
</tr>
<tr>
<td>3D</td>
<td>Three-Dimensional</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AP</td>
<td>Anterior-to-Posterior</td>
</tr>
<tr>
<td>CI</td>
<td>Confidence Intervals</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>LCL</td>
<td>Lateral Collateral Ligament</td>
</tr>
<tr>
<td>LUCL</td>
<td>Lateral Ulnar Collateral Ligament</td>
</tr>
<tr>
<td>MCL</td>
<td>Medial Collateral Ligament</td>
</tr>
<tr>
<td>ORIF</td>
<td>Open Reduction and Internal Fixation</td>
</tr>
<tr>
<td>PA</td>
<td>Posterior-to-Anterior</td>
</tr>
<tr>
<td>PRUJ</td>
<td>Proximal Radio-Ulnar Joint</td>
</tr>
<tr>
<td>RCL</td>
<td>Radial Colleteral Ligament</td>
</tr>
<tr>
<td>SDA</td>
<td>Screw Displacement Axis</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
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CHAPTER 1

Introduction

OVERVIEW

This Chapter outlines the normal anatomy, function and kinematics of the elbow joint with special attention to the coronoid process of the ulna. Coronoid fractures, the focus of this thesis, are described including the mechanism, classification, biomechanics, treatment and outcomes. The current state of coronoid fracture repair and reconstruction is highlighted. Finally, the rationale for this work as well as the objectives and hypotheses are discussed.
1.1 ELBOW ANATOMY

1.1.1 OSTEOLOGY

The elbow joint is formed by the articulation of three bones: the distal humerus, proximal radius and proximal ulna. The distal humerus terminates distally at the articular surface as the trochlea, medially, and the capitellum, laterally. These three bones form three articulations: the ulnohumeral (ulnotrochlear), radiohumeral (radiocapitellar) and proximal radioulnar articulations (Figure 1.1). The three articulations enable the elbow to move with two degrees of freedom: flexion-extension and pronation-supination (rotation). The flexion-extension is accomplished by the ulnohumeral joint, which acts like a loose hinge (ginglymus), and the pronation-supination occurs via the radioulnar and radiohumeral joints (trochoid) (Figure 1.2). Therefore the elbow is known as a trochoginglymoid joint, or “pivoting hinge” joint (1-4).

1.1.1.1 DISTAL HUMERUS

As illustrated in Figure 1.3, the humeral shaft flares out distally to form the medial and lateral condyles. Two bony prominences, the medial and lateral epicondyles, protrude from each condyle and serve as attachment sites for the elbow ligaments and wrist and forearm muscles (2). The distal humerus has two discrete articular surfaces, the trochlea and the capitellum. The trochlea has the shape of a spool and is covered by 300° of articular surface and articulates with the greater sigmoid notch of the proximal ulna. The trochlear groove runs in the middle of the trochlea from anterior to posterior and articulates with the guiding ridge of the proximal ulna. The capitellum is nearly spherical and is covered by 180° of articular surface. It articulates with the dish of the radial head.
Three osseous depressions (fossae), two anteriorly and one posteriorly, lie within the distal humerus above the articular surface. Anteriorly, the coronoid and radial fossae accept the coronoid process and the radial head during elbow flexion. Posteriorly, the olecranon fossa accepts the olecranon tip during extension of the elbow (2-4).

1.1.1.2 Proximal Radius

The proximal radius (Figure 1.4) consists of the non-circular radial head sitting on the radial neck and shaft. At its most proximal aspect, the radial head has a nearly spherical concave dish-shaped articular surface called the radial dish. The radial dish is fully covered with cartilage and articulates with the capitellum. The cylindrical perimeter of the radial head is covered with 240° of articular cartilage and articulates with the lesser sigmoid notch of the proximal ulna, forming the proximal radioulnar joint (PRUJ) (2).

1.1.1.3 Proximal Ulna

The proximal ulna (Figure 1.5) consists of the coronoid and olecranon processes as well as the greater and lesser sigmoid notches. The greater sigmoid notch is bounded distally by the coronoid and proximally by the olecranon. It has an ellipsoid articulation of approximately 190°. It is covered distally and proximally with cartilage with a variable bare area in the middle. The lesser sigmoid notch (radial notch) is concave in shape with 60-80° of cartilage and represents the ulnar half of the PRUJ. This joint has a maximal range of rotation of 180° (2). The flat spot of the ulna is a flat area on the posterior/dorsal surface of the proximal ulna, distal to the triceps insertion.
FIGURE 1.1: ELBOW OSTEOLOGY

The bones of the entire upper extremity (A) with a close-up view of the elbow joint, illustrating the articulations of the humerus, radius and ulna producing the ulnohumeral (or humeroulnar), radiocapitellar (or radiohumeral) and proximal radioulnar joints. All figures in this thesis have been created/taken at the Roth|McFarlanae Hand and Upper Limb Centre laboratory, London, Ontario, Canada unless otherwise specified.
**Figure 1.2: Motion of the Elbow**

Lateral (A) and anterior (B) views of the elbow showing the flexion-extension and pronation-supination motions of the elbow, respectively. Note the radius rotating around a constant ulna, to produce the pronation and supination.
**Figure 1.3: Osteology of the Distal Humerus**

Anterior (A) and posterior (B) views of the distal humerus illustrating the two parts of the articular surface, the capitellum and trochlea (yellow), the medial epicondyle (green) and the coronoid, radial and olecranon fossae (red).
**Figure 1.4: Osteology of the Proximal Radius**

An anterior view (A) of the proximal radius and ulna (right arm) in their correct anatomical relationships. The proximal radius (B) consists of the radial head, neck, and tubercle. The radial head has two articulations: the radial dish (yellow) articulates with the capitellum and the cylindrical rim around the radial head articulates with the lesser sigmoid notch of the proximal ulna, at the proximal radioulnar joint. The radial head and neck (purple) are angled approximately 15° to the long axis of the radial shaft. The radial tubercle (orange) is the insertion of the biceps tendon.
FIGURE 1.5: OSTEOLGY OF THE PROXIMAL ULNA

Lateral (A) and anterior (B) views of the proximal ulna of a right arm. The proximal ulna consists of the olecranon process (red), greater sigmoid notch (green), lesser sigmoid notch (yellow), and the coronoid (purple).
1.1.1.4 Coronal Process

The coronoid process is a complex osseous structure projecting anteriorly from the proximal ulna. It has a somewhat triangular shape with variable anatomy (Figure 1.6) (5,6). The coronoid tip is the most anterior point of the process and represents the most distal aspect of the greater sigmoid notch. The height of the coronoid is the distance between the coronoid tip and its base. The definition of the base is controversial in the literature; however, most studies define it by a plane parallel to the flat spot of the proximal ulna intersecting with the deepest portion of the greater sigmoid notch. The average height of the coronoid has been reported in a number of morphological studies to be between 16 and 19 mm with males having a slightly larger coronoid than females (6-9). The guiding ridge of the coronoid, which tracks within the trochlear groove, divides the coronoid into the medial and lateral facets. The lateral facet is flat or slightly concave. Adjacent and lateral to the lateral facet is the lesser sigmoid notch. The medial facet is concave and it contains the anteromedial facet, which projects medially from the greater sigmoid notch. It is vulnerable to injury due to the fact that it is mostly unsupported by the ulnar body (10). The sublime tubercle, a medial osseous eminence protruding from the ulnar body, under/posterior to the anteromedial facet, serves as the attachment site for one of the medial elbow ligaments (2,5).

The coronoid is covered with articular cartilage. The thickness of the cartilage has been shown to be variable at different regions of the coronoid and ranges between 1-3 mm. The cartilage is thickest at the coronoid tip (Figure 1.7) (11).
The congruity of the coronoid with the trochlea provides the elbow with inherent stability and renders the ulnohumeral joint, and specifically the coronoid process, the most important osseous stabilizer of the elbow (1,12,13).

1.1.2 JOINT CAPSULE

The elbow joint capsule encloses all three articulations of the elbow. The capsule is composed of two layers: fibrous tissue makes up the outer layer while the inner layer is composed of a synovial membrane, responsible for the production of synovial fluid, which acts as a lubricant for the joint (14). As illustrated in Figure 1.8, anteriorly, this capsule originates from the coronoid and radial fossae and attaches over the radial neck and annular ligament, laterally, and just distal to the coronoid process, medially. Posteriorly, the capsule encompasses the olecranon fossa and inserts on the perimeter of the olecranon (2,3).

Studies have demonstrated that the anterior capsule inserts at a mean (± standard deviation) of 2.36 ± 0.39 mm distal to the coronoid tip, suggesting that almost all coronoid fractures involve the anterior capsule (7).

1.1.3 LIGAMENTS

The medial and lateral collateral ligaments are thickenings of the elbow capsule composed of fibrous connective tissue (2). Their main function is to offer static stabilization to the elbow joint. They offer minimal resistance to normal joint motion, but protect the elbow from injury by offering resistance to abnormal elbow translation and rotation (2,14,15).
FIGURE 1.6: THE CORONOID PROCESS

An axial illustration of the proximal ulna of a left forearm, highlighting the important landmarks of the coronoid process. The olecranon process has been removed to allow visualization of the full coronoid.
**Figure 1.7: The Coronoid Process Cartilage**

A picture of a sagittal slice of the coronoid illustrating the bony and cartilage parts of the coronoid process. Note how the thickness of the cartilage covering the coronoid is thicker at the tip. Picture taken from Rafehi et al. (11).
A posterior (A) and anterior (B) view of the elbow capsule illustrating its attachment around the elbow joint (pink). A medial view (C) showing the MCL with the two important functional bundles, the anterior bundle (green) and the posterior bundle (violet). A lateral view (D) demonstrating the LCL and its three components, the RCL (red), annular ligament (yellow) and LUCL (purple).

**FIGURE 1.8: ELBOW CAPSULE AND LIGAMENTS**
### 1.1.3.1 The Medial Collateral Ligament (MCL)

The MCL is comprised of three components, the anterior, posterior and transverse bundles (Figure 1.8) (1-3). The anterior bundle, the strongest and most discrete of the medial ligaments, arises from the anterior inferior aspect of the medial epicondyle of the distal humerus and inserts on the sublime tubercle (3,14,16,17). It is considered the primary constraint to valgus instability (12,18,19). The posterior bundle, is a fan shaped thickening of the posteromedial capsule originating from the medial epicondyle and inserting next to the medial olecranon articular surface (3,16,19). It acts as a secondary stabilizers and contributes to only a small degree of elbow stability (19-21). The transverse bundle has horizontally-oriented fibers and does not contribute to elbow stability as it connects the coronoid to the olecranon (2,4,16-18,20).

### 1.1.3.2 The Lateral Collateral Ligament (LCL)

The LCL is comprised of three main components: the lateral ulnar collateral ligament (LUCL), the radial collateral ligament (RCL) and the annular ligament (Figure 1.8) (2,17,22). The LCL as a complex acts as a main elbow stabilizer against posterolateral rotatory instability and against varus instability (18,19,22-26). The LCL is more variable and less discreet relative to the MCL (4,17). The LUCL originates from the lateral epicondyle at the center of the flexion axis of the elbow and inserts on the crista supinatory tubercle of the ulna and also blends with the annular ligament. It is uniformly taught throughout elbow range of motion (2,18,23). The RCL originates from the lateral epicondyle and blends into the annular ligament (1,2,4,14). The annular
ligament attaches to the anterior and posterior rims of the lesser sigmoid notch and wraps around the radial neck and head. It forms four-fifth of a circle and is funnel shaped as it tapers distally (17). It functions to maintain contact between the radial head and the lesser sigmoid notch at the PRUJ while allowing unrestricted rotation (2-4,14).

1.1.4 Musculature

A number of muscle groups originate on the distal humerus and cross the elbow joint to insert on the forearm or the hand. These muscle groups are not only responsible for the motions of the elbow, but also the motion of the wrist and fingers (Figure 1.9). They are divided into 5 groups:

1.1.4.1 The Flexors

Three muscles cross the elbow joint anteriorly and are responsible for elbow flexion: the brachialis, the biceps brachii and the brachioradialis. The brachialis originates from the anterior surface of the humerus and inserts on the coronoid process and the ulnar tuberosity. The biceps brachii has two origins: the long head arises from the superior glenoid tubercle, while the short head originates from the coracoid process of the scapula. Distally these two heads converge to form one tendon that attaches to the bicipital tuberosity on the proximal radius. Due to its insertion on the medial aspect of the proximal radius, the biceps brachii also acts as a strong supinator. The brachioradialis arises from the lateral supracondylar ridge of the humerus between the triceps and the brachialis, and inserts distally on the radial styloid. Although the brachioradialis has the
longest moment arm of all flexors, it has the smallest cross sectional area and thus is the weakest of the three flexors (2).

1.1.4.2 THE EXTENSORS

The principle elbow extensor is the triceps muscles which has three origins: the long head stems from the infraglenoid tubercle of the scapula, the lateral head arises from the lateral intermuscular septum and the humerus and the medial head originates broadly from the medial intermuscular septum and the humeral shaft. All three heads merge to form one tendon distally that inserts on the olecranon process (2).

1.1.4.3 THE PRONATORS

Forearm pronation is achieved by two pronator muscles: the pronator teres and pronator quadratus. Pronator teres has two origins, one from the common flexor-pronator origin at the medial epicondyle of the distal humerus, and one from the coronoid process. The muscle passes beneath the brachioradialis to insert at the junction of the middle and proximal thirds of the radius. It acts as a strong pronator but also has a slight contribution to elbow flexion. The pronator quadratus is a small flat muscle originating from the distal ulna and inserting on the distal radius, on the volar surface. It is a weak pronator but contributes to stability by compression of the distal radioulnar joint (2).

1.1.4.4 THE SUPINATORS

Two muscles produce supination of the forearm. The main supinator in flexion is the biceps brachii, as mentioned above. The supinator muscle originates at the anterolateral aspect of the lateral epicondyle, the lateral collateral ligament and the crista supinatorus of the ulna. It wraps around the proximal radius and inserts broadly on the
posterior aspect of the proximal radius. The supinator is not as strong as the biceps but due to its isolated function, it can be active throughout the flexion range (2,4).

### 1.1.4.5 Other Muscles

Several muscles cross the elbow joint and contribute to wrist and hand function. The medial epicondyle serves as the origin for the flexor-pronator group, which includes the flexor carpi radialis and the flexor carpi ulnaris. These muscles contribute to wrist flexion as well as radial or ulnar wrist deviation, respectively.

The lateral epicondyle serves as the common extensor origin. These muscles produce wrist and digit extension and include the extensor digitorum communis, the extensor carpi radialis longus, the extensor carpi radialis brevis and the extensor carpi ulnaris. The extensor carpi radialis longus also contributes to radial deviation of the wrist, while the extensor carpi ulnaris contributes to wrist ulnar deviation (2).
FIGURE 1.9: MUSCLES CROSSING THE ELBOW JOINT

Posterior (A) and anterior (B) views of the right arm demonstrating the origins and insertions of the following muscles: triceps (TRI), biceps brachii (BIC), brachialis (BRA), brachioradialis (BRD), supinator (SUP), pronator teres (PT), pronator quadratus (PQ), common extensor origin (EXT) and common flexor origin (FLX).
1.2 Elbow Kinematics and Stability

1.2.1 Kinematics

The flexion-extension axis of the elbow is an axis that passes through the centers of the capitellum and the trochlear sulcus (28). This axis lies anterior to the humeral shaft. It is 6-8° valgus and 5-7° internally rotated with respect to the humerus (Figure 1.10). Elbow flexion and extension occur about this axis, yet the elbow is not perfectly uniaxial, and behaves more like a loose hinge joint with 3-4° of coronal motion during the flexion arc (29). Forearm rotation is achieved by the radius pronating and supinating around the stationary ulna (2).

The normal elbow has a range of motion from 0° (full extension) to 145° in flexion, and an arc of 150-160° of rotation (around 75° of pronation and 85° of supination) (2). The actual range of motion attainable for each person is influenced by soft tissue, prior elbow trauma or pathology and elbow ligamentous laxity. Morrey et al. suggested that an arc of flexion from 30 to 130° and rotation from 50° of pronation to 50° of supination is sufficient for most activities of daily living (27).

The bones of the forearm also exhibit coupled motion patterns. The proximal ulna rotates relative to the humerus with the ulna internally rotating during pronation and externally rotating during supination. The radius also moves proximally with pronation and distally with supination (2,30).

The ulna has a valgus angulation with respect to the humerus, which results in lateral deflection of the forearm with respect to the humerus. This angulation is known as the carrying angle and is defined as the angle between the humerus and ulna. It varies
depending on the flexion arc and is at its maximum during full extension. The average carrying angle is 11° in men and 14° in women (2-4,30,31).

