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A biomechanical comparison of a subacromial balloon spacer, superior capsular reconstruction, and a rigid subacromial spacer in a massive irreparable rotator cuff cadaveric model

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Abstract

Massive irreparable rotator cuff tears are a common cause of pain and disability. Several different treatments exist; however, they are associated with poor clinical outcomes and survivorship in younger patients without glenohumeral arthritis. The purpose of this thesis was to compare the impact of a subacromial balloon spacer, superior capsular reconstruction, and a rigid subacromial implant on the glenohumeral kinematics and mechanical efficiency of a massive rotator cuff deficient shoulder. The results indicate that each surgical state improves the glenohumeral kinematics of a massive irreparable rotator cuff tear. The subacromial implant leads to mild overcorrection of humeral head translation. No surgical state achieves the mechanical efficiency of the intact shoulder, except for the superior capsular reconstruction at 0-degrees and the subacromial implants at 60-degrees abduction. Each surgical state appears to correct the biomechanical abnormalities of rotator cuff deficiency, each with their own unique limitations.

Keywords

Massive irreparable rotator cuff tear, cadaver shoulder, superior capsule reconstruction, subacromial balloon, subacromial implant, glenohumeral kinematics, functional abduction force

Summary for Lay Audience

The shoulder is a complex joint in the human body. With a spherical humeral head and a shallow glenoid, it is also inherently unstable. It relies on muscles, ligaments, and joint capsule for stability. The rotator cuff is an important group of muscles that are critical to shoulder motion and stability. Disruption of the rotator cuff can lead to pain and loss of shoulder function. Tears of more than 5cm or those that involve 2 or more tendons are considered massive and can often be irreparable. Chronic loss of rotator cuff function can lead to progressive shoulder arthritis and worsened shoulder function.

The standard of care for older patients (>65 years) with massive irreparable rotator cuff tears is a reverse shoulder replacement. However, when used in younger patients (<65 years) the clinical outcomes are worse with an increased need for reoperation. Therefore, several surgical options have been developed to treat this patient population. Common surgical procedures include the subacromial balloon spacer and the superior capsular reconstruction. There is currently no preferred surgical treatment. Recently, a metallic subacromial implant was developed which aims to improve upon the deficiencies of the subacromial balloon spacer and the superior capsular reconstruction.

The aim of this thesis was to perform a biomechanical comparison of the subacromial balloon spacer, the superior capsular reconstruction, and the metallic subacromial implant in a massive irreparable rotator cuff deficient cadaver model. Testing compared the normal intact shoulder to a massive irreparable rotator cuff tear, subacromial balloon spacer, superior capsular reconstruction, and two iterations of the subacromial implant.

Results indicate that each surgical treatment improves the stability of the humeral head compared to the massive irreparable rotator cuff tear state. The test states were unable to reproduce the mechanical efficiency of the intact shoulder, however the superior capsular reconstruction and the subacromial implants were able to improve upon the mechanical efficiency of the shoulder at 0-degrees and 60-degrees abduction, respectively. Each surgical treatment could be a viable treatment option; however, clinical studies are required.

Co-Authorship Statement

Chapter 1: DP Ferguson – Sole Author

Chapter 2: DP Ferguson – Study design, specimen preparation, implant evaluation, data collection, statistical analysis, wrote manuscript

CT Fleet – Study design, implant evaluation, data collection, statistical analysis

GS Athwal – Study design, reviewed manuscript

JA Johnson – Study design, reviewed manuscript

Chapter 3: DP Ferguson – Study design, specimen preparation, implant evaluation, data collection, statistical analysis, wrote manuscript

CT Fleet – Study design, implant evaluation, data collection, statistical analysis

GS Athwal – Study design, reviewed manuscript

JA Johnson – Study design, reviewed manuscript

Chapter 4: DP Ferguson – Sole author

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Chapter 1

This chapter is an introduction to the shoulder joint. Initial emphasis will be placed on the osteology and articulations that make up the shoulder girdle. Focus will then be turned to the glenohumeral joint, as this is the joint of interest for this thesis. The stability of the shoulder joint will be discussed including the complex relationship with the surrounding soft tissue structures. Following this, the rotator cuff and the pathological process of rotator cuff tears will be discussed. The classification and treatment of rotator cuff tears will then be introduced. Furthermore, emphasis will be placed on massive irreparable rotator cuff tears and their impact on shoulder function, stability, and degeneration. Several treatment options for massive irreparable rotator cuff tears will be introduced. Lastly, a novel subacromial implant will be briefly discussed. This will provide context for the rationale of the thesis which is a biomechanical comparison of surgical treatments for massive irreparable rotator cuff tears. Each objective will be discussed in detail.

1 Introduction to the shoulder

The glenohumeral joint is one of the most freely mobile joints in the body. Comprised of the articulations between the humeral head and the shallow glenoid fossa of the scapula, as such, the glenohumeral joint sacrifices stability for freedom of mobility. The glenohumeral joint relies on a series of ligaments, muscles, and other forces to maintain stability. The planes of motion of the shoulder include flexion, extension, adduction, abduction, internal and external rotation, and circumduction (Figure 1-1). Each position is critical to the function of the arm as a whole and provides patients with the ability to perform vital activities of daily living.

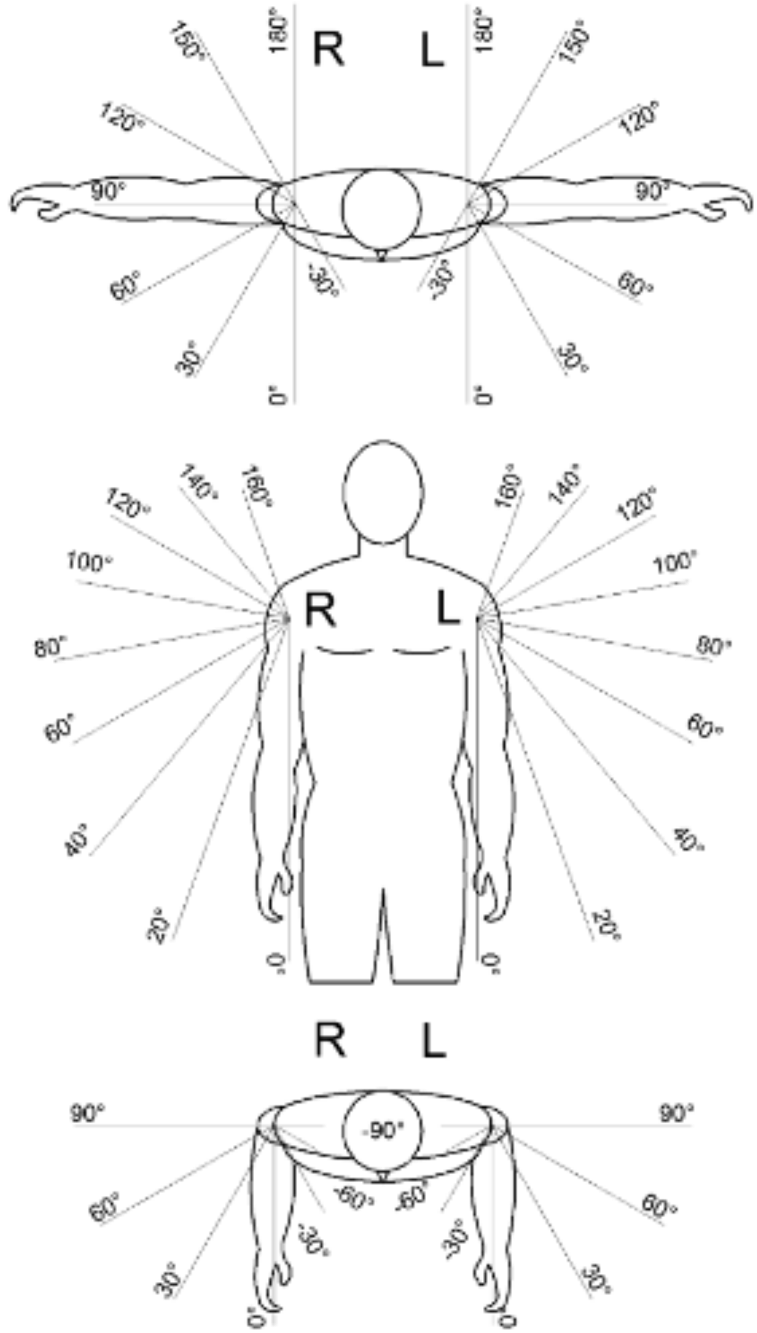

Figure 1-1: Planes of motion of the shoulder joint

The top image illustrates the different planes of arm elevation with 90 degrees representing abduction, 0 degrees representing forward elevation, and 180 degrees representing extension. The middle image shows abduction range of motion. The bottom image demonstrates humeral internal and external rotation.

1.1 Osteology

The shoulder is made up of the shoulder girdle, the humerus, and their respective articulations. The shoulder girdle is responsible for suspending the arm from the axial skeleton. It consists of the clavicle anteriorly and the scapula posteriorly.

1.1.1 Clavicle

The clavicle is an S-shaped bone that connects the shoulder girdle and the arm to the axial skeleton via the sternoclavicular joint. It is relatively circular in cross-section medially, and towards its mid-section, but becomes flat as it approaches its lateral articulation with the acromion. Ligamentous attachments include the costoclavicular ligaments as well as the coracoclavicular ligaments. The trapezoid ligament is the lateral coracoclavicular ligament, and the conoid ligament is the medial coracoclavicular ligament, extending from 25mm to 45mm medial to the acromioclavicular joint respectively. The deltoid, sternocleidomastoid, pectoralis major, and sternohyoid muscles all take origin from the clavicle, whereas the trapezius and subclavius insert on the clavicle.[53]

1.1.2 Scapula

The scapula (Figure 1-2) is a triangular shaped bone that is very thin except for the bony processes and the attachment sites for many muscles, including the superior angle, the inferior angle, and the lateral border. Four bony processes exist on the scapula. The scapular spine is a posterior based structure and is responsible for suspending the acromion in an anterior and lateral direction, as well as separating the supraspinous and infraspinous fossae of the scapular body. The scapular spine and acromion are attachment sites for the trapezius as well as the origin for the posterior and middle heads of the deltoid. The coracoid is an anterior and lateral projection from the superior portion of the glenoid. It is the origin of the coracoacromial, coracohumeral, and coracoclavicular ligaments. The pectoralis minor inserts on the medial coracoid. The coracobrachialis and short head of the biceps, also known as the conjoint tendon, originate on the coracoid tip. Lastly, the glenoid fossa is a laterally based projection from the lateral border of the scapular body. It serves as the scapular portion of the glenohumeral articulation. Its surface is covered in articular cartilage and its borders are the attachment site for the labrum, capsule, and many ligamentous structures. Other muscles that originate from the scapula include the rotator cuff musculature (supraspinatus, infraspinatus, subscapularis, and teres minor), long head of the biceps, long head of the triceps, omohyoid, and teres major. Inserting on the scapula are the scapulothoracic muscles: rhomboid major and minor, trapezius, serratus anterior, pectoralis minor, and the levator scapulae.[53]

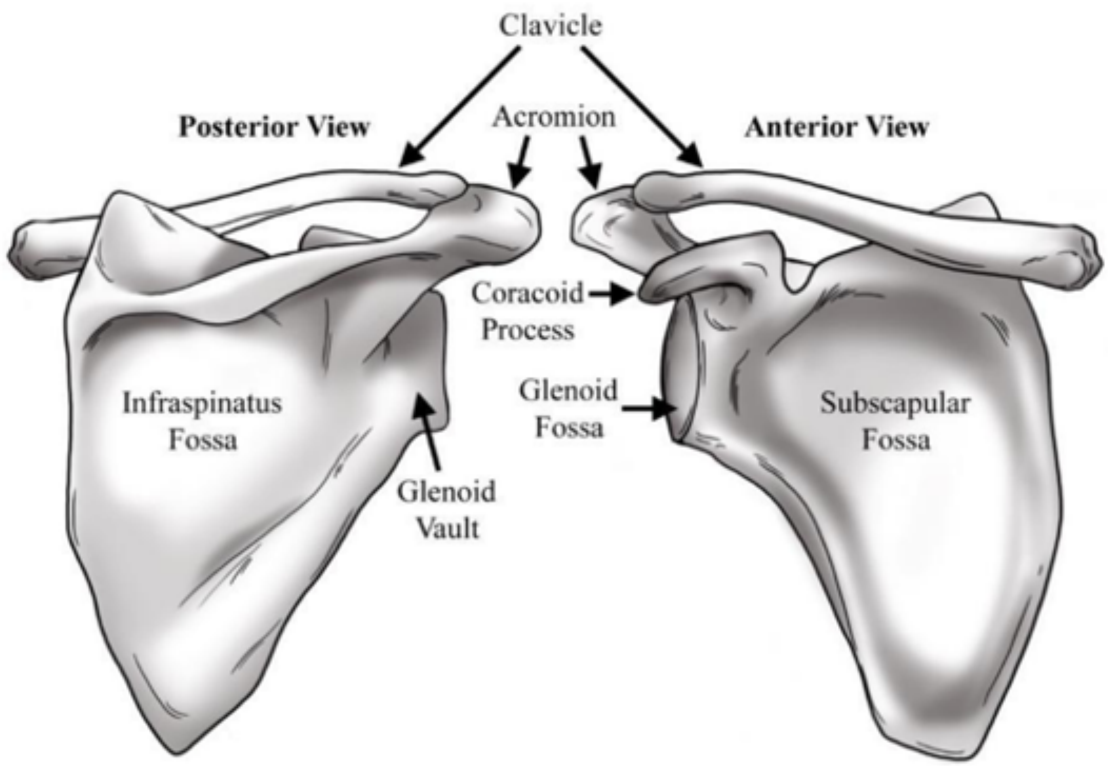

Figure 1-2: Anterior (right) and posterior (left) views of the scapula

The scapula and clavicle are visualized. The acromioclavicular joint is comprised of the clavicle's lateral connection with the acromion. Several important bony landmarks are identified.

1.1.3 Humerus

The humerus (Figure 1-3) is a long bone of the upper appendicular skeleton. Proximally, the humerus has a spherical head covered in articular cartilage that forms the glenohumeral joint with the glenoid fossa of the scapula. The anatomic neck is the location of capsular and ligamentous attachment and separates the articular surface from the tendon attachment sites of the rotator cuff. The lesser tuberosity is located anterior and distal to the articular surface. It serves as the attachment of the subscapularis muscle. The greater tuberosity is located superior and lateral to the lesser tuberosity and serves as the attachment of the supraspinatus, infraspinatus, and teres minor muscles. The intertubercular groove runs between the two tuberosities and houses the tendon of the long head of the biceps. The surgical neck is an area distal to the rotator cuff attachments where the humerus narrows in diameter. The distal extension of the intertubercular groove serves as attachment for other muscles of the shoulder joint. The medial lip is the insertion site for the latissimus dorsi and teres major, while the pectoralis major inserts on the lateral lip. The deltoid tuberosity is a prominence on the lateral humeral shaft and serves as the attachment of the deltoid muscle. Conversely, the coracobrachialis inserts medially. Distally, the humerus terminates in a trochleoginglymoid joint (elbow), articulating with the ulna and radius of the forearm. For the purposes of this thesis, the focus will be on the proximal humeral anatomy as it pertains to the glenohumeral joint.[53]

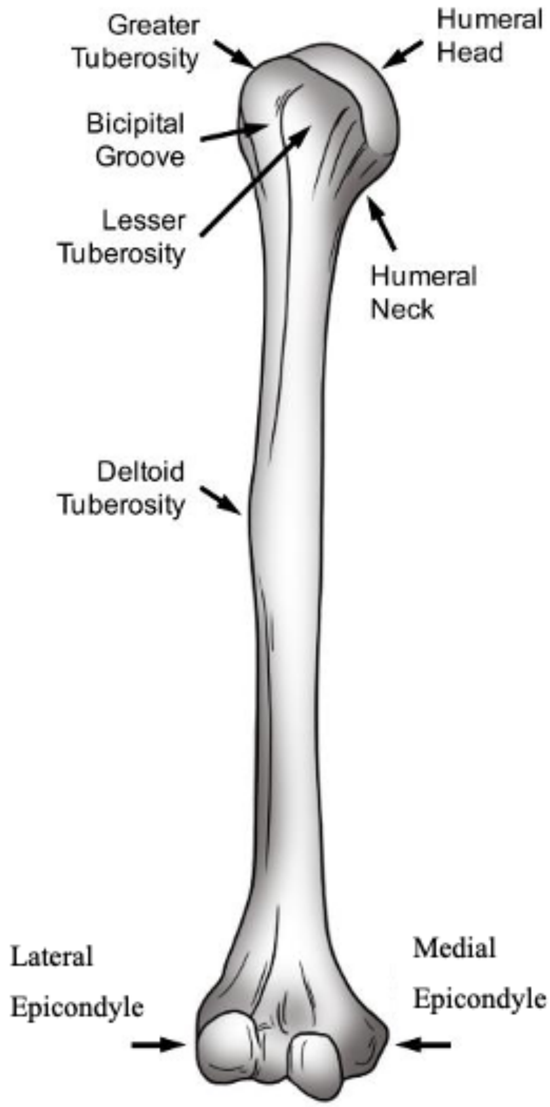

Figure 1-3: Anterior view of the humerus osteology

Important bony landmarks for soft-tissue attachment are labelled on the humerus

1.2 Articulations

There are three bony diarthrodial articulations near the shoulder: the sternoclavicular joint, acromioclavicular joint, and glenohumeral joint. The scapulothoracic joint is referred to as a physiological joint as there are no true bony articulations (Figure 1-4).

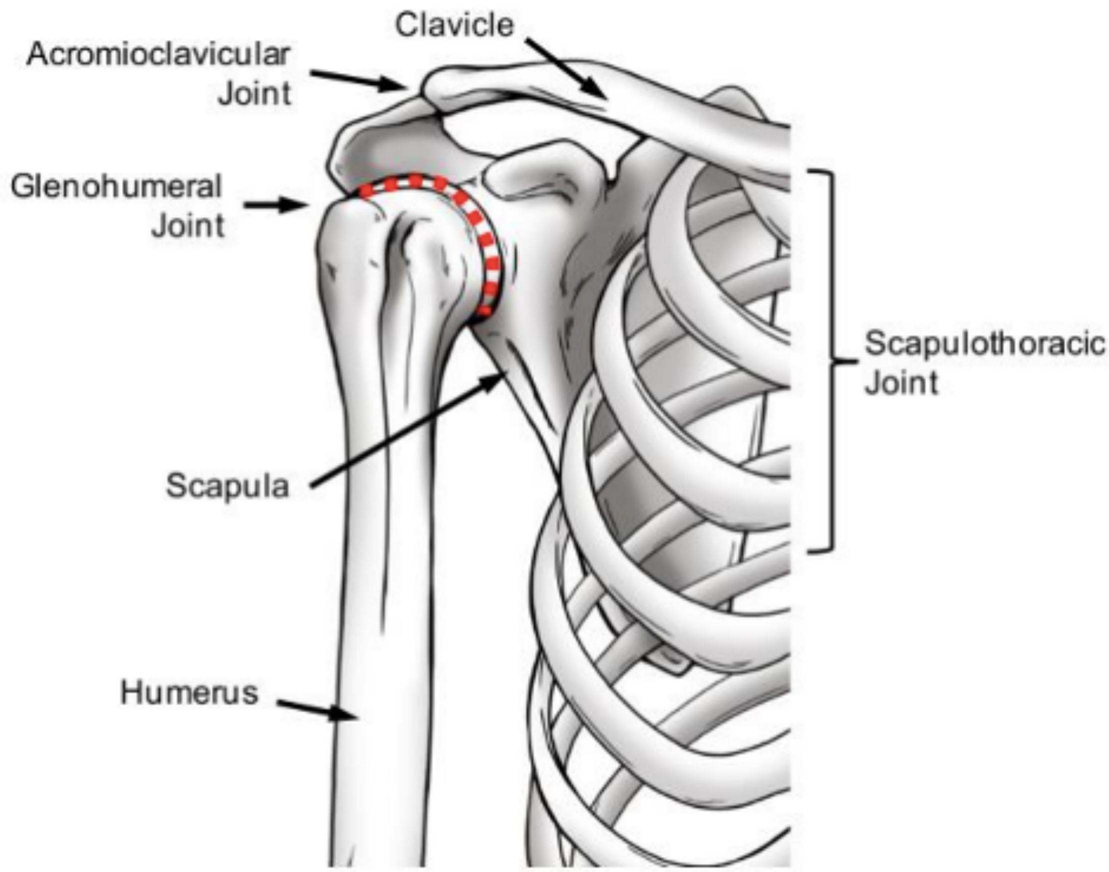

Figure 1-4: Articulations of the shoulder girdle

Anterior view of the shoulder girdle demonstrating the articulations. Glenohumeral joint is represented by the dashed red line. Acromioclavicular and scapulothoracic joints are visualized. The sternoclavicular joint is not shown.

1.2.1 Sternoclavicular joint

The only true bony articulation between the shoulder girdle and the axial skeleton is the sternoclavicular joint. It is composed of the medial end of the clavicle, the sternum, and an intra-articular disc that is like the meniscus in the knee. The medial end of the clavicle is slightly superior and posterior to the sternum, allowing for a sternal notch between the two ends of each clavicle. There is relatively little bony stability to this joint with the ligamentous structures providing the bulk of the stability. The main ligaments are the anterior and posterior sternoclavicular ligaments with the posterior sternoclavicular ligament being the strongest. These ligaments, with help from the interclavicular ligament, prevent rotation through the sternoclavicular joint during clavicular depression. The costoclavicular ligaments run from the first rib to the inferior surface of the clavicle, anterior and posterior fibers prevent lateral and medial translation of the clavicle on the thoracic cage respectively. Range of motion includes elevation, depression, anterior translation, posterior translation, and rotation. Elevation and depression occur between the clavicle and the intra-articular disc and averages 30-35 degrees. Anterior and posterior translation is roughly 35 degrees, and the rotation is roughly 45 degrees. These movements occur between the intra-articular disc and the sternum. Sternoclavicular elevation occurs during arm elevation from 30-90 degrees. Rotation occurs after 70-80 degrees of arm elevation.[53,104]

1.2.2 Acromioclavicular joint

The acromioclavicular joint is the articulation between the lateral end of the clavicle and the medial aspect of the acromion of the scapula. Like the sternoclavicular joint, there is an intra-articular disc, however it is generally incomplete with a central perforation. Vertical stability of the acromioclavicular joint is secondary to the coracoclavicular ligaments (trapezoid and conoid) between the coracoid process and the inferior surface of the lateral clavicle. Horizontal stability of the acromioclavicular joint is secondary to the acromioclavicular ligaments that consists of superior, anterior, posterior, and inferior fibers. The superior fibers are the thickest and strongest fibers, blending with the deltoid and trapezial muscles. It is estimated that roughly 20 degrees of internal and external rotation can occur through the acromioclavicular joint, generally within the first 20 degrees or final 40 degrees of arm elevation.[53,104]

1.2.3 Glenohumeral joint

The glenohumeral joint is the main articulation in the shoulder. It consists of a shallow glenoid fossa of the scapula and a spherical humeral head. The glenoid fossa is oriented in a near perpendicular fashion to the scapular body, and takes the shape of a pear, being wider inferiorly than it is superiorly. The shoulder is an inherently unstable joint as it relies on both static and dynamic stabilizers to keep the humeral head centered throughout range of motion. At any given time, only 20-30% of the humeral head is in contact with the glenoid articular cartilage. However, the glenoid fossa is deepened through a circumferential fibrocartilaginous ring called the labrum. Together, with the capsuloligamentous complex and the surrounding muscles, the glenohumeral joint is stabilized. Planes of motion include flexion-extension, adduction-abduction, internal-external rotation, and circumduction.[53,104]

1.2.4 Scapulothoracic joint

Conversely, the scapulothoracic joint is a physiological joint due to muscular connections between the concave undersurface of the scapula and the convex posterior rib cage. This space is occupied by muscular, neurovascular, and bursal structures allowing smooth gliding motion. Seventeen muscles attach to or originate from the scapula. The serratus anterior maintains the position of the medial scapular border against the posterior thorax, while the trapezius helps synchronize scapular elevation and rotation during glenohumeral motion.[104]

The scapulothoracic articulation works in concert with the glenohumeral joint to allow motion beyond 120 degrees of elevation. This was first described by Inman et al.[50] as scapulohumeral rhythm. Although, likely variable, it is traditionally accepted that the glenohumeral and scapulothoracic articulations contribute to glenohumeral motion in a 2:1 ratio.