1.2.2 **Elbow Stability**

The stability of the elbow is a result of the highly congruous articular surface, ligaments and dynamic stabilizers. These static and dynamic stabilizers make the elbow a very stable joint relative to other joints in the body (2).

1.2.2.1 **Static Stabilizers**

The congruent articular surfaces of the three joint in the elbow represent the most important static stabilizer of the elbow. The greater sigmoid notch conforms closely to the anatomy of the trochlea providing resistance to medial-lateral as well as anterior-posterior translation (2). The coronoid process anteriorly is the most important articular stabilizer of the elbow (13). It acts as a buttress preventing posterior and varus subluxation of the elbow, and the anteromedial facet of the coronoid provides a constraint against posteromedial rotatory instability (32,33). The coronoid is also an insertion site for the anterior bundle of the MCL (2). The olecranon process is thought to contribute to varus and valgus angular stability especially with the elbow in terminal extension when the olecranon tip is engaged in the olecranon fossa (34). The radial head is an important secondary stabilizer under valgus loading of the elbow in the absence of a functional MCL (2,13,35-37).

The MCL, LCL and elbow capsule also play an important role as static stabilizers of the elbow. The anterior band of the MCL provides primary stability against valgus
stresses. The LCL has a number of functions with the annular ligament stabilizing the PRUJ and the LUCL and RCL preventing varus instability and posterolateral rotatory instability. The anterior capsule of the elbow also provides stability, especially in full extension, where it prevents hyperextension (2).

1.2.2.2 Dynamic Stabilizers

The muscles that cross the elbow joint all contribute to the dynamic stability of the joint. Muscle activation results in compression and reduction of all three joints, causing their articular surfaces to conform (2,38,39). Moreover, the common extensor origin as well as the flexor-pronator mass play a role in both varus and valgus stability (40). There is a correlation between instability and the extent of injury of one or both of these muscular origins (2).
Figure 1.10: The Flexion-Extension Axis of the Elbow Joint

The axis passes through the centers of the capitellum and the trochlear sulcus (A). This axis lies anterior to the humeral shaft and is 6-8° valgus (left) and 5-7° internally rotated (right) with respect to the humerus (B).
1.3 CORONOID FRACTURES

1.3.1 CLASSIFICATION

Regan and Morrey (41) classified coronoid fractures based on the height of the fracture relative to the height of the coronoid. This classification assumes a horizontal fracture line and includes three types. Type I fractures comprise the tip of the coronoid process and were originally thought to be avulsion fractures of the coronoid tip. Subsequently it has been proposed that they are a result of shear injury of the tip of the coronoid during elbow subluxation or dislocation. Type II fractures comprise less than 50% of the coronoid height. Any fracture involving more than 50% of the coronoid is considered a type III fracture (Figure 1.11) (41,42). Since this classification was based on radiographs, and later extrapolated for use with Computed Tomography (CT) scans, it takes into account only the height of the bony fracture fragment excluding the cartilage. However, due to the thick cartilage over the coronoid tip, fracture fragments are often bigger intra-operatively than expected (11).

More recently, O’Driscoll et al. (43) developed a more comprehensive classification which includes fractures of the anteromedial facet of the coronoid. This classification involves three major categories with each category consisting of a number of subtypes (Figure 1.12).

For the purposes of this thesis, the Regan and Morrey classification system will be used for describing coronoid fractures or deficiencies.
FIGURE 1.11: REGAN AND MORREY CLASSIFICATION OF CORONOID FRACTURES

The classification (41) is based on the height of the fracture relative to the height of the coronoid. Type I fractures involve the tip of the coronoid process. Type II fractures involve less than 50% of the coronoid. Type III fractures involve more than 50% of the coronoid.
FIGURE 1.12: O’DRISCOLL CLASSIFICATION OF CORONOID FRACTURES

Type 1 fractures involve the coronoid tip (A). Type 2 fractures involve fractures of the anteromedial facet of the coronoid and are subdivided into: subtype I involves the rim, subtype II involves the rim and tip, and subtype III involves the rim and sublime tubercle with or without the tip (B). Type 3 fractures involve the base and body of the coronoid process (C). Picture taken from O’Driscoll et al. (43).
1.3.2 Fracture Patterns and Mechanisms of Injury

Coronoid fractures usually occur in the setting of complex elbow trauma and thus often involve injury to one or both of the collateral ligaments and/or fractures of the radial head. Isolated injuries to the coronoid process are uncommon (2,42,44-47). Moreover, coronoid fractures are often associated with elbow dislocations or subluxations. Regan and Morrey demonstrated that 56% of type II coronoid fractures and 80% of type III coronoid fractures occur in association with an elbow dislocation (42).

Coronoid fractures are thought to occur when the elbow is subjected to axial loading when it is at 0-20 degrees of flexion. This mechanism resembles that of elbow dislocations (2,48). Coronoid fractures frequently present as a part of a complex injury pattern termed the “Terrible Triad of the Elbow” (49,50). This triad involves coronoid and radial head fractures as well as an elbow dislocation. The dislocation entails injury to at least one of the collateral ligaments, with the LCL almost always being involved. The terrible triad obtains its name due to the inferior clinical outcomes associated with this injury, including stiffness, instability, arthritis and pain (33,49,50). The average height of a coronoid fracture associated with a terrible triad injury has been shown to be around 38% of the height of the coronoid (i.e. type II coronoid fractures) (51). This type of fracture often has a characteristic transverse pattern (51,52).

On the other hand, fractures of the anteromedial facet of the coronoid have a different pattern and mechanism. The fracture line is often more vertically or obliquely oriented and results due to varus posteromedial rotatory loads with the elbow subluxing or completely dislocating. These injuries often spare the radial head but result in posteromedial rotatory instability (43,53,54).


1.3.3 **TREATMENT OPTIONS AND OUTCOMES**

A number of clinical and biomechanical studies have demonstrated the critical role the coronoid plays in maintaining elbow stability. Coronoid deficiency can result in significant changes to elbow kinematics and lead to instability and post-traumatic arthritic changes (2,13,32,33,49,54-62). Coronoid fractures can be treated operatively or non-operatively, depending on the size and displacement of the fracture, the associated bony or ligament injuries, patient function and comorbidities, and the presence of elbow instability (2). Studies have suggested that types II and III coronoid fractures, in general, should be treated with open reduction and internal fixation, when possible (2,32,33,55-59). On the other hand, type I coronoid fractures can often be treated with nonoperative management, except in certain cases when reducing even small coronoid fractures may be important (2,61-63).

The outcomes of coronoid fracture treatment are variable with some studies demonstrating a good outcome and others reporting poor outcomes. The outcome often depends on other associated injuries. Nevertheless, larger coronoid fractures and coronoid fractures associated with terrible triad injuries are more likely to be associated with unsatisfactory outcomes (2,42,47,49,50,64-66). Complications from coronoid fractures include pain, stiffness, nonunion, avascular necrosis, heterotopic ossification, recurrent instability, re-dislocation and post-traumatic arthritis (42,47,49,64,65,67). Improved outcomes have been reported with radial head replacement, LCL repair and open reduction and internal fixation of the coronoid (68). A stable construct allowing early motion is critical, as immobilization has been linked to poor outcomes (42,65).
1.3.4 **Coronoid Reconstruction**

When coronoid fractures are comminuted, fracture fixation may not be possible. Moreover, when a previous coronoid fracture fails to unite, whether treated surgically or not, revision fixation is often not possible as well. In these cases, instability ensues unless the coronoid is reconstructed.

Reconstruction of the coronoid process has been described using a number of techniques including the use of iliac crest bone graft, a fragment of the fractured radial head, rib osteochondral graft as well as structural allograft (69-72). Using the ipsilateral olecranon tip to reconstruct the coronoid deficiency has also been described (73). Nonetheless, there are potential disadvantages to these reconstruction methods. The iliac crest bone graft acts as a bone block or buttress preventing dislocation. Although the graft may be shaped to reconstruct the coronoid deficiency to some extent, it may be difficult to recreate a congruent articular surface matching the ridges and facets of the coronoid that conform well to the trochlea. Also, the iliac crest bone graft lacks cartilage. These downfalls raise concern of eroding the trochlear articular surface and creating degenerative changes in the ulnohumeral joint (69-71). The radial head fragment has the advantage of being covered with cartilage. However, this can only be used when there is an associated radial head fracture, with a large enough fracture fragment to reconstruct the coronoid defect, and a radial head that needs to be replaced. Moreover, although the radial head fragment may allow reconstruction of the coronoid guiding ridge, the mismatch between its shape and that of the coronoid does not allow reconstruction of the medial facet. Rib osteochondral grafts share similar mismatch concerns and they are associated with the morbidity of the graft site. Allograft reconstruction from a matching
proximal ulna may provide the best match with regards to shape. However, concern with graft resorption and lack of healing, especially with such a small surface area, makes it an undesirable choice (70). Finally, the ipsilateral olecranon represents a promising reconstruction option, as it can be taken from the elbow at the same time of the reconstruction and it is covered with cartilage. Furthermore, since the olecranon tip also articulates with the trochlea, its shape is likely to resemble to some extent that of the coronoid tip. Nevertheless, there is concern that the resection of the olecranon tip may further aggravate instability and alter elbow kinematics and that there is some mismatch between the shapes of the two tips (33,74).

Although all of these techniques have been described clinically, none of them has been tested biomechanically and only short-term clinical results have been reported. Therefore, they remain unreliable techniques.
1.4 RATIONALE

The important stabilizing role of the coronoid has been well established. Coronoid fractures and deficiency significantly alter elbow kinematics and can result in elbow instability and poor clinical outcomes (2,13,32,33,42,47,49,50,54-66). Therefore, open reduction and internal fixation of larger coronoid fractures has been recommended (2,32,33,55-59). There have been many described techniques for open reduction and internal fixation of coronoid fractures, especially of type II coronoid fractures (50,52,55,64,68,75). Yet very few studies have compared these techniques to evaluate their strength and effectiveness (76,77).

Furthermore, in the setting of comminuted coronoid fractures or coronoid nonunions, where fixation is not an option, there are no reliable treatment options to restore stability to the elbow with minimal long-term sequelae (70,78). Although, as mentioned previously, a number of reconstruction methods have been reported (69-72), they remain unreliable as there have been no long-term results on any of these techniques and no biomechanical studies to demonstrate their effectiveness.

Finally, in many joints in the body, when a fracture is too comminuted to be fixed, or when the results of fixation are far from optimal, replacement of the fractured fragment with an implant is often utilized. An anatomic coronoid replacement has been recently described and evaluated for 40% coronoid fractures (15,79). However, this implant was only tested in the setting of intact ligaments. Since these severe fractures are often associated with ligament injuries, evaluation of this prosthesis, as well as a coronoid prosthesis with an extended tip, would be beneficial in the setting of collateral ligament insufficiency.
1.5 OBJECTIVES

The thesis research objectives are:

1) To compare the strength of fixation of 5 different fixation methods for a simulated 40% coronoid fracture (type II Regan & Morrey (41)).

2) To determine if reconstructing a 40% coronoid deficiency using the tip of the ipsilateral olecranon restores baseline elbow kinematics and stability.

3) To assess if replacing 40% of the coronoid using an anatomic or an extended tip coronoid prosthesis restores elbow kinematics in the setting of repaired collateral ligaments, and if the extended tip prosthesis improves stability relative to the anatomic implant or the intact coronoid in the setting of ligament insufficiency.
1.6 HYPOTHESES

We hypothesized that:

1) Plate fixation would provide the strongest fixation method for 40% simulated coronoid fractures, followed by two screws and followed by one screw. Suture fixation would likely be unreliable.

2) Coronoid reconstruction using the ipsilateral olecranon tip would improve but not restore the normal kinematics to the 40% coronoid-deficient elbow.

3) The anatomic coronoid replacement would restore elbow kinematics when the collateral ligaments are repaired but would not restore baseline kinematics in the setting of collateral ligament insufficiency. The extended tip prosthesis would improve but not fully restore the stability of the coronoid-deficient elbow in the setting of collateral ligament insufficiency.
1.7 REFERENCES


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CHAPTER 2

Strength of Coronoid Fracture Fixation:
A Biomechanical Study

OVERVIEW

Coronoid fractures often occur as a result of elbow dislocations in combination with other osseous and/or ligamentous injuries. These fractures can lead to elbow instability and future degenerative changes if not treated properly. In choosing a suitable fixation method for coronoid fractures, a method that offers strong initial fixation strength is important to prevent redisplacement or nonunion of the fracture, and decrease the risk of post-traumatic stiffness, instability and arthritis. In this chapter, the initial fixation strength of five different fixation techniques for coronoid fractures is compared. Cadaveric ulnae with simulated coronoid fractures treated with one of five fixation methods were subjected to cyclic loading with a staircase protocol using a materials testing machine, until failure.

1) A version of this work has been submitted for publication to the Journal of Hand Surgery: Alolabi B, Deluce SR, Gray A, Ferreira LM, Athwal GS, Johnson JA, King GJ. Strength of Coronoid Fracture Fixation: A Biomechanical Study.
2.1 INTRODUCTION

The coronoid is the most important osseous stabilizer of the elbow, preventing posterior and varus subluxation and dislocation (1-11). Complex elbow dislocations commonly result in a fractured radial head and coronoid, and are often called a ‘terrible triad’ injury (12-14). The average height of a coronoid fracture associated with a terrible triad injury is 38% (12). This size of fracture fragment is classified as a type II fracture using the Regan and Morrey classification (15). These coronoid fractures lead to partial loss of the anterior and medial buttress, often resulting in elbow subluxation or instability and the early onset of degenerative changes (1,2,8,9). As a result, it has been recommended that the treatment of terrible triad injuries should include radial head repair or replacement, open reduction and internal fixation of larger coronoid fractures, as well as collateral ligament repair (14).

A stable coronoid fixation construct is critical as fixation failure or nonunion can result in persistent elbow instability, which requires more complex and less reliable surgical procedures, such as coronoid reconstruction (16-18). The best fixation method for coronoid fractures has not been established. Many fixation methods have been described including suture fixation, one or two screw fixation from an anterior-to-posterior (AP) direction or from a posterior-to-anterior (PA) direction, as well as plate fixation (10,12,14,16,19,20). The purpose of this biomechanical study was to compare the strength of 5 different fixation methods for simulated coronoid fractures comprising 40% of the coronoid height.
2.2 METHODS

2.2.1 SPECIMEN PREPARATION

Twenty-four fresh frozen ulnae (average age 75.0 ± 9.6 years; 20 males; 12 right arms) were denuded of all soft tissues and the distal segments were potted in bone cement so that the distance from the tip of the coronoid to the cement was approximately 6 cm. The height of each coronoid process was measured using digital calipers (Digimatic CD-6; Mitutoyo, Tokyo, Japan) from the level of the base of the greater sigmoid notch to the tip of the coronoid. An oscillating saw was then used to simulate a 40% transverse coronoid fracture (Regan and Morrey type II fracture (15)). The olecranon tip was resected to allow a custom designed load applicator to apply a distal orthogonal load to the coronoid fracture fragment. Optical trackers (Optotrak Certus®, NDI, Waterloo, ON, Canada) were mounted on the proximal ulna and on the 40% coronoid fracture fragment (Figure 2.1), in order to quantify motion at the simulated fracture site (motion of the coronoid fragment relative to proximal ulna).
Figure 2.1: Specimen Preparation

A photograph illustrating the coronoid fragment optical tracker (C), proximal ulna optical tracker (U) as well as the custom-designed load applicator (L) applying load on the coronoid fragment (black arrow). The three digitized points (ridge, medial and lateral) are indicated with the white arrows. Note the olecranon tip is resected to allow the load applicator to apply load to the coronoid tip.
2.2.2 **Fixation Methods and Loading Protocol**

Five fixation methods were compared: suture fixation, one PA screw, two AP screws, two PA screws and plate fixation (Figure 2.2). A #2 Ethibond (Ethicon, Somerville, New Jersey) suture was used for suture fixation through two 1.8 mm drill holes just distal to the subchondral bone of the coronoid process. The PA and AP screws were 2.7 mm (Synthes, Mississauga, ON, Canada) and a 2.4 mm T-Plate with 2.4 mm screws (Synthes, Mississauga, ON, Canada) was used for plate fixation. The plate fixation was performed with the T part of the plate over the coronoid fragment to function as a buttress plate. Two 2.4 mm subchondral screws were inserted through the fragment perpendicular to the fracture line. These screws were inserted into the same 1.8 mm drill holes previously used for the suture fixation. Three screws were then inserted distal to the fracture secure the plate to the proximal ulna. Each fixation method was tested on 6 specimens. Because the suture fixation failed at very low loads without any damage to the coronoid fragment, the same 6 specimens were subsequently used for plate fixation testing.

Two reduction clamps (Synthes, Mississauga, ON, Canada) were used to reduce and compress the fractured fragment before fixation. For suture fixation, a double throw surgeon’s knot was applied, tightened and secured with a thin needle holder by an assistant while a second square knot was applied to ensure that the fixation was tight. Five more knots were then added to secure the fixation.

All ulnae were subjected to mechanical testing using a materials testing machine (Instron 8501®, Instron, Canton, MA, USA). A custom designed fixture, developed to fit congruently against the coronoid ridge (Figure 2.3) was used to apply a distally directed
load (parallel to the flat spot of the ulna) to the coronoid fragment. The applicator was situated to apply the load halfway between the fracture site and the coronoid tip (Figure 2.4) to simulate loading imparted by the distal humerus.

Cyclic sinusoidal loading was applied to the coronoid fracture fragment using a staircase method until failure or a maximum load of 800 N. Loading was initially applied at 10 N increments until 50 N and then at 25 N increments, up to a maximum of 800 N. One-hundred cycles at 1 Hz were applied for each loading increment. Each cycle returned to a base of 0 N.
FIGURE 2.2: CORONOID FRACTURE FIXATION METHODS

A schematic representation of the 5 coronoid fixation methods using suture fixation (A), one PA screw (B), two AP screws (C), two PA screws (D), and plate fixation (E). These figures are for representation only and may not reflect the exact scaling or exact location of the screws.
FIGURE 2.3: STUDY SETUP

A photograph demonstrating the set-up of the material testing machine with the proximal ulna potted in cement (Cm) and the custom designed load applicator (L) fitting congruently over the ridge of the coronoid fragment (black arrow). The coronoid fragment optical tracker (C) and the proximal ulna tracker (U) can also be seen.
**FIGURE 2.4: LOAD APPLICATION**

A photograph of the load applicator (L) exerting load on the coronoid fracture fragment (black arrow). Note the distal displacement of the coronoid fragment. Note how the load applicator was situated to apply load halfway between the fracture site and the coronoid tip.
2.2.3 **Testing Protocol**

To quantify motion at the simulated fracture site, optical trackers were mounted on the proximal ulna and on the coronoid fracture fragment (Figure 2.1). The proximal ulnar tracker was secured to the bone with 3.5mm screws (Synthes, Missisagua, ON, Canada). The tracker for the coronoid fragment was secured to the anteromedial facet using a 1.3 mm plate and screws (Synthes, Missisagua, ON, Canada) (Figures 2.3).

A third optical tracker attached to a stylus was used to digitize three points on the coronoid fracture fragment at the level of the fracture site (coronoid ridge, medial facet, lateral facet) to track the relative motion between the coronoid fragment and the proximal ulna. Three additional points on the coronoid fracture fragment (coronoid tip, medial rim and lateral rim) were also repeatedly digitized every 100 N to ensure the tracker mounted onto the coronoid fracture fragment was not moving relative to the fragment. The greater sigmoid notch and two flat points on the posterior surface of the ulna were also digitized in order to generate an anatomical coordinate system for each specimen using a method previously described (21).

2.2.4 **Outcome Measures**

The maximum total three-dimensional (3D) displacement of the coronoid fragment was quantified at each of the three digitized points at the simulated fracture interface (ridge, medial and lateral) (Figure 1). The average failure load was calculated for each fixation method. Failure was defined as a 2 mm 3D displacement of the coronoid
fragment at any of the three digitized points or fracture of the coronoid fragment. Specimens that reached 800 N without failure were assigned a failure load of 800 N.

### 2.2.5 Statistical Analysis

Statistical analysis was performed using a one way Analysis of Variance (ANOVA) test with a Bonferroni correction with significance set at $p \leq 0.05$. 
2.3 RESULTS

Suture fixation provided the weakest fixation strength with an average failure load ± standard deviation (SD) of 48 ± 23 N due to 2 mm 3D fragment motion (p≤0.01) (Figure 2.5). Fixation with two PA screws was stronger than fixation with one PA screw with a failure load of 396 ± 158 N and 179 ± 99 N, respectively (p=0.02). The failure load of the two AP screws (358 ± 110 N) was similar to the two PA screws (p=0.64). All the screw fixation constructs failed with 3D displacement; none fractured. Plate fixation provided the strongest fixation with an average failure load of 683 ± 134 N (p<0.01). Three specimens with plate fixation reached the maximum load of 800 N without failing. Two specimens in the plate fixation group failed due to fracture of the coronoid fragment and one specimen failed due to greater than 2mm 3D displacement.

A Kaplan-Meier survivorship plot demonstrating the failure results of all fixation methods is shown in Figure 2.6.
FIGURE 2.5: AVERAGE FAILURE LOAD OF FIXATION METHODS

The average (± SD) failure load of each fixation technique (n=6). 1PA = one posterior to anterior screw; 2AP = two anterior to posterior screws; 2PA = two posterior to anterior screws. * represents 1PA being significantly stronger than suture fixation. + represents 2AP and 2PA being significantly stronger than both 1PA and suture fixation, but not significantly different from each other. ** represents plate fixation being significantly stronger than all other fixation techniques.
**FIGURE 2.6: KAPLAN-MEIER SURVIVORSHIP PLOT**

A Kaplan-Meier Survivorship plot demonstrating the survivorship of the different fixation techniques against load and cycles applied. 1PA = one posterior to anterior screw; 2AP = two anterior to posterior screws; 2PA = two posterior to anterior screws.
2.4 Discussion

This biomechanical study demonstrates that for Regan and Morrey type II coronoid fractures (15) comprising 40% of the height of the coronoid, fixation with plate and screws provided the strongest fixation, followed by two screws, regardless of the orientation of the screws, followed by a single screw. Suture fixation failed at very small loads suggesting that this fixation method should be avoided when other fixation methods are feasible.

To our knowledge, this is the first biomechanical study that compares different fixation techniques in type II coronoid fractures. Moon et al. (22) demonstrated in a study on type II coronoid fractures comprising approximately 50% of the coronoid height, that one PA screw was biomechanically stronger than one AP screw. However, they only compared different orientations of the same construct and did not compare other fixation techniques. Budoff et al. (23) compared screw fixation versus plate fixation versus screw and plate fixation using an incremental cyclic loading protocol and found that screw and plate fixation was stronger than plate fixation, which was in turn stronger than screw fixation alone. However, their study was performed on saw bones evaluating type III coronoid fractures, and the type of plate utilized in their study was a buttress plate with no screws in the coronoid fragment. Nevertheless, similar to their findings, this study found plate fixation to be superior to screw fixation alone.

We did not choose to study the strength of one AP screw in our study, as Moon et al. (22) had already shown that one PA screw is stronger than one AP screw. However, in our study, there was no difference in fixation strength between two PA and two AP screws. This is likely related to the fact that, the addition of a second screw helps stabilize
the fracture from rotational failure, which cannot be controlled with one screw. Therefore, from a clinical perspective, the orientation of the screws to fix the coronoid fracture should be dependent on the exposure. In most cases, it is technically easier to fix the coronoid with PA screws rather than AP screws, unless an anterior surgical approach has been utilized. Furthermore, since fixation with two screws was significantly stronger than fixation with one screw, we recommend the use of two screws when possible. We found that a 40% non-comminuted coronoid fragment easily accommodated two 2.7 mm screws. However, in comminuted fractures, this may not be possible.

Although plate fixation demonstrated the strongest fixation strength, clinically this fixation technique requires a medial or anterior surgical approach, which may not always be required for the treatment of the rest of the injury. If a medial approach is necessary, plate fixation is recommended especially for larger fragments, as it offers the strongest fixation. In cases where a medial approach is not required, fixation with two PA screws is recommended. This can be done while visualizing and reducing the coronoid from a lateral surgical approach used to fix or replace the radial head and repair the lateral collateral ligament.

We chose to model a 40% coronoid fracture since this is the most commonly encountered height of coronoid fracture (12). We used a cyclic staircase loading model with 100 cycles at 1 Hz applied at 25 N intervals as this loading protocol may better represent the failure mechanism experienced in vivo rather than a single load to failure test. This loading protocol was based on typical loads thought to be experienced by the elbow. With heavy lifting at 90 degrees of elbow flexion, where the maximum elbow flexion strength occurs, a force approximately three times the weight of the body passes
through the elbow (24). In a 70 kg patient, this leads to a force of approximately 2000 N in highly aggressive lifting situations. According to Halls and Travill (25), 40% of this load would cross through the ulnohumeral joint and 60% through the radiocapitellar articulation. Therefore, a maximum load of 800 N may be applied to the ulnohumeral articulation. Our maximum load of at 800 N is a worst-case scenario as this load would normally be distributed over the entire coronoid surface and not only the anterior 40%. Furthermore, it is unlikely that a patient would start heavy lifting immediately following fracture fixation. Only 3 specimens reached the maximum 800 N load before failing, and all 3 specimens were in the plate fixation group.

With respect to the loading direction, we used a custom-designed applicator to apply the load to the fracture fragment in a distally directed manner, parallel to the flat spot of the ulna. This represents the most aggressive loading application challenging the fixation techniques. In vivo, the load vector within the greater sigmoid notch has been shown to point somewhat posteriorly when the elbow is at 90 degrees of flexion. Therefore, our model again represents a worst-case scenario.

The main limitation of our study is that we used in vitro elderly denuded ulnae to evaluate the effect of coronoid fixation techniques on fracture stability. In younger people, the fixation strength is likely to be stronger than determined in this study due to the superior bone quality. However, this may be somewhat different in vivo with the stabilizing forces of some of the soft tissue structures. This may also be important in the suture repair of coronoid fractures since the anterior capsule is usually incorporated into the repair to add stability to the fixation construct. Moreover, we simulated a non-comminuted transverse coronoid fracture in order to be consistent with our fracture
pattern between specimens. However, this may not represent what is typically encountered clinically due to a lack of comminution and fragment interdigitation; as such these findings may not be applicable to all types of coronoid fractures.
2.5 CONCLUSION

Plate fixation provided the strongest method of fixation of type II 40% height coronoid fractures. Fixation with two screws was stronger than a single screw for the posterior-to-anterior screw repair. Placement of two screws from either an AP or PA direction did not affect the fixation strength. Suture fixation failed at relatively low loads, suggesting this fixation method should not be used clinically when other fixation methods are possible.
2.6 REFERENCES


CHAPTER 3

Reconstruction of the Coronoid Process Using the Tip of the Ipsilateral Olecranon

OVERVIEW

Autograft reconstruction of the coronoid using the tip of the olecranon has been described as a clinical treatment for coronoid deficiency; however, the effectiveness has not been documented either clinically or experimentally. In this chapter, the in-vitro effectiveness of this technique in restoring elbow kinematics is assessed in a coronoid-deficient model. Elbow kinematics are quantified during active and passive extension with the arm in the horizontal, valgus, varus and vertical orientations using an elbow motion simulator. The effects of coronoid deficiency followed by coronoid reconstruction using the tip of the ipsilateral olecranon are evaluated with the collateral ligaments repaired.¹

¹) A version of this work has been published: Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJ. Reconstruction of the coronoid process using the tip of the ipsilateral olecranon. J Bone Joint Surg Am. 2014 Apr 2;96(7):590-6 (See Appendix C).
3.1 **INTRODUCTION**

The coronoid process is one of the primary stabilizers of the ulnohumeral joint (1-12). It plays an important role in preventing posterior displacement and subluxation of the elbow, as well as in preventing varus instability (13). Large coronoid fractures have been associated with elbow instability and mal-tracking (1, 3, 11, 12, 14). Untreated, these fractures often lead to poor outcomes due to elbow stiffness, recurrent instability and degenerative changes (15-17). Open reduction and internal fixation (ORIF) of large coronoid fractures, with repair of the lateral collateral ligament (LCL) and possibly the medial collateral ligament (MCL) has been recommended, as it has been shown to restore elbow stability and kinematics (11, 16, 18, 19). However, ORIF of the coronoid may not be possible due to comminution or non-union, necessitating coronoid reconstruction (16).

Moritomo et al. (20) described two patients who underwent reconstruction of the coronoid using the ipsilateral olecranon tip, but the long-term outcomes of this procedure have not been reported. Also, there is concern with this technique since the resection of the olecranon tip may further aggravate instability and lead to changes in elbow kinematics as reported by Bell *et al.* (21). Other methods of reconstruction of the coronoid have been published, including the use of iliac crest bone graft, a fragment of the radial head, rib osteochondral graft and structural allograft (22-25). Many of these methods, however, are not reliable for restoring congruous ulnohumeral alignment (16), involve some degree of donor site morbidity, and/or they have had unpredictable outcomes with insufficient long-term follow-up (23). Moreover, none of these methods has been tested biomechanically to show how well they restore elbow kinematics.

The purpose of this in-vitro biomechanical study was to determine if
reconstructing the coronoid using the tip of the ipsilateral olecranon would restore baseline kinematics to the coronoid-deficient elbow. Our hypothesis was that coronoid reconstruction of the 40% coronoid-deficient elbow using the ipsilateral olecranon tip would improve but not fully restore normal kinematics, due to the likely mismatch in the shapes of the two tips.
3.2 METHODS

3.2.1 SPECIMEN PREPARATION

Six fresh-frozen male cadaveric upper limbs with a mean age (± SD) of 77.8 ± 8.0 years were thawed for 18 hours at room temperature (22 ± 2 °C). Computed Tomography (CT) images (Light Speed VCT, GE Medical Systems, New Berlin, Wisconsin) of the specimens were obtained prior to testing to confirm that the elbows demonstrated no evidence of degenerative or post-traumatic changes. Sutures (#2 Ethibond, Ethicon, Somerville, New Jersey) were secured to the tendons of the wrist flexors (flexor carpi ulnaris and flexor carpi radialis), of the wrist extensors (extensor carpi ulnaris and carpi radialis longus), and of the brachioradialis, pronator teres, supinator, biceps, brachialis, and triceps, using a running, locking suturing technique, as previously described (10). The humerus was secured in an elbow motion simulator (1, 2, 10, 11, 26) that allowed unconstrained elbow and forearm motion. The sutures connected to the triceps, biceps, and brachialis were directed through alignment guides mounted to the base of the simulator, to reproduce their physiologic line of action. Additional alignment guides were placed at the medial epicondyle for the pronator and wrist flexors, at the lateral epicondyle for the wrist extensors, and at the supracondylar ridge for the brachioradialis (Figures 3.1 and 3.2). The sutures were attached to stainless steel cables, which were connected to computer-controlled pneumatic actuators and servomotors to simulate active elbow and forearm motion. A universal hinge allowed the simulator to be positioned in the horizontal, valgus, varus and vertical orientations (Figure 3.3).
FIGURE 3.1: MEDIAL ELBOW ALIGNMENT GUIDE

Photograph of the medial side of the elbow showing the alignment guide (yellow arrow) at the medial epicondyle to reproduce the lines of action of the pronator and wrist flexors.
**FIGURE 3.2: LATERAL ELBOW ALIGNMENT GUIDES**

Photograph of the lateral side of the elbow illustrating the alignment guides at the lateral epicondyle (solid white arrow) and supracondylar ridge (dotted white arrow) to reproduce the lines of action of the wrist extensors and the brachioradialis, respectively.
FIGURE 3.3: SIMPLIFIED ILLUSTRATION OF ELBOW MOTION SIMULATOR

Schematic representations of the elbow motion simulator showing the mounted specimen and the different components of the simulator. The simulator is depicted in the (a) vertical, (b) valgus, (c) horizontal and (d) varus orientations. Depictions are of a right pronated arm.
3.2.2 Data Acquisition

An anatomic coordinate reference system for each bone was established by digitizing osseous landmarks during and following the completion of testing (27, 28). The motion of the ulna relative to the humerus was tracked using a Flock of Birds™ (Acension Technology Corporation, Burlington, VT) electromagnetic tracking system that had an accuracy of 1.8 mm RMS and 0.5° RMS. Three-dimensional kinematics of the ulna relative to the humerus were expressed using screw displacement axes (SDA) (27, 29-35). The SDA angular deviations (a measure of data dispersion) were calculated in both the coronal (frontal) and transverse (axial) planes. The SDA angular deviation, in this context, is a measure of the instability of the elbow: the larger the SDA angular deviation, the more unstable the elbow. The SDAs were calculated from the recordings at 10° intervals during elbow extension from 120-20°. An electromagnetic tracking receiver was mounted to the ulna, which recorded motion relative to the transmitter, mounted rigidly relative to the humerus. In this configuration, the SDA algorithm had an orientation accuracy of 1.04±0.03° (32).