1.3 Stability of the glenohumeral joint

As mentioned, the glenohumeral joint is inherently unstable. Two groups of stabilizing structures maintain joint congruence and humeral head centering throughout motion (Figure 1-5). The static stabilizing structures include: the articular surface, labrum, joint capsule, and ligaments. The dynamic stabilizing structures include the rotator cuff muscles and the biceps tendon.[104]

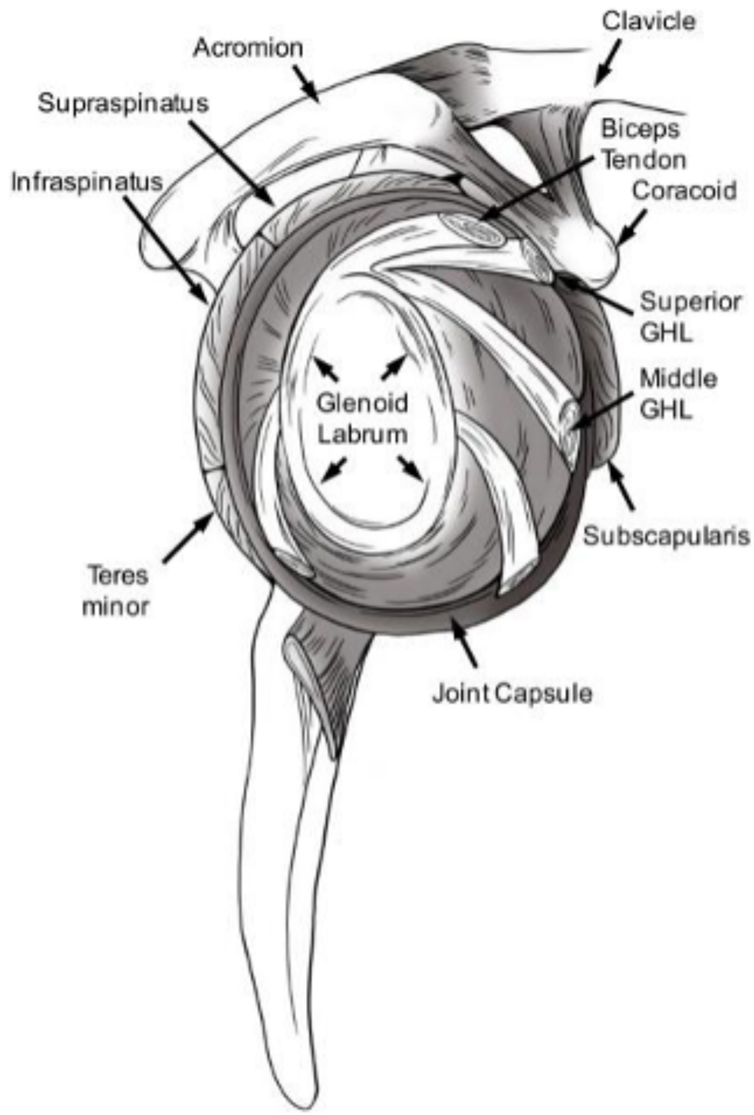

Figure 1-5: Lateral view of a right glenoid with the associated soft tissue

This image demonstrates the associated static and dynamic soft tissue stabilizing structures of the glenohumeral joint. The labrum is continuous with the peripheral margins of the glenoid. The joint capsule is intimately connected to the glenohumeral ligaments.

1.3.1 Static stabilizers

The articular surfaces of the glenoid is flatter than that of the humeral head, however, the articular cartilage is thicker at the peripheral margins, giving a natural concavity to a relatively flat surface. This improves the conformity with the spherical humeral head. Additionally, the joint capsule typically contains less than 1 milliliter of synovial fluid with relative negative intra-articular pressure. This creates a suction effect to prevent humeral head translation, as adhesion and cohesion forces try to prevent movement between the humeral head and glenoid fossa. The labrum is a circumferential fibrocartilaginous ring that is attached to the glenoid peripheral margins. It acts to deepen the glenoid fossa as well as increase the conformity of the articular surfaces and act as an attachment point for capsuloligamentous structures. The joint capsule and glenohumeral ligaments are anatomically separate structures, however, they are intimately connected in the human shoulder. Together, they prevent extremes of motion, as the capsuloligamentous structures tighten in various positions to prevent subluxations and dislocations of the humeral head on the glenoid fossa. The coracohumeral ligament runs from the base of the lateral coracoid to the lesser and greater tuberosities and is tight in adduction and external rotation. The superior glenohumeral ligament travels from the anterosuperior glenoid to the upper portion of the lesser tuberosity. Together, these structures constitute the rotator interval region between the supraspinatus and subscapularis tendons. The middle glenohumeral ligament originates from the supraglenoid tubercle, superior glenoid, or scapular neck and attaches to the medial lesser tuberosity. The inferior glenohumeral ligament has three sections: the anterior band, middle band (axillary pouch), and posterior band. Each of these attaches to the medial surgical neck while originating from the anteroinferior, inferior, and posteroinferior labrum, respectively.[104]

1.3.2 Dynamic stabilizers

The rotator cuff muscles include the supraspinatus, infraspinatus, teres minor, and subscapularis (Figure 1-6). Contraction of the rotator cuff musculature increases glenohumeral joint stability through the concavity-compression phenomenon. Appropriate neuromuscular control and co-contraction of the rotator cuff through the force-couple mechanism maintains the humeral head in a central position on the glenoid fossa while preventing excessive humeral head translation in various arm positions (Figure 1-7). These two mechanisms allow the glenohumeral joint to work as an effective fulcrum for the larger periscapular muscle groups to move the arm in space. Asymmetric contraction of the rotator cuff allows for rotational movements of the humeral head on the glenoid fossa, otherwise known as internal and external rotation.

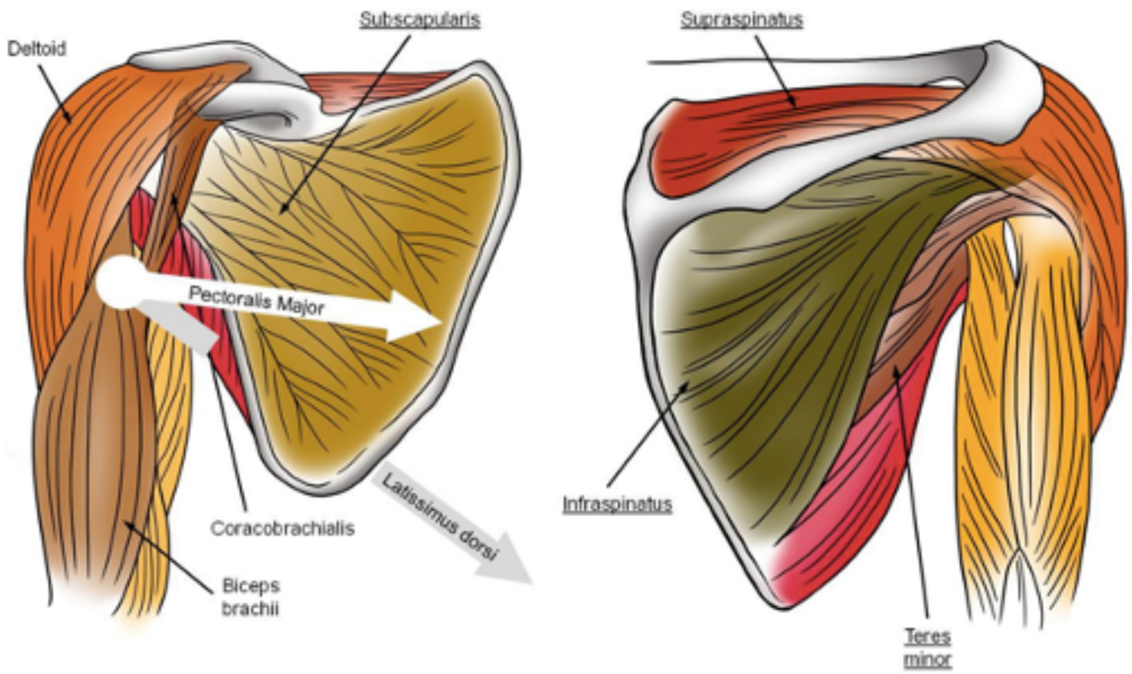

Figure 1-6: Anterior (left) and posterior (right) views of shoulder musculature

The various surrounding musculature is colour coded and labelled for ease of interpretation. The pectoralis and latissimus dorsi muscles are not visualized, however, their line of action is shown.

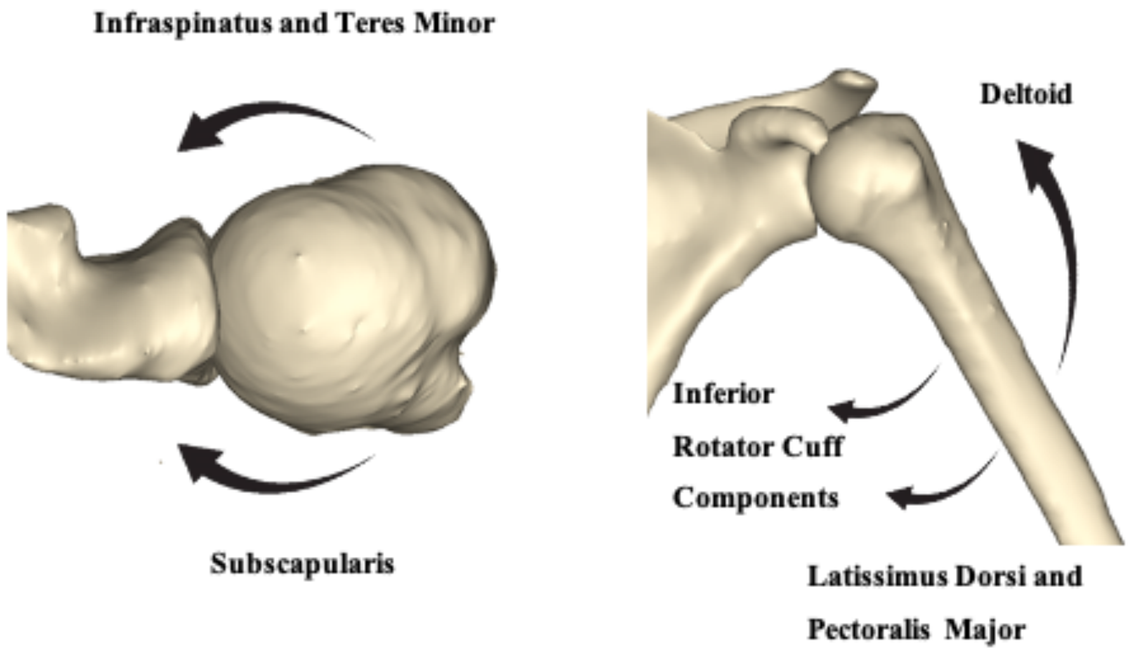

Figure 1-7: Glenohumeral force-couples

The force-couple mechanism of a left shoulder is shown above. The left image represents the transverse force-couple comprised of the anterior rotator cuff (subscapularis) and posterior cuff (infraspinatus and teres minor). The right image represents the coronal force-couple comprised of the deltoid, latissimus dorsi, pectoralis major, and inferior components of the rotator cuff.

The supraspinatus originates from the supraspinous fossa of the scapula and inserts on the superolateral greater tuberosity. Its functions are to compress glenohumeral joint, counteract the proximal pull of the deltoid, work with the deltoid to abduct the shoulder, as well as provide a small amount of assistance in rotation.[26] At low angles of scaption, the supraspinatus is a humeral head depressor, preventing superior humeral head migration during deltoid activation.[2] Contribution to glenohumeral scaption peaks around 30-60 degrees, following this, relative contributions decrease at higher angles of abduction due to a decreasing supraspinatus moment arm.[2,48,89] Additionally, the supraspinatus provides a minor contribution to rotation of the glenohumeral joint. Specifically, the anterior portion provides mild internal rotation at 0 degrees abduction, no rotation at 30 degrees abduction, and mild external rotation beyond 60 degrees abduction, whereas the posterior supraspinatus is primarily a weak external rotator throughout glenohumeral motion.[89]

The infraspinatus and teres minor work together as the posterior rotator cuff. The infraspinatus originates from the infraspinous fossa of the scapula and inserts on the middle portion of the greater tuberosity. The teres minor originates from the superolateral border of the scapular body and inserts on the inferior portion of the greater tuberosity. Similar to the remaining rotator cuff, the infraspinatus and teres minor provide glenohumeral compression as well as balancing the anterior-posterior force couple with the subscapularis. Additionally, the posterior rotator cuff will provide external rotation of the humeral head, a movement that is critical for clearing the greater tuberosity from underneath the coracoacromial arch during overhead movements.[94] Both the infraspinatus and teres minor work in concert to provide the glenohumeral joint with external rotation. The infraspinatus is most effective at low angles of abduction due to its moment arm, an effect that decreases with increasing abduction.[89] Conversely, the teres minor moment arm remains constant throughout abduction and contributes to external rotation in all positions.[89] At low angles of abduction, the infraspinatus primarily prevents superior and anterior humeral head translation. However, as abduction angle increases, the infraspinatus does contribute to glenohumeral abduction.[67,89,94] This effect is not seen with the teres minor, as it has inferior origin and insertion sites. Instead, the teres minor provides a net adduction force, increasing glenohumeral compression and preventing excessive superior humeral head translation.[48,67,89,94]

The subscapularis originates on the subscapular fossa of the scapula. It inserts on the lesser tuberosity. Its line of pull is medial and inferior to the center of rotation of the humeral head. Its primary function is glenohumeral stability through the concavity-compression and force-coupling mechanisms. Functionally, the subscapularis is an internal rotator. The ability to internally rotate the humeral head is greatest at zero degrees of abduction and decreases with increasing amounts of abduction due to a diminishing moment arm.[89] Although minimal, the subscapularis will also contribute to glenohumeral scaption. The contribution of the subscapularis is mitigated with internal rotation of the arm and enhanced with external rotation of the arm.[67,89]

Lastly, the long head of the biceps tendon acts as a sling in various arm positions as well as a humeral head depressor. Its intimate relationship with the superior labrum provides improved glenohumeral stability.[104]

1.3.3 Other relevant musculature

As mentioned previously, numerous muscles cross the glenohumeral joint and act on the shoulder girdle. However, the deltoid muscle is particularly relevant for glenohumeral motion. It has anterior, middle, and posterior heads that originate on the lateral clavicle, acromion, and scapular spine, respectively. They converge into a single tendon that inserts on the deltoid tuberosity of the humerus. Together, they are critical to glenohumeral motion as they are responsible for forward elevation, abduction, extension, and possibly external rotation of the shoulder.[104] At zero degrees of scaption the moment arms for the anterior and middle deltoid are 0cm and 1.4cm, respectively.[67,89] This increases to 1.5-2cm and 2.7-3.2cm at 60 degrees of abduction. In low angles of abduction (0-40 degrees), the moment arms for the supraspinatus, infraspinatus, and subscapularis are larger than that of the anterior and middle deltoid.[67,89] This implies that the anterior and middle deltoids are not effective glenohumeral abductors at low angles of abduction, a claim that has been supported by electromyography studies showing peak activity of the deltoid between 60-90 degrees of glenohumeral scaption, whereas the rotator cuff activity peaks around 30-60 degrees of glenohumeral scaption.[2] The posterior deltoid is not an effective abductor, in fact, its line of pull contributes more to scapular plane adduction. This effect decreases with increasing glenohumeral abduction, and the posterior deltoid has been shown to contribute to abduction beyond 110 degrees.[2,67,89]

1.4 Rotator cuff disease

Shoulder pain is a major cause of disability in society leading to loss of productivity and work hours. Rotator cuff pathology, ranging from tendinosis to tears, is one of the most common reasons for referral to an orthopaedic surgeon.[108] Rotator cuff tears (Figure 1-8) can be described in a variety of ways, including acute or chronic, partial or full-thickness, symptomatic or asymptomatic, and traumatic or degenerative. Epidemiologic studies have demonstrated the burden of shoulder pathology in our society, with nearly 25% of patients over the age of 60, and more than 50% of patients over the age of 80 having rotator cuff tears.[96,103,110] With this degree of involvement in our population, the prevention of rotator cuff tears as well as the appropriate diagnosis and management of known tears has rightfully been in the spotlight of orthopaedic literature.

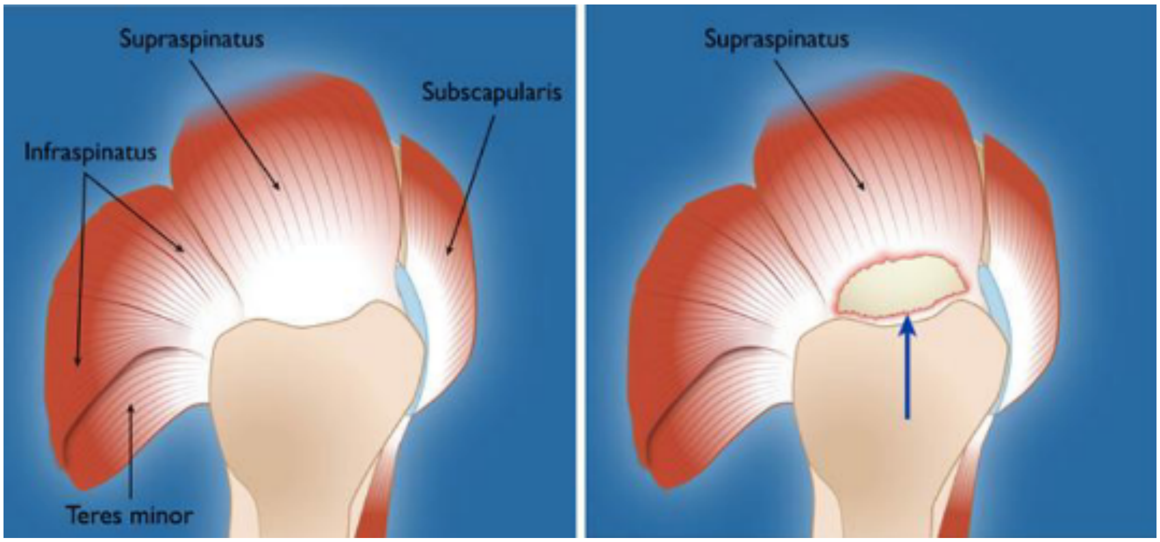

Figure 1-8: Intact (left) and torn (right) rotator cuff tendons in the right shoulder[3]

Two images of the right rotator cuff demonstrating an intact rotator cuff and a common insertional tear with retraction of the supraspinatus tendon.

1.4.1 Pathophysiology

Rotator cuff degeneration is very common. The causative factors have traditionally been subdivided into intrinsic and extrinsic mechanisms.[86] Intrinsic factors represent the underlying pathologic processes that occur within the tendon leading to its degeneration. These include degeneration-microtrauma synergy, cuff vascularity, and the neural theory of tendinopathy.[86] Rotator cuff tendinopathy and degeneration appears to be characterized by loss of cellularity, vascularity, and tissue architecture, as well as development of a fibrocartilaginous mass within the tendon itself. This leads to a mechanically inferior tendon, that when exposed to repetitive microtraumas and mechanical loading may develop several small tears that could coalesce into a full-thickness tear.[86] The concept of a critical zone of hypovascularity is controversial, however, there may be an area 10-15mm proximal to the insertion of supraspinatus that could predispose a patient to rotator cuff tears.[69] The neural theory of tendinopathy proposes that neural over-stimulation in response to overuse of the rotator cuff tendon can lead to recruitment of inflammatory cells, causing symptoms associated with tendinopathy and architectural changes within the tendon leading to structural weakness.[41]

Conversely, the extrinsic processes represent the patient's anatomic and individual variables that interact over time that may predispose the rotator cuff to long-term damage.[86] Subacromial impingement, acromial shape, and patient demographics are common causes of extrinsic compression of the rotator cuff tendon. Bigliani et al.[6] demonstrated the morphology of the acromion varied in its sagittal plane when investigating cadavers with full-thickness rotator cuff tears (Figure 1-9). They classified these into three main categories: type I acromion (flat), type II acromion (curved), and type III acromion (hooked). The prevalence of rotator cuff tears increased with a curved or hooked acromion, 17% compared to 43% and 39%, respectively. Coronal plane variations have also been shown to be associated with rotator cuff tears.[70] However, there is still controversy as to whether acromion morphological changes are acquired or congenital. Common patient-related factors that have been postulated to increase the risk of rotator cuff tears include increasing age, over-use of affected extremity, overhead activity, pro-inflammatory medical conditions, and smoking.[86]

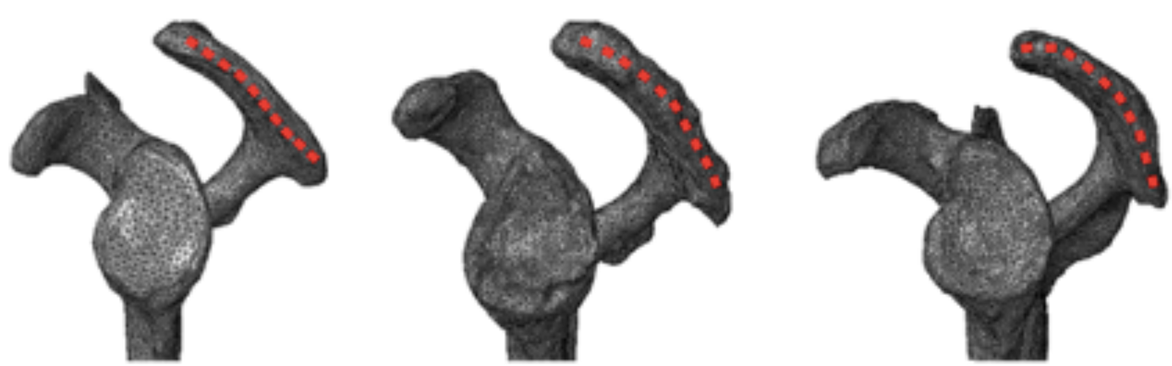

Figure 1-9: Variations in acromion morphology.[6] Adapted from Lockhart[68]

Left image demonstrates a type I acromion (flat). Middle image represents a type II acromion (curved). A type III acromion (hooked) is shown in the right image.

1.4.2 Natural history of rotator cuff disease

The natural history of rotator cuff disease and rotator cuff tears has been revealed through rigorous study, demonstrating a naturally progressive condition. Kim et al.[58] analyzed ultrasound data from 272 patients demonstrating that the area 13-17mm posterior to the biceps tendon was most frequently involved in full-thickness degenerative rotator cuff tears. This area corresponds to the mid-portion of the rotator cuff crescent tissue, as described by Burkhart.[10] It was postulated that degenerative tears likely develop in this region and then extend anteriorly and posteriorly as they enlarge. As tears progress, it has been shown that tendon retraction, muscle atrophy, and fatty infiltration of the muscle belly can occur. Kim et al.[59] demonstrated that tears extending into the anterior supraspinatus rotator cable were at a high risk of retraction and subsequent fatty infiltration of the supraspinatus, while large crescent tears and those extending into the infraspinatus footprint tend to cause infraspinatus and supraspinatus retraction and fatty infiltration. As mentioned above, the rotator cuff tendons are critical to the normal kinematics of the glenohumeral joint. With disruption of the rotator cuff tendons, proximal humeral migration will occur with de-centering of the humeral head on the glenoid fossa.[57] Symptomatic tears and those involving the infraspinatus are more likely to predispose to proximal humeral migration. The critical tear area for predisposition to proximal humeral migration was previously investigated and found to be 175mm^2.[57] Left untreated, this can progress and lead to pseudoarticulation between the superior humeral head and the undersurface of the acromion, intractable pain and dysfunction, and end-stage glenohumeral arthritis. This process is referred to as rotator cuff tear arthropathy (Figure 1-10).[22,71]

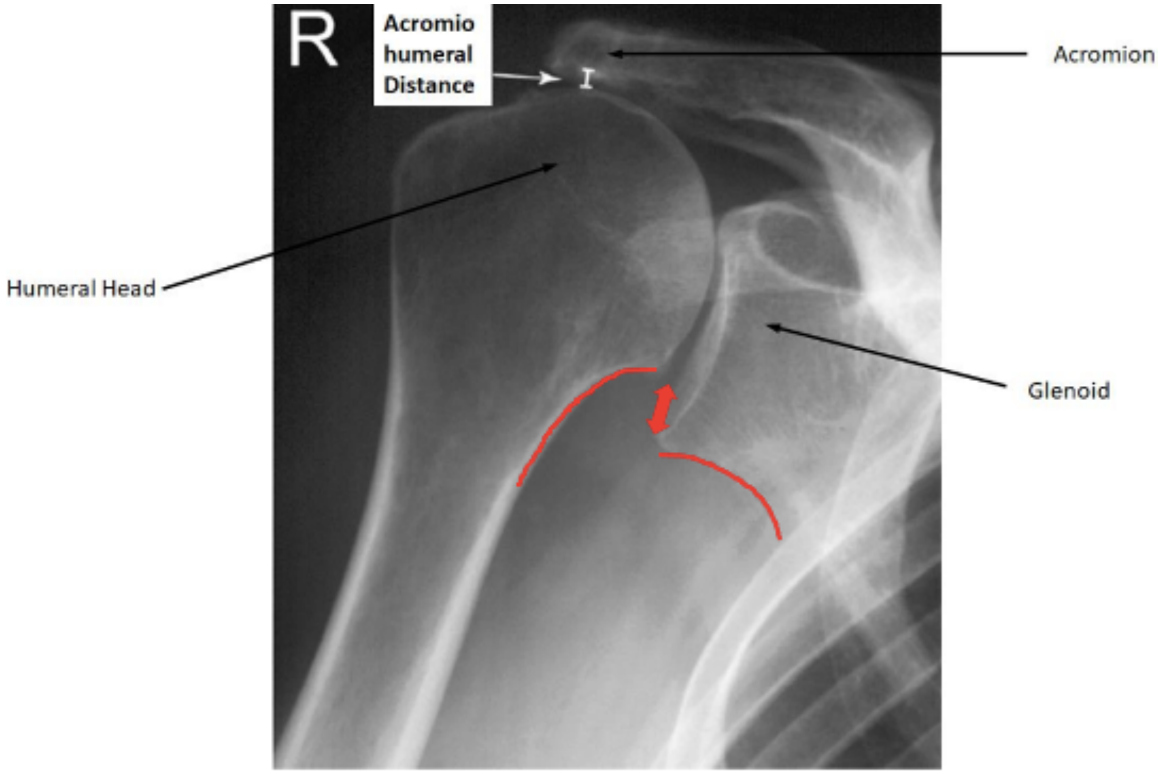

Figure 1-10: Radiographic superior migration of humeral head[98]

Radiograph of the right glenohumeral joint demonstrating proximal translation of the humeral head on the glenoid articular surface. The red lines and red arrow illustrate the change in humeral head position. Also pictured is a narrowed acromiohumeral distance with articulation of the humeral head with the undersurface of the acromion. These static changes are seen in chronic rotator cuff deficiency.