3.2.3 Testing Protocol

Active and passive elbow extension were simulated with the arm in all 4 orientations of the simulator. Testing was performed with the forearm in both pronation and supination. For active extension, forces were applied to the tendons by the actuators and servomotors after the forearm was manually positioned in full pronation or supination. The forearm rotation was maintained during active extension by means of the
forces applied by the actuators to the relevant tendons. The muscle loading protocol was based on electromyographic data and muscle cross-sectional area (10, 11, 36-39). During passive motion, a single investigator manually extended the arm while maintaining the forearm in full pronation or supination.

First, the testing was completed on the intact arm. Afterwards, a straight posterior midline incision was made and medial and lateral skin flaps were elevated. The anterior and posterior capsules, as well as the posterior band of the MCL were sectioned. The extensor muscle mass was separated from the LCL and reflected off the lateral epicondyle. Medially, the flexor muscle mass was separated from the MCL and reflected off the medial epicondyle. Both the LCL and MCL were sectioned from their humeral insertions and repaired with a running locking suture (#2 Hi-Fi, ConMed Linvatec, Largo, Florida) using a transosseous bone tunnel method (10, 11, 40, 41). To simulate ligament repair, actuators applied 20N of tension to the sutures of both collateral ligaments. This magnitude of force was chosen as it has been shown to restore normal elbow kinematics in previous studies (40, 41). The ligament sutures were tensioned simultaneously while the elbow was manually reduced at 60° of flexion with the forearm in neutral rotation. Once tensioned, two clamps secured the cables attaching the ligaments to the actuators. The intact coronoid state with repaired ligaments was then tested. In order to focus on the effects of coronoid deficiency and reconstruction rather than on the effectiveness of collateral ligament repair, the intact coronoid state with repaired ligaments was considered the control, and all measurements and statistical analyses were compared to this condition (hereafter designated as “coronoid control”).

A medial approach was utilized through the floor of the cubital tunnel (splitting
the two heads of flexor carpi ulnaris) to access the coronoid. A plane to create a 40% transverse coronoid deficiency (Figure 3.4), parallel to the posterior proximal ulnar flat spot, was identified using digital calipers (Digimatic CD-6; Mitutoyo, Tokyo, Japan), and was cut with a 0.4 mm oscillating saw. The total height of the coronoid was measured from the tip to the base. The base was defined by a plane parallel to the flat spot intersecting with the deepest portion of the greater sigmoid notch (Figure 3.4). The ligaments were re-tensioned and the coronoid-deficient elbow was tested. An osteotomy was performed, perpendicular to the articular surface, from a location on the guiding ridge of the ipsilateral olecranon at a distance equal to 40% of the coronoid height from the tip of the olecranon. The olecranon tip was positioned over the coronoid deficiency so that the guiding ridges of the coronoid and the olecranon tip were collinear and the articular surfaces of the coronoid and olecranon were best optimized. The olecranon tip was compressed using a reduction clamp and secured with two fully threaded 2.7 mm screws (Synthes Canada Ltd. Mississauga, Ontario, Canada) placed anterior-to-posterior, just distal to the subchondral region of the coronoid/olecranon tip articular surface (Figures 3.5 and 3.6). The elbow with the olecranon autograft was tested after re-tensioning of the collateral ligaments.
**Figure 3.4: Creating the Coronoïd and Olecranon Osteotomies**

Schematic representation of a proximal ulna demonstrating (F) the flat spot of the proximal ulna, (H) the total height of the coronoid, (C) 40% of the height of the coronoid, (O) the height of the olecranon tip equivalent to 40% of the coronoid, (L) the total length of the olecranon articular surface, and (x) the amount of olecranon articular surface resected by the olecranon osteotomy. The solid red and blue lines represent the coronoid and olecranon osteotomies performed in this study, respectively. The dashed white line represents the orientation of the osteotomy created by Bell *et al.* (21).
FIGURE 3.5: CORONOID RECONSTRUCTION – MEDIAL VIEW

Photograph demonstrating the coronoid reconstruction with the ipsilateral olecranon tip (O). Note the coronoid osteotomy site (Co), olecranon osteotomy site (Oo), the intact triceps tendon insertion (Ti) and the tip of the fully threaded 2.7mm screws used to fix the olecranon tip from an anterior-to-posterior direction. This demonstrates how the olecranon tip restores the coronoid guiding ridge (CR).
**Figure 3.6: Coronoid Reconstruction – Top View**

Photograph demonstrating the coronoid reconstruction with the ipsilateral olecranon tip (O). Note the olecranon osteotomy site (Oo) and the two fully threaded 2.7mm screws used to fix the olecranon tip from an anterior-to-posterior direction. This demonstrates how the medial (MF) and lateral facets (LF) of the coronoid are not perfectly congruent with the olecranon tip, with the most medial and lateral aspects of the coronoid facets being somewhat proud and the olecranon tip recessed.
3.2.4 **Statistical Analysis**

Statistical analyses of SDA angular deviations were completed using a one-way repeated measures ANOVA with a Bonferroni correction to adjust for multiple comparisons. The factor for the one-way analysis was coronoid condition (levels: coronoid control, coronoid deficiency and coronoid reconstruction with olecranon tip). Statistical significance was set at $p<0.05$ and 95% Confidence Intervals (CI) were determined for values that reached statistical significance. Clinical relevance was set at 2 degrees. A-priori and post-hoc power analyses performed using our data demonstrated sufficient power to detect a 2 degree difference ($\text{power} > 0.8$) between study conditions.
3.3 RESULTS

All values in this section represent average SDA angular deviations across the six specimens (± SD).

3.3.1 HORIZONTAL ORIENTATION

Table 3.1 demonstrates the results of the SDA angular deviations in the horizontal orientation.

The coronoid-deficient elbow displayed a $7.9° ± 6.7°$ ($p=0.22$) increase in SDA coronal angular deviation and a $3.9° ± 4.9°$ ($p=0.65$) increase in SDA transverse angular deviation, relative to the coronoid control during active extension with forearm pronation. These findings, however, were not statistically significant.

There were also no differences in SDA angular deviations between the coronoid control, the coronoid deficiency or the coronoid reconstruction during active or passive motion, regardless of forearm rotation ($p>0.05$).
### Table 3.1: SDA Angular Deviations in the Horizontal Orientation

Mean (± 1 SD) SDA angular deviations and statistical p values in the horizontal orientation for the coronoid control, the coronoid-deficient elbow and the elbow with the coronoid reconstruction. $p_1$ indicates the p value from the ANOVA pairwise comparison of coronoid control and coronoid deficiency and $p_2$ indicates the p value from the ANOVA pairwise comparison of coronoid control and coronoid reconstruction. SDA = screw displacement axis.

<table>
<thead>
<tr>
<th>SDA Angular Deviations (°)</th>
<th>Coronoid Control</th>
<th>Coronoid Deficiency</th>
<th>Coronoid Reconstruction</th>
<th>p₁</th>
<th>p₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal Plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>Pro</td>
<td>1.7 ± 0.9</td>
<td>9.5 ± 6.6</td>
<td>0.22</td>
<td>1.00</td>
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<tr>
<td></td>
<td>Sup</td>
<td>1.4 ± 0.4</td>
<td>4.6 ± 3.3</td>
<td>0.42</td>
<td>1.00</td>
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<tr>
<td>Passive</td>
<td>Pro</td>
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<td>3.4 ± 1.3</td>
<td>0.16</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Sup</td>
<td>1.8 ± 0.7</td>
<td>1.9 ± 0.5</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Transverse Plane</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>Pro</td>
<td>1.1 ± 0.8</td>
<td>5.0 ± 4.8</td>
<td>0.65</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Sup</td>
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<td>0.15</td>
<td>1.00</td>
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<tr>
<td>Passive</td>
<td>Pro</td>
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<td>0.45</td>
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<tr>
<td></td>
<td>Sup</td>
<td>2.1 ± 0.6</td>
<td>1.8 ± 1.0</td>
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<td>1.00</td>
</tr>
</tbody>
</table>
3.3.2 Valgus Orientation

Figures 3.7-3.10 demonstrate the results of the SDA angular deviations in the valgus orientation. Instantaneous SDA kinematics in the valgus orientation are presented in Appendix B.

During active motion with forearm pronation or supination, there were no differences in SDA angular deviations between the coronoid control, the coronoid deficiency or the coronoid reconstruction (p>0.05) (Figures 3.7, 3.9).

Passive motion with forearm pronation did not result in any difference in SDA kinematics between the coronoid control, the coronoid deficiency or the coronoid reconstruction (p>0.05) (Figure 3.8).

However, during passive motion with forearm supination, there was a very small, likely clinically insignificant, yet statistically significant difference (0.4° ± 0.2°) between the coronoid control and the coronoid reconstruction in SDA angular deviation in the transverse plane (95% CI 0.04-0.84; p=0.03) (Figure 3.10). No other differences in SDA angular deviations were detected between the coronoid control, the coronoid deficiency or the coronoid reconstruction (p>0.05) (Figure 3.10).
FIGURE 3.7: ACTIVE EXTENSION IN VALGUS WITH FOREARM PRONATION

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during active elbow extension in the valgus orientation with forearm pronation plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. There were no significant differences between the coronoid control, the coronoid deficiency or the coronoid reconstruction. SDA = screw displacement axis.
**FIGURE 3.8: PASSIVE EXTENSION IN VALGUS WITH FOREARM PRONATION**

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during passive elbow extension in the valgus orientation with forearm pronation plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. There were no significant differences between the coronoid control, the coronoid deficiency or the coronoid reconstruction. SDA = screw displacement axis.
FIGURE 3.9: ACTIVE EXTENSION IN VALGUS WITH FOREARM SUPINATION

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during active elbow extension in the valgus orientation with forearm supination plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. There were no significant differences between the coronoid control, the coronoid deficiency or the coronoid reconstruction. SDA = screw displacement axis.
FIGURE 3.10: PASSIVE EXTENSION IN VALGUS WITH FOREARM SUPINATION

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during passive elbow extension in the valgus orientation with forearm supination plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. The asterisk (*) indicates a statistically significant difference (0.4° ± 0.2°) between the coronoid reconstruction and the coronoid control in the transverse plane. SDA = screw displacement axis.
3.3.3 Varus Orientation

Figures 3.11-3.14 demonstrate the results of the SDA angular deviations in the varus orientation. Instantaneous SDA kinematics in the varus orientation are presented in Appendix B.

Compared to the coronoid control, during active extension with forearm pronation, the coronoid-deficient elbow demonstrated significant changes in SDA coronal angular deviation (10.9° ± 5.0°; 95% CI 2.2-19.3; p=0.02) (Figure 3.11) and transverse angular deviation (10.6° ± 5.5°; 95% CI 1.1-18.8; p=0.03) (Figure 3.11).

During active extension with forearm supination, the coronoid-deficient elbow demonstrated significant changes in SDA coronal angular deviation (9.0° ± 2.7°; 95% CI 4.4-13.6; p<0.01) (Figure 3.13) and transverse angular deviation (7.0° ± 2.7°; 95% CI 2.4-11.7; p=0.01) (Figure 3.13), relative to the coronoid control.

No other significant changes in SDA angular deviations were detected between the coronoid control, the coronoid deficiency or the coronoid reconstruction during active motion with forearm pronation or supination (p>0.05) (Figures 3.11 and 3.13).

During passive motion with forearm pronation, the coronoid-deficient elbow displayed changes in SDA coronal angular deviation (3.6° ± 1.8°; 95% CI 0.5-6.8; p=0.03), relative to the coronoid control (Figure 3.6B), but no changes in the transverse plane (p>0.05) (Figure 3.12).

During passive motion with forearm supination, relative to the coronoid control, the coronoid-deficient elbow displayed changes in SDA coronal angular deviation (3.6° ± 2.0°; 95% CI 0.1-7.0; p=0.04) (Figure 3.14), but no significant changes in the transverse angular deviations were detected (p>0.05) (Figure 3.14).
No other significant differences in SDA angular deviations were seen between the coronoid control, the coronoid deficiency or the coronoid reconstruction during passive motion with forearm pronation or supination (p>0.05) (Figures 3.12 and 3.14).
**Figure 3.11: Active Extension in Varus with Forearm Pronation**

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during active elbow extension in the varus orientation with forearm pronation plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. The asterisk (*) indicates a statistically significant difference between the coronoid deficiency and the coronoid control in the coronal and transverse planes. SDA = screw displacement axis.
**FIGURE 3.12: PASSIVE EXTENSION IN VARUS WITH FOREARM PRONATION**

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during passive elbow extension in the varus orientation with forearm pronation plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. The asterisk (*) indicates a statistically significant difference between the coronoid deficiency and the coronoid control in the coronal plane. SDA = screw displacement axis.
Figure 3.13: Active Extension in Varus with Forearm Supination

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during active elbow extension in the varus orientation with forearm supination plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. The asterisk (*) indicates a statistically significant difference between the coronoid deficiency and the coronoid control in the coronal and transverse planes. SDA = screw displacement axis.
Figure 3.14: Passive Extension in Varus with Forearm Supination

Mean (+ 1 SD) SDA angular deviations in the coronal and transverse planes during passive elbow extension in the varus orientation with forearm supination plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction using the olecranon tip. The asterisk (*) indicates a statistically significant difference between the coronoid deficiency and the coronoid control in the coronal plane. SDA = screw displacement axis.
3.3.4 Vertical Orientation

Table 3.2 demonstrates the results for the SDA angular deviations in the vertical orientation.

There were no changes in elbow SDA kinematics between the coronoid control, the coronoid deficiency or the coronoid reconstruction during either active or passive extension with forearm pronation or supination (p>0.05).
### Table 3.2: SDA Angular Deviation in the Vertical Orientation

Mean (± 1 SD) SDA angular deviations and statistical p values in the vertical orientation for the coronoid control, the coronoid-deficient elbow and the elbow with the coronoid reconstruction. $p_1$ indicates the p value from the ANOVA pairwise comparison of coronoid control and coronoid deficiency and $p_2$ indicates the p value from the ANOVA pairwise comparison of coronoid control and coronoid reconstruction. SDA = screw displacement axis.

<table>
<thead>
<tr>
<th>SDA Angular Deviations (°)</th>
<th></th>
<th>Coronoid Control</th>
<th>Coronoid Deficiency</th>
<th>Coronoid Reconstruction</th>
<th>$p_1$</th>
<th>$p_2$</th>
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<td>Coronal Plane</td>
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<td></td>
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<td>Sup</td>
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<td>2.4 ± 1.5</td>
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</tr>
</tbody>
</table>
3.4 **DISCUSSION**

This study demonstrates that a 40% transverse coronoid deficiency causes substantial alterations in the kinematics of the elbow in the varus orientation as demonstrated by the increased SDA angular deviations relative to the coronoid with sectioned and repaired collateral ligaments. These findings confirm those of other studies, demonstrating that a 40% coronoid deficiency results in substantial alterations in elbow kinematics, even with an intact radial head and repaired collateral ligaments (1, 11, 15). Therefore, it is important to repair larger coronoid fractures with open reduction and internal fixation, when possible, or with other means, such as using the ipsilateral olecranon tip, when the coronoid fracture is unrepairable.

Moreover, this study suggests that reconstructing the 40% coronoid-deficient elbow with the ipsilateral olecranon tip restores kinematics similar to that of the coronoid-intact elbow when the collateral ligaments are repaired. The small difference between the coronoid control and the olecranon tip reconstruction seen in the valgus orientation during passive motion with forearm supination may be due to differences in shape between the olecranon and coronoid as well as the loss of stability provided by the olecranon tip, specifically the posteromedial aspect of the olecranon. However, the magnitude of this difference was quite small with 95% CI (0.04-0.84), less than 1 degree, and may not be clinically important.

Preoperative imaging is important to determine the size of the coronoid fracture, as it is difficult to judge intraoperatively, especially if there is significant comminution. The percentage of coronoid deficiency can be estimated by analyzing the CT scan of the fractured elbow or by comparing lateral radiographs of the injured and the contralateral
normal elbow.

The SDA angular deviations of the coronoid-deficient elbow showed a larger variation during active motion with the forearm in pronation rather than supination. These differences are possibly a result of the stabilizing effect of supination on the coronoid-deficient elbow and are consistent with previous studies (1, 11). These effects presumably become more apparent during active motion due to the stabilizing effects of the musculature pulling the greater sigmoid notch into the trochlear groove.