Keener et al.[56] performed a 5-year longitudinal study on asymptomatic full-thickness tears, partial-thickness tears, and control patients. Tear progression occurred in 49% of shoulders. Full-thickness tears were 1.5 times more likely, and 4 times more likely to progress than partial-thickness and control shoulders. Muscle degeneration occurred more frequently in full-thickness tears. Nearly half of patients developed pain in their shoulder. This was more common in those patients with tear progression.

The natural history of symptomatic rotator cuff tears is less clear. Many receive some form of treatment whether it be injection, physiotherapy, or surgical intervention. This confounds the natural progression. However, like asymptomatic tears, there is roughly a

50% probability that a rotator cuff tear will progress in size, with full-thickness tears progressing more commonly than partial-thickness tears.[72] Increasing age is a risk factor, with those patients over 60 years of age having a 54% risk of progression. Despite these results, the Multicenter Orthopaedic Outcomes Network (MOON) Shoulder Group has shown that satisfactory results can be achieved with non-operative therapy in those patients with full-thickness degenerative rotator cuff tears at two years.[65]

1.4.3 Classification of rotator cuff tears

Rotator cuff tears can be classified in a variety of ways, including time (acute vs. chronic), tendon(s) involved, size of the tear, shape of the tear, pathophysiology (degenerative vs. traumatic), presence or absence of symptoms, location (articular vs. bursal), and if it is full-thickness or partial-thickness. DeOrio and Cofield[20] initially classified the size of rotator cuff defects as <1cm (small), 1-3cm (medium), 3-5cm (large), and >5cm (massive). This classification, although widely used, has its limitations. Other authors have adopted tears that involve 2 or more tendons as being massive rotator cuff tears.[112]

With the advent of three-dimensional imaging, additional classifications for rotator cuff tears have been developed. Goutallier et al.[37] developed a CT classification system for the degree of fat infiltration into the muscle bellies of torn rotator cuff tendons. This progression was determined to represent the chronicity of the rotator cuff tendon tear. This classification system was as follows: Stage 0 = normal muscle, Stage I = some fatty streaks within the muscle belly, Stage II = significant fat infiltration, but more muscle than fat, Stage III = significant fat infiltration, equal muscle and fat, and Stage IV = more fat than muscle.[37]

1.4.4 Treatment of rotator cuff tears

The treatment of rotator cuff tears is complex. It can vary, depending on factors including age, activity level, medical co-morbidities, symptoms, and willingness to pursue treatment, to tear characteristics such as size, response to conservative treatment, chronicity, ability to be repaired, and time since injury. Generally, treatment can be divided into three categories: early operative repair, trial of initial conservative management, and those who would benefit from maximizing conservative therapy.[47]

Early operative repair has been advocated for those patients that have a distinct, acute event with imaging that corroborates an acute injury.[47]

Initial conservative therapy in the form of physical therapy, activity modification, subacromial corticosteroid injections, stretching, and strengthening can be employed for nearly all rotator cuff tears. Although there are risks of tear progression and symptom worsening, as mentioned above, the results of conservative therapy are generally favorable. Those patients that do not respond fully to conservative therapy can then be considered for surgical management, if indicated.[47]

Lastly, there are patients that require maximization of conservative therapy. These patients include the medically frail, large irreparable tears, tears with proximal migration of the humeral head, and patients where successful tendon healing is unlikely.[47]

The American Academy of Orthopaedic Surgeons (AAOS) released an updated clinical practice guideline in 2020[108] providing 33 recommendations to the practicing surgeon. Of note, there is moderate to strong evidence to support the following statements: 1) long-term nonsurgical management and surgery are effective treatments for small-to-medium full-thickness symptomatic rotator cuff tears, 2) healed rotator cuff tears following surgery show improvement upon unhealed repairs and those tears that are managed conservatively, 3) surgery provides a benefit for failed repairs, 4) corticosteroids injected into the subacromial space are effective for pain relief, 5) surgical management of high-grade partial-thickness rotator cuff tears is beneficial after exhausting conservative measures, and 6) there is no distinct difference in patient outcome of arthroscopic or open rotator cuff repair.[108]

1.5 Massive irreparable rotator cuff tears

As previously stated, massive rotator cuff tears include those >5cm in dimension or involving 2 or more tendons.[20,112] It is very difficult to determine the ability to repair these tears based on size or number of involved tendons alone. Many preoperative factors have been associated with low likelihood of successful repair. These include retraction of the torn tendon to the level of the glenoid, muscle atrophy on examination, severe fatty infiltration of supraspinatus or infraspinatus (Goutallier stage 3 or 4), a positive tangent sign, and fixed proximal migration of the humerus.[21,60] However, the gold standard for determining reparability is intraoperative assessment after debridement, mobilization, and attempted repair. In fact, previous studies determined that 85% of massive rotator cuff tears were reparable, but that only 57% of those with Goutallier stage 3 or 4 fatty infiltration of the supraspinatus were successfully repaired.[19,95] Unfortunately, massive rotator cuff tears that are successfully repaired still possess a high likelihood of subsequent re-tear, ranging from 25-94%.[30,61]

1.5.1 Changes in muscle activity due to massive irreparable rotator cuff tears

As previously mentioned, the primary role of the rotator cuff is to minimize humeral head translation on the glenoid surface during glenohumeral motion, whilst also contributing to glenohumeral motion in various planes. In the context of a massive irreparable rotator cuff tear this function is compromised. Electromyography (EMG) studies have compared muscle activity and coordination in control subjects to those with massive irreparable rotator cuff tears during glenohumeral elevation.[44] Overall, the degree of flexion, abduction, and external rotation achieved was substantially lower, indicating an inefficient system. Increased electromyography activity was noted within the muscle bellies of the torn rotator cuff muscles (subscapularis, supraspinatus, and infraspinatus) but also in all the periscapular muscles such as the trapezius, serratus anterior, latissimus dorsi, teres major, and deltoid.[44] In the rotator cuff deficient group, the latissimus dorsi and teres major muscles compensated for the lack of rotator cuff by exerting an inferiorly directed force in direct opposition of the deltoid muscle. Additionally, increased activity from upper trapezius and serratus anterior contributed to scapular elevation and rotation. This “shoulder shrug” movement is often seen in shoulder pathology and is thought reduce the elevation required from the glenohumeral joint.[44,52] Lastly, contributions from biceps brachii and brachioradialis were increased in the massive rotator cuff tear group, further limiting the amount of elevation required at the glenohumeral joint to position the hand in the overhead position. Overall, this demonstrates the importance of the rotator cuff in maintaining efficient movement of the glenohumeral joint.

1.5.2 Natural history of massive irreparable rotator cuff tears

The natural history of massive, irreparable rotator cuff tears is unclear. Alterations in the compressive force generated by the rotator cuff secondary to rotator cuff insufficiency can lead to instability and translation of the humeral head on the glenoid, ultimately resulting in joint degeneration.[22] The final result of this process is fixed proximal migration of the humeral head, articulation with the undersurface of the acromion, and degenerative changes of both the humeral head and glenoid. This is referred to as rotator cuff tear arthropathy (Figure 1-11).[51,85] Neer et al.[85] were the first to describe this phenomenon, hypothesizing that in the context of a massive irreparable tear of the rotator cuff there is disuse of the shoulder and increased glenohumeral instability. This leads to a painful inflammatory state with an effusion and leakage of synovial fluid through the capsular defects causing a nutritionally deplete state for the articular cartilage of the humeral head and glenoid. Eventually, the soft and atrophic humeral head collapses due to repetitive mechanical impingement on the undersurface of the acromion leading to irreversible degenerative changes of the joint.[85] Although, the exact progression of events is unclear, and not all patients progress from a massive rotator cuff tear to rotator cuff tear arthropathy, Collins and Harryman[14] hypothesized that a chronic degenerative rotator cuff tear begins in the supraspinatus leading to proximal migration of the humerus during arm elevation, impingement of the surrounding tissue, further tear propagation and damage to articular structures. This ultimately leads to cartilage fragmentation, synovial thickening, effusion, calcium crystal deposition, and an enzymatic response due to particulate debris causing further intra-articular damage.[14]

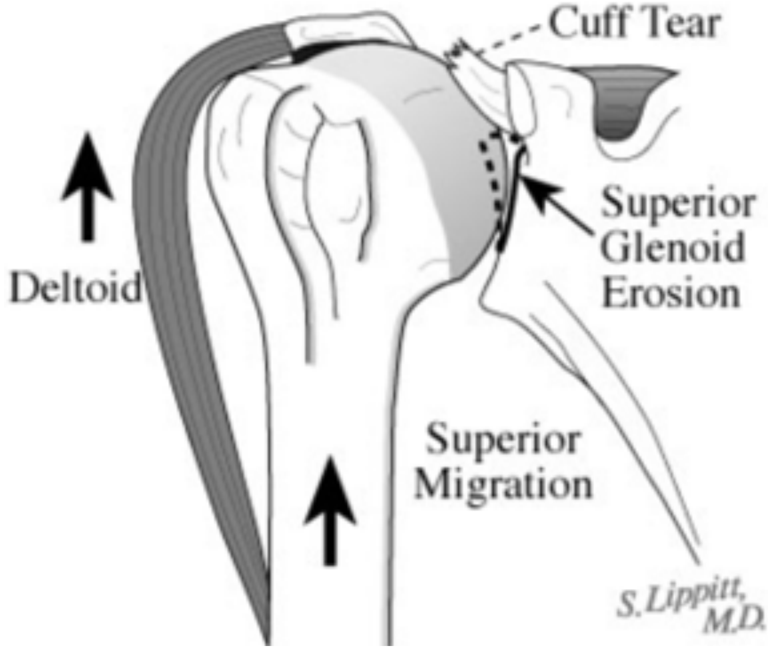

Figure 1-11: Rotator cuff tear arthropathy progression[73]

Pathological process of rotator cuff tear arthropathy. Proximal pull of the deltoid with chronic loss of rotator cuff integrity leads to superior migration of the humeral head. In turn, articulation with the undersurface of the acromion occurs with superior glenoid erosion due to eccentric wear of the joint surface.

Hamada et al.[39] attempted to characterize rotator cuff tear arthropathy based on its radiographic appearance. In Grade 1, the acromiohumeral distance reduced from normal range (9-14mm) but remains greater than 6mm. Grade 2 is associated with further decrease in acromiohumeral distance with measurements of 5mm or less. Grade 3 demonstrates an acromiohumeral distance of 5mm or less with associated acetabularization of the undersurface of the acromion with reciprocal changes on the humeral head, a process termed femoralization. Grade 4 is classified as having glenohumeral arthritis, typically superior involvement, with (B) or without (A) acetabularization of the undersurface of the acromion. Lastly, Grade 5 has glenohumeral arthritis and humeral head collapse.[39]

1.5.3 Treatment options

When approaching a massive irreparable rotator cuff tear, there is a wide array of surgical and nonsurgical options, including established surgical techniques and new emerging technologies. Much of the surgical decision making depends on the status of the patient, including their age, medical status, tear characteristics, level of activity, and expectations. Broadly, there are non-surgical options, joint replacement options, and joint preserving options.[5,17,64]

Generally, each patient can be initially managed non-surgically with physical therapy, anti-inflammatories, corticosteroid injections, and activity modification.[5,17,64] Despite the high likelihood of progression, arthropathy, and fatty infiltration, this may be acceptable to lower demand patients or those with multiple medical comorbidities.

Joint replacement surgeries typically include a reverse total shoulder arthroplasty, as a humeral hemiarthroplasty or anatomic total shoulder arthroplasty require an intact rotator cuff. Joint preserving procedures available for massive irreparable rotator cuff tears include partial rotator cuff repair, interpositional grafts, tendon transfers, subacromial spacers, superior capsule reconstruction, and subacromial implants.[5,17,64]

1.5.3.1 Reverse total shoulder arthroplasty

The reverse total shoulder arthroplasty was originally described by French surgeon Paul Grammont in 1985 and was originally indicated for rotator cuff tear arthropathy in elderly patients with low baseline activity levels.[38] As the design and technology of the implant have evolved over the years, the indications for this surgical procedure have expanded to include proximal humerus fractures, primary glenohumeral arthritis, revision for failed primary arthroplasty, revision for failed rotator cuff repair, inflammatory arthritis, tumour, and rotator cuff tear arthropathy with and without glenohumeral arthritis.[4,12,15,82]

Early reports of reverse total shoulder arthroplasty usage for rotator cuff tear arthropathy with glenohumeral arthritis demonstrated improved clinical outcomes but high rates of implant complications. Frankle et al.[29] reported good to excellent outcomes in 62% of patients, with average improvements in forward elevation and abduction from 55 and 41 degrees respectively to more than 100 degrees with significant reductions in pain. Complication rates were high, however, with 17% of patients experiencing a complication and 12% of patients requiring revision of components due to early mechanical failure of the glenoid baseplate. Addition of peripheral locking screws on the glenoid baseplate and lateralization of the center of rotation of the glenosphere led to reduction in early mechanical failure of the glenoid baseplate with maintenance of improved clinical outcomes and patient satisfaction.[15] Several studies have since reproduced the outcomes previously identified in the elderly population with rotator cuff tear arthropathy and glenohumeral arthritis.[1,87]

The use of reverse total shoulder arthroplasty in massive rotator cuff tears without glenohumeral arthritis has generally been utilized for patients with failed rotator cuff surgery, intractable pain, pseudoparalysis, or anterior-superior escape.[8,43,83] Both Boileau et al.[8] and Mulieri et al.[83] demonstrated similar improvements in shoulder function, pain scores, and patient satisfaction to previous reports for reverse total shoulder arthroplasty in patients with glenohumeral arthritis. Complication rates and reoperation rates remained consistent with the previous literature with a range of 12-20% and 5-7%, respectively. Interestingly, both groups identified that patients with preserved active anterior elevation greater than 90 degrees preoperatively had worse outcomes, higher complication rates, and lower satisfactions than those patients with preoperative active anterior elevation less than 90 degrees. Hartzler et al.[43] further expanded upon the risk factors for poor functional improvement in this patient population. They identified age less than 60 years, high preoperative shoulder function, and preexisting ipsilateral upper extremity neurologic dysfunction as independent risk factors for poor functional improvement following reverse total shoulder arthroplasty for massive rotator cuff tears in patients without glenohumeral arthritis.

Young age has always been a concern for surgeons considering a reverse total shoulder arthroplasty as little is known about the implant's longevity in this high demand and high functioning patient population. Positive short-term[81,91] and long-term[25] outcomes have been reported in patients younger than 65 years of age when considering pain and shoulder function, however, patient satisfaction is lower when compared to that which was reported in the literature for more elderly patients.[81] The complication rate varies widely with reports as low as 9%[91] and as high as 39%[25], the latter being more than double the rate of expected complications for this operation.[13] Aside from postoperative complications, the longevity of the implants in a younger population is also a concern. Chelli et al.[13] investigated the survivorship of their reverse shoulder arthroplasties over a 17-year period. 10-year survival rates of 95.3% and 91.9% were reported for patients with massive rotator cuff tears without glenohumeral arthritis and with glenohumeral arthritis, respectively. When considering age at time of surgery, 10-year survival rates of 75.7% (less than 60 years), 88.8% (60-69 years), 91.3% (70-79 years), and 94.3% (more than 80 years) were reported.[13] The 2022 annual report from the Australian Orthopaedic Association National Joint Registry[4] supported these findings with higher rates of revision surgery in patients less than 65 years of age when compared to those more than 65 years of age. These findings of higher complication rates, worse satisfaction, and higher revision rates are why the young patient with a massive rotator cuff tear and no glenohumeral arthritis is a particularly challenging case.

1.5.3.2 Partial rotator cuff repair

A complete, anatomic repair of the torn rotator cuff tendons is not always possible due to poor tendon quality, degree of tendon retraction, tension of tendon repair, and progression of rotator cuff tear arthropathy. Historically, massive irreparable rotator cuff tears were addressed with a combination of arthroscopic decompression, subacromial debridement, management of the biceps tendon (tenotomy or tenodesis) and partial repair of the torn rotator cuff tendons.[17,106] The concept behind this approach was to convert a massive irreparable rotator cuff tear into a functional rotator cuff tear with restoration of the force-couple mechanism of the rotator cuff through the use of margin convergence and implantation into bone.[9,11] This is often achieved through rotator cuff footprint medialization, with medialization beyond 10mm resulting in reductions in glenohumeral motion. [36,62,66,111] Initial improvement was observed in this patient population; however, functional improvement was unpredictable and patient deterioration often occurred over time.[17,97] Despite the theory of restoration of the force-couple mechanism of the rotator cuff, longer term follow-up of patients with partial repair of massive irreparable rotator cuff tears demonstrated further progression of rotator cuff tear arthropathy and worsened symptoms of pain and dysfunction.[16,17] Although not a solution to the underlying mechanical deficiency in massive irreparable rotator cuff tears, partial repair with debridement and management of the biceps tendon remains a surgical option for this challenging population, particularly as a bridging solution for those patients that are nearing the age of consideration for a reverse shoulder arthroplasty.

1.5.3.3 Tendon transfers

Tendon transfers have been described as a surgical technique for restoring the force couples of the shoulder in the context of massive rotator cuff deficiency.[5,17] This operation is often used in young, active patients with good tissue quality and significant functional deficits. Examples include the latissimus dorsi, teres major, trapezius, and pectoralis major.

The latissimus dorsi tendon transfer is generally employed for irreparable posterosuperior cuff tears (Figure 1-12). It can be used in isolation or with a concomitant transfer of the teres major tendon, a technique referred to as the L'Episcopo procedure which was originally described for use in pediatric brachial plexus palsy which has now been modified for use in massive rotator cuff deficiency.[7,34] The latissimus dorsi is a large muscle with significant muscle excursion and a broad tendon, whereas, the teres major is a smaller muscle, with lesser excursion.[32] Both muscle-tendon units provide slight humeral head depression, adduction, extension, and internal rotation in their native locations. When transferred to the superolateral greater tuberosity, the line of pull changes and subsequent the muscle-tendon unit now provides external rotation and humeral head depression.[45,107]

Long-term follow up of latissimus dorsi transfer for irreparable posterosuperior cuff tears demonstrated improvements in pain scores, Constant scores, forward elevation, active external rotation, and active abduction.[33,84] Inferior outcomes in this patient population were reported in those patients with subscapularis deficiency, glenohumeral arthritis, teres minor fatty infiltration, and revision surgery. Additionally, although the shoulder force-couples are thought to be restored following the tendon transfers, progression of glenohumeral arthritis was observed in up to 50% of patients at long-term follow up.[33,84] Additionally, the importance of postoperative rehabilitation cannot be understated. Iannotti et al.[49] utilized EMG to demonstrate that patients with synchronous in-phase contraction of the transferred latissimus dorsi tendon during active elevation and external rotation had superior results to those without contraction of the latissimus dorsi. This illustrates the importance of appropriate patient selection and postoperative rehabilitation for the success of this procedure.

Originally used as a reconstructive procedure for brachial plexus palsy, the lower trapezius tendon transfer is gaining traction as an option for reconstruction of the irreparable posterosuperior rotator cuff tear.[23,24] The line of action of the lower trapezius tendon more accurately reflects that of the rotator cuff when compared to the latissimus dorsi tendon. Biomechanical studies demonstrate superior external rotation, joint reactive forces, and better restoration of glenohumeral kinematics when comparing the lower trapezius tendon transfer to the latissimus dorsi tendon transfer.[42,88] This could theoretically lead to an easier rehabilitative process for the patient as the transferred muscle is already in-phase, an issue that has previously led to poorer outcomes in the latissimus dorsi tendon transfer population.[49]

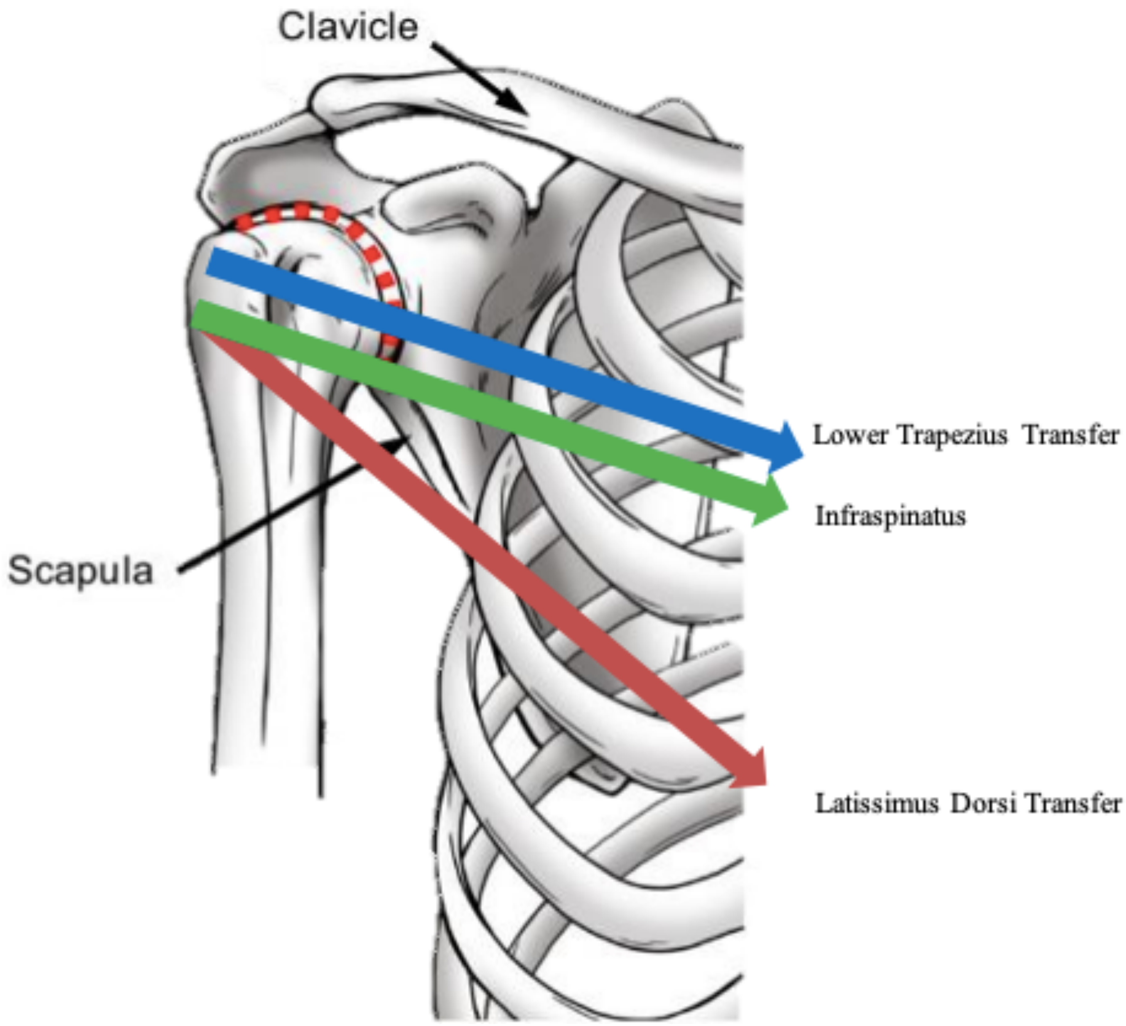

Figure 1-12: Line of action of tendon transfer options relative to infraspinatus

Colour coded arrows demonstrating native infraspinatus line of action (green), as well as lines of action of a latissimus dorsi tendon transfer (red) and lower trapezius tendon transfer (blue).

At the present time, limited clinical evidence exists for the use of the lower trapezius tendon transfer in massive irreparable rotator cuff tears. Elhassan et al.[24] describe a technique in which an Achilles tendon allograft is woven into the lower trapezius tendon and transferred to the greater tuberosity of the humerus. At nearly 4 years follow up, improvements were reported in their 33-patient cohort for pain, subjective scores, and range of motion in forward elevation, abduction, and external rotation. However, long-term studies do not exist, therefore further study is required to determine the risk of infection with use of allograft material, the progression of degenerative arthritis, and the failure rate.