The olecranon osteotomy required to reconstruct 40% of the coronoid resulted in an excision of an average of 23% (range 18-24%) of the olecranon articular surface, using the method described by Bell et al. (21) (Figure 3.2). The fact that we found only small differences between the coronoid control and the coronoid reconstruction suggests that the structural deficiency due to resection of this portion of the olecranon process was minimal. This finding is in contrast to that of Bell et al. (21), who reported that even small amounts of olecranon resection (e.g. 12.5% or 25.0%) resulted in significant increases in varus-valgus angulation and in ulnohumeral rotation. This discrepancy, however, can be explained by the difference in the method of the olecranon osteotomy between the two studies. In our study, the olecranon osteotomy was performed perpendicular to the articular surface. Conversely, Bell et al. (21) performed the osteotomy perpendicular to the flat spot of the proximal ulna. As illustrated in Figure 3.2, an osteotomy perpendicular to the flat spot results in a significantly larger amount of olecranon articular surface resection relative to an osteotomy perpendicular to the articular surface. Also, Bell et al. (21) detached and repaired the triceps tendon, whereas the insertion of the triceps was preserved in the current investigation. Therefore, this
study suggests that a resection of the olecranon tip of 20-25% or less, to reconstruct up to a 40% coronoid deficiency, does not result in substantial alterations in elbow kinematics.

It was our observation that the olecranon osteotomy required to reconstruct 40% of the coronoid height, generally exited the posterior ulna just proximal and anterior to the insertion of the triceps. Therefore, there is a limit on how much of the coronoid can be reconstructed with the tip of olecranon before damaging the triceps insertion. It is important when performing this technique to clearly identify the insertion of the triceps and ensure that the insertion is not violated during the osteotomy. Further studies are required to demonstrate if larger amounts of olecranon can be safely used for coronoid reconstruction.

Although the ipsilateral olecranon tip demonstrated reasonable congruency with the remainder of the coronoid, especially with regards to the guiding ridge, we observed that there was a mismatch between the shape of the medial and lateral facets of the ipsilateral olecranon tip and the excised coronoid tip. We speculate that the effectiveness of the olecranon tip in restoring elbow kinematics demonstrates that matching the exact shape of the deficient coronoid is perhaps not critical, as long as the anterior buttress effect of the coronoid is restored and the guiding ridge reconstructed. However, this mismatch may result in subtle alterations in kinematics and abnormal articular contact pressures with the potential for degenerative changes to develop over time.

This is the first biomechanical study to examine the effect of autograft reconstruction of the coronoid process, specifically using the ipsilateral olecranon tip. Moritomo et al. reported using this technique in two patients with good short-term results (20). Other reports of reconstructing the coronoid with parts of the ipsilateral fractured
radial head, iliac crest bone graft, an osteochondral graft from a rib and allograft have been published (22-25). However, these techniques have not been tested biomechanically and the short-term clinical results have been mixed.

The chief limitation of this study is that it was conducted in vitro, which is different than the in-vivo setting where ligaments and soft tissues have the ability to heal. Also, we did not have a control with an olecranon tip resection in the setting of an intact coronoid. However, we did not include this step in our protocol, as it is a scenario that would not occur clinically, since this procedure would only be performed in the face of a non-repairable coronoid fracture. Given the repeated measures design of the study, we had to choose one size and orientation for the coronoid deficiency. As such, we chose a horizontal osteotomy comprising 40% of the coronoid size, since this would most closely resemble the size of coronoid fractures in terrible-triad injuries (42). Therefore, the results of this study may have less direct application to other types of coronoid fractures. Moreover, due to the natural variation in the range of motion of elderly cadaveric elbows, our study only examined the SDA kinematics from 20° to 120° of elbow flexion. Since the elbow is most stable in deep flexion, it is unlikely that changes in elbow kinematics would have been observed at >120° of elbow flexion. It is theoretically possible that the deficiency of the olecranon process would cause some kinematic alterations at terminal extension, or in hyperextension. However, most patients requiring this procedure would generally have undergone previous surgeries to their elbow, so some degree of stiffness would be expected. Therefore, we believe that a range from 20° to 120° is clinically relevant. The stepwise design of the study also necessitated reuse of the specimen for testing different conditions and necessitated repeated tensioning of the ligaments. The
effectiveness of the olecranon tip transfer in restoring kinematics similar to the coronoid control elbow supports the repeated measures design of the study, as the last condition tested was similar to the first. Finally the ability of an avascular osteochondral fragment to heal without displacement and to re-vascularize without collapse will need to be examined in prospective clinical studies.
3.5 CONCLUSION

In conclusion, reconstruction of the coronoid using the tip of the ipsilateral olecranon is an effective method for restoring normal kinematics in elbows with a 40% transverse coronoid deficiency, over a range of motion between 20° and 120°. This may prove beneficial for patients with unstable elbows due to unreconstructable comminuted coronoid fractures and non-unions. Clinical studies are needed to determine if these osteochondral autografts will unite and if the mismatch in shape between the olecranon and coronoid will predispose the elbow to progressive degenerative changes over time.
3.6 REFERENCES


CHAPTER 4
Coronoid Replacement Using Anatomic and Extended Prostheses

OVERVIEW

Coronoid deficiency can result in elbow instability and recurrent dislocations. In this chapter, the effectiveness of replacing the coronoid process with an anatomic and an extended prosthesis is examined in a coronoid-deficient cadaveric model with the collateral ligaments insufficient and repaired.¹ Using an elbow motion simulator, changes in varus-valgus laxity during passive extension and the incidence of elbow dislocations in the horizontal orientation during active and passive extension are examined.

4.1 INTRODUCTION

The coronoid is an important stabilizer of the elbow joint (1-12). Coronoid fractures usually occur in combination with injuries to the collateral ligaments (13-19). Regan and Morrey Type II coronoid fractures have been associated with elbow instability (1, 3, 11, 12), and therefore, surgical treatment with open reduction and internal fixation as well as ligament repair has been recommended for these injuries. However, in cases of comminuted unfixable coronoid fractures and nonunions, coronoid reconstruction with allograft or autograft bone has been performed with mixed results (20, 21). Furthermore, a stable ligament repair is not always achievable, particularly in the setting of delayed or failed treatment, further challenging the success of coronoid reconstruction.

The concept of partial joint replacement is well established and successful in various joints (22, 23). Specific to the elbow, distal humerus hemiarthroplasty as well as radial head arthroplasty have been used clinically (24, 25). In comparison to total joint replacement, these partial replacements preserve native bone and soft tissue structures and are more suitable in younger patients (23). Recently, coronoid replacement using an anatomic prosthesis has been shown to restore kinematics and stability to the coronoid-deficient elbow when the collateral ligaments are repaired (26). However, there are no reports on the effects of anatomic coronoid replacement in the presence of collateral ligament insufficiency or on the effectiveness of an extended coronoid prosthesis. We hypothesized that the anatomic coronoid replacement would restore elbow kinematics when the collateral ligaments are repaired but would not restore baseline kinematics in the setting of ligament insufficiency. We also hypothesized that the addition of an
extended tip to a coronoid process implant would improve the stability of the coronoid-deficient elbow where secure ligament repair cannot be achieved.
4.2 METHODS

4.2.1 PROSTHESIS DESIGN

An anatomic coronoid implant was designed and developed using SolidWorks 3D Computer Assisted Design Software ® (SolidWorks ®, Dassault Systems, Velizy-Villacoublay, France) (27). The design was based on anthropometric measurements of the coronoid derived from CT scans of 11 male arms free of disease, with a mean age (± SD) of 65.9±15.9 years. These measurements were adjusted for coronoid-specific cartilage thickness (28). The implant was designed to replicate the anterior 40% of the coronoid process, since this is the commonest fracture size seen clinically (29). An extended coronoid implant was then designed and developed by extending the tip of the anatomic implant (Figure 4.1). The tip of the anatomic implant was extended around the radius of curvature to complete a quarter of a circle (90°). This resulted in an increase of 2.8 mm in the height of the implant, 7.2 mm in the length of the tip, and 36.5° around the radius of curvature relative to the anatomic implant (Figure 4.2). Both implants were fabricated in stainless steel using Computer-Assisted Design and Manufacturing technology and incorporated a detachable post, which was secured using a setscrew mechanism.
Figure 4.1: Coronoid Prostheses

Photograph showing lateral view of anatomic prosthesis (left) and extended prosthesis (right).
**Figure 4.2: Design of Extended Prostheses**

The extended prosthesis was derived from the anatomic implant by extending the tip around the radius of curvature of the guiding ridge of the implant to complete a quarter of a circle (90°). In comparison, the anatomic implant occupies 53.5° of the radius of curvature. As a result of this extension, the height of the implant and the length of tip were increased by 2.8 mm and 7.2 mm, respectively, relative to the anatomic implant. $R =$ radius.
4.2.2 Specimen Preparation

Similar to the setup described in section 3.2.1, seven fresh-frozen male cadaveric right arms with a mean age (± SD) of 76.9 ± 7.8 years were amputated at the mid-humerus level. The arms were imaged with a CT scanner (Light Speed VCT, GE Medical Systems, New Berlin, Wisconsin) to examine for any evidence of osseous or ligamentous abnormalities and to confirm appropriate sizing for the implants. Following thawing for 18 hours at room temperature (22 ± 2°C), specimens were prepared for mounting in an elbow motion simulator, which could be oriented to allow for testing with the arm in the varus, valgus and horizontal orientations (1, 2, 10, 11, 30).

The tendons of the wrist flexors (flexor carpi radialis and flexor carpi ulnaris), wrist extensors (extensor carpi radialis brevis and extensor carpi ulnaris), brachioradialis, pronator teres, supinator, biceps, brachialis and triceps were sutured using a locking Krackow technique. To simulate the function of the supinator, a suture anchor was inserted into the radial tuberosity and the suture was passed through a plastic sleeve inserted in the radial aspect of the ulnar shaft. The suture then traveled through the medullary canal and exited the proximal aspect of the olecranon. The humerus was mounted to the simulator in neutral rotation using a clamp, which securely held the arm in place while allowing full elbow motion. The sutures were attached to stainless steel cables, which were connected to computer-controlled pneumatic actuators and servomotors to simulate active elbow extension. The sutures attached to the biceps, brachialis, and triceps were passed through alignment guides mounted to the base of the testing device to simulate their physiologic lines of action. To replicate native muscle moment arms, additional alignment guides were placed at the medial epicondyle for
pronator teres and wrist flexors, at the lateral epicondyle for wrist extensors, and at the supracondylar ridge for brachioradialis.

4.2.3 Testing Protocol

Passive elbow extension was simulated with the arm oriented in the varus and valgus orientations, whereas both active and passive elbow extension were simulated in the horizontal orientation. During passive motion, a single tester maintained the forearm in full supination or pronation while slowly extending the elbow from full flexion to full extension. For active motion, the actuators and servomotors applied forces to the tendons to simulate active extension of the elbow with the forearm maintained in both pronation and supination. The muscle-loading protocol was based on electromyographic data and muscle cross-sectional area (31, 32).

Testing was performed with the forearm in supination and pronation and with the LCL and MCL both sectioned and repaired. Testing was first performed on the intact arm and was repeated after the posterior band of the MCL and the anterior and posterior capsules were sectioned. The LCL and MCL were repaired with 2 Hi-Fi (Conmed Linvatec, Largo, FL) sutures using a transosseous drill hole technique as previously described (10, 11, 33, 34). The actuators applied a tension of 20N to both ligaments. The ligaments were tensioned simultaneously with the elbow at 60 degrees of flexion and the forearm in neutral rotation. Once tensioned, the cables connecting the ligaments to the actuators were secured to a clamp fixed to the base of the simulator. This collateral ligament repair technique has previously been reported to effectively restore the kinematics and stability of the elbow similar to those of the intact joint (33). The intact
coronoid state was then tested with the ligaments sectioned and tensioned (repaired). For the purposes of this study, the intact coronoid state with both collateral ligaments tensioned was considered our ‘coronoid control’, and all other measurements, for statistical purposes, were compared to this condition.

A 40% transverse coronoid deficiency was then created using an oscillating saw after measurement with digital calipers (Digimatic CD-6; Mitutoyo, Tokyo, Japan). The coronoid osteotomy was made parallel to the flat spot of the posterior proximal ulna. The total coronoid height was measured as the distance from the tip of the coronoid to its base. The base was defined by a plane parallel to the flat spot and intersecting with the deepest part of the greater sigmoid notch (Figure 4.3). After testing, the anatomic coronoid implant was inserted. A 6.35mm diameter hole was drilled into the cancellous bone in the central region of the fracture surface just distal to the subchondral bone of the guiding ridge of the coronoid. The post for the prosthesis was then cemented into the cavity with surgical bone cement (Simplex™ P, Stryker, Hamilton, ON, Canada) (Figure 4.4). During cementation, the anatomic prosthesis was coupled to the post and the guiding ridge and medial and lateral facets of the prosthesis were aligned with the coronoid articular surface and held in place until the cement cured (Figures 4.5-4.7). The anatomic prosthesis was tested. After testing was completed, the anatomic implant was uncoupled from the cemented post using the setscrew, and the extended coronoid prosthesis was attached to the post, using the same mechanism (Figures 4.8 and 4.9). A fenestration was made between the coronoid and the olecranon fossae in the distal humerus to allow the elbow with the extended prosthesis to fully flex (Figure 4.10). The extended prosthesis was then tested with the simulator.
FIGURE 4.3: CREATING THE CORONOID DEFICIENCY

Schematic representations of coronoid showing method used to measure height of coronoid and simulated 40% coronoid fracture.
FIGURE 4.4: PROSTHESIS POST MECHANISM

Photograph showing the post (black arrow) used to secure the anatomic and extended prostheses. The prosthesis was secured using a setscrew mechanism that fits into a divot in the post (black doted arrow). The post was cemented into osteotomized bone surface using bone cement (blue arrow).
Figure 4.5: The Anatomic Prosthesis – Frontal View

Photograph showing the anatomic prosthesis in situ from a frontal view. Note the congruence of the prosthesis facets with the remainder of the coronoid.
**FIGURE 4.6: THE ANATOMIC PROSTHESIS – MEDIAL VIEW**

Photograph showing the anatomic prosthesis in situ from a medial view. Note the congruence of the prosthesis ridge with the remainder of the coronoid ridge.
Figure 4.7: The Anatomic Prosthesis – Reduced

Photograph showing the anatomic prosthesis in situ from a medial view with the prosthesis reduced to the distal humerus. Note the congruence of the prosthesis with the trochlear groove.
**Figure 4.8: The Extended Prosthesis – Medial View**

Photographs showing the anatomic prosthesis in situ from a medial view with the prosthesis reduced to the distal humerus. Note the congruence of the prosthesis ridge with the remainder of the coronoid ridge and the longer tip of the prosthesis relative to the anatomic prosthesis.
Figure 4.9: The Extended Prosthesis - Reduced

Photographs depicting a medial view of the extended prosthesis in situ reduced to the distal humerus. Note the congruence of the prosthesis with the trochlear groove and the longer tip of the extended prosthesis relative to the anatomic prosthesis.
Figure 4.10: The Fenestration in the Distal Humerus

A photograph illustrating the fenestration (solid black arrow) created in the distal humerus between the olecranon and coronoid fossae to allow the elbow with the extended prosthesis (dotted black arrow) to fully flex.
4.2.4 **Data Acquisition**

Kinematic data were obtained using an electromagnetic tracking system (Flock of Birds, Ascension Technologies, Burlington, VT) (32, 35, 36). A transmitter was mounted onto the base of the elbow testing apparatus, and a receiver was secured to the ulna. An anatomical coordinate reference system for the ulna and humerus was established by digitizing appropriate osseous landmarks (32, 35). For the varus and valgus orientations, varus-valgus laxity was measured by calculating the difference between the varus angulation in the varus orientation and the valgus angulation in the valgus orientation for each angle of extension. For the horizontal orientation, the incidence of ulnohumeral dislocation during extension was quantified. Dislocation was defined as translation of the distal humerus, distally along the ulnar long axis, equal to or greater than the radius of the greater sigmoid notch.

4.2.5 **Statistical Analysis**

Varus-valgus laxity was analyzed with a three-way repeated-measures ANOVA with the extension angle, coronoid state and forearm rotation as the three dependent variables. Significance was defined as a p value of <0.05. The rate of dislocation was analyzed with a Wilcoxon signed rank test, comparing the translation of each condition to the dislocation criteria for the corresponding specimen.
4.3 RESULTS

Due to the variability in available range of motion between arms, the varus-valgus laxities reported in this study were average values over an arc of extension from 120° to 20°. There was no statistical difference in varus-valgus laxity between the intact elbow and after sectioning of the posterior band of the MCL and the anterior and posterior capsules (p>0.05). There was no significant difference (p=0.2) in laxity between both of these conditions and the intact coronoid with repaired collateral ligaments. Also, there was no difference in the results of the statistical analyses whether they were performed relative to the intact elbow or relative to the intact coronoid with repaired ligaments. Therefore, in order to simplify the results and focus on the effects of coronoid deficiency and prosthetic replacement, all results are compared to the intact coronoid with repaired collateral ligaments: the ‘coronoid control’.

4.3.1 VARUS-VALGUS LAXITY

4.3.1.1 REPAIRED COLLATERAL LIGAMENTS

For the coronoid control, there was a small but statistically significant difference in varus-valgus laxity between pronation and supination, with pronation showing an average of 1.5 ± 1.0° greater laxity relative to supination. The laxity values presented in the remainder of the results section will be for supination unless otherwise specified. The average varus-valgus laxity for the intact coronoid was 12.6 ± 2.5°. After a 40% coronoid deficiency was simulated and the collateral ligaments were repaired, there was an increase in laxity of 6.7 ± 3.5° (p=0.01). There was no significant difference in laxity between the intact coronoid (coronoid control), the anatomic coronoid prosthesis (p=1.0)
or the extended coronoid prosthesis (p=1.0) with the collateral ligaments repaired (Figure 4.11).

**Figure 4.11: Varus-Valgus Laxity with Repaired Collateral Ligaments**

Simulated passive extension with forearm in supination showing effect of type II coronoid fracture and prosthetic replacement on average varus-valgus laxity with collateral ligaments repaired. A 40% coronoid deficiency increases elbow laxity relative to the coronoid control (p=0.01). Prosthetic replacement with both the anatomic and extended implants restores elbow stability similar to that of the coronoid control (p>0.99 for both). Error bars indicate the SD.
4.3.1.2 **INSUFFICIENT COLLATERAL LIGAMENTS**

With the collateral ligaments sectioned and not repaired, there was no difference in laxity between pronation and supination (p=0.1). Sectioning of the collateral ligaments alone, even with an intact coronoid, resulted in clinically obvious elbow instability with ulnohumeral dislocation occurring in all specimens and a significant increase in mean varus-valgus laxity of 42.8 ± 11.5° (p<0.01), relative to the coronoid control. Laxity further increased by 15.2 ± 6.6° with a 40% coronoid deficiency (p<0.01). There was no difference in laxity between the anatomic prosthesis and the intact coronoid (p=0.2). The extended implant significantly reduced laxity by 21.6 ± 17.7° compared to the intact coronoid (p=0.02) and by 24.6 ± 16.8° compared to the anatomic implant (p<0.01). However, relative to the coronoid control, the extended implant with insufficient ligaments still demonstrated a significant increase in laxity (p<0.01) (Figure 4.12).
Simulated passive extension with the forearm in supination demonstrating the effect of the intact coronoid, type II coronoid fracture and prosthetic replacement on average varus-valgus laxity with the collateral ligaments sectioned. Sectioning the ligaments alone, even with the intact coronoid, significantly increases elbow laxity (p<0.01). A 40% coronoid deficiency further increases laxity (p<0.01). With the collateral ligaments sectioned, there was no difference in laxity between the anatomic implant and the intact coronoid (p=0.2). The extended prosthesis reduced laxity relative to both the intact coronoid (p=0.02) and the anatomic implant (p<0.01), but it was still demonstrated a significant increase in laxity compared to the coronoid control (p<0.01). Error bars indicate the standard deviation.
4.3.2 **Dislocation in the Horizontal Orientation**

4.3.2.1 **Repaired Collateral Ligaments**

When the collateral ligaments were repaired, the translations were significantly less than the dislocation criteria in all arms and conditions during active and passive motion for any coronoid state regardless of the angle of extension or the rotation of the forearm (p=0.02).

4.3.2.2 **Insufficient Collateral Ligaments**

During active extension, with the collateral ligaments sectioned, the ulnohumeral joint did not dislocate for the intact coronoid, the anatomic prosthesis or the extended prosthesis regardless of the angle of extension or the rotation of the forearm (p=0.02). With a 40% coronoid deficiency, no specimens dislocated with the forearm in supination regardless of the extension angle, however, 2 out of 7 specimens dislocated with the forearm in pronation (p=0.06).

During passive extension, the ulnohumeral joint did not dislocate with the intact coronoid regardless of the forearm rotation (p=0.02). After resecting 40% of the coronoid, 3 out of 7 elbows dislocated in supination (p=1.0) and 4 elbows dislocated in pronation (p=0.5). When the anatomic prosthesis was implanted, the elbow dislocated in 2 out of 7 specimens in supination (p=0.3) and in 1 specimen in pronation (p=0.03). With the extended prosthesis, no elbows dislocated irrespective of the extension angle or the forearm rotation (p=0.02) (Figure 4.13).
Simulated passive and active extension in the horizontal orientation with insufficient collateral ligaments showing the effect of a coronoid deficiency and prosthetic replacement on elbow dislocation. This shows that the intact coronoid with insufficient ligaments did not dislocate. The incidence of elbow dislocations increased after a 40% coronoid deficiency. The anatomic prosthesis decreased elbow dislocations but did not eliminate them, whereas the extended prosthesis completely prevented elbow dislocation. Pronation was generally associated with more elbow instability.
4.4 Discussion

This study demonstrates that coronoid process replacement with either an anatomic or an extended implant restores stability to the coronoid-deficient elbow, when the collateral ligaments are repaired. When the collateral ligaments are insufficient, the elbow becomes grossly unstable and not surprisingly the anatomic implant, while an improvement over the coronoid-deficient elbow, is unable to restore stability. Although the extended prosthesis reduces laxity relative to both the intact coronoid and the anatomic prosthesis with sectioned ligaments, the current design of the extended prosthesis still demonstrates significant increased laxity compared to the intact coronoid with repaired ligaments, suggesting that repair or reconstruction of the collateral ligaments is still needed.

The main goal of the study was to evaluate if an extended prosthesis would further stabilize the elbow, relative to an anatomic implant, when the ligaments are insufficient. We chose varus-valgus laxity as a measure of stability since it is a simple combined measure of how the elbow performs in both the varus and valgus orientations. These two orientations are the most provocative on the ligament-insufficient elbow and the varus orientation in particular is most stressful on the coronoid as has been previously reported (1, 10, 11). In pilot studies, we were unable to perform active extension in the varus and valgus orientations using the elbow motion simulator since the ligament-insufficient elbow was so unstable that the specimens tended to forcefully dislocate creating fractures and damaging the articulation. Therefore, only passive extension could be safely performed with the arm in the varus and valgus orientations. Due to the variability in available range of motion between arms, the varus-valgus laxities reported
in this study were average values over an arc of extension from 120° to 20°.

Although the current design of the extended prosthesis still leaves the ligament-insufficient elbow significantly less stable than the ligament-intact elbow, it does decrease laxity significantly relative to both the intact coronoid and the anatomic implant in the setting of insufficient collateral ligaments. This suggests that a prosthesis with an even longer tip that further constrains the ulnohumeral joint would restore stability to the elbow in the setting of insufficient ligaments. However, further studies are required to evaluate this consideration.

This study also demonstrated that in the horizontal orientation of the forearm, the collateral ligaments play a primary role in preventing elbow dislocation as the elbow extends, since no elbow dislocations occurred when the collateral ligaments were repaired. In the setting of sectioned ligaments, a smaller number of elbows dislocated under active motion than under passive motion, demonstrating the important secondary role of muscle activation in stabilizing the elbow. With a 40% coronoid deficiency an increased incidence of elbow dislocations was observed, with both active and passive motion, especially with the forearm in pronation. This finding supports previous studies demonstrating that the coronoid-deficient elbow is more stable in supination than in pronation (1, 10, 11). The anatomic prosthesis decreased the incidence of elbow dislocations in the horizontal orientation relative to the 40% coronoid deficiency, but it did not eliminate it. The extended prosthesis, on the other hand, prevented the elbow from dislocating even in the setting of collateral ligament insufficiency.

The fact that the intact coronoid with sectioned ligaments did not dislocate, whereas the anatomic implant did, is unexpected and somewhat difficult to explain. Due
to our study design and the testing protocol, the intact coronoid was always tested first followed by the 40% coronoid deficiency and then the anatomic implant. The difference in the dislocation rate between the intact coronoid and the anatomic implant when the collateral ligaments were sectioned may be due to the increased amount of surgical dissection required to perform the coronoid osteotomy and implant the prosthesis in this in-vitro study. While to some extent our biomechanical model represents a worst-case scenario, the fact that the anatomic implant restored stability when ligaments were repaired and that the extended implant prevented dislocation with insufficient ligaments, only strengthens the results and conclusions of the study. The implant would only be expected to perform better clinically, since less dissection would be required to excise an unreconstructable coronoid and insert a coronoid prosthesis. Alternatively, the anatomic implant likely did not precisely replicate the size and shape of the intact coronoid. A family of coronoid implants with a more precise replication of the normal coronoid anatomy may improve the success of the anatomic prosthesis.

We chose to study dislocations in the horizontal orientation because as the elbow extends in this orientation, the weight of the arm provocatively stresses the coronoid, highlighting its role in posterior elbow stability. Dislocation was defined in this study as a distal translation of the humerus relative to the ulna equal to the length of one radius of curvature of the greater sigmoid notch. In other words, this means a translation of the ulna proximally, along its long axis, relative to its position in the intact elbow. The average radius of curvature of the greater sigmoid notch was 10.1 mm (9.14 – 11.92 mm). We chose the length of one radius of curvature as our cut-off since a translation of that amount would mean the tip of the coronoid is articulating with the most distal point
of the distal humerus and thus would necessitate the elbow to be dislocated. This cut-off is conservative and may under-estimate the dislocation rate since it is possible for the elbow to dislocate with much smaller translations when coupled with ulnar rotations.

Previous biomechanical studies have demonstrated that type II coronoid fractures are associated with altered elbow kinematics and instability even if the collateral ligaments are repaired (1, 11). Pollock et al also showed that fixing type II coronoid fractures as well as repairing the collateral ligaments restored elbow stability (11). These studies, however, did not examine elbow kinematics and stability in the horizontal orientation. Our study confirms their findings by demonstrating that a 40% coronoid deficiency was associated with increased varus-valgus laxity, even when the collateral ligaments were repaired. Additionally, there was an increased rate of dislocation in the horizontal orientation with a type II coronoid deficiency, especially in extension, when the collateral ligaments were insufficient.

This is the first paper, to our knowledge, that addresses the effectiveness of a coronoid prosthesis especially in the setting of collateral ligament insufficiency. The extended implant is a novel concept in an attempt to solve a difficult clinical situation: stabilizing the coronoid and ligament-insufficient elbow. The prosthesis was designed to replace 40% of the height of the coronoid since that height closely approximates the average height of the terrible triad coronoid fracture, which has been reported to be 38% (29). However, given the semi-constrained design of the extended implant, it is likely to experience increased stresses, which would likely result in higher loosening and failure rates relative to an anatomic implant. The limitations of our study include the fact that it is an in vitro study, which is different than the in-vivo setting where ligaments and soft
tissues have the ability to heal. Also, the stepwise design of the study and the sequence of the testing protocol made progressive soft tissue dissection and repeated loading of specimens necessary.
4.5 CONCLUSION

This study demonstrates that an anatomic coronoid implant restores the stability of the coronoid-deficient elbow when the collateral ligaments are repaired or reconstructed. In the setting of collateral ligament insufficiency, an extended prosthesis prevented dislocation and reduces elbow laxity relative to the intact coronoid and to the anatomic prosthesis, but is not enough to restore full stability similar to that of the intact elbow. Therefore, collateral ligament repair or reconstruction is still recommended even if the coronoid is replaced. Further studies are required to evaluate modified designs of the extended prosthesis, perhaps increasing the height and width of the tip to further stabilize the elbow and allow the collateral ligament repairs or reconstructions to heal. Studies are also needed to address contact pressures between the prosthesis and the native cartilage, to find the optimum method of fixing the implants to the ulna and to evaluate the feasibility of the prosthesis clinically.
REFERENCES


CHAPTER 5

General Discussion and Conclusions

OVERVIEW

In this chapter, the objectives and hypotheses that were established in Chapter 1 will be reviewed. The results of our research studies, their fulfillment of the objectives and their contribution to the field in the greater context will be demonstrated. The strengths and limitations of this work will be discussed followed by a highlight of future directions and areas of research.
5.1 SUMMARY OF OBJECTIVES

The studies in this work have fulfilled the objectives that were set out at the outset of this thesis focusing on the treatment of coronoid fractures and deficiency. These objectives were to:

1) Compare the strength of fixation of 5 different fixation methods for a simulated type II coronoid fracture, comprising 40% of the coronoid height.

2) Determine if reconstructing a 40% coronoid deficiency using the tip of the ipsilateral olecranon restores baseline elbow kinematics and stability.

3) Assess if replacing 40% of the coronoid using an anatomic and extended tip coronoid prosthesis restores elbow kinematics in the setting of repaired collateral ligament, and if the extended tip prosthesis improves stability relative to the anatomic implant or the intact coronoid in the setting of ligament insufficiency.
5.2 GENERAL DISCUSSION

5.2.1 OVERVIEW OF FINDINGS

The research studies in this thesis addressed a continuum of injuries and solutions for fractures of the coronoid process of the elbow. The focus of the studies was on Regan and Morrey Type II fractures (1) as they are the most commonly encountered, clinically relevant, fracture type (2).

The coronoid fixation study (chapter 2) addressed the first objective evaluating simple coronoid fractures amenable to open reduction and internal fixation. This study examined the strength of fixation for simulated transverse type II Regan and Morrey (1) coronoid fractures comprising 40% of the coronoid height. Five different fixation methods were assessed: plate fixation, two PA screws, two AP screws, one PA screw and suture fixation. We found that plate fixation was the strongest fixation method, which was significantly stronger than two screw fixation. There was no difference in strength between two PA and two AP screws and both were stronger than one PA screw. Suture fixation failed at very low loads suggesting that it is an unreliable fixation method.

However, in cases where the coronoid fracture or deficiency is not amenable to open reduction and internal fixation with one of these techniques, coronoid reconstruction is warranted. The coronoid reconstruction study (chapter 3) evaluated the second objective focusing on reconstructing the coronoid process using the ipsilateral olecranon tip. We tested elbow kinematics with an intact coronoid, a 40% coronoid deficiency and after coronoid reconstruction with the tip of the ipsilateral olecranon. We demonstrated that a 40% coronoid deficiency results in significant changes to elbow kinematics,
especially when the elbow is positioned in the varus orientation. These alterations are restored back to baseline levels—similar to those of the intact coronoid—after the coronoid is reconstructed using the tip of the ipsilateral olecranon. Moreover, in this study, the extent of deficiency in the olecranon tip needed to reconstruct 40% of the coronoid height did not result in any instability to the elbow. Although a number of different reconstruction techniques have been described in the literature, including iliac crest bone graft, olecranon tip, radial head fragments, rib osteochondral graft and allograft, none of these has been evaluated biomechanically or in long term clinical studies (3-7). The ipsilateral olecranon tip has many advantages over all the other reconstruction methods; it is a local structure that is easily accessible during surgical treatment of the coronoid, it is an autograft with better healing potential than allograft, it is covered with cartilage, and it resembles the structure of the coronoid to large extent (8). This study is the first biomechanical validation for any coronoid reconstruction technique and demonstrates the reliability and effectiveness of using the ipsilateral olecranon tip to reconstruct the coronoid.

Nevertheless, when coronoid reconstruction with the olecranon tip cannot be performed due to concomitant fractures, coronoid replacement is an option (9). The coronoid replacement study (chapter 4) addressed the third and last objective of this thesis, examining the effects of coronoid replacement on elbow kinematics in the setting of collateral ligament insufficiency. The focus of the study was to specifically evaluate if an extended tip coronoid prosthesis would improve the stability of the coronoid-deficient elbow with ligament insufficiency relative to an anatomic prosthesis. We examined elbow varus-valgus laxity after a 40% coronoid deficiency, after replacing the coronoid
with an anatomic prosthesis and after replacing the coronoid with an extended tip prosthesis. This evaluation was performed with the collateral ligaments repaired and in the setting of collateral ligament insufficiency.

We demonstrated that coronoid replacement with either an anatomic or an extended implant restored elbow stability to the coronoid-deficient elbow, when the collateral ligaments were repaired. In the setting of insufficient collateral ligaments, the anatomic implant, while an improvement over the coronoid-deficient elbow, was unable to restore stability. The extended prosthesis reduced laxity relative to both the intact coronoid and the anatomic prosthesis with insufficient ligaments, yet it still exhibited increased laxity compared to the intact coronoid with repaired ligaments. These results suggest that repair or reconstruction of the collateral ligaments is required even if the coronoid process is to be replaced.