Irreparable anterior rotator cuff tears of the subscapularis have been historically managed with pectoralis major tendon transfers or more recently a latissimus dorsi tendon transfer.[55,80] The line of action of the pectoralis major muscle permits it to contribute to humeral adduction and internal rotation. This muscle is generally synergistic to the subscapularis, making it a great option for tendon transfer. Due to its superficial location relative to the subscapularis, biomechanical studies have evaluated the subconjoint and supraconjoint pectoralis major tendon transfer. Konrad et al.[63] demonstrated that transfer of the pectoralis major tendon beneath the conjoint tendon more reliably restored normal glenohumeral kinematics when compared to its normal position superficial to the conjoint tendon. Long-term outcome of the pectoralis major tendon transfer for irreparable subscapularis deficiency led to improvements in pain and shoulder function, however, as seen with previous tendon transfers, the rate of progression of glenohumeral arthritis was 67%.[80]

1.5.3.4 Subacromial balloon spacer

In 2012, a novel surgical technique involving a biodegradable subacromial balloon spacer (InSpace balloon; OrthoSpace, Kfar Saba, Israel) was proposed as an alternative solution to patients with massive, irreparable rotator cuff tears (Figure 1-13).[92] The balloon spacer is composed of a biodegradable co-polymer of poly-lactide and ε-caprolactone, meant to degrade over the course of 12 months. The design concept was to inflate the subacromial balloon spacer to prevent superior humeral head migration during deltoid activation, thus centering the humeral head on the glenoid fossa and maintaining normal shoulder kinematics.[17] Indications for the surgery range from irreparable supraspinatus tears, to larger irreparable tears including the supraspinatus and infraspinatus.[92] If the patient has a subscapularis tear, it must be repairable for the patient to be indicated for the balloon. Contraindications include pseudoparalysis, lag signs, irreparable subscapularis tears, active or latent joint infection, glenohumeral arthropathy, axillary nerve palsy, allergy to implant material, and tissue necrosis or loss.[92]

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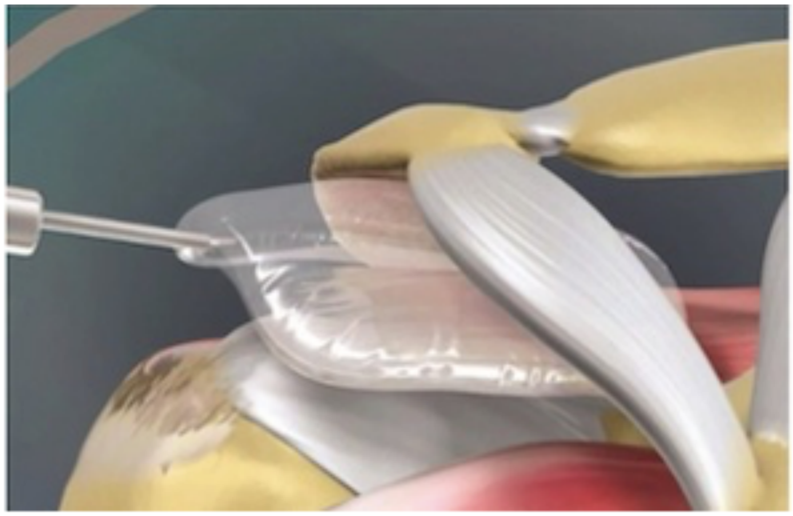

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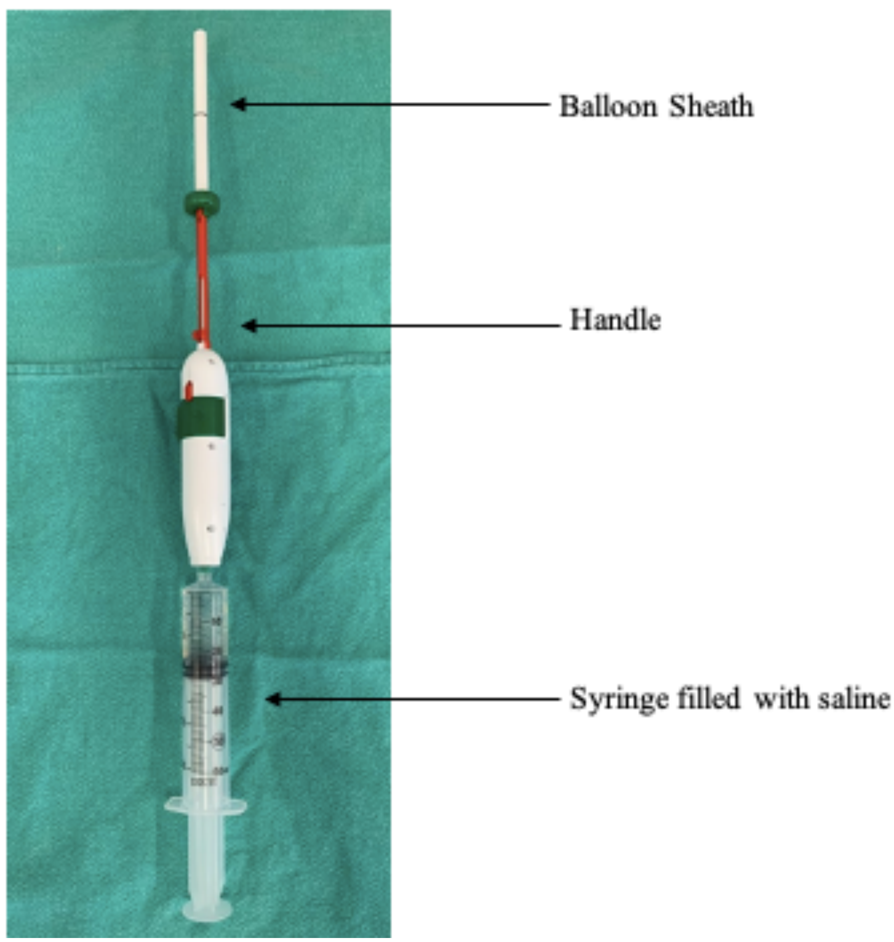

Figure 1-13: Subacromial balloon spacer

(A) Placement of inflated subacromial balloon within the subacromial space.[109] *(B) Equipment required for placement of the subacromial balloon.*

The InSpace balloon spacer is available in three sizes: small (40mm x 50mm), medium (50mm x 60 mm), and large (60mm x 70 mm). Standard arthroscopic assessment of the shoulder is completed, followed by subacromial bursectomy and debridement as well as partial rotator cuff repair if indicated. The subacromial balloon spacer is sized from a position 1cm medial to the glenoid rim to the lateral edge of the acromion. Maximum and recommended inflation volumes are as follows: small (15-17mL [9 - 11mL]), medium (22 – 24mL [14 – 16mL]), and large (40mL [23 – 25mL]). It is recommended that the balloon be filled to a volume that allows maximal range of motion.[92] This technique was further refined in 2014, with a fluoroscopic guided technique that could be performed in a day surgery suite under local anesthetic for patients with medical contraindications to general anesthesia.[35]

From a kinematic perspective, limited study has been performed on the subacromial balloon spacer. Singh et al.[99] demonstrated that creation of a massive irreparable rotator cuff tear in a cadaveric specimen result in a 3.5mm superior migration of the humeral head when compared to an intact shoulder. They also reported that a subacromial balloon spacer inflated to 25mL will reduce the humeral head by 3.2mm inferiorly, returning to a near normal state.[99] Similarly, Singh et al.[100] demonstrated that massive irreparable rotator cuff tears result in a significant decrease in functional abduction force. This reduction in functional abduction force is restored with implantation of the subacromial balloon spacer.

Much of the clinical-based investigation of the subacromial balloon has been limited to observational case series and prospective patient cohorts with demonstration of improved patient range of motion and function as measured by the Constant-Murley (CM), Oxford Shoulder (OSS), and American Shoulder and Elbow Surgeons (ASES) scores.[54,102] However, two recently published multicenter randomized controlled trials have compared the subacromial balloon to both arthroscopic shoulder debridement and partial rotator cuff repair.[74,105] Metcalfe et al.[74] compared the subacromial balloon spacer paired with shoulder arthroscopic debridement to a debridement only group. This included 117 patients with one year follow up. Both control and treatment groups showed improvement compared to preoperative state, however, there was a significantly larger improvement at one year in the control group compared to the experimental group despite similar levels of baseline intervention. Verma et al.[105] compared the subacromial balloon spacer in isolation to that of arthroscopic partial rotator cuff repair. Several concomitant procedures were performed in each study group. With 184 patients, they concluded that the partial repair group and the subacromial balloon spacer group had no significant difference between groups in terms of the ASES scores at two years. It was felt that the subacromial balloon spacer would provide a shorter operative time and an alternative to partial rotator cuff repair in patients with irreparable massive rotator cuff tears with an intact subscapularis. However, as previously discussed, several concomitant procedures were not controlled within this trial and may have confounded the results of both experimental and control groups. Therefore, the exact clinical benefit of the subacromial balloon spacer in massive irreparable rotator cuff tears is still in question.

Complications associated with implantation of the subacromial spacer appear to be infrequent, with reoperation occurring in 1-3% of patients. Transient lateral cutaneous nerve of the forearm irritation, adhesive capsulitis, persistent pain, superficial wound infection, and persistent synovitis have also been reported.[54,74,102,105]

The long-term effects of the subacromial balloon spacer are unknown. Two studies have reported on the balloon's integrity at mid-term follow-up showing decreasing size and overall degradation of the implant at 3-, 6-, and 12 months, with complete degradation in all patients by 24 months.[90,93] It is felt that some of the beneficial effects of the surgery last beyond the lifetime of the implant, which is supported by the work of Verma et al.[105] However, it is unclear if this is due to the effects of the subacromial balloon spacer or that of concomitant procedures addressed at the time of surgery. Additionally, what remains to be seen is if the natural history of an irreparable rotator cuff tear has been significantly changed with implantation of a degradable subacromial balloon spacer, or if the degenerative changes will occur once the balloon itself has resorbed.

1.5.3.5 Superior capsule reconstruction

The superior capsule lines the undersurface of the infraspinatus and supraspinatus tendons and serves a vital role in prevention of superior translation of the humerus on the glenoid during glenohumeral motion. In a massive irreparable rotator cuff tear the superior capsule is disrupted from its insertion. The result is a disruption of normal shoulder kinematics and superior migration of the humeral head on the glenoid fossa during active glenohumeral motion. Reconstruction of this structure could theoretically lead to centering of the humeral head on the glenoid fossa and allow the larger muscles groups (deltoid, latissimus dorsi, and pectoralis major) to function appropriately (Figure 1-14).

Thus, attempts have been made to reconstruct this anatomic structure to improve glenohumeral kinematics in the context of irreparable rotator cuff tears. The superior capsule reconstruction (SCR) was initially described in 1993 by Hanada et al.[40] for paraplegic patients, and later by Mihata et al.[77,79] as an alternative joint preserving surgical intervention aimed towards improving function and pain in the patient with an irreparable rotator cuff tear. Using autograft fascia lata (5 – 8 mm thickness), the superior capsule was recreated by attaching the graft medially to the superior glenoid and laterally to the greater tuberosity.[77,79] This technique was further modified to include posterior side-to-side sutures between the posterior cuff and the posterior edge of the graft.[78] Many modifications have been made to this technique, most notably Hirahara et al.[46] utilized a dermal allograft rather than a fascia lata autograft for their reconstruction. This variation is utilized in most centers in North America.

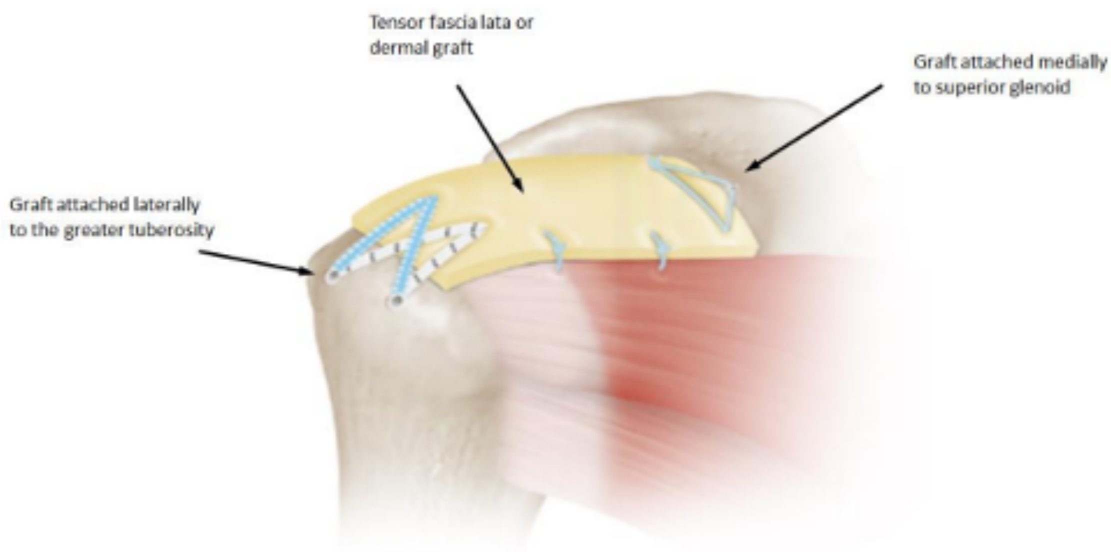

Figure 1-14: Superior capsule reconstruction

Illustration of a completed superior capsular reconstruction with suture anchor fixation medially at the level of the glenoid, side-to-side suturing the intact rotator cuff tendon, and double-row transosseous equivalent fixation into the greater tuberosity laterally.[98]

Surgical indications for superior capsule reconstruction include a patient with a symptomatic, massive, irreparable rotator cuff tear in the absence of rotator cuff arthropathy, with an intact or reparable subscapularis tendon and a functional deltoid.[28] Contraindications include: glenohumeral arthritis, advanced rotator cuff arthropathy (Hamada grade 3 and above), and irreparable subscapularis tendon tears.[28]

From a biomechanical perspective, the superior capsule reconstruction has been found to restore glenohumeral stability and decrease peak subacromial contact pressures significantly when compared to a shoulder with an irreparable rotator cuff tear and capsular disruption.[78] Additionally, when compared to a torn rotator cuff state, the superior capsule reconstruction returned the functional abduction force and humeral head position to values like that of an intact shoulder.[100] However, as shown in several biomechanical studies, the superior capsular reconstruction may lead to overall decrease in rotational shoulder range of motion when compared to both intact shoulders and those with rotator cuff tears.[75,78,79]

The long-term clinical effectiveness of the superior capsule reconstruction has yet to be shown, however, multiple studies exist that demonstrate a statistically significant improvement in short-term outcome measures for both pain and function in younger patients with massive irreparable rotator cuff tears.[31] In a 5-year follow up study, Mihata et al.[76] reported that those patients with healed superior capsule reconstructions had improved shoulder function, however, in those with failed reconstructions there was a fairly quick progression to rotator cuff arthropathy. The rate of failure was 10% of patients in this study. Similarly, Denard et al.[18] demonstrated good functional outcomes at one year, however, only 45% of patients had complete healing of their reconstruction on follow up MRI.

The complication profile of the superior capsule reconstruction was recently well summarized.[101] Graft re-tear ranges from 8-70%, with higher rates occurring in allograft reconstructions (19-70%) compared to autografts (8-29%). Additionally, up to 36% of patients required a revision operation, typically in the form of conversion to a reverse shoulder arthroplasty.[101]

1.5.3.6 Subacromial implant

The identification of an underserved population of patients has led to the development of a rigid subacromial implant (Reach Orthopaedics, Halifax, Canada) meant to treat young patients with irreparable rotator cuff tears in the absence of arthritis. This implant is designed to be rigidly fixed to the posterior scapular spine and occupy the subacromial space with a polished articular surface for the superior humeral head (Figure 1-15). The design concept is to ensure that the implant will prevent the excessive posterosuperior translation of the humeral head seen in the cuff deficient shoulder, thus centering the humeral head on the glenoid fossa, and optimizing shoulder function. As a metallic structure, the implant is designed to remain within the subacromial space permanently providing lasting effects to the rotator cuff deficient shoulder. Preliminary laboratory work has demonstrated that this implant restores humeral head position in scapular plane abduction in massive irreparable rotator cuff tear model to values like that of the intact shoulder.[27] The initial design of the implant does however limit the total range of motion in scapular plane abduction due to lateral edge impingement of the greater tuberosity.

This effect was mitigated with a tuberoplasty of the bare footprint of the greater tuberosity.[27]

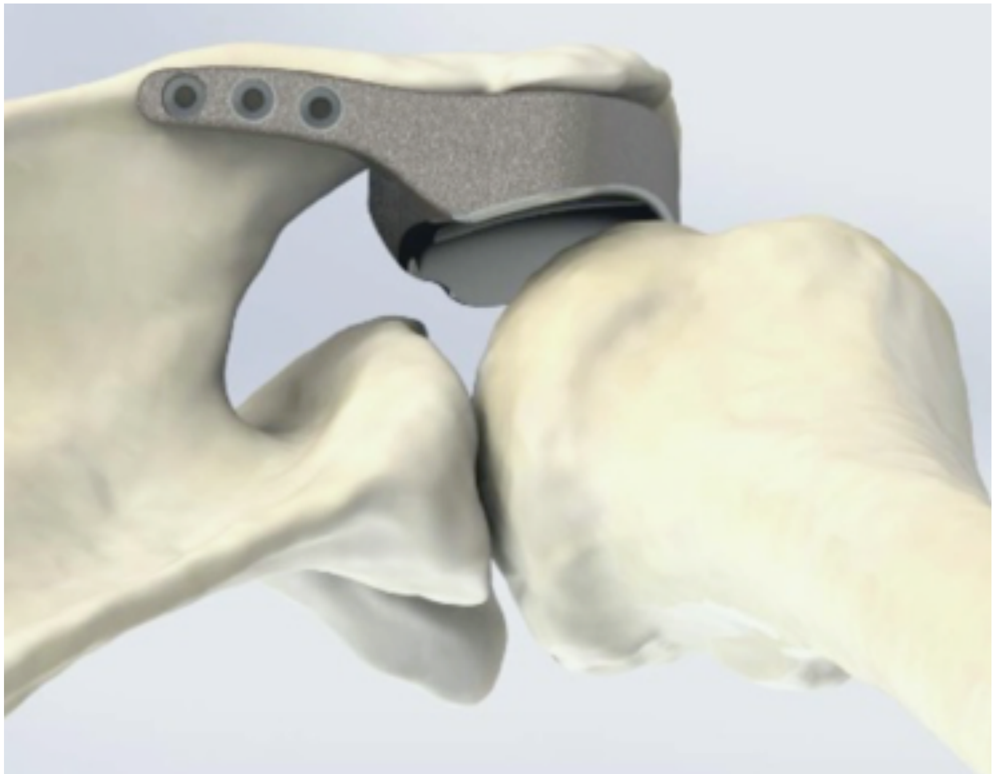

Figure 1-15: Rigid metallic subacromial implant

Initial illustrations of the rigid subacromial implant. There is bony fixation into the scapular spine through a metallic plate extension posteriorly. There is a polished metallic surface immediately subjacent to the acromion to articulate with the humeral head.

1.6 Thesis Rationale

The goal of any joint preserving treatment in a younger patient with an irreparable rotator cuff tear is to recreate the normal shoulder kinematics, restore deltoid function, and limit complications. If successful in preventing or delaying the progression to rotator cuff arthropathy, the salvage option of a reverse shoulder arthroplasty will be available to the patient when their day-to-day demands decrease with age. Early clinical results of the superior capsule reconstruction are promising, whereas randomized controlled trials of the subacromial balloon compared to both debridement and partial cuff repair are inconsistent. Additionally, long term data are lacking for both implants. As time passes, the superior capsule reconstruction is hindered by the risk of graft failure at the glenoid or humerus. Whereas the subacromial balloon spacer is designed to degrade, possibly necessitating reinsertion to preserve any beneficial effects. Lastly, both treatments have unknown effects on the natural progression of rotator cuff tear arthropathy and the prevention of arthritis of the glenohumeral joint.

The novel rigid subacromial implant has yet to be studied. Any new surgical technology requires rigorous laboratory testing and comparison to current surgical options prior to clinical application in a patient. The first step of this is assessment is the biomechanical evaluation of the implant in its ability to treat the rotator cuff deficient specimen.

Therefore, the purpose of this thesis is to compare the subacromial implant with the common joint preserving surgical options for this patient population. This will be a biomechanical analysis using a simulated massive irreparable rotator cuff tear cadaveric model, comparing the subacromial balloon spacer, superior capsular reconstruction, and the novel rigid subacromial implant.

1.7 Objectives and Hypotheses

The aim of this thesis is to compare three surgical treatment options for management of a massive irreparable rotator cuff in a cadaveric model.

The specific objectives of this thesis are:

1. To compare the glenohumeral kinematics during glenohumeral scaption of an intact shoulder, a simulated massive irreparable rotator cuff tear, a subacromial balloon spacer, a superior capsule reconstruction, and a rigid subacromial implant This will be evaluated by quantifying the anterior-posterior and superior-inferior translation of the humeral head when compared to an intact and rotator cuff deficient shoulder (Chapter 2).

2. To compare the functional abduction force during glenohumeral scaption of the intact shoulder, a simulated massive irreparable rotator cuff tear, a subacromial balloon spacer, a superior capsule reconstruction, and a rigid subacromial implant. (Chapter 3).

The hypotheses of this thesis are:

1. Each surgical state will restore superior-inferior humeral head position to the intact state when compared to the rotator cuff deficient shoulder. The subacromial balloon spacer will lead to increased anterior translation of the humeral head compared to the superior capsule reconstruction and the subacromial implant (Chapter 2).
2. Each surgical state will improve functional abduction force of the deltoid when compared to the rotator cuff deficient shoulder. No surgical state will restore the functional abduction force of the intact shoulder (Chapter 3).

1.8 Thesis Summary

This thesis is a comparative biomechanical study of the subacromial balloon spacer, superior capsule reconstruction, and a novel rigid subacromial implant in a rotator cuff deficient cadaveric model. This chapter is an introduction to the shoulder as well as a literature review of massive irreparable rotator cuff tears and the management of this difficult patient presentation. The second chapter compares the glenohumeral kinematics during glenohumeral scaption of an intact shoulder, a massive irreparable rotator cuff tear and three surgical states. The third chapter compares the functional abduction force during glenohumeral scaption of an intact shoulder, a massive irreparable rotator cuff tear, and the three surgical states. Lastly, the final chapter summarizes the key findings of the thesis and presents the overall conclusions from each chapter.

1.9 References

1. Al-Hadithy N, Domos P, Sewell MD, Pandit R. Reverse shoulder arthroplasty in 41 patients with cuff tear arthropathy with a mean follow-up period of 5 years. *J Shoulder Elbow Surg*. 2014;23(11):1662-1668. doi:10.1016/j.jse.2014.03.001

2. Alpert SW, Pink MM, Jobe FW, McMahon PJ, Mathiyakom W. Electromyographic analysis of deltoid and rotator cuff function under varying loads and speeds. *J Shoulder Elbow Surg*. 2000;9(1):47-58. doi:10.1016/s1058-2746(00)90009-0

3. Athwal GS, Armstrong A. Rotator Cuff Tears. OrthoInfo.

4. Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR). *Hip, Knee & Shoulder Arthroplasty Annual Report 2022*.; 2022.

5. di Benedetto P, Mancuso F, Tosolini L, Buttironi MM, Beltrame A, Causero A. Treatment options for massive rotator cuff tears: a narrative review. *Acta Biomed*. 2021;92(S3):e2021026. doi:10.23750/abm.v92iS3.11766

6. Bigliani LU, Morrison DS, April EW. The Morphology of the Acromion and Its Relationship to Rotator Cuff Tears. In: *Orthopaedic Transactions*. ; 1986.

7. Boileau P, Chuinard C, Roussanne Y, Neyton L, Trojani C. Modified latissimus dorsi and teres major transfer through a single delto-pectoral approach for external rotation deficit of the shoulder: as an isolated procedure or with a reverse arthroplasty. *J Shoulder Elbow Surg*. 2007;16(6):671-682. doi:10.1016/j.jse.2007.02.127

8. Boileau P, Gonzalez JF, Chuinard C, Bicknell R, Walch G. Reverse total shoulder arthroplasty after failed rotator cuff surgery. *J Shoulder Elbow Surg*. 2009;18(4):600-606. doi:10.1016/j.jse.2009.03.011

9. Burkhart SS. Partial repair of massive rotator cuff tears: the evolution of a concept. *Orthop Clin North Am*. 1997;28(1):125-132. doi:10.1016/s0030-5898(05)70270-4

10. Burkhart SS, Esch JC, Jolson RS. The rotator crescent and rotator cable: an anatomic description of the shoulder's "suspension bridge". *Arthroscopy*. 1993;9(6):611-616. doi:10.1016/s0749-8063(05)80496-7

11. Burkhart SS, Nottage WM, Ogilvie-Harris DJ, Kohn HS, Pachelli A. Partial repair of irreparable rotator cuff tears. *Arthroscopy*. 1994;10(4):363-370. doi:10.1016/s0749-8063(05)80186-0

12. Chelli M, Boileau P, Domos P, et al. Survivorship of Reverse Shoulder Arthroplasty According to Indication, Age and Gender. *J Clin Med*. 2022;11(10). doi:10.3390/jcm11102677

13. Chelli M, Boileau P, Domos P, et al. Survivorship of Reverse Shoulder Arthroplasty According to Indication, Age and Gender. *J Clin Med*. 2022;11(10). doi:10.3390/jcm11102677

14. Collins DN, Harryman DT. Arthroplasty for arthritis and rotator cuff deficiency. *Orthop Clin North Am*. 1997;28(2):225-239. doi:10.1016/s0030-5898(05)70282-0

15. Cuff D, Pupello D, Virani N, Levy J, Frankle M. Reverse shoulder arthroplasty for the treatment of rotator cuff deficiency. *J Bone Joint Surg Am*. 2008;90(6):1244-1251. doi:10.2106/JBJS.G.00775

16. Cuff DJ, Pupello DR, Santoni BG. Partial rotator cuff repair and biceps tenotomy for the treatment of patients with massive cuff tears and retained overhead elevation: midterm outcomes with a minimum 5 years of follow-up. *J Shoulder Elbow Surg*. 2016;25(11):1803-1809. doi:10.1016/j.jse.2016.04.001

17. Cvetanovich GL, Waterman BR, Verma NN, Romeo AA. Management of the Irreparable Rotator Cuff Tear. *J Am Acad Orthop Surg*. 2019;27(24):909-917. doi:10.5435/JAAOS-D-18-00199

18. Denard PJ, Brady PC, Adams CR, Tokish JM, Burkhart SS. Preliminary Results of Arthroscopic Superior Capsule Reconstruction with Dermal Allograft. *Arthroscopy*. 2018;34(1):93-99. doi:10.1016/j.arthro.2017.08.265

19. Denard PJ, Jiwani AZ, Lädermann A, Burkhart SS. Long-term outcome of arthroscopic massive rotator cuff repair: the importance of double-row fixation. *Arthroscopy*. 2012;28(7):909-915. doi:10.1016/j.arthro.2011.12.007

20. DeOrio JK, Cofield RH. Results of a second attempt at surgical repair of a failed initial rotator-cuff repair. *J Bone Joint Surg Am*. 1984;66(4):563-567.

21. Dwyer T, Razmjou H, Henry P, Gosselin-Fournier S, Holtby R. Association between pre-operative magnetic resonance imaging and reparability of large and massive rotator cuff tears. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(2):415-422. doi:10.1007/s00167-013-2745-z

22. Ecklund KJ, Lee TQ, Tibone J, Gupta R. Rotator cuff tear arthropathy. *J Am Acad Orthop Surg*. 2007;15(6):340-349. doi:10.5435/00124635-200706000-00003

23. Elhassan B, Bishop A, Shin A. Trapezius transfer to restore external rotation in a patient with a brachial plexus injury. A case report. *J Bone Joint Surg Am*. 2009;91(4):939-944. doi:10.2106/JBJS.H.00745

24. Elhassan BT, Wagner ER, Werthel JD. Outcome of lower trapezius transfer to reconstruct massive irreparable posterior-superior rotator cuff tear. *J Shoulder Elbow Surg*. 2016;25(8):1346-1353. doi:10.1016/j.jse.2015.12.006

25. Ernstbrunner L, Suter A, Catanzaro S, Rahm S, Gerber C. Reverse Total Shoulder Arthroplasty for Massive, Irreparable Rotator Cuff Tears Before the Age of 60 Years: Long-Term Results. *J Bone Joint Surg Am*. 2017;99(20):1721-1729. doi:10.2106/JBJS.17.00095

26. Escamilla RF, Yamashiro K, Paulos L, Andrews JR. Shoulder muscle activity and function in common shoulder rehabilitation exercises. *Sports Med*. 2009;39(8):663-685. doi:10.2165/00007256-200939080-00004

27. Fleet C. *The Design and Evaluation of a Subacromial Implant in Restoring Normal Glenohumeral Joint Stability in the Presence of a Massive Irreparable Rotator Cuff Tear*. Western University; 2022.

28. Frank RM, Cvetanovich G, Savin D, Romeo AA. Superior Capsular Reconstruction: Indications, Techniques, and Clinical Outcomes. *JBJS Rev*. 2018;6(7):e10. doi:10.2106/JBJS.RVW.17.00141

29. Frankle M, Siegal S, Pupello D, Saleem A, Mighell M, Vasey M. The Reverse Shoulder Prosthesis for glenohumeral arthritis associated with severe rotator cuff deficiency. A

minimum two-year follow-up study of sixty patients. *J Bone Joint Surg Am*. 2005;87(8):1697-1705. doi:10.2106/JBJS.D.02813

30. Galatz LM, Ball CM, Teefey SA, Middleton WD, Yamaguchi K. The outcome and repair integrity of completely arthroscopically repaired large and massive rotator cuff tears. *J Bone Joint Surg Am*. 2004;86(2):219-224. doi:10.2106/00004623-200402000-00002

31. Galvin JW, Kenney R, Curry EJ, et al. Superior Capsular Reconstruction for Massive Rotator Cuff Tears: A Critical Analysis Review. *JBJS Rev*. 2019;7(6). doi:10.2106/JBJS.RVW.18.00072

32. Gerber C, Maquieira G, Espinosa N. Latissimus dorsi transfer for the treatment of irreparable rotator cuff tears. *J Bone Joint Surg Am*. 2006;88(1):113-120. doi:10.2106/JBJS.E.00282

33. Gerber C, Rahm SA, Catanzaro S, Farshad M, Moor BK. Latissimus dorsi tendon transfer for treatment of irreparable posterosuperior rotator cuff tears: long-term results at a minimum follow-up of ten years. *J Bone Joint Surg Am*. 2013;95(21):1920-1926. doi:10.2106/JBJS.M.00122

34. Gerhardt C, Lehmann L, Lichtenberg S, Magosch P, Habermeyer P. Modified L'Episcopo tendon transfers for irreparable rotator cuff tears: 5-year follow-up. *Clin Orthop Relat Res*. 2010;468(6):1572-1577. doi:10.1007/s11999-009-1030-4

35. Gervasi E, Cautero E, Dekel A. Fluoroscopy-guided implantation of subacromial "biodegradable spacer" using local anesthesia in patients with irreparable rotator cuff tear. *Arthrosc Tech*. 2014;3(4):e455-8. doi:10.1016/j.eats.2014.05.010

36. Ghazanfari A, Henderson DJH, Nourissat G. An Arthroscopic Humeral Medializing Repair of the Supraspinatus. *Arthrosc Tech*. 2017;6(6):e2211-e2215. doi:10.1016/j.eats.2017.08.029

37. Goutallier D, Bernageau J, Patte D. Assessment of the trophicity of the muscles of the ruptured rotator cuff by CT scan. In: Post M, Morrey B, Hawkins R, eds. *Surgery of the Shoulder*. Mosby; 1990:11-13.

38. Grammont PM, Baulot E. Delta shoulder prosthesis for rotator cuff rupture. *Orthopedics*. 1993;16(1):65-68. doi:10.3928/0147-7447-19930101-11

39. Hamada K, Yamanaka K, Uchiyama Y, Mikasa T, Mikasa M. A radiographic classification of massive rotator cuff tear arthritis. *Clin Orthop Relat Res*. 2011;469(9):2452-2460. doi:10.1007/s11999-011-1896-9

40. Hanada K, Fukuda H, Hamada K, Nakajima T. Rotator cuff tears in the patient with paraplegia. *J Shoulder Elbow Surg*. 1993;2(2):64-69. doi:10.1016/1058-2746(93)90002-X

41. Hart DA, Frank CB, Bray RC. Inflammatory Processes in Repetitive Motion and Over-Use Syndromes: Potential Role of Neurogenic Mechanisms in Tendons and Ligaments. In: Gordon SL, Blair SJ, Fine LJ, eds. *Repetitive Motion Disorders of the Upper Extremity*. AAOS; 1995:247-262.

42. Hartzler RU, Barlow JD, An KN, Elhassan BT. Biomechanical effectiveness of different types of tendon transfers to the shoulder for external rotation. *J Shoulder Elbow Surg*. 2012;21(10):1370-1376. doi:10.1016/j.jse.2012.01.026

43. Hartzler RU, Steen BM, Hussey MM, et al. Reverse shoulder arthroplasty for massive rotator cuff tear: risk factors for poor functional improvement. *J Shoulder Elbow Surg*. 2015;24(11):1698-1706. doi:10.1016/j.jse.2015.04.015

44. Hawkes DH, Alizadehkhaiyat O, Kemp GJ, Fisher AC, Roebuck MM, Frostick SP. Shoulder muscle activation and coordination in patients with a massive rotator cuff tear: an electromyographic study. *J Orthop Res*. 2012;30(7):1140-1146. doi:10.1002/jor.22051

45. Henseler JF, Nagels J, Nelissen RGHH, de Groot JH. Does the latissimus dorsi tendon transfer for massive rotator cuff tears remain active postoperatively and restore active external rotation? *J Shoulder Elbow Surg*. 2014;23(4):553-560. doi:10.1016/j.jse.2013.07.055

46. Hirahara AM, Adams CR. Arthroscopic Superior Capsular Reconstruction for Treatment of Massive Irreparable Rotator Cuff Tears. *Arthrosc Tech*. 2015;4(6):e637-41. doi:10.1016/j.eats.2015.07.006

47. Hsu J, Keener JD. Natural History of Rotator Cuff Disease and Implications on Management. *Oper Tech Orthop*. 2015;25(1):2-9. doi:10.1053/j.oto.2014.11.006

48. Hughes RE, An KN. Force analysis of rotator cuff muscles. *Clin Orthop Relat Res*. 1996;(330):75-83. doi:10.1097/00003086-199609000-00010

49. Iannotti JP, Hennigan S, Herzog R, et al. Latissimus dorsi tendon transfer for irreparable posterosuperior rotator cuff tears. Factors affecting outcome. *J Bone Joint Surg Am*. 2006;88(2):342-348. doi:10.2106/JBJS.D.02996

50. Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. *Clin Orthop Relat Res*. 1996;(330):3-12. doi:10.1097/00003086-199609000-00002

51. Jensen KL, Williams GR, Russell IJ, Rockwood CA. Rotator cuff tear arthropathy. *J Bone Joint Surg Am*. 1999;81(9):1312-1324. doi:10.2106/00004623-199909000-00013

52. Jia X, Ji JH, Petersen SA, Keefer J, McFarland EG. Clinical evaluation of the shoulder shrug sign. *Clin Orthop Relat Res*. 2008;466(11):2813-2819. doi:10.1007/s11999-008-0331-3

53. Jobe C, Phipatanakul W, Petkovic D. Gross anatomy of the shoulder. In: Rockwood Jr C, Matsen III F, Wirth M, Lippitt S, Fehringer E, Sperling J, eds. *Rockwood and Matsen's The Shoulder*. 5th ed. Elsevier; 2017:35-95.

54. Johns WL, Ailaney N, Lacy K, Golladay GJ, Vanderbeck J, Kalore N v. Implantable Subacromial Balloon Spacers in Patients With Massive Irreparable Rotator Cuff Tears: A Systematic Review of Clinical, Biomechanical, and Financial Implications. *Arthrosc Sports Med Rehabil*. 2020;2(6):e855-e872. doi:10.1016/j.asmr.2020.06.011

55. Kany J, Guinand R, Croutzet P, Valenti P, Werthel JD, Grimberg J. Arthroscopic-assisted latissimus dorsi transfer for subscapularis deficiency. *Eur J Orthop Surg Traumatol*. 2016;26(3):329-334. doi:10.1007/s00590-016-1753-3

56. Keener JD, Galatz LM, Teefey SA, et al. A prospective evaluation of survivorship of asymptomatic degenerative rotator cuff tears. *J Bone Joint Surg Am*. 2015;97(2):89-98. doi:10.2106/JBJS.N.00099

57. Keener JD, Wei AS, Kim HM, Steger-May K, Yamaguchi K. Proximal humeral migration in shoulders with symptomatic and asymptomatic rotator cuff tears. *J Bone Joint Surg Am*. 2009;91(6):1405-1413. doi:10.2106/JBJS.H.00854

58. Kim HM, Dahiya N, Teefey SA, et al. Location and initiation of degenerative rotator cuff tears: an analysis of three hundred and sixty shoulders. *J Bone Joint Surg Am*. 2010;92(5):1088-1096. doi:10.2106/JBJS.I.00686

59. Kim HM, Dahiya N, Teefey SA, Keener JD, Galatz LM, Yamaguchi K. Relationship of tear size and location to fatty degeneration of the rotator cuff. *J Bone Joint Surg Am*. 2010;92(4):829-839. doi:10.2106/JBJS.H.01746

60. Kim JY, Park JS, Rhee YG. Can Preoperative Magnetic Resonance Imaging Predict the Reparability of Massive Rotator Cuff Tears? *Am J Sports Med*. 2017;45(7):1654-1663. doi:10.1177/0363546517694160

61. Kim SJ, Kim SH, Lee SK, Seo JW, Chun YM. Arthroscopic repair of massive contracted rotator cuff tears: aggressive release with anterior and posterior interval slides do not improve cuff healing and integrity. *J Bone Joint Surg Am*. 2013;95(16):1482-1488. doi:10.2106/JBJS.L.01193

62. Kim YK, Jung KH, Won JS, Cho SH. Medialized repair for retracted rotator cuff tears. *J Shoulder Elbow Surg*. 2017;26(8):1432-1440. doi:10.1016/j.jse.2016.11.007

63. Konrad GG, Sudkamp NP, Kreuz PC, Jolly JT, McMahon PJ, Debski RE. Pectoralis major tendon transfers above or underneath the conjoint tendon in subscapularis-deficient

shoulders. An in vitro biomechanical analysis. *J Bone Joint Surg Am*. 2007;89(11):2477-2484. doi:10.2106/JBJS.F.00811

64. Kucirek NK, Hung NJ, Wong SE. Treatment Options for Massive Irreparable Rotator Cuff Tears. *Curr Rev Musculoskelet Med*. 2021;14(5):304-315. doi:10.1007/s12178-021-09714-7

65. Kuhn JE, Dunn WR, Sanders R, et al. Effectiveness of physical therapy in treating atraumatic full-thickness rotator cuff tears: a multicenter prospective cohort study. *J Shoulder Elbow Surg*. 2013;22(10):1371-1379. doi:10.1016/j.jse.2013.01.026

66. Liu J, Hughes RE, O'Driscoll SW, An KN. Biomechanical effect of medial advancement of the supraspinatus tendon. A study in cadavera. *J Bone Joint Surg Am*. 1998;80(6):853-859. doi:10.2106/00004623-199806000-00009

67. Liu J, Hughes RE, Smutz WP, Niebur G, Nan-An K. Roles of deltoid and rotator cuff muscles in shoulder elevation. *Clin Biomech (Bristol, Avon)*. 1997;12(1):32-38. doi:10.1016/s0268-0033(96)00047-2

68. Lockhart J. *A Computational Investigation Into Acromial Fractures After Reverse Total Shoulder Arthroplasty*. Western University; 2020.

69. Lohr JF, Uhthoff HK. The microvascular pattern of the supraspinatus tendon. *Clin Orthop Relat Res*. 1990;(254):35-38.

70. MacGillivray JD, Fealy S, Potter HG, O'Brien SJ. Multiplanar analysis of acromion morphology. *Am J Sports Med*. 1998;26(6):836-840. doi:10.1177/03635465980260061701

71. Mall NA, Kim HM, Keener JD, et al. Symptomatic progression of asymptomatic rotator cuff tears: a prospective study of clinical and sonographic variables. *J Bone Joint Surg Am*. 2010;92(16):2623-2633. doi:10.2106/JBJS.I.00506

72. Maman E, Harris C, White L, Tomlinson G, Shashank M, Boynton E. Outcome of Nonoperative Treatment of Symptomatic Rotator Cuff Tears Monitored by Magnetic

Resonance Imaging. *The Journal of Bone and Joint Surgery-American Volume*. 2009;91(8):1898-1906. doi:10.2106/JBJS.G.01335

73. Matsen FI, Lippitt S. *Shoulder Surgery: Principles and Procedures*. Saunders; 2004.

74. Metcalfe A, Parsons H, Parsons N, et al. Subacromial balloon spacer for irreparable rotator cuff tears of the shoulder (START:REACTS): a group-sequential, double-blind, multicentre randomised controlled trial. *The Lancet*. 2022;399(10339):1954-1963. doi:10.1016/S0140-6736(22)00652-3

75. Mihata T, Bui CNH, Akeda M, et al. A biomechanical cadaveric study comparing superior capsule reconstruction using fascia lata allograft with human dermal allograft for irreparable rotator cuff tear. *J Shoulder Elbow Surg*. 2017;26(12):2158-2166. doi:10.1016/j.jse.2017.07.019

76. Mihata T, Lee TQ, Hasegawa A, et al. Five-Year Follow-up of Arthroscopic Superior Capsule Reconstruction for Irreparable Rotator Cuff Tears. *Journal of Bone and Joint Surgery - American Volume*. 2019;101(21):1921-1930. doi:10.2106/JBJS.19.00135

77. Mihata T, Lee TQ, Watanabe C, et al. Clinical results of arthroscopic superior capsule reconstruction for irreparable rotator cuff tears. *Arthroscopy - Journal of Arthroscopic and Related Surgery*. 2013;29(3):459-470. doi:10.1016/j.arthro.2012.10.022

78. Mihata T, McGarry MH, Kahn T, Goldberg I, Neo M, Lee TQ. Biomechanical role of capsular continuity in superior capsule reconstruction for irreparable tears of the supraspinatus tendon. *American Journal of Sports Medicine*. 2016;44(6):1423-1430. doi:10.1177/0363546516631751

79. Mihata T, McGarry MH, Pirolo JM, Kinoshita M, Lee TQ. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: A biomechanical cadaveric study. *American Journal of Sports Medicine*. 2012;40(10):2248-2255. doi:10.1177/0363546512456195

80. Moroder P, Schulz E, Mitterer M, Plachel F, Resch H, Lederer S. Long-Term Outcome After Pectoralis Major Transfer for Irreparable Anterosuperior Rotator Cuff Tears. *J Bone Joint Surg Am*. 2017;99(3):239-245. doi:10.2106/JBJS.16.00485

81. Muh SJ, Streit JJ, Wanner JP, et al. Early follow-up of reverse total shoulder arthroplasty in patients sixty years of age or younger. *J Bone Joint Surg Am*. 2013;95(20):1877-1883. doi:10.2106/JBJS.L.10005

82. Mulieri P, Dunning P, Klein S, Pupello D, Frankle M. Reverse shoulder arthroplasty for the treatment of irreparable rotator cuff tear without glenohumeral arthritis. *J Bone Joint Surg Am*. 2010;92(15):2544-2556. doi:10.2106/JBJS.I.00912

83. Mulieri P, Dunning P, Klein S, Pupello D, Frankle M. Reverse shoulder arthroplasty for the treatment of irreparable rotator cuff tear without glenohumeral arthritis. *J Bone Joint Surg Am*. 2010;92(15):2544-2556. doi:10.2106/JBJS.I.00912

84. Namdari S, Voleti P, Baldwin K, Glaser D, Huffman GR. Latissimus dorsi tendon transfer for irreparable rotator cuff tears: a systematic review. *J Bone Joint Surg Am*. 2012;94(10):891-898. doi:10.2106/JBJS.K.00841

85. Neer CS, Craig E V, Fukuda H. Cuff-tear arthropathy. *J Bone Joint Surg Am*. 1983;65(9):1232-1244.

86. Nho SJ, Yadav H, Shindle MK, Macgillivray JD. Rotator cuff degeneration: etiology and pathogenesis. *Am J Sports Med*. 2008;36(5):987-993. doi:10.1177/0363546508317344

87. Nolan BM, Ankerson E, Wiater JM. Reverse total shoulder arthroplasty improves function in cuff tear arthropathy. *Clin Orthop Relat Res*. 2011;469(9):2476-2482. doi:10.1007/s11999-010-1683-z

88. Omid R, Heckmann N, Wang L, McGarry MH, Vangsness CT, Lee TQ. Biomechanical comparison between the trapezius transfer and latissimus transfer for irreparable posterosuperior rotator cuff tears. *J Shoulder Elbow Surg*. 2015;24(10):1635-1643. doi:10.1016/j.jse.2015.02.008

89. Otis JC, Jiang CC, Wickiewicz TL, Peterson MG, Warren RF, Santner TJ. Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. *J Bone Joint Surg Am*. 1994;76(5):667-676. doi:10.2106/00004623-199405000-00007

90. Ricci M, Vecchini E, Bonfante E, et al. A clinical and radiological study of biodegradable subacromial spacer in the treatment of massive irreparable rotator cuff tears. *Acta Biomed*. 2017;88(4S):75-80. doi:10.23750/abm.v88i4 -S.6797

91. Samuelsen BT, Wagner ER, Houdek MT, et al. Primary reverse shoulder arthroplasty in patients aged 65 years or younger. *J Shoulder Elbow Surg*. 2017;26(1):e13-e17. doi:10.1016/j.jse.2016.05.026

92. Savarese E, Romeo R. New Solution for Massive, Irreparable Rotator Cuff Tears: The Subacromial "Biodegradable Spacer." *Arthrosc Tech*. 2012;1(1). doi:10.1016/j.eats.2012.02.002

93. Senekovic V, Poberaj B, Kovacic L, et al. The biodegradable spacer as a novel treatment modality for massive rotator cuff tears: a prospective study with 5-year follow-up. *Arch Orthop Trauma Surg*. 2017;137(1):95-103. doi:10.1007/s00402-016-2603-9

94. Sharkey NA, Marder RA. The rotator cuff opposes superior translation of the humeral head. *Am J Sports Med*. 1995;23(3):270-275. doi:10.1177/036354659502300303

95. Sheean AJ, Hartzler RU, Denard PJ, et al. Preoperative Radiographic Risk Factors for Incomplete Arthroscopic Supraspinatus Tendon Repair in Massive Rotator Cuff Tears. *Arthroscopy*. 2018;34(4):1121-1127. doi:10.1016/j.arthro.2017.09.046

96. Sher JS, Uribe JW, Posada A, Murphy BJ, Zlatkin MB. Abnormal findings on magnetic resonance images of asymptomatic shoulders. *J Bone Joint Surg Am*. 1995;77(1):10-15. doi:10.2106/00004623-199501000-00002

97. Shon MS, Koh KH, Lim TK, Kim WJ, Kim KC, Yoo JC. Arthroscopic Partial Repair of Irreparable Rotator Cuff Tears: Preoperative Factors Associated With Outcome Deterioration Over 2 Years. *Am J Sports Med*. 2015;43(8):1965-1975. doi:10.1177/0363546515585122

98. Singh S. *A Biomechanical Study Examining The Subacromial Balloon Spacer and Superior Capsular Reconstruction in the Treatment of Massive, Irreparable Rotator Cuff Tears*. Western University; 2017.

99. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The effect of the subacromial balloon spacer on humeral head translation in the treatment of massive, irreparable rotator cuff tears: a biomechanical assessment. *J Shoulder Elbow Surg*. 2019;28(10):1841-1847. doi:10.1016/j.jse.2019.03.036

100. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The Subacromial Balloon Spacer Versus Superior Capsular Reconstruction in the Treatment of Irreparable Rotator Cuff Tears: A Biomechanical Assessment. *Arthroscopy - Journal of Arthroscopic and Related Surgery*. 2019;35(2):382-389. doi:10.1016/j.arthro.2018.09.016

101. Sommer MC, Wagner E, Zhu S, et al. Complications of Superior Capsule Reconstruction for the Treatment of Functionally Irreparable Rotator Cuff Tears: A Systematic Review. *Arthroscopy*. 2021;37(9):2960-2972. doi:10.1016/j.arthro.2021.03.076

102. Stewart RK, Kaplin L, Parada SA, Graves BR, Verma NN, Waterman BR. Outcomes of Subacromial Balloon Spacer Implantation for Massive and Irreparable Rotator Cuff Tears: A Systematic Review. *Orthop J Sports Med*. 2019;7(10). doi:10.1177/2325967119875717

103. Tempelhof S, Rupp S, Seil R. Age-related prevalence of rotator cuff tears in asymptomatic shoulders. *J Shoulder Elbow Surg*. 1999;8(4):296-299. doi:10.1016/s1058-2746(99)90148-9

104. Terry GC, Chopp TM. Functional anatomy of the shoulder. *J Athl Train*. 2000;35(3):248-255. www.journalofathletictraining.org

105. Verma N, Srikumaran U, Roden CM, et al. InSpace Implant Compared with Partial Repair for the Treatment of Full-Thickness Massive Rotator Cuff Tears: A Multicenter, Single-Blinded, Randomized Controlled Trial. *J Bone Joint Surg Am*. 2022;104(14):1250-1262. doi:10.2106/JBJS.21.00667

106. Walch G, Edwards TB, Boulahia A, Nové-Josserand L, Neyton L, Szabo I. Arthroscopic tenotomy of the long head of the biceps in the treatment of rotator cuff tears: clinical and radiographic results of 307 cases. *J Shoulder Elbow Surg*. 2005;14(3):238-246. doi:10.1016/j.jse.2004.07.008

107. Warner JJ, Parsons IM. Latissimus dorsi tendon transfer: a comparative analysis of primary and salvage reconstruction of massive, irreparable rotator cuff tears. *J Shoulder Elbow Surg*. 2001;10(6):514-521. doi:10.1067/mse.2001.118629

108. Weber S, Chahal J. Management of Rotator Cuff Injuries. *J Am Acad Orthop Surg*. 2020;28(5):e193-e201. doi:10.5435/JAAOS-D-19-00463

109. Wright MA, Abboud JA, Murthi AM. Subacromial Balloon Spacer Implantation. *Curr Rev Musculoskelet Med*. 2020;13(5):584-591. doi:10.1007/s12178-020-09661-9

110. Yamamoto A, Takagishi K, Osawa T, et al. Prevalence and risk factors of a rotator cuff tear in the general population. *J Shoulder Elbow Surg*. 2010;19(1):116-120. doi:10.1016/j.jse.2009.04.006

111. Yamamoto N, Itoi E, Tuoheti Y, et al. Glenohumeral joint motion after medial shift of the attachment site of the supraspinatus tendon: a cadaveric study. *J Shoulder Elbow Surg*. 2007;16(3):373-378. doi:10.1016/j.jse.2006.06.016

112. Zumstein MA, Jost B, Hempel J, Hodler J, Gerber C. The clinical and structural long-term results of open repair of massive tears of the rotator cuff. *J Bone Joint Surg Am*. 2008;90(11):2423-2431. doi:10.2106/JBJS.G.00677

Chapter 2

2 Glenohumeral Joint Kinematics in a Massive Rotator Cuff Deficient Cadaveric Model: Comparing the Subacromial Balloon Spacer, Superior Capsule Reconstruction, and a Novel Rigid Subacromial Implant

This chapter describes the testing conducted to compare the effectiveness of the subacromial balloon spacer, the superior capsular reconstruction, and a subacromial implant in restoring normal glenohumeral joint position in a massive irreparable rotator cuff tear cadaveric model. Testing was conducted on all test states using a previously developed shoulder testing apparatus. Static muscle loading was employed at varying angles of glenohumeral abduction, with translation of the humerus relative to the glenoid recorded in both anterior-posterior and superior-inferior directions.