5.2.2 Clinical Implications

From a clinical perspective, the studies in this thesis provide multiple solutions to coronoid fractures depending on the severity of the injury. When faced with a simple Regan and Morrey type II coronoid fracture (1), the use of two screws is recommended, when the fracture pattern and size make this technically possible. Two screws provide sufficient stability to the fracture construct against typical forces postulated to pass across the ulnohumeral joint (10,11). The orientation of the two screws should be determined by the surgical approach, since there was no difference in fixation strength between the AP and the PA screws. Plate fixation, despite being the strongest method, often requires increased operative time and exposure, which can increase the surgical risks. Therefore
the increased fixation strength should be weighed against the risk of adding an anterior or medial approach to the more standard lateral approach to the elbow. In certain fracture patterns, fixation with two screws may not be possible due to small fragment size or comminution and it is recommended in these cases to use one PA screw. However, rotational failure of the construct may occur with a single screw construct. This study also demonstrated that suture fixation should not be used for coronoid fracture fixation when other techniques are possible.

These results however, are limited to a simple transverse coronoid fracture comprising 40% of the coronoid height and may not be applicable to other fracture patterns such as those involving the anteromedial facet of the coronoid or comminuted fractures.

In these cases where the coronoid fracture is too comminuted for fixation, where there is a nonunion of a previous coronoid fracture or where the coronoid tip has become deficient due to erosion from chronic elbow subluxation, the coronoid needs to be reconstructed, as fixation is not possible. Since other reported coronoid reconstruction methods are unproven (5,12), we believe that this method represents the most reliable treatment option for coronoid deficiencies comprising less than 50% of the coronoid height. However, this method may not be suitable for larger deficiencies as a larger olecranon resection and the violation of the triceps insertion is likely to have negative consequences and lead to instability. Moreover, since coronoid fractures are often associated with other fractures, including olecranon fractures, this technique may not always be possible (13).
Therefore, when coronoid reconstruction with the ipsilateral olecranon cannot be performed, coronoid replacement combined with ligament repair is a good option. Furthermore, due to the previously noted limitations of reconstructing the coronoid with the ipsilateral olecranon tip, coronoid replacement may represent a more effective technique for large coronoid fracture or deficiencies comprising more than 40% of the coronoid height.

Due to the encouraging outcomes of the coronoid replacement, we have used the anatomic implant clinically by successfully implanting it into a patient who had a 70% coronoid deficiency. This represented the first case of clinical use of a coronoid replacement.

5.2.3 Future Directions

Future studies are necessary to correlate these findings of these studies with clinical outcomes. With respect to the coronoid fixation study (chapter 2), the lack of the stabilizing effects of soft tissues may affect how the results translate into the in-vivo clinical setting. Moreover, since this is a cadaver bone fixation model, which lacks the ability for bone healing and represents time-zero fixation strength. Thus, it is a worst-case scenario model. Therefore, in-vivo clinical studies are needed to confirm these results. Further studies are required to compare the fixation strengths of different constructs, including different screw diameters and plate designs as well as other fracture patterns.

Regarding the coronoid reconstruction study (chapter 3), clinical studies are needed to correlate these biomechanical results with clinical findings, including long-term follow-up. Moreover, as noted previously, there is a limit to the size of a coronoid
defect that can be reconstructed using the olecranon tip, since a large olecranon tip resection may lead to instability as well as the need to detach and repair the triceps tendon. Therefore, future studies should assess the biomechanical effects of reconstructing various levels of coronoid deficiencies using this technique to identify the maximum height of a coronoid defect that can be reconstructed with the olecranon tip. Furthermore, due to the observed mismatch in the shapes of the coronoid and the ipsilateral olecranon, we believe that the contralateral olecranon may provide a better shape match for the coronoid. Hence, future studies should examine the geometry of the ipsilateral versus contralateral olecranon tips relative to the coronoid tip and evaluate the biomechanical effects of reconstructing the coronoid deficiency with the contralateral olecranon tip.

In relation to the coronoid replacement study (chapter 4), future studies should involve testing coronoid replacement on larger coronoid deficiencies and then designing a small family of implants that could be manufactured by industry for ‘off-the-shelf’ clinical use. These implants would need to have a range of sizes to accommodate different patient profiles and would also need to be left-right specific. Optimization of implant fixation is also required. Moreover, long-term follow-up of patients who receive a coronoid prosthesis is needed to assure that these implants function in-vivo as effective as they did in this in-vitro study, without long-term complications.

Furthermore, further research and modification of the current design of the extended prosthesis, especially in further extending the tip, may enable stabilization of the elbow even in the setting of collateral ligament insufficiency.
5.3 STRENGTHS AND LIMITATIONS

This work is novel in many ways. The fixation study is the first study to compare different fixation methods in type II coronoid fractures. The olecranon reconstruction study is the first to comprehensively test a coronoid reconstruction method biomechanically. Moreover, the study on coronoid replacement represents the first description of a coronoid replacement and thoroughly evaluates the effectiveness of this implant in restoring elbow kinematics after a coronoid deficiency. The methods of all studies were rigorous and utilized well described and reliable biomechanical testing models. Finally, the results of these results have direct implications on patient care and surgical treatment of elbow injuries involving the coronoid process.

However, this work is limited in that all studies were in-vitro using cadaveric specimens. Despite the fact that testing on human cadavers is more relevant and clinically applicable than testing on animal models, yet they have a number of inherent limitations. Since most cadaveric specimens are from older donors, the fixation strength is often underestimated in relation to younger patients (14). Also, cadaveric soft tissues and bone have no healing potential and thus represent time-zero fixation strength. Moreover, soft tissues experience a slight change in characteristics with time. Therefore, future studies are required to correlate these in-vitro studies to clinical results in patients.
5.4 Conclusions

In conclusion, this thesis addresses a significant clinical problem encountered following elbow trauma, focusing on coronoid fixation, reconstruction and replacement. It compares the strength of different fixation methods for fixing 40% coronoid fractures; it demonstrates the effectiveness of reconstructing a 40% coronoid deficiency using the ipsilateral olecranon tip; and evaluates the value of replacing a 40% coronoid deficiency with an anatomic and extended coronoid prosthesis in the setting of repaired or insufficient collateral ligaments.
5.5 REFERENCES


11. Halls AA, Travill A. Transmission of pressures across the elbow joint. The Anatomical Record. 1964;150:243-7


APPENDIX A

Glossary and Medical Terms

This appendix contains a list of the medical terms used throughout this thesis, to provide assistance to the reader who may be unfamiliar with this terminology.

<table>
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<th>Term</th>
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<tr>
<td>Active Motion</td>
<td>Achieving motion by applying forces to bone or tendons</td>
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<tr>
<td>Anterior</td>
<td>Pertaining to or toward the front plane of the body; opposite of posterior</td>
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<tr>
<td>Anthropometry</td>
<td>The science of quantifying anatomic features of the body, where the size, weight, and proportions of the human body may be measured</td>
</tr>
<tr>
<td>Arthritis</td>
<td>Inflammation of the joint characterized by pain, swelling, and structural changes</td>
</tr>
<tr>
<td>Arthroplasty</td>
<td>The surgical replacement or reconstruction of a joint</td>
</tr>
<tr>
<td>Articular</td>
<td>Pertaining to a joint</td>
</tr>
<tr>
<td>Articular Surface</td>
<td>The end of a bone which forms a synovial joint</td>
</tr>
<tr>
<td>Articulation</td>
<td>The point of contact formed by bones composing a joint</td>
</tr>
<tr>
<td>Axial/transverse Plane</td>
<td>The anatomical plane passing horizontally through the body, dividing the body into superior and inferior parts</td>
</tr>
<tr>
<td>Cancellous</td>
<td>Spongy bone</td>
</tr>
<tr>
<td>Capitellum</td>
<td>A small eminence on the lateral end of the distal humerus, which it articulates with the proximal radius</td>
</tr>
<tr>
<td>Capsule</td>
<td>A ligamentous sac surrounding the articular cavity of a joint composed of an outer fibrous membrane and an inner synovial membrane</td>
</tr>
<tr>
<td>Cartilage</td>
<td>A specialized fibrous connective tissue found in throughout the body, including the joints between osseous structures</td>
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<tr>
<td><strong>Comminuted</strong></td>
<td>Broken or crushed into several small fragments</td>
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<tr>
<td><strong>Contralateral</strong></td>
<td>Relating to the opposite side</td>
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<tr>
<td><strong>Coronal Plane</strong></td>
<td>The anatomical plane passing longitudinally through the body, dividing the body into anterior and posterior sections</td>
</tr>
<tr>
<td><strong>Coronoid Process</strong></td>
<td>The anterior-most aspect of the proximal ulna, which forms the distal portion of the greater sigmoid notch</td>
</tr>
<tr>
<td><strong>Digitization</strong></td>
<td>The act of physically acquiring the three-dimensional location of points on an object’s surface</td>
</tr>
<tr>
<td><strong>Distal</strong></td>
<td>Situated away from the point of origin or attachment; opposite of proximal</td>
</tr>
<tr>
<td><strong>Dislocation</strong></td>
<td>Displacement of a bone from its native articulation</td>
</tr>
<tr>
<td><strong>Epicondyle</strong></td>
<td>A projection upon a bone above its condyle</td>
</tr>
<tr>
<td><strong>Extension</strong></td>
<td>Movement causing straightening or an increase in flexion angle</td>
</tr>
<tr>
<td><strong>External Rotation</strong></td>
<td>A rotation away from the mid-line of the body (i.e. forearm supination)</td>
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<tr>
<td><strong>Flexion</strong></td>
<td>Movement bending the limb or reducing the angle between two bones</td>
</tr>
<tr>
<td><strong>Fossa</strong></td>
<td>In anatomy, a depression or hollow area</td>
</tr>
<tr>
<td><strong>Greater Sigmoid Notch</strong></td>
<td>A depression located in the proximal ulna formed by the olecranon and the coronoid process, which articulates with the trochlea of the humerus. Also referred to as the semilunar or trochlear notch of the ulna</td>
</tr>
<tr>
<td><strong>Humeroulnar</strong></td>
<td>See ulnohumeral</td>
</tr>
<tr>
<td><strong>Instability</strong></td>
<td>A pathologic condition in which there is an inability to maintain the normal relationship of the distal humeral articular surface with the proximal articular surfaces of the ulna and radius</td>
</tr>
<tr>
<td><strong>Internal Fixation</strong></td>
<td>The fixation of screws and/or plates underneath the soft tissues to facilitate healing</td>
</tr>
<tr>
<td><strong>Internal Rotation</strong></td>
<td>A rotation towards the mid-line of the body (i.e. forearm pronation)</td>
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<tr>
<td><strong>Ipsilateral</strong></td>
<td>Relating to the same side</td>
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<tr>
<td><strong>Joint</strong></td>
<td>A location at which two or more bones unite to form an articulation</td>
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<tr>
<td><strong>Kinematics</strong></td>
<td>The study of the relative motion between two or more physical bodies</td>
</tr>
<tr>
<td><strong>Lateral</strong></td>
<td>Denoting a position further from the mid-line of the body</td>
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<tr>
<td><strong>Laxity</strong></td>
<td>The quality or state of being loose</td>
</tr>
<tr>
<td><strong>Lesser Sigmoid Notch</strong></td>
<td>An articular depression on the lateral side of the coronoid process, which serves to receive the articular surface of the head of the radius. Also referred to as the radial notch of the ulna</td>
</tr>
<tr>
<td><strong>Ligament</strong></td>
<td>A band of fibrous tissue serving to connect bones or cartilage, which supports and strengthens joints</td>
</tr>
<tr>
<td><strong>Medial</strong></td>
<td>Situation toward the mid-line of a body</td>
</tr>
<tr>
<td><strong>Morphology</strong></td>
<td>The study of the form or shape of a structure</td>
</tr>
<tr>
<td><strong>Nonunion</strong></td>
<td>The failure of bone union or healing after a fracture</td>
</tr>
<tr>
<td><strong>Orthopedic</strong></td>
<td>The branch of surgery dealing with the preservation and restoration of the function of the skeletal system, its articulations and associated structures</td>
</tr>
<tr>
<td><strong>Osseous</strong></td>
<td>Consisting of bone</td>
</tr>
<tr>
<td><strong>Osteochondral</strong></td>
<td>A fragment containing both bony and cartilage components</td>
</tr>
<tr>
<td><strong>Osteotomy</strong></td>
<td>The dividing of a bone, or the excision of part of it</td>
</tr>
<tr>
<td><strong>Passive Motion</strong></td>
<td>Achieving joint motion without muscle activation (i.e. movement is achieved manually)</td>
</tr>
<tr>
<td><strong>Posterior</strong></td>
<td>Pertaining to or toward the back of the body; opposite of anterior</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Pronation</td>
<td>In relation to the hand, rotation of the forearm so the surface of the palm is facing downward or toward the back</td>
</tr>
<tr>
<td>Prosthesis</td>
<td>A device, either external or implanted, that substitutes for or supplements a missing or defective part of the body.</td>
</tr>
<tr>
<td>Proximal</td>
<td>Anatomically situation close to the origin or line of attachment</td>
</tr>
<tr>
<td>Radial head</td>
<td>An anatomical structure forming the proximal end of the radius, which articulates with the capitellum of the humerus and the lesser sigmoid notch of the ulna</td>
</tr>
<tr>
<td>Radiocapitellar</td>
<td>Pertaining to the radius and capitellum</td>
</tr>
<tr>
<td>Radiohumeral</td>
<td>See radiocapitellar</td>
</tr>
<tr>
<td>Radioulnar</td>
<td>Pertaining to the radius and ulna</td>
</tr>
<tr>
<td>Range of Motion</td>
<td>Amount of motion attained during an activity</td>
</tr>
<tr>
<td>Resection</td>
<td>The excision of all or part of an organ or tissue</td>
</tr>
<tr>
<td>Sagittal Plane</td>
<td>The anatomical plane traveling vertically from the top to the bottom of the body, dividing it into left and right portions</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>Tissues connecting, supporting, or surrounding other structures of the body (muscles, tendons, ligaments)</td>
</tr>
<tr>
<td>Supination</td>
<td>In relation to the hand, rotation of the forearm so the surface of the palm is facing upwards or toward the front</td>
</tr>
<tr>
<td>Supracondylar</td>
<td>Situated above a condyle or condyles</td>
</tr>
<tr>
<td>Tendon</td>
<td>A fibrous cord of connective tissue attaching the muscle to bone or cartilage</td>
</tr>
<tr>
<td>Translation</td>
<td>A finite linear displacement</td>
</tr>
<tr>
<td>Trochlea</td>
<td>An anatomical structure, resembling a pulley, found at the distal end of the humerus, which articulates with the proximal ulna</td>
</tr>
<tr>
<td>Ulnohumeral</td>
<td>Pertaining to the ulna and humerus</td>
</tr>
<tr>
<td>Valgus</td>
<td>Bent outwards; angulation of part of the body away from the mid-line of the body</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>Varus</td>
<td>Bent inwards; angulation of part of the body toward the mid-line of the body</td>
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APPENDIX B

Appendix to Chapter 3

B.1 SDA KINEMATICS IN THE VALGUS ORIENTATION

As discussed in Chapter 3, instantaneous SDA kinematics for active and passive extension in the valgus orientation are presented below in Figures B.1 and B.2. These figures complement Figures 3.7-3.10, presented in Chapter 3.
**FIGURE B.1: SDA KINEMATICS – ACTIVE EXTENSION IN THE VALGUS ORIENTATION**

Instantaneous SDA kinematics plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction with the olecranon graft. Rows (A) and (B) represent SDAs in the coronal and transverse planes, respectively, with the forearm in pronation. Rows (C) and (D) represent SDAs in the coronal and transverse, respectively, with the forearm in supination. Axes are in mm.
**FIGURE B.2: SDA KINEMATICS – PASSIVE EXTENSION IN THE VALGUS ORIENTATION**

Instantaneous SDA kinematics plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction with the olecranon graft. Rows (A) and (B) represent SDAs in the coronal and transverse planes, respectively, with the forearm in pronation. Rows (C) and (D) represent SDAs in the coronal and transverse, respectively, with the forearm in supination. Axes are in mm. Asterisks (*) indicate significance.
B.2 SDA KINEMATICS IN THE VARUS ORIENTATION

As discussed in Chapter 3, instantaneous SDA kinematics for active and passive extension in the varus orientation are presented below in Figures B.3 and B.4. These figures complement Figures 3.11-3.14, presented in Chapter 3.
**Figure B.3: SDA Kinematics – Active Extension in the Varus Orientation**

Instantaneous SDA kinematics plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction with the olecranon graft. Rows (A) and (B) represent SDAs in the coronal and transverse planes, respectively, with the forearm in pronation. Rows (C) and (D) represent SDAs in the coronal and transverse, respectively, with the forearm in supination. Axes are in mm. Asterisks (*) indicate significance.
Instantaneous SDA kinematics plotted for the coronoid control, the coronoid deficiency and the coronoid reconstruction with the olecranon graft. Rows (A) and (B) represent SDAs in the coronal and transverse planes, respectively, with the forearm in pronation. Rows (C) and (D) represent SDAs in the coronal and transverse, respectively, with the forearm in supination. Axes are in mm. Asterisks (*) indicate significance.
APPENDIX C