2.1 Introduction

As documented in Chapter 1, the shoulder is an inherently unstable joint, free to move in space. With a hemi-spherical humeral head and a shallow glenoid fossa, the shoulder heavily relies on the static capsulolabral tissues and the dynamic forces of the surrounding musculature for stability.[6,15,43] Humeral head centering through co-contraction of the rotator cuff musculature and the force-couple and concavity-compression mechanisms are critical to optimal shoulder function.[19]

Humeral head position on the glenoid does not remain perfectly central during shoulder range of motion and is likely a function of the proximal line of pull of the deltoid, the relative contributions of the rotator cuff in different arm positions, and the bony anatomy of the proximal humerus. Several studies have attempted to quantify the amount of expected humeral head translation that occurs on the glenoid articular surface during normal shoulder range of motion. Using imaging studies such as fluoroscopy, CT scans, and MRI scans this has been observed in healthy individuals.[9,11,22] Although likely highly variable, the humeral head appears to sit slightly posterior and superior to the central bare spot of the glenoid.[9] From here, superior and anterior translation of the humeral head can be expected during initial shoulder abduction and can range between 1-2mm.[9,11,22]

Following this, the humeral head will typically translate slightly posterior and inferior at higher angles of abduction.[9,11,22] The degree of humeral head translation will vary depending on the plane of movement of the arm, with more translation being visualized in glenohumeral abduction than scapular plane abduction.[9] Additionally, greater amounts of humeral head translation were visualized during passive shoulder motion than during active shoulder motion.[11] This observation likely reinforces the importance of active co-contraction of the rotator cuff muscles in stabilizing the shoulder through the force-couple and concavity-compression mechanisms. Although imaging studies have their limitations, these humeral head translation observations have been reproduced in several cadaveric studies investigating rotator cuff deficiency.[33,38,39]

The impact of rotator cuff disease and rotator cuff tears on glenohumeral kinematics has been observed in patients and modelled in the laboratory in cadaveric models. When compared to normal asymptomatic shoulders, patients with symptomatic rotator cuff tears and asymptomatic rotator cuff tears both demonstrate significant superior migration of the humeral head on the glenoid from 30-150 degrees of arm elevation.[46] Keener et al.[16] reported that symptomatic rotator cuff tears greater than 175mm^2 and tears that extend into the infraspinatus were associated with disruption of glenohumeral kinematics and a greater degree of humeral head translation. These findings were confirmed in a subsequent biomechanical study investigating the effect of rotator cuff deficiency on glenohumeral kinematics. Oh et al.[30] reported that supraspinatus deficiency in isolation led to greater rotational range of motion and decreased abduction capability of the shoulder. However, it was only when tears involved at least half of the infraspinatus tendon that significant changes in humeral head translation were observed. Subsequently, Tempelaere et al.[41] coined the term “looseness” of the shoulder to describe the increase in glenohumeral translation in the anterior-posterior and superior-inferior directions observed on dynamic MRI in massive rotator cuff tear patients when compared to normal shoulders and those with tendinopathy. Conversely, both Millet et al.[27] and Kozono et al.[18] showed no significant differences in superior translation of the humeral head in patients with and without rotator cuff tears during elevation and scapular plane abduction, respectively.

In the laboratory setting, rotator cuff deficiency has been examined in cadaveric shoulders to identify the relationship with glenohumeral kinematics. Terrier et al.[42] used a cadaveric shoulder as a base model for a computer simulation investigating normal shoulder kinematics and the changes with supraspinatus deficiency. The normal shoulder demonstrated small amounts of superior translation during abduction. These values significantly increased with supraspinatus deficiency, as did the amount of eccentric loading of the glenoid, joint forces, and muscle forces. Mura et al.[28] and Itami et al.[12] reported that posterior and superior migration of the humeral head increased with sequential sectioning of the infraspinatus tendon when compared to supraspinatus deficiency alone. Maximal superior migration was observed with complete infraspinatus detachment, illustrating the importance of the infraspinatus tendon on humeral depression and glenohumeral stability.[28] Berthold et al.[2] investigated the effects of different rotator cuff tear combinations on superior translation of the humeral head. Unlike the aforementioned studies, the torn rotator cuff was not retracted until the final test state. The other states had non-retracted rotator cuff tears allowing the tendon to act as a passive barrier. Their results illustrated that significant superior humeral migration occurred in the retracted tendon test state representing an irreparable posterosuperior rotator cuff tear. This suggested that non-retracted rotator cuff tears may provide some resistance to excessive humeral head translation through a passive barrier mechanism.

Deficiency of the rotator cuff can lead to unopposed pull of the deltoid muscle during shoulder range of motion. The loss of force-couple and concavity-compression effects of the rotator cuff can ultimately lead to shoulder instability and increased translation of the humeral head on the glenoid. This could in turn result in articulation of the humeral head with the undersurface of the acromion with increased shear forces on the articular cartilage resulting in joint degeneration.[5,29] This pathological process is referred to as rotator cuff tear arthropathy.[14,29] The final stage of this process is fixed proximal migration of the humeral head, acetabularization of the acromion with sclerosis, and degenerative changes of both the humeral head and glenoid.

The current surgical options for massive irreparable rotator cuff tears include arthroscopic debridement with or without biceps tenotomy, partial rotator cuff repair, graft reconstruction, tendon transfers, subacromial balloon spacers, superior capsular reconstructions, bursal acromial replacements, and reverse shoulder arthroplasties. For non-arthroplasty treatments to be effective at preventing progression to rotator cuff tear arthropathy, they would likely have to provide a lasting correction to the altered glenohumeral kinematics of rotator cuff deficiency.

The subacromial balloon spacer has been investigated biomechanically to determine its impact on humeral head translation in the context of rotator cuff deficient cadaveric models. Lobao et al.[20] utilized an irreparable supraspinatus cadaveric model for testing with the subacromial balloon. They demonstrated significant superior translation of the cuff deficient state at 0-, 30-, and 60-degrees glenohumeral abduction when compared to the intact state. The subacromial balloon significantly depressed the humeral head at all measured positions. The humeral head was translated 0.8mm, 3.7mm, and 5.6mm inferiorly relative to the intact rotator cuff state at 0-, 30-, and 60-degrees abduction, respectively.[20] Similarly, the cuff deficient state showed significant posterior humeral head translation relative to the intact state. The subacromial balloon caused significant anterior translation of the humeral head compared to the intact state with average displacements of 4.5mm, 5.3mm, and 7.8mm at 0-, 30-, and 60-degrees abduction.[20] Singh et al.[38] used a massive rotator cuff deficient cadaveric model and used varying fill volumes of the subacromial balloon spacer and examined the impact on humeral head position. At low fill volumes inadequate correction was achieved from a posterior and superior translation perspective, whereas at max fill volumes there was significant overcorrection both anteriorly and inferiorly. At the recommended fill volume, the subacromial balloon consistently caused inferior and anterior translation of the humeral head relative to the intact shoulder state by an average of 1.7mm and 3.4mm, respectively.[38] Although the subacromial balloon appears to mitigate the excessive posterior and superior humeral head translation visualized in rotator cuff deficiency, the current surgical recommendations lead to overcorrection with inferior and anterior humeral head translation relative to the intact shoulder. The effects of this are currently unknown. Additionally, the balloon is designed to be a temporary solution to the disrupted glenohumeral kinematics with a reported lifespan of 12 months prior to biodegradation, although, in clinical practice this timeline may be shorter.[34,35]

In terms of the superior capsular reconstruction, much work has been completed from a biomechanical standpoint using rotator cuff deficient cadaveric models in shoulder simulators.[4,23–26,39,44] In these studies, glenohumeral translation was recorded in several test states with a common reference state being the intact shoulder with a balanced muscle loading protocol. To promote superior translation of the humeral head on the glenoid, the deltoid muscle load was doubled compared to the balanced shoulder state. Comparison was made between the intact rotator cuff state with balanced muscles loads and each of the test states with unbalanced muscle loads to demonstrate the effect on glenohumeral translation. Mihata et al.[26] first demonstrated the effects of a superior capsular reconstruction using fascia lata graft in a supraspinatus deficient cadaveric model. The introduction of complete supraspinatus deficiency significantly increased the superior glenohumeral translation at 0 degrees and 45 degrees of glenohumeral abduction, compared to the intact shoulder state. This effect was lost at 90 degrees glenohumeral abduction. The use of the superior capsular reconstruction reduced the superior translation seen in supraspinatus deficiency to levels similar to the intact shoulder state at all angles of glenohumeral abduction. In a follow up study, it was further demonstrated that superior capsular reconstruction with side-to-side suturing of the graft to the intact posterior cuff only or to the intact posterior and anterior cuff resulted in additional correction of the superior translation of the humeral head when compared to no suturing.[25] Additionally, thickness of the fascia lata graft played an important role in maintenance of humeral head position in a supraspinatus deficient cadaveric model.[24] Graft thicknesses of 8mm demonstrated significantly less superior translation of the humeral head compared to the supraspinatus deficient test state at 0 degrees and 30 degrees of glenohumeral abduction. These results were not appreciated with grafts of 4mm thickness. When using 8mm grafts and comparing the tension position of the graft there was no difference between tensioning the graft at 10 degrees or 30 degrees of glenohumeral abduction. Both test states resulted in significantly less superior glenohumeral translation when compared to the supraspinatus deficient model.[24] Conversely, Tibone et al.[44] demonstrated improved reduction in superior translation of the humeral head measured at 0 degrees glenohumeral abduction when the dermal allograft was tensioned at 40 degrees glenohumeral abduction compared to tensioning at 20 degrees glenohumeral abduction.

As mentioned previously, surgical practice patterns vary with use of either autograft (fascia lata or dermis) or commercially available allografts for superior capsule reconstruction being described. Comparative biomechanical studies have evaluated the differences in each graft's ability to maintain humeral head position in rotator cuff deficient cadaveric models.[4,23] Mihata et al.[23] reported that an 8mm thick fascia lata graft resulted in significantly less superior translation when compared to a 3.5mm single-layer dermal allograft in the setting of supraspinatus deficiency. However, this difference was no longer observed in a subsequent study comparing 7.3mm thick fascia lata superior capsular reconstruction to a double-layer dermal allograft of 6.4mm thickness.[4] Both allograft and autograft options seem to be sufficient, as long as thickness is maintained. Unfortunately, each study demonstrated that both fascia lata and dermal allograft tissues stretched (i.e., crept) during testing with a significant decrease in mean thickness, suggesting that the effectiveness of the grafts may decrease over time.

Currently, no optimal treatment option exists for the management of massive, irreparable rotator cuff tears. Several options have demonstrated an ability to prevent the altered glenohumeral kinematics seen in rotator cuff deficiency in vitro. However, graft failure, graft stretching, and resorption of the subacromial balloon could result in loss of the glenohumeral kinematic benefit over time.

Previous cadaveric work on a massive irreparable rotator cuff deficient shoulder demonstrated that a 5mm high constraint rigid subacromial implant restored humeral head position during scapular plane abduction such that it was not statistically different than the native intact shoulder state at 0-, 30-, and 60-degrees of glenohumeral scaption.[7] A follow-up investigation revealed that when paired with a tuberoplasty of the exposed greater tuberosity the lateral impingement was mitigated resulting in improved range of motion. The intention of this device would be to provide a permanent implantable solution to the altered glenohumeral kinematics that occurs in rotator cuff deficiency.

In light of the foregoing, the objective of this study was to perform a biomechanical comparison of a rigid subacromial implant, a superior capsular reconstruction, and a subacromial balloon spacer in a massive rotator cuff deficient cadaveric model. The effects on glenohumeral kinematics, namely superior-inferior and anterior-posterior humeral head translation will be investigated. It was hypothesized that each surgical state would restore near normal humeral head position in the presence of a massive, irreparable rotator cuff tear state in terms of superior-inferior translation. Furthermore, it was hypothesized that the superior capsular reconstruction and the rigid subacromial implant would restore anterior-posterior humeral head position, whereas the subacromial balloon spacer will increase anterior humeral head translation relative to the intact shoulder state.

2.2 Methods

2.2.1 Cadaver & Simulator Preparation

Nine male right cadaver shoulders with a mean age of 74 ± 15 years (age range: 49 – 101 years) were utilized for testing. All shoulders were screened with computerized tomography (CT) scans and inspected to confirm the absence of glenohumeral joint pathology or rotator cuff insufficiency. Specimens were transected at the mid-humeral level with the scapula, clavicle, and respective soft tissues preserved. Each shoulder was thawed for 18 hours prior to testing. The overlying skin, soft-tissue, muscle, ligaments, and joint capsules were maintained.

Each rotator cuff muscle was identified and tagged at its tendon insertion with heavy, non-absorbable, braided suture (#5 Ethibond, Ethicon, Johnson & Johnson, New Jersey, USA). The supraspinatus, infraspinatus, and teres minor were identified and tagged through a lateral deltoid split approach. The subscapularis was identified and tagged along the anterior surface of the exposed scapula with two sutures to represent the upper and lower aspects of the tendon. The deltoid muscle and its anterior, middle, and posterior heads were tagged with three transosseous sutures through a single 2.0mm corticotomy located at the deltoid tuberosity on the lateral aspect of the transected humerus.

Full thickness dermis was harvested from the skin overlying the posteromedial border of the scapula at time of specimen preparation for later use as an autograft dermal superior capsular reconstruction.

Each specimen was affixed to a previously developed custom shoulder simulator (Figure 2-1 & Figure 2-2).[7,8] Two metal brackets were connected by two transosseous bolts to the medial scapular body inferior to the scapular spine. This allowed the scapula to be rigidly fixed to the testing apparatus in a physiologic position with roughly 10-20 degrees of anterior tilt and roughly 10-20 degrees of external rotation. An intramedullary humeral rod assembly was cemented into the prepared humeral canal. Optical tracking markers (Certus, Northern Digital, Ontario, Canada) were secured to the superomedial scapular body and the intramedullary humeral rod assembly. This allowed tracking of the relative position of the scapula and humerus during testing. A six degree of freedom load cell (ATI, Apex, North Carolina, USA) was attached to the intramedullary humeral rod assembly.

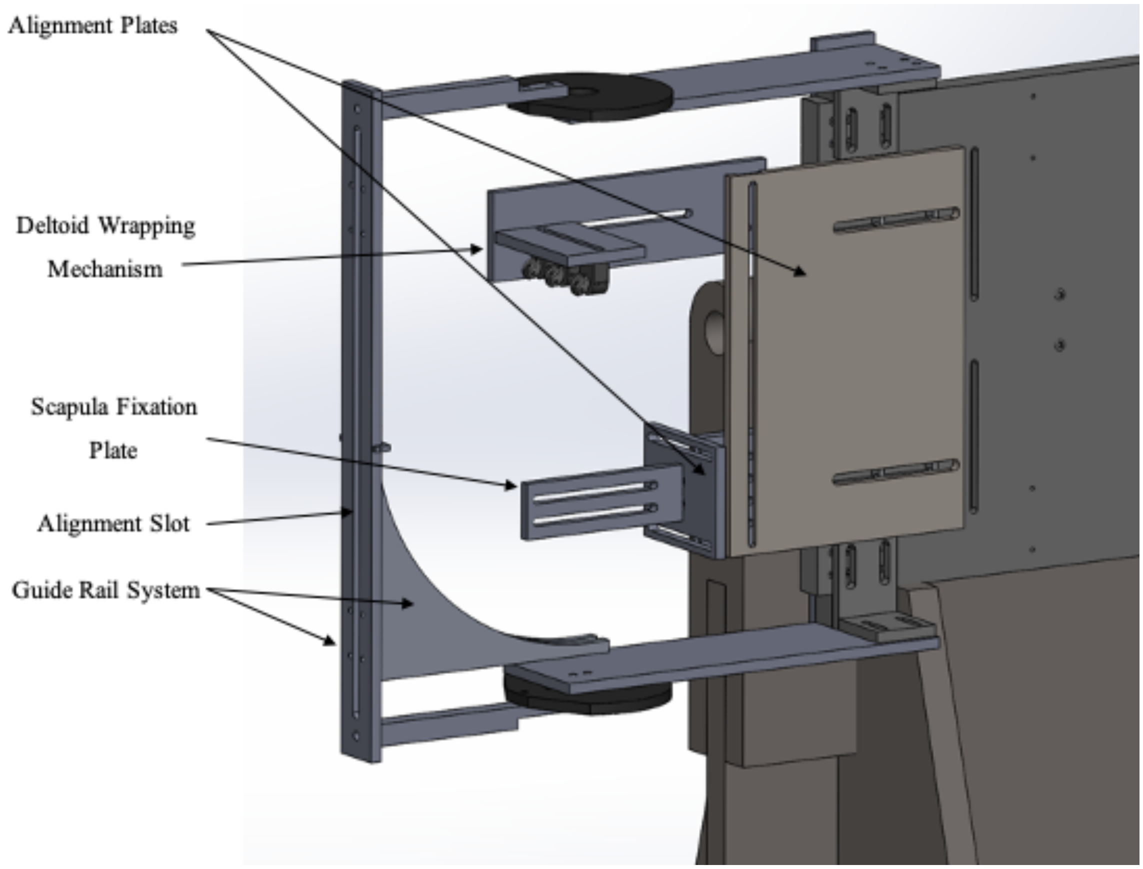

Figure 2-1: Shoulder simulator design for testing

The specimen is attached to the scapular fixation plate. The alignment plates allow medial-lateral and anterior-posterior translation of the specimen to centralize the glenohumeral joint. The guide rail system and alignment slot are positioned to permit abduction within the scapular plane. The deltoid wrapping mechanism allows precise positioning of the pulley system.

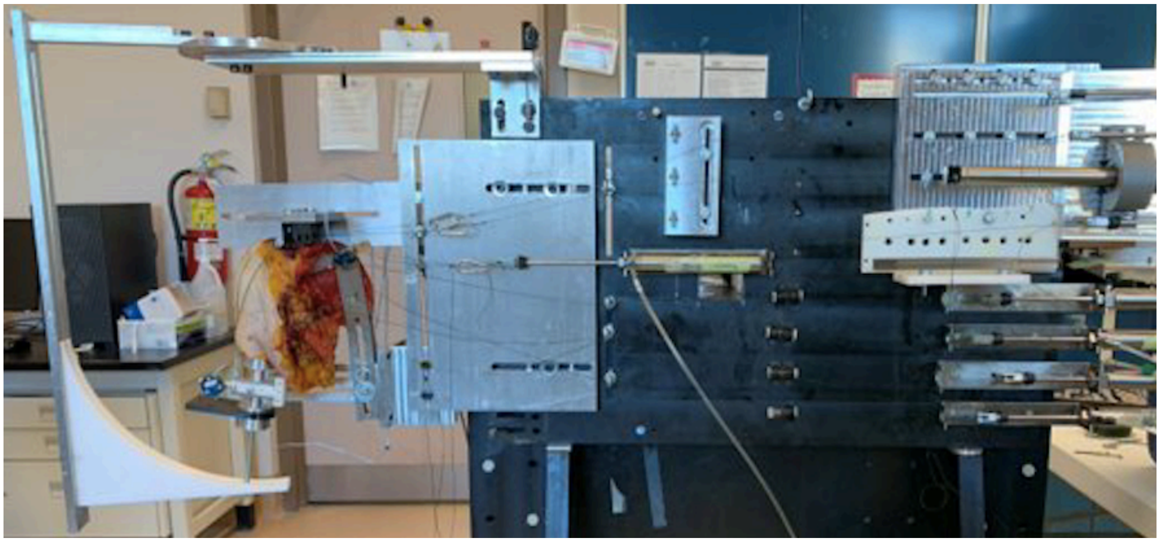

Figure 2-2: Specimen affixed to the shoulder simulator

Demonstration of a right shoulder specimen attached to the shoulder simulation with illustration of the component parts of the simulator. The pneumatic actuators are pictured to the far right of the image.

The intramedullary humeral rod assembly was positioned within the alignment slot of the abduction guide rail in the scapular plane. The abduction guide rail permitted free internal and external rotation of the humerus during testing while promoting abduction within the scapular plane. Scaption angles of interest (0, 15, 30, 45, and 60 degrees) were marked on the abduction guide rail with use of a digital goniometer. Since the scapula was rigidly fixed to the simulator, all motion observed was through the glenohumeral joint and therefore represented 0-, 20-, 45-, 68-, and 90-degrees of combined abduction assuming the typical 2:1 ratio of glenohumeral to scapulothoracic motion. The humeral head was free to rotate and translate in all planes.

Braided, high-strength line was used to connect each sutured tendon to its dedicated pneumatic actuator. Each rotator cuff tendon line was positioned within the shoulder simulator to best replicate the physiologic line of action of the muscle-tendon unit. The deltoid tendon lines were routed through a custom two degree of freedom deltoid pulley system (Figure 2-3). This allowed each head of the deltoid to alter its line of action independent of the other deltoid lines as the position of the shoulder changed during testing. The posterior pulley was positioned superior to the posterolateral corner of the acromion. The middle pulley was positioned superior to the middle of the acromion. The anterior pulley was positioned superior to the anterolateral corner of the acromion. Each pulley was medialized to the level of the scapular notch to simulate the deltoid wrapping effect over external soft tissues of the shoulder.

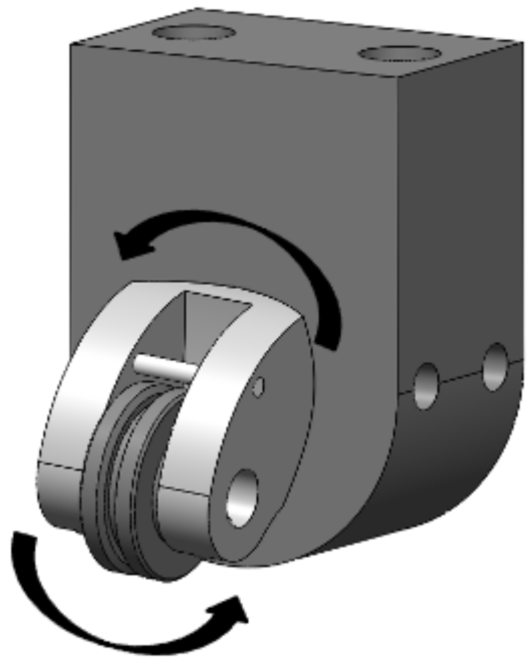

Figure 2-3: Two degree of freedom deltoid pulley

The custom system allows the pulley to rotate to maintain the deltoid muscle line of pull during shoulder range of motion.

A custom LabVIEW (Texas Instruments, Austin, Texas, USA) code was developed to provide static muscle loading to each individual muscle using the pneumatic actuators. Static muscle loads were based on previous cadaveric studies investigating superior humeral head translation in massive rotator cuff tear models.[26,33,39]

2.2.2 Testing Variables

2.2.2.1 Intact Rotator Cuff (Balanced Load)

The initial test state was that of a healthy shoulder with an intact rotator cuff. This test state was utilized to establish baseline values for humeral head translation during scaption in both superior-inferior and anterior-posterior directions. The rotator cuff force-couples were in a balanced state as previously described in the literature.[4,24–26,33,37–39]

2.2.2.2 Intact Rotator Cuff (Unbalanced Load)

This test state was identical to the intact balanced test state except that the force spread across the three heads of the deltoid was increased from 40N to 80N. This protocol has been established in several biomechanical studies and promotes superior migration of the humeral head on the glenoid articular surface.[4,24–26,33,37–39] This state was also utilized as a baseline reference test state.

2.2.2.3 Massive Irreparable Rotator Cuff Tear

The lateral deltoid split was used to expose the rotator cuff tendon insertions. A massive irreparable rotator cuff tear was simulated by excising the supraspinatus and the upper infraspinatus tendon from its insertion (Figure 2-4). Beginning at the bicipital groove, the rotator interval was opened to identify the anterior edge of the supraspinatus tendon. The biceps tendon was transected at its labral attachment. The rotator cuff footprint was then elevated off the anterior greater tuberosity and the supraspinatus and anterior half of the infraspinatus tendons were excised with their superior capsule attachments as far as the glenoid rim medially.[4,30] The subscapularis and teres minor tendons were left intact. The actuator lines for the supraspinatus and infraspinatus were removed.

Figure 2-4: Simulated massive irreparable rotator cuff tear

Lateral view of a right shoulder through a deltoid split. Demonstration of a simulated massive rotator cuff tear with resection of the supraspinatus and anterior half of the infraspinatus tendon.

The lateral shoulder incision was utilized again for exposure of the subacromial space and preparation of implantation of the subacromial balloon spacer. Following the surgical technique of the manufacturer, the distance was measured from 1cm medial to the glenoid rim to the greater tuberosity and an appropriate implant was selected.[34] Each specimen measured to fit the large subacromial balloon spacer.

The subacromial balloon was then inflated with normal saline to its maximal fill volume (40mL) before withdrawing fluid until the final recommended fill volume (25mL) was achieved.[34] The subacromial balloon was secured with a custom device to prevent back-flow of fluid and positioned within the subacromial space (Figure 2-5). Following completion of testing the final resting position of the subacromial balloon was noted relative to its initial implantation position.

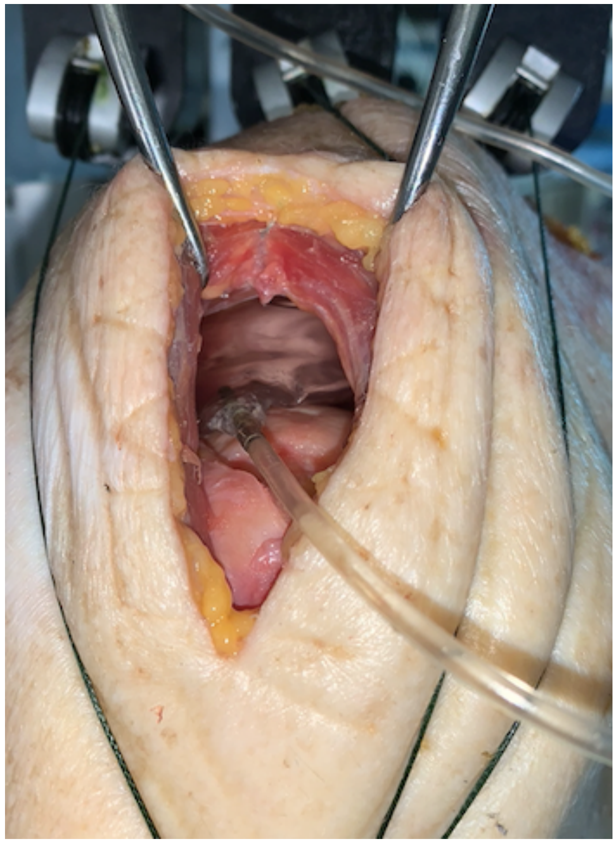

Figure 2-5: Inflated subacromial balloon spacer

Visualization of the right shoulder through a deltoid split approach. Inflated subacromial balloon spacer sits within the subacromial space. Custom tubing is seen exiting the lateral deltoid split.

2.2.2.4 Superior Capsular Reconstruction

Through the same lateral exposure, the subacromial balloon was deflated and retrieved from the subacromial space and a superior capsule reconstruction was completed through the deltoid split exposure. Glenoid measurements were taken from the remaining posterosuperior capsule to the level of the superior glenoid tubercle (12 o’clock position) as well as from the glenoid articular surface to the greater tuberosity.

Previously harvested autograft dermis was then prepared for implantation. Subcutaneous tissue was excised, leaving a full-thickness dermal graft. The graft was folded on itself to create a double thickness construct which was shaped to the appropriate dimensions.[4] A heavy braided suture (#1 Vicryl, Ethicon, Johnson & Johnson, New Brunswick, New Jersey, USA) was used to secure the graft circumferentially in its doubled position. Graft thickness was measured with digital calipers.

The graft was visualized within the joint to ensure sizing was correct. Once this was confirmed, two 2.8mm Q-FIX^{TM} all-suture anchors (Smith & Nephew, London, UK) were placed in the glenoid. The first was in the posterosuperior glenoid near the edge of remaining infraspinatus and posterosuperior capsule. The second was placed in the superior glenoid tubercle at the 12 o'clock position. Each of these anchors allowed placement of mattress stitches within the medial aspect of the graft. The graft was then tied securely to the glenoid with a series of sliding, locking knots followed by alternating half-hitches. Laterally, two 5.5mm Healicoil^{TM} suture anchors (Smith & Nephew, London, UK) were placed in the humerus medial to the greater tuberosity at the site of previous capsule insertion. The arm was maintained in 30 degrees of scaption, and the graft was tensioned with lateral traction. Mattress stitches were placed through the graft at the site of each medial anchor. A suture bridge construct was created with use of a lateral row 4.5mm knotless anchor (Footprint Ultra PK, Smith & Nephew, London, UK) that was placed laterally into the greater tuberosity. Excess lateral graft was excised to prevent impingement during motion. The graft was secured to the remaining posterosuperior capsule with interrupted figure-of-eight stitches (#2 FiberWire, Arthrex, Naples, Florida, USA) as described by Mihata et al.[25] (Figure 2-6).

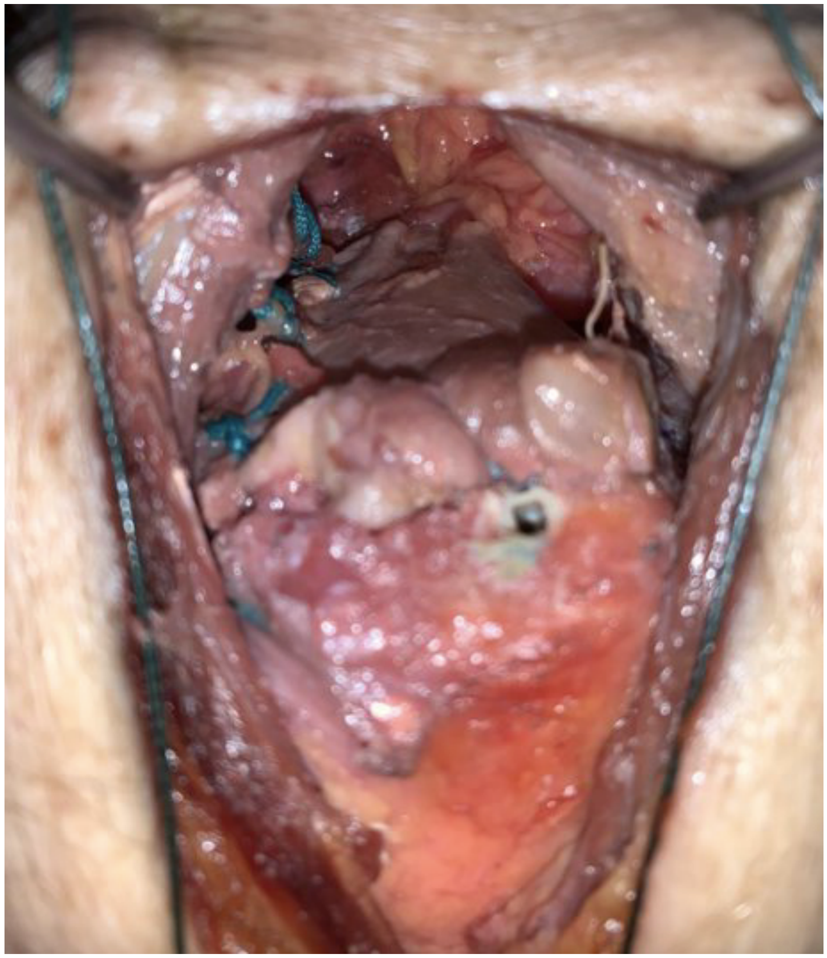

Figure 2-6: Superior capsular reconstruction with dermal autograft

Superior capsular reconstruction is visualized in the right shoulder through a deltoid split approach. The doubled dermal autograft is secured to the glenoid medially, the infraspinatus posteriorly, and the greater tuberosity laterally.

2.2.2.5 Rigid Subacromial Implant

Utilizing the previous lateral incision, the superior capsule reconstruction was removed along with all suture material, ensuring no further damage to the rotator cuff or capsule. The rigid subacromial implant was introduced through the lateral incision such that the articular plate sat flush with the undersurface of the acromion with little to no extension beyond the lateral or anterior aspect of the acromion (Figure 2-7). A transverse posterior incision was created along the inferior margin of the scapular spine. The posterior deltoid and trapezius were sectioned to allow exposure of the posterior scapular spine. The implant's fixation arm was secured to the scapular spine superior to the suprascapular nerve (Figure 2-8). Fixation was obtained through multiple 3.5mm bicortical locking screws.

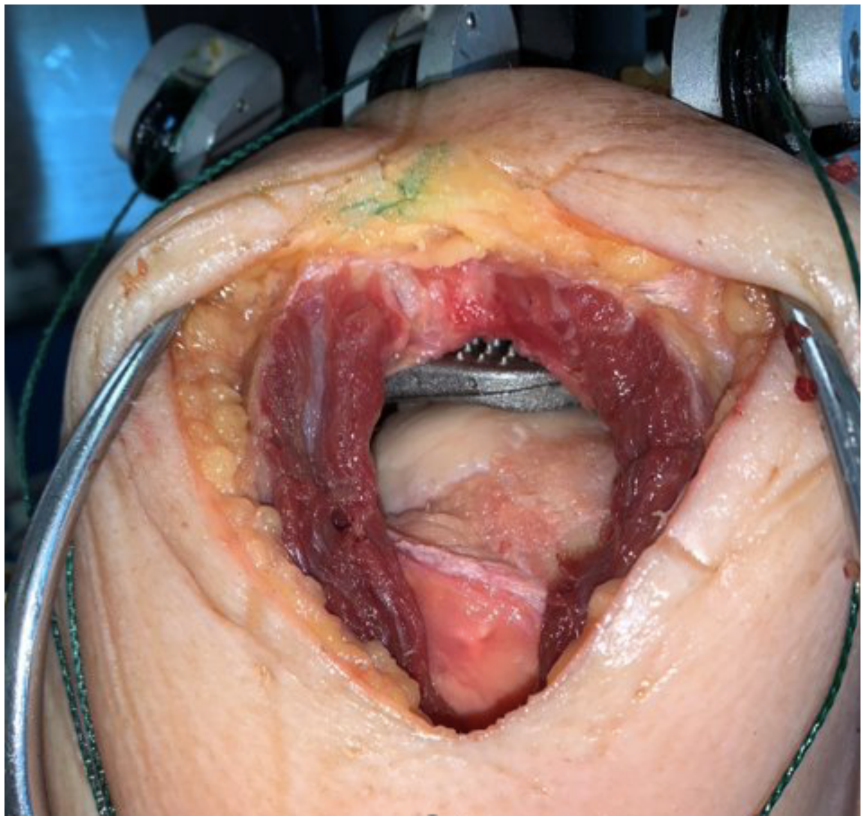

Figure 2-7: Lateral view of rigid subacromial implant

The metallic subacromial implant is positioned in the subacromial space of the right shoulder through a deltoid split approach. The articular component of the device is seen extending from the undersurface of the acromion.

Figure 2-8: Posterior view of rigid subacromial implant

Demonstration of the fixation of the metallic subacromial implant to the posterior scapular spine. Also visualized is the fixation screw for the modular articular components which were inserted posteriorly.

The 5mm low constraint and 5mm high constraint modular articular inserts were then placed from the posterior based incision and secured to the implant with a posterior fixation screw (Figure 2-9).

A B

Figure 2-9: Metallic subacromial implants

Lateral view of the subacromial implant illustrating the difference in the articular radius of curvature. (A) 5mm high constraint and (B) 5mm low constraint models.

The shoulder was passively taken through a full range of motion to identify regions of greater tuberosity impingement on the undersurface of the implant. A tuberoplasty was then performed on the portion of the greater tuberosity that was devoid of rotator cuff attachment to prevent impingement as previously described in our lab (Figure 2-10).[7]

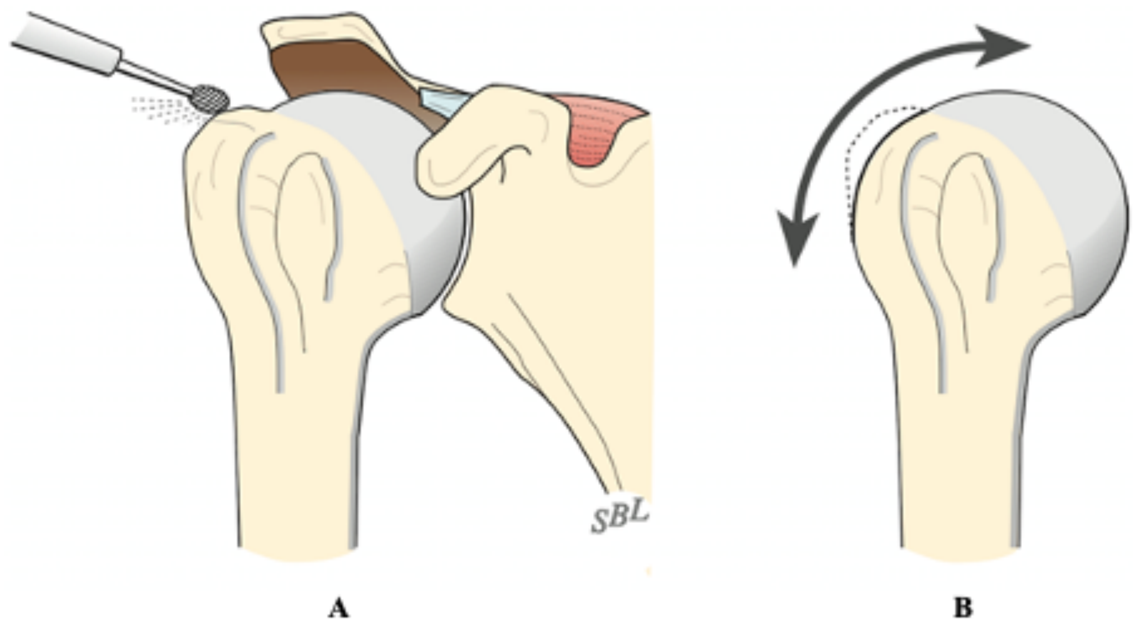

Figure 2-10: Depiction of tuberoplasty procedure

(A) Demonstration of the tuberoplasty procedure being performed with a burr. (B) Completed tuberoplasty procedure demonstrating the smooth transition between the humeral head and the lateral proximal humerus.[21]

2.2.2.6 Testing Protocol

Prior to each test state, the surgical incisions were closed in a layered fashion. The muscle splits and subcutaneous tissues were closed with 2-0 Vicryl (Ethicon, Johnson & Johnson, New Brunswick, New Jersey, USA) and the skin was closed with a non-absorbable stitch to maintain specimen integrity. The shoulder was taken through full passive range of motion in flexion, extension, abduction, adduction, internal rotation, and external rotation to eliminate any residual stiffness within the tissues. Normal saline was utilized to keep the overlying soft-tissues and articular surfaces well hydrated.

Muscle loads of 10N were applied through the supraspinatus, infraspinatus, teres minor, superior subscapularis, and inferior subscapularis. In the initial intact balanced rotator cuff test state, a 40N load was spread equally across each head of the deltoid through a custom pulley system. For the intact unbalanced rotator cuff test state, and for each subsequent test state, the deltoid load was increased to 80N. This protocol has been well established in the literature when facilitating proximal humeral head translation in the normal shoulder as well as the shoulder with rotator cuff deficiency.[4,24–26,33,37–39] Following the introduction of a massive irreparable rotator cuff tear there was no longer any load applied through the discarded supraspinatus and infraspinatus. Additionally, the remaining rotator cuff force-couples were restored maintaining a 10N load in the teres minor muscle and decreasing the load to 5N in the superior subscapularis and 5N in the inferior subscapularis.

Each test state began with initiation of the pneumatic actuators. The humerus was then positioned within the alignment slot of the abduction guide rail at 0-degrees of glenohumeral abduction and optical tracking data was recorded from the scapula and humerus for 5 seconds. The humerus was subsequently positioned at 15-, 30-, 45-, and 60-degrees of glenohumeral abduction, following a similar protocol.

2.2.2.7 Digitization

Following completion of testing, the specimen was denuded of all soft tissue. The articular surfaces of the humeral head and glenoid were traced using a stylus attached to an optical tracker. Point data from the humeral head articular tracings were sphere-fit[13] in MATLAB (MathWorks, Natick, MA, USA) to determine the center of rotation of the humeral head. The central bare spot of the glenoid as well as the superior, anterior, inferior, and posterior margins of the glenoid were recorded to provide the reference value for superior-inferior and anterior-posterior axes. A coordinate system was then developed to quantify the position of the humeral head center of rotation relative to the glenoid articular surface in superior-inferior and anterior-posterior axes.[7,33,37–39]

2.2.3 Outcome Variables

The outcome variables of interest were the translation of the humeral head center of rotation on the glenoid in the superior-inferior direction and anterior-posterior direction. Superior translation and anterior translation were expressed as positive integer values. All translation values were initially recorded as values relative to the central bare spot of the glenoid. Following this, the intact balanced state was utilized as the reference value for the reporting of the subsequent test states. This allowed for direct comparison of the rotator cuff deficient and surgical test states relative to the intact balanced test state.

2.2.4 Statistical Analysis

Statistical analysis was carried out using a two-way repeated measures analysis of variance (RM-ANOVA) in SPSS (IBM, Armonk, NY, USA). The independent variables were the abduction angle and test state, and the dependent variables were superior-inferior (SI) and anterior-posterior (AP) translation of the humeral head. A Bonferroni correction was used to correct for the multiple statistical analyses performed, with the significance value set as $p<0.05$.

2.3 Results

2.3.1 Superior-Inferior Translation

The intact rotator cuff with balanced loading resulted in an average of 2.6 ± 2.1mm of superior translation relative to the central bare spot of the glenoid across all tested angles of scapular abduction (Figure 2-11). The use of the unbalanced loading condition in the intact rotator cuff state led to an additional 0.7 ± 0.9mm of superior translation. The simulation of a massive irreparable rotator cuff tear resulted in 1.6 ± 1.3mm of superior translation relative to the intact reference state. This increase in superior translation was not statistically significant compared to the intact unbalanced test state ($P > 0.05$).

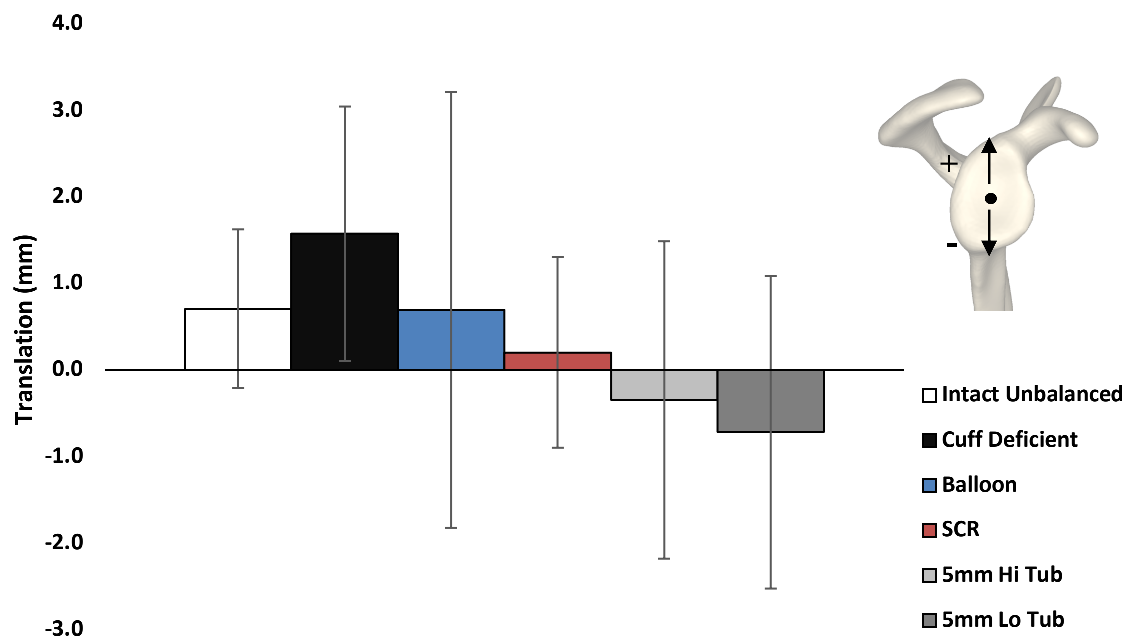

Figure 2-11: Superior-inferior translation (mean ± 1 SD) of the humeral head

Values are averaged across all angles of abduction and are reported relative to the intact balanced shoulder state. Superior translation is represented as a positive value whereas inferior translation is a negative value. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint implant with tuberoplasty. 5mm Lo Tub = 5mm low constraint implant with tuberoplasty.

All four surgical test states were successful in reducing the overall mean superior translation seen in the massive irreparable rotator cuff tear state. The subacromial balloon restored the humeral head position to that of the intact unbalanced shoulder with superior translation of 0.7 ± 2.2mm, however this difference was not statistically significant when compared to the massive irreparable rotator cuff tear state ($P > 0.05$). The superior capsular reconstruction reduced the superior translation observed in the massive rotator cuff tear state by 1.4mm to a mean of 0.2 ± 0.8mm of superior translation ($P = 0.015$). This value demonstrates relative inferior translation compared to the intact unbalanced rotator cuff state ($P > 0.05$). Both the 5mm high constraint and 5mm low constraint subacromial implants resulted in less superior translation than the intact rotator cuff with balanced loading. The 5mm high constraint implant demonstrated 0.3 ± 1.6mm of inferior translation compared to the intact balanced shoulder. This represented 1.9mm less superior translation than was observed in the simulated massive irreparable rotator cuff tear ($P = 0.018$). Whereas the 5mm low constraint implant resulted in 0.7 ± 1.8mm of inferior translation relative to the intact balanced shoulder. This represented 2.3mm less superior translation than the massive irreparable rotator cuff tear state ($P = 0.027$).

There were no statistically significant differences noted between the subacromial balloon spacer, superior capsular reconstruction, or the rigid subacromial implants at any shoulder angle ($P > 0.05$). Figure 2-12 demonstrates the average superior-inferior translation of the humeral head for the test states at each of the 5 arm positions tested. The values are reported relative to the translation observed in the intact rotator cuff test state with balanced muscle loading. At 0 degrees of scaption, the massive irreparable rotator cuff state resulted in significantly more superior translation than the intact state, superior capsular reconstruction, and both the 5mm high constraint and 5mm low constraint implants, respectively (2.1mm, $P = 0.003$; 2.6mm, $P = 0.002$; 2.5, $P = 0.041$; 2.8mm, $P = 0.035$). No significant differences were observed between any test states at 15 degrees of scaption. At 30 degrees of scaption, the 5mm high constraint implant demonstrated significantly less superior translation than the intact unbalanced rotator cuff state (1.2mm, $P = 0.026$). At 45 degrees of scaption, the 5mm high constraint and the 5mm low constraint implant resulted in significantly less superior translation than the intact unbalanced shoulder and the massive irreparable rotator cuff tear state (5mm high: 1.4mm, $P = 0.048$; 1.5mm, $P = 0.016$; 5mm low: 1.9mm, $P = 0.038$; 2.0mm, $P = 0.008$, respectively). Lastly, at 60 degrees scaption, the 5mm high constraint implant resulted in 1.4mm less superior translation than the massive irreparable rotator cuff tear state ($P = 0.041$). Whereas the 5mm low constraint implant demonstrated 1.9mm less superior translation than the intact unbalanced rotator cuff tear state and the rotator cuff deficient state, respectively ($P = 0.029$, $P = 0.015$).

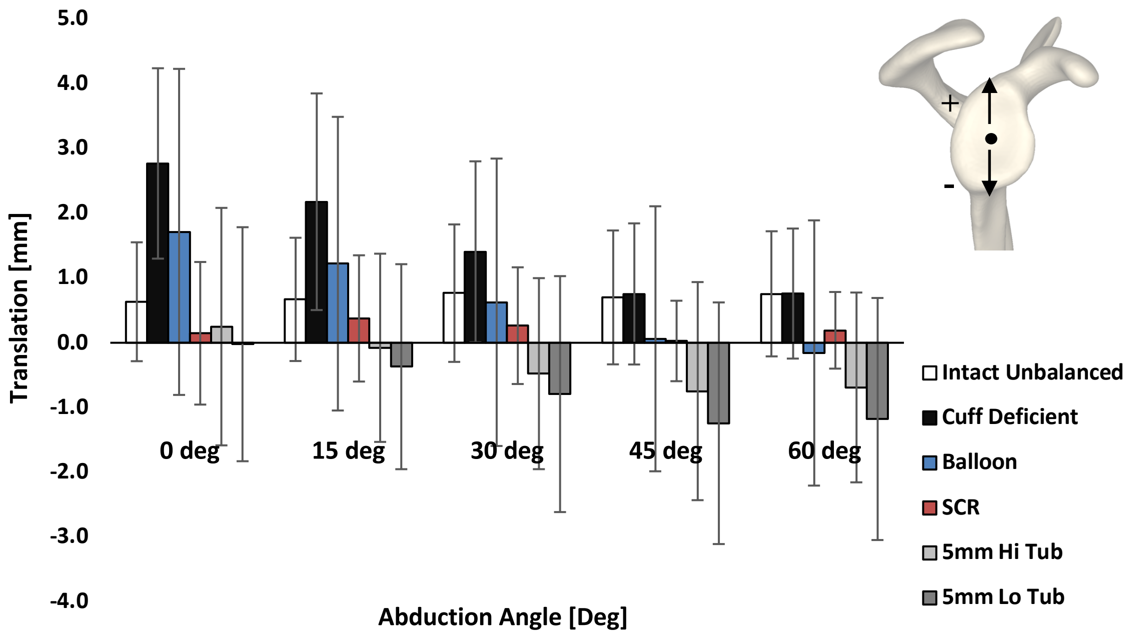

Figure 2-12: Superior-inferior humeral head translation (mean ± 1 SD)

Values are provided for each angle of abduction tested. Each value is reported relative to the intact balanced shoulder state. Superior translation is represented as a positive value whereas inferior translation is a negative value. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint implant with tuberoplasty. 5mm Lo Tub = 5mm low constraint implant with tuberoplasty.

2.3.2 Anterior-Posterior Translation

The intact rotator cuff with balanced loading resulted in an average of 1.2 ± 1.1mm of anterior translation relative to the central bare spot of the glenoid across all tested angles of scapular abduction (Figure 2-13). The use of an unbalanced loading condition in the intact rotator cuff state led 0.8 ± 0.9mm of posterior translation relative to the balanced state. Following the simulation of a massive irreparable rotator cuff tear there was 3.8 ± 2.7mm of posterior translation relative to the intact balanced rotator cuff state. This was an increase of 3.0mm compared to the intact unbalanced state ($P = 0.045$).

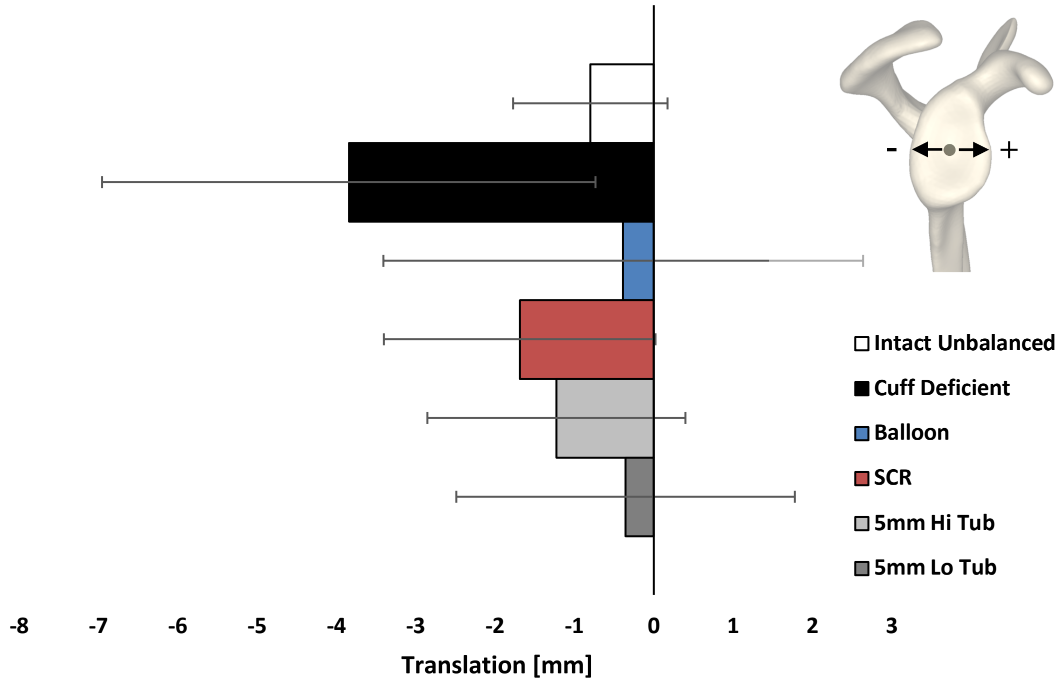

Figure 2-13: Anterior-posterior humeral head translation (mean ± 1 SD)

Values are averaged across all angles of abduction and are reported relative to the intact balanced shoulder state. Anterior translation is represented as a positive value whereas posterior translation is a negative value. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint implant with tuberoplasty. 5mm Lo Tub = 5mm low constraint implant with tuberoplasty.