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CURRICULUM VITAE

BASHAR ALOLABI, MD, FRCSC

EDUCATION

Aug 2013 – Jul 2014  Fellowship – Orthopedic Trauma and Lower Extremity Reconstruction  
Sunnybrook Health Sciences Centre, University of Toronto  
Toronto, Ontario, Canada

Aug 2012 – Jul 2013  Fellowship - Shoulder & Elbow Surgery  
Cleveland Clinic Foundation  
Cleveland, Ohio, USA

Sep 2011 – June 2014  Masters of Science – Medical Biophysics  
University of Western Ontario  
London, Ontario, Canada  
Supervisor: Drs. G. King and J. Johnson

Class of 2012, University of Western Ontario  
London, Ontario, Canada

Aug 2004 – May 2007  Doctor of Medicine Degree  
School of Medicine, Class of 2007, McMaster University  
Hamilton, Ontario, Canada

Sep 2001 – May 2004  Honours Bachelor of Science, Physiology Specialist  
Faculty of Arts and Science, University of Toronto  
Toronto, Ontario, Canada

ACADEMIC APPOINTMENTS

Sep 2013 – Present  Orthopedic Surgery Sports Medicine Consultant  
Athletes Care Sports Medicine Clinic, Toronto, Ontario

Sep 2013 – Present  Courtesy Staff  
Scarborough General Hospital, Toronto, Ontario

Sep 2013 – Present  Temporary Staff  
Ross Memorial Hospital, Lindsay, Ontario
### SPECIALTY QUALIFICATIONS

1. Fellow: Royal College of Surgeons of Canada – Orthopedic Surgery: June 2012
2. Board Eligible: American Board of Orthopedic Surgeons: July 2013

### MEDICAL LICENSING

2. State Medical Board of Ohio Permanent Licensure (No. 35.099610): Aug 2012 – July 2015

### REVIEWER AND EDITORIAL ACTIVITIES

2014 – Present
Reviewer, International Journal of Shoulder Surgery

### BOOK CHAPTERS


### PEER REVIEWED PUBLICATIONS


PUBLICATIONS IN PROGRESS


RESEARCH GRANTS & SCHOLARSHIPS


3. CIHR Health Professional Student Research Award. School of Medicine, McMaster University. Fixation versus Hemiarthroplasty for Displaced Femoral Neck Fractures: A Decision Board Analysis. $4,000. Principle Investigator: Alolabi B. Supervisor: Bhandari M. July 2005

RESEARCH AWARDS

1. Best Clinical Research Award
   Radiographic Assessment of Prosthetic Humeral Head Size Following Shoulder Arthroplasty
   Cleveland Clinic Department of Orthopedic Surgery Research Day
   Cleveland, Ohio, June 6, 2013.

2. J.A. Nutter Award for Best Paper
   Reconstruction of the Coronoid Process Using the Tip of the Ipsilateral Olecranon.

3. **The Canadian Orthopedic Association’s Best Poster Award**
   Reconstruction of the Coronoid Process Using the Tip of the Ipsilateral Olecranon.

4. **H. Bailey Award for Best Basic-Science Paper**
   Reconstruction of the Coronoid Process Using the Tip of the Ipsilateral Olecranon.
   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW

5. **2011 PSI Foundation Resident Research Prize**
   Reconstruction of the Coronoid Using an Extended Prosthesis: an In-Vitro Biomechanical Study.
   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW

6. **Runner-up, H. Bailey Award for Best Basic-Science Paper**
   Coronoid Process Replacement: Biomechanical Testing of an Anatomic and Extended Prosthesis

7. **CORA’s Top 3rd Paper Award**
   Graft Choice in Medial Opening Wedge High Tibial Osteotomy: Auto vs Allograft

8. **John D. Schultz Heart and Stroke Foundation Research Scholarship**
   Toronto General Hospital – University Health Network. 2003.

### RESEARCH PRESENTATIONS

**Podium Presentations:**
1. **Predictors of Functional Outcome in Operatively Treated Pelvis Ring Fractures.**

2. **Strength of Coronoid Fracture Fixation: A Biomechanical Study.**
3. Early versus late culture growth characteristics in P. acnes positive periprosthetic shoulder Infections.
   Frangiimore, S, Grosso M, Alolabi B, Saleh A, Ricchetti E, Bauer T, Iannotti J
   American Academy of Orthopedic Surgeons Annual Meeting
   New Orleans, Lioussiana. March 11, 2014

4. Revision Shoulder Arthroplasty.
   Alolabi B
   The 2nd Emirates International Orthopedic Conference
   Dubai, Emirates. November 29, 2013

5. Combined Bone Loss in Shoulder Instability: Fix it on the Humerus, the Glenoid or Both?
   Alolabi B
   The 2nd Emirates International Orthopedic Conference
   Dubai, Emirates. November 29, 2013

   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   The Canadian Orthopedic Association’s (COA) 68th Annual Meeting

7. Strength of Coronoid Fracture Fixation: A Biomechanical Study.
   Alolabi B, Studer A, Gray A, Ferreira LM, King GJW, Johnson JA, Athwal GA.
   The Canadian Orthopedic Association’s (COA) 68th Annual Meeting

   Cleveland Clinic Department of Orthopedic Surgery Research Day
   Cleveland, Ohio, June 6, 2013.

   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   Guest Speaker, McMaster University Orthopedic Grand Rounds

10. Glenohumeral Arthritis and Arthroplasty
    Alolabi B, Ricchetti ET, Iannotti JP
    Cleveland Clinic Resident Teaching Rounds
    Cleveland, Ohio, November 20, 2012.

    Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
    The Ontario Orthopedic Association’s (OOA) Annual Meeting

    Pereira I, Alolabi B, Gray A, Athwal GA, Johnson JA, King GJW.
    The Canadian Orthopedic Association’s (COA) 67th Annual Meeting
   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW. 
   The Canadian Orthopedic Residents Association (CORA) 38th Annual Meeting 

   Gray A, **Alolabi B**, Deluce S, Ferreira LM, Athwal GA, King GJW, Johnson JA. 
   American Academy of Orthopedic Surgeons’ (AAOS) Annual Meeting 

   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW. 
   39th Orthopedic Residents’ Research Day, University of Western Ontario 

16. An Extended Tip Coronoid Prosthesis Improves the Stability of the Coronoid and 
    Ligament Deficient Elbow. 
    **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW. 
    The Canadian Orthopedic Association’s (COA) 66th Annual Meeting 
    St. John’s, Newfoundland. July 7-9, 2011.

17. Determining the Diameter of a Radial Head Implant: Assessment of Local 
    Landmarks. 
    **Alolabi B**, Studer A, Gray A, King GJW, Athwal GA. 
    The Canadian Orthopedic Association’s (COA) 66th Annual Meeting 
    St. John’s, Newfoundland. July 7-9, 2011.

18. An Anatomically Shaped Coronoid Prosthesis Restores the Stability of the Coronoid- 
    Deficient Elbow 
    Gray A, **Alolabi B**, Ferreira LM, Athwal GA, King GJW, Johnson JA. 
    The Canadian Orthopedic Association’s (COA) 66th Annual Meeting 
    St. John’s, Newfoundland. July 7-9, 2011.

19. Surgical Preferences of Patients at Risk of Hip Fractures: Hemiarthroplasty versus 
    Total Hip Arthroplasty. 
    Alolabi N, **Alolabi B**, Mundi R, Karanicolas PJ, Adachi JD, Bhandari M. 
    The Canadian Orthopedic Association’s (COA) 66th Annual Meeting 
    St. John’s, Newfoundland. July 7-9, 2011.

20. Coronoid Process Replacement: Biomechanical Testing of an Anatomic and 
    Extended Prosthesis 
    **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW. 
    The Canadian Orthopedic Residents Association (CORA) 37th Annual Meeting 
    St. John’s, Newfoundland. July 6, 2011.

21. Reconstruction of the Coronoid Using an Anatomic and Augmented Prosthesis: An 
    In-Vitro Biomechanical Study 
    **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW. 
    American Shoulder & Elbow Surgeons, Open Meeting. 
    San Diego, CA. February 19, 2011.

22. Graft Choice in Medial Opening Wedge High Tibial Osteotomy: Auto vs Allograft 
    **Alolabi B**, Bryant D, Willits K, Fowler PJ, Giffin JR. 
    The Ontario Orthopedic Association’s (OOA) Annual Meeting 
23. Reconstruction of the Coronoid Using an Anatomic and Augmented Prosthesis: An In-Vitro Biomechanical Study
   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW.
   American Shoulder & Elbow Surgeons, Closed Meeting.
   Scottsdale, AZ. October 22, 2010

24. Coronoid Process Replacement: Biomechanical Testing of an Anatomic and Extended Prosthesis
   Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW.
   38th Orthopedic Residents’ Research Day, University of Western Ontario
   London, Ontario. October 13, 2010

25. Graft Choice in Medial Opening Wedge High Tibial Osteotomy: Auto vs Allograft
   Alolabi B, Bryant D, Willits K, Fowler PJ, Giffin JR.
   The Canadian Orthopedic Association’s (COA) 65th Annual Meeting
   Edmonton, Alberta. June 19, 2010

26. Graft Choice in Medial Opening Wedge High Tibial Osteotomy: Auto vs Allograft
   Alolabi B, Bryant D, Willits K, Fowler PJ, Giffin JR.
   The Canadian Orthopedic Residents Association (CORA) 36th Annual Meeting
   Edmonton, Alberta. June 18, 2010

27. Coronoid Arthroplasty
   King GJ, Gray A, Alolabi B, Ferreira LM, Athwal GS, Johnson JA.
   Mayo Clinic Elbow Club Meeting

28. Graft Choice in Medial Opening Wedge High Tibial Osteotomy: Auto vs Allograft
   Alolabi B, Bryant D, Willits K, Fowler PJ, Giffin JR.
   37th Orthopedic Residents’ Research Day, University of Western Ontario
   London, Ontario. October 13, 2009

29. Operative vs. Non-Operative Management of Isolated Fibular Fractures: Is the Ankle Reduced on CT Assessment?
   Alolabi B, Sanders DW.
   36th Orthopedic Residents’ Research Day, University of Western Ontario

30. Patient Preferences for the Treatment of Displaced Femoral Neck Fractures: A Decision Board Analysis of Internal Fixation versus Hemiarthroplasty
   Bajammal S, Alolabi B, Shirali J, Karanicolas PJ, Zlowodzki M, Bhandari M.
   The 2008 Combined Meeting of the AOA and COA
   Quebec City, Quebec. June 5, 2008

   Alolabi B, Shirali J, Bajammal SS, Karanicolas PJ, Zlowodzki M, Gafni A, Bhandari M.
   Orthopedic Trauma Association’s (OTA) Annual Meeting
   Boston, MA. October 18, 2007

32. The Use of Calcium Phosphate Bone Cement in Fractures Treatment: A Meta-Analysis of Randomized Controlled Trials.
   Alolabi B, Bajammal S, Schmitz-Lelwica A, Bhandari M.
   The Canadian Orthopedic Resident Association (CORA) 32nd Annual Meeting
Toronto, Ontario. June 1, 2006

   Bajammal S, **Alolabi B**, Gafni, A, Bhandari M.
   Resident’s Annual Research Day, McMaster University
   Hamilton, Ontario. September 30, 2005

**Poster Presentations:**

1. Radiographic Assessment of Prosthetic Humeral Head Size Following Anatomic Shoulder Arthroplasty.
   The Canadian Orthopedic Association’s (COA) 69th Annual Meeting

2. Early versus late culture growth characteristics in P. acnes positive periprosthetic shoulder Infections
   Frangiamore S, Grosso M, **Alolabi B**, Saleh A, Ricchetti ET, Iannotti JP.
   The Canadian Orthopedic Association’s (COA) 69th Annual Meeting

   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   American Academy of Orthopedic Surgeons Annual Meeting.

   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   American Shoulder & Elbow Surgeons, Closed Meeting.
   Sea Island, Georgia. October 11-14, 2012

   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   The Canadian Orthopedic Association’s (COA) 67th Annual Meeting
   Ottawa, Ontario. June 8-10, 2012

   **Alolabi B**, Gray A, Ferreira LM, Johnson JA, Athwal GA, King GJW.
   The Canadian Orthopedic Association’s (COA) 67th Annual Meeting
   Ottawa, Ontario. June 8-10, 2012

7. Surgical Preferences of Patients at Risk of Hip Fractures: Hemiarthroplasty versus Total Hip Arthroplasty.
   Alolabi N, **Alolabi B**, Mundi R, Karanicolas PJ, Adachi JD, Bhandari M.
   American Academy of Orthopedic Surgeons’ (AAOS) Annual Meeting
   San Francisco, California. February 7-11, 2012

8. A Novel Process for Anatomic Measurement of the Proximal Ulna to Guide Prosthesis Design
   Pereira I, **Alolabi B**, Gray A, Athwal GS, Johnson JA, King GJW
   Canadian Arthritis Network Annual Scientific Conference
   Quebec City, Quebec. October 27-29, 2011

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   Alolabi N, Alolabi B, Mundi R, Karanicolas PJ, Adachi JD, Bhandari M.
   Orthopedic Trauma Association’s (OTA) 27th Annual Meeting
    The Canadian Orthopedic Association’s (COA) 66th Annual Meeting
    St. John’s, Newfoundland. July 7-9, 2011
11. Reconstruction of the Coronoid Using an Anatomic and Extended Prosthesis: An In-Vitro Biomechanical Study
    Alolabi B, Gray A, Ferreira LM, Johnson JA, Athwal GS, King GJW.
    Lawson Health Research Institute Research Day
    Alolabi B, Shirali J, Bajammal SS, Karanicolas PJ, Zlowodzki M, Gafni A, Bhandari M
    11th Internarnional Society for Fracture Repair (ISFR) Conference
    Alolabi B, Shirali J, Bajammal SS, Karanicolas PJ, Zlowodzki M, Gafni A, Bhandari M
    9th Congress of the European Federation of National Associations of Orthopaedics and Traumatology (EFFORT)
    Nice, France. May 29 - June 1, 2008
    Alolabi B, Bajammal SS, Shirali J, Karanicolas PJ, Gafni A, Bhandari M.
    International Society for Pharmacoeconomics and Outcome Research (ISPOR)
    13th Annual International Meeting
    Toronto, Ontario. May 4-7, 2008
15. The Use of Calcium Phosphate Bone Cement in Fracture Treatment: A Meta-Analysis.
    Alolabi B, Bajammal S, Schmitz-Lelwica A, Bhandari M.
    The Canadian Orthopedic Association’s (COA) 61st General Annual Meeting
    Toronto, Ontario. June 2-4, 2006

MEDICAL EXAMINATIONS AND CERTIFICATES

2. The Royal College of Surgeons of Canada, Orthopedic Examination: 2012
3. OTA Advanced Trauma Techniques, OTA: 2011
4. Principles of Surgery Examination, Royal College of Surgeons of Canada: 2009
7. Medical Council of Canada Qualifying Examination – Part Two: 2008
10. Advanced Cardiac Life Support Certification, American Heart Association: 2007

PROFESSIONAL ASSOCIATIONS

1. Orthopedic Trauma Association, Candidate Member, 2014-Present
2. Fellow of the Royal College of Surgeons of Canada, 2012-Present.

HONOURS & AWARDS

1. Canadian Millennium Scholarship x 3 years
   School of Medicine, McMaster University. 2004-2007.
2. University of Toronto Scholar x 3 years – Awarded to top 0.1% of students
   Faculty of Arts and Science, University of Toronto. 2001-2004.
3. Dean’s List x 3 years (Top 5%)
   University of Toronto. 2002-2004.
4. The Victoria College Faculty Award (top 1%)
   Faculty of Arts and Science, University of Toronto. 2003.
5. Professor R. K. Arnold In-course Scholarship (top 1%)
   Faculty of Arts and Science, University of Toronto. 2002.
6. The George and Elizabeth Rutherford Admission Scholarship (top 1%)
   Faculty of Arts and Science, University of Toronto. 2001.
7. Governor General’s Medallion – Awarded to the top graduating student

ADMINISTRATIVE & LEADERSHIP POSITIONS

1. Chief Fellow: Sunnybrook Health Care Centre,
   University of Toronto. 2013 – 2014
2. Kids In Developing Societies (KIDS): Co-Founder, Founding President & Director
3. McMaster University Medical Journal (MUMJ): Medical Education Section Editor
   School of Medicine, McMaster University. 2005 – 2007.
4. Medical Student Selection and Interview Committee
   School of Medicine, McMaster University. 2006 – 2007.
5. Medical Student Leadership Training Forum
   Schumacher Institute, Leamington, Ontario. 2006.