Each of the four surgical test states reduced the posterior translation observed in the massive irreparable rotator cuff tear state. However, despite the subacromial balloon restoring humeral head position to 0.4 ± 2.8mm of posterior translation, there was no statistically significant difference compared to the massive irreparable rotator cuff tear state ($P > 0.05$). The superior capsular reconstruction demonstrated 1.7 ± 1.6mm of posterior translation relative to the intact balanced state. This was a 2.2mm reduction in the posterior translation of the massive irreparable rotator cuff tear state ($P = 0.013$). The 5mm high constraint subacromial implant exhibited 1.2 ± 1.7mm of posterior translation, which was a reduction of 2.6mm of posterior translation as compared to the massive irreparable rotator cuff tear state ($P = 0.037$). Whereas the 5mm low constraint subacromial implant performed like the subacromial balloon with an average posterior translation of 0.4 ± 2.1mm and a reduction of 3.5mm of posterior translation compared to the massive irreparable rotator cuff tear state (P = 0.008). When comparing the 5mm high constraint to the 5mm low constraint implant, the 5mm low constraint implant resulted in 0.9mm less posterior translation (P = 0.021).

Figure 2-14 demonstrates the average anterior-posterior humeral head translation of each test state for the scapular abduction angles tested. The massive irreparable rotator cuff tear state demonstrated significantly more posterior translation than the intact rotator cuff test state at 0-, 15-, and 30- degrees of glenohumeral abduction (3.9mm, P = 0.033; 3.8mm, P = 0.048; 3.8mm, P = 0.036). However, at 45 and 60 degrees of glenohumeral abduction, these differences no longer remained significant (2.6mm, P > 0.05; 1.0mm, P > 0.05). No significant differences were observed between the intact rotator cuff tear state and any of the surgical states at any arm position (P > 0.05). The subacromial balloon did not demonstrate statistically significant improvements upon the massive irreparable rotator cuff tear state at any arm angle (P > 0.05). The superior capsule reconstruction significantly improved the posterior translation observed in the massive irreparable rotator cuff tear test state at 0-, 15-, and 30-degrees of glenohumeral abduction (3.5mm, P = 0.009; 2.8mm, P = 0.021; 2.3mm, P = 0.042). The 5mm high constraint implant corrected the posterior translation observed in the massive irreparable rotator cuff tear state, however there were no statistically significant differences seen compared to the intact or cuff deficient test state at any arm position (P > 0.05). The 5mm low constraint implant reduced the posterior translation of the rotator cuff deficient test state at 0-, 15-, 30-, 45-, and 60- degrees glenohumeral abduction (3.7mm, P = 0.037; 3.7mm, P = 0.034; 3.8mm, P = 0.019; 3.4mm, P = 0.017; 3.0mm; P = 0.012). Additionally, the 5mm low constraint implant resulted in further reduction of posterior translation when compared to the 5mm high constraint implant at 0 degrees and 45 degrees of glenohumeral abduction (1.1mm, P = 0.011; 0.8mm, P = 0.018). Similarly, at 45 degrees glenohumeral abduction the 5mm low constraint implant led to a further 1.9mm correction of posterior translation compared to the superior capsular reconstruction (P = 0.011).

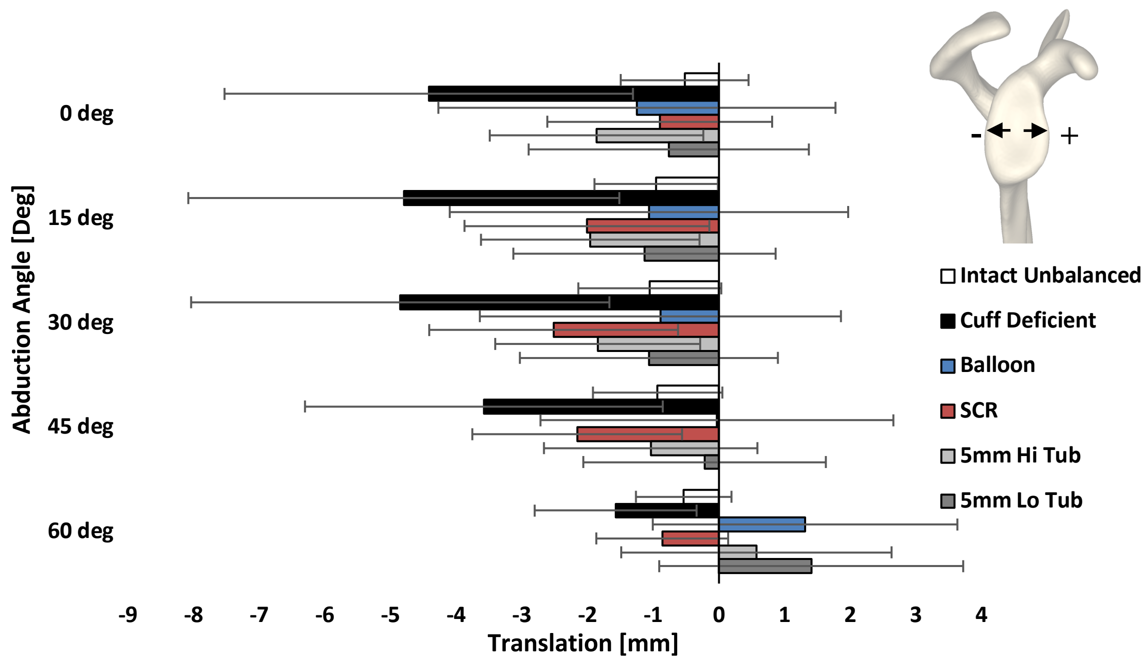

Figure 2-14: Anterior-posterior humeral head translation (mean ± 1 SD)

Values are provided for each angle of abduction tested. Each value is reported relative to the intact balanced shoulder state. Anterior translation is represented as a positive value whereas posterior translation is a negative value. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint implant with tuberoplasty. 5mm Lo Tub = 5mm low constraint implant with tuberoplasty.

2.4 Discussion

In this study, a cadaveric shoulder simulator was utilized to perform a comparative study of the subacromial balloon spacer, superior capsular reconstruction, and a rigid subacromial implant in a massive irreparable rotator cuff deficient model. Both the shoulder simulation apparatus and the testing protocol appeared to replicate the glenohumeral kinematics of an intact shoulder as well as a rotator cuff deficient shoulder. During balanced muscle loading, the intact shoulder state demonstrated 2.6 ± 2.1mm of superior humeral head translation and 1.2 ± 1.1mm of anterior humeral head translation. Relative posterior and inferior translation were observed at higher angles of abduction. Both these values, and these trends in motion, are consistent with what has been previously reported in the shoulders of healthy individuals during scapular plane abduction.[9,11,22] With increased deltoid muscle loads in the unbalanced test state there was additional posterior and superior translation of the humeral head. This has been observed in several cadaveric studies that have implemented a similar protocol for promoting proximal migration of the humeral head.[4,23–26,33,38,39,44] Following the simulated massive irreparable rotator cuff tear there was additional superior humeral head translation as well as significantly more posterior humeral head translation when compared to the intact unbalanced test state. Again, these observed changes have been previously well documented both *in vivo* as well as *in vitro*.[4,12,16,18,23–28,30,33,38,39,41,42,44,46]

The greatest amount of superior humeral head translation was observed at 0 degrees of scapular plane abduction for all test states. Superior translation of the humeral head relative to the intact balanced shoulder decreased in magnitude with increasing angle of scapular plane abduction for all test states except for the superior capsular reconstruction at 15-degrees abduction. A probable explanation for this would be the muscle forces acting on the humerus during scapular plane abduction. In our simulator, the primary deforming force was that of the deltoid muscle. At low angles of abduction, the line of action of the deltoid muscle is primarily in the superior direction. This has been previously established when examining the moment arm of the deltoid muscle in various arm positions.[1,31] Whereas at higher angles of scapular abduction, the abduction moment arm of the deltoid increases as the line of pull moves more medial creating increased glenohumeral compressive forces. This is particularly important in rotator cuff deficiency as there is decreased capacity to mitigate the deforming forces of the deltoid muscle, specifically at low angles of abduction, due to loss of the force-couple and concavity-compression mechanisms. Our results demonstrated increased posterosuperior translation of the humeral head in this context. The superior capsular reconstruction differed in that it was tensioned at 30-degrees of glenohumeral abduction, therefore, as the arm was positioned at 0-degrees of abduction the resistance to superior migration was the greatest. This effect dissipated at 15-degrees abduction as tension was decreased, and thus a subtle increase in superior translation was observed.

It has been previously hypothesized that excessive glenohumeral superior translation, eccentric wear on the glenoid, impingement and articulation with the undersurface of the acromion, poor nutritional environments, and fragmentation of the cartilage surfaces of the humerus can precipitate the progression of rotator cuff tear arthropathy.[3,14] Therefore, that any surgical intervention that can mitigate this process in part or in whole may have beneficial effects of delaying the progression of rotator cuff tear arthropathy.

Each surgical state was effective at reducing the posterosuperior translation observed in the simulated massive irreparable rotator cuff tear. However, only the superior capsular reconstruction and the subacromial implants significantly improved upon the massive irreparable rotator cuff tear state for both planes of motion. Specifically, at 0 degrees of abduction where superior translation was the greatest magnitude, only the superior capsular reconstruction and the subacromial implants provided a statistically significant correction in the context of a massive irreparable rotator cuff tear. The balloon demonstrated no statistically significant differences from either the intact unbalanced state or the massive irreparable rotator cuff tear state at any time point. When considering the balloon in isolation, the data was highly variable in terms of the impact on superior-inferior translation and anterior-posterior translation of the humeral head. In our study, we filled the balloon to the recommended volumes based on the manufacturer's guidelines. However, as the balloon is unconstrained and free to move within the subacromial space, we observed that the balloon would often shift its position during testing. Following our protocol, the balloon was identified in several positions including the subacromial space, posterior to the teres minor tendon, anterior to the subscapularis tendon, or along the lateral deltoid recess. This does not seem to be as apparent in the clinical literature with only three reported cases of balloon displacement, therefore it may be a limitation of our cadaveric simulation.[32,36,45] Compared to previous studies, we did not observe consistent excessive inferior and anterior translation of the humeral head relative to the intact rotator cuff tear state, except for at 60-degrees glenohumeral abduction.[20,38] This may be explained by the degree of balloon displacement observed in our study as the implantation protocols were similar in each study.

The superior capsular reconstruction provided significant correction of the posterior and superior humeral head translation seen in the massive irreparable rotator cuff tear state at 0-degrees abduction. Beyond this, there were no significant differences between the superior capsular reconstruction, intact shoulder, or rotator cuff deficient shoulder in terms of superior humeral head migration. The superior capsular reconstruction also provided significant corrections in posterior humeral head translation at 15- and 30-degrees of abduction when compared to the rotator cuff tear deficient state. Although the superior capsular reconstruction appears to control the posterosuperior translation of the humeral head observed in rotator cuff deficiency, a common trend is that the difference between the rotator cuff deficient state and superior capsular reconstruction diminishes at higher angles of abduction.[24–26,39] There is a likely anatomical explanation for this. The superior capsule reconstruction is typically tensioned in about 15-45 degrees of abduction. During low angles of abduction, the superior capsule reconstruction has increased tension resulting in depression of the humeral head. At midrange of abduction, the superior capsular reconstruction loses its tension and acts as a biologic spacer and a passive barrier to translation of the humeral head. As a result, the thickness of the graft would contribute to the ability of the graft to prevent translation. At high angles of abduction, the greater tuberosity clears the acromion, and the passive effect of the graft is lost. At this juncture, the glenohumeral translation is primarily affected by the line of pull of the deltoid muscle and the abutment of the lateral humeral shaft on the undersurface of the acromion. This relationship between the proximal humeral bony anatomy and the undersurface of the acromion was previously described using fluoroscopy.[10] From resting position to roughly 30 degrees of scaption the point of minimal acromiohumeral distance was located at the superior humeral articular margin. As scaption increased from 30 degrees to roughly 70 degrees, the point of minimal distance was between the acromion and the rotator cuff footprint. Beyond this, the area of minimal acromiohumeral distance was between the acromion and the lateral humeral shaft.[10] This could explain the similarities between intact shoulder states, rotator cuff deficient states, and the superior capsular reconstruction at higher angles of abduction as the graft would no longer be contributing as a spacer.

The 5mm low constraint and 5mm high constraint subacromial implants significantly reduced the posterior and superior humeral head translation observed in the massive irreparable rotator cuff tear state. With the addition of a tuberoplasty procedure there was no visualized impingement between the implant and the proximal humerus. This is consistent with previous reports.[7] Both subacromial implants lead to an overcorrection of the superior and posterior humeral head translation seen in the rotator cuff tear state such that there was relative inferior and anterior translation when compared to the intact balanced shoulder state. Anterior translation relative to the intact balanced shoulder state was noted at 60-degrees abduction. The 5mm low constraint implant demonstrated more anterior translation than the 5mm high constraint implant. The smaller radius of curvature of the high constraint implant appears to prevent anterior translation of the humeral head compared to the low constraint implant. With a larger radius of curvature, the low constraint implant has a flatter surface and may promote increased anterior translation. The increased inferior translation relative to the intact balanced state was observed beginning at 15-degrees of scapular plane abduction. The amount of relative inferior translation increased with larger angles of abduction. There were significant differences noted when compared to the intact unbalanced state for the 5mm high constraint implant at 30 and 45-degrees, and the 5mm low constraint implant at 45 and 60-degrees. It should be noted that the humeral head position, although inferior to the intact balanced shoulder state, was still superior to the central bare spot of the glenoid. These results are consistent with the previous work completed on this implant.[7]

This study has limitations. Cadaveric specimens may not replicate the clinical scenario seen *in-vivo*. However, measures were taken to reduce the discrepancies. Soft-tissue structures including skin, fat, muscle, tendon, ligament, and capsule were left intact to replicate the normal shoulder environment. All tissues were kept hydrated with normal saline throughout testing to maintain their integrity. Total test time was kept under the previously documented critical time threshold for maintenance of mechanical properties of soft-tissues *in-vitro*.[17] Additionally, this testing protocol was based off previous work on massive irreparable rotator cuff tears in cadaveric shoulders.[24–26,33,38,39] Another limitation of the study is that the shoulder simulator applied static muscle loads which may not reflect the true dynamic loading of the muscles of the shoulder girdle. Although this has been accomplished in the past, several biomechanics studies utilize static muscle loads when assessing glenohumeral kinematics.[4,23–26,33,38,39] Lastly, our shoulder simulator did not permit scapulohumeral rhythm as the scapula was rigidly fixed to the simulator. Mixed protocols exist within the literature with respect to scapulohumeral rhythm. Our aim was to isolate glenohumeral motion during scapular plane abduction, conceding that our tested angles of 0-, 15-, 30-, 45-, and 60-degrees of abduction may in fact roughly represent 0, 20-, 45-, 70-, and 90-degrees of combined abduction and that glenohumeral translation may in fact change with motion at the scapulothoracic articulation. With respect to surgical test states, our simulation represents surgical time zero. The effects of cyclical loading and attritional wear are not apparent in our study. This has bearings on the performance of the surgical implants over time as there are reports and biomechanical studies demonstrating graft failure, graft tearing, graft stretching, balloon displacement, and balloon resorption.[4,23,32,34–36,40,45] Lastly, the optimal design and positioning of the subacromial implant is unknown. Currently, it demonstrates overcorrection both inferiorly and anteriorly relative to the intact shoulder, particularly at higher angles of abduction. Additionally, the use of a tuberoplasty requires the disruption of normal patient anatomy and indicates that the articular surface could be optimized to mitigate this requirement.

2.5 Conclusion

A comparative study was performed on a cadaveric shoulder simulation of a massive irreparable rotator cuff tear assessing glenohumeral kinematics. The superior capsular reconstruction and both rigid subacromial implants significantly reduced the posterior and superior translation associated with the massive irreparable rotator cuff tear. No statistical differences were observed between the intact shoulder and any of the surgical states. Relative overcorrection of superior translation was seen with the rigid subacromial implants from 15-60 degrees of glenohumeral abduction, as well as the balloon at 60-degrees glenohumeral abduction. Relative overcorrection of posterior translation was observed for the subacromial balloon, 5mm high constraint, and 5mm low constraint subacromial implants at 60-degrees glenohumeral abduction. When comparing the subacromial implants, the 5mm high constraint implant appears to be more effective at restoring native humeral head position while avoiding excessive overcorrection.

2.6 References

1. Alpert SW, Pink MM, Jobe FW, McMahon PJ, Mathiyakom W. Electromyographic analysis of deltoid and rotator cuff function under varying loads and speeds. *J Shoulder Elbow Surg*. 2000;9(1):47-58. doi:10.1016/s1058-2746(00)90009-0

2. Berthold DP, Muench LN, Dyrna F, Beitzel K. Biomechanical Consequences of Rotator Cuff Tears on the Glenohumeral Joint. In: *The Failed Rotator Cuff*. Springer International Publishing; 2021:15-22. doi:10.1007/978-3-030-79481-1_3

3. Collins DN, Harryman DT. Arthroplasty for arthritis and rotator cuff deficiency. *Orthop Clin North Am*. 1997;28(2):225-239. doi:10.1016/s0030-5898(05)70282-0

4. E Cline K, Tibone JE, Ihn H, et al. Superior Capsule Reconstruction Using Fascia Lata Allograft Compared With Double- and Single-Layer Dermal Allograft: A Biomechanical Study. *Arthroscopy*. 2021;37(4):1117-1125. doi:10.1016/j.arthro.2020.11.054

5. Ecklund KJ, Lee TQ, Tibone J, Gupta R. Rotator cuff tear arthropathy. *J Am Acad Orthop Surg*. 2007;15(6):340-349. doi:10.5435/00124635-200706000-00003

6. Escamilla RF, Yamashiro K, Paulos L, Andrews JR. Shoulder muscle activity and function in common shoulder rehabilitation exercises. *Sports Med*. 2009;39(8):663-685. doi:10.2165/00007256-200939080-00004

7. Fleet C. *The Design and Evaluation of a Subacromial Implant in Restoring Normal Glenohumeral Joint Stability in the Presence of a Massive Irreparable Rotator Cuff Tear*. Western University; 2022.

8. Giles JW, Ferreira LM, Athwal GS, Johnson JA. Development and performance evaluation of a multi-PID muscle loading driven in vitro active-motion shoulder simulator and application to assessing reverse total shoulder arthroplasty. *J Biomech Eng*. 2014;136(12):121007. doi:10.1115/1.4028820

9. Giphart JE, Brunkhorst JP, Horn NH, Shelburne KB, Torry MR, Millett PJ. Effect of plane of arm elevation on glenohumeral kinematics: a normative biplane fluoroscopy study. *J Bone Joint Surg Am*. 2013;95(3):238-245. doi:10.2106/JBJS.J.01875

10. Giphart JE, van der Meijden OAJ, Millett PJ. The effects of arm elevation on the 3-dimensional acromiohumeral distance: a biplane fluoroscopy study with normative data. *J Shoulder Elbow Surg*. 2012;21(11):1593-1600. doi:10.1016/j.jse.2011.11.023

11. Graichen H, Stammberger T, Bonel H, Karl-Hans Englmeier, Reiser M, Eckstein F. Glenohumeral translation during active and passive elevation of the shoulder - a 3D open-MRI study. *J Biomech*. 2000;33(5):609-613. doi:10.1016/s0021-9290(99)00209-2

12. Itami Y, Park MC, Lin CC, et al. Biomechanical analysis of progressive rotator cuff tendon tears on superior stability of the shoulder. *J Shoulder Elbow Surg*. 2021;30(11):2611-2619. doi:10.1016/j.jse.2021.04.012

13. Jennings A. Sphere Fit (Least Squared). MatLab Central-File Exchange.

14. Jensen KL, Williams GR, Russell IJ, Rockwood CA. Rotator cuff tear arthropathy. *J Bone Joint Surg Am*. 1999;81(9):1312-1324. doi:10.2106/00004623-199909000-00013

15. Jobe C, Phipatanakul W, Petkovic D. Gross anatomy of the shoulder. In: Rockwood Jr C, Matsen III F, Wirth M, Lippitt S, Fehringer E, Sperling J, eds. *Rockwood and Matsen's The Shoulder*. 5th ed. Elsevier; 2017:35-95.

16. Keener JD, Wei AS, Kim HM, Steger-May K, Yamaguchi K. Proximal humeral migration in shoulders with symptomatic and asymptomatic rotator cuff tears. *J Bone Joint Surg Am*. 2009;91(6):1405-1413. doi:10.2106/JBJS.H.00854

17. King GJ, Pillon CL, Johnson JA. Effect of in vitro testing over extended periods on the low-load mechanical behaviour of dense connective tissues. *J Orthop Res*. 2000;18(4):678-681. doi:10.1002/jor.1100180422

18. Kozono N, Okada T, Takeuchi N, et al. Dynamic kinematics of the glenohumeral joint in shoulders with rotator cuff tears. *J Orthop Surg Res*. 2018;13(1):9. doi:10.1186/s13018-017-0709-6

19. Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Relat Res*. 1993;(291):20-28.

20. Lobao MH, Canham RB, Melvani RT, Abboud JA, Parks BG, Murthi AM. Biomechanics of Biodegradable Subacromial Balloon Spacer for Irreparable Superior Rotator Cuff Tears. *Journal of Bone and Joint Surgery*. 2019;101(11):e49. doi:10.2106/JBJS.18.00850

21. Matsen III FA. www.shoulderarthritis.blogspot.com. Rotator cuff tears - what to do if they are irreparable?

22. Matsuki K, Matsuki KO, Yamaguchi S, et al. Dynamic in vivo glenohumeral kinematics during scapular plane abduction in healthy shoulders. *J Orthop Sports Phys Ther*. 2012;42(2):96-104. doi:10.2519/jospt.2012.3584

23. Mihata T, Bui CNH, Akeda M, et al. A biomechanical cadaveric study comparing superior capsule reconstruction using fascia lata allograft with human dermal allograft for irreparable rotator cuff tear. *J Shoulder Elbow Surg*. 2017;26(12):2158-2166. doi:10.1016/j.jse.2017.07.019

24. Mihata T, McGarry MH, Kahn T, Goldberg I, Neo M, Lee TQ. Biomechanical Effect of Thickness and Tension of Fascia Lata Graft on Glenohumeral Stability for Superior Capsule Reconstruction in Irreparable Supraspinatus Tears. *Arthroscopy*. 2016;32(3):418-426. doi:10.1016/j.arthro.2015.08.024

25. Mihata T, McGarry MH, Kahn T, Goldberg I, Neo M, Lee TQ. Biomechanical role of capsular continuity in superior capsule reconstruction for irreparable tears of the supraspinatus tendon. *American Journal of Sports Medicine*. 2016;44(6):1423-1430. doi:10.1177/0363546516631751

26. Mihata T, McGarry MH, Pirolo JM, Kinoshita M, Lee TQ. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: A

biomechanical cadaveric study. *American Journal of Sports Medicine*. 2012;40(10):2248-2255. doi:10.1177/0363546512456195

27. Millett PJ, Giphart JE, Wilson KJ, Kagnes K, Greenspoon JA. Alterations in Glenohumeral Kinematics in Patients With Rotator Cuff Tears Measured With Biplane Fluoroscopy. *Arthroscopy*. 2016;32(3):446-451. doi:10.1016/j.arthro.2015.08.031

28. Mura N, O'Driscoll SW, Zobitz ME, et al. The effect of infraspinatus disruption on glenohumeral torque and superior migration of the humeral head: a biomechanical study. *J Shoulder Elbow Surg*. 2003;12(2):179-184. doi:10.1067/mse.2003.9

29. Neer CS, Craig E V, Fukuda H. Cuff-tear arthropathy. *J Bone Joint Surg Am*. 1983;65(9):1232-1244.

30. Oh JH, Jun BJ, McGarry MH, Lee TQ. Does a critical rotator cuff tear stage exist?: a biomechanical study of rotator cuff tear progression in human cadaver shoulders. *J Bone Joint Surg Am*. 2011;93(22):2100-2109. doi:10.2106/JBJS.J.00032

31. Otis JC, Jiang CC, Wickiewicz TL, Peterson MG, Warren RF, Santner TJ. Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. *J Bone Joint Surg Am*. 1994;76(5):667-676. doi:10.2106/00004623-199405000-00007

32. Prat D, Tenenbaum S, Pritsch M, Oran A, Vogel G. Sub-acromial balloon spacer for irreparable rotator cuff tears: Is it an appropriate salvage procedure? *J Orthop Surg (Hong Kong)*. 2018;26(2):2309499018770887. doi:10.1177/2309499018770887

33. Reeves JM, Singh S, Langohr GDG, Athwal GS, Johnson JA. An in-vitro biomechanical assessment of humeral head migration following irreparable rotator cuff tear and subacromial balloon reconstruction. *Shoulder Elbow*. 2020;12(4):265-271. doi:10.1177/1758573219865479

34. Savarese E, Romeo R. New Solution for Massive, Irreparable Rotator Cuff Tears: The Subacromial "Biodegradable Spacer." *Arthrosc Tech*. 2012;1(1). doi:10.1016/j.eats.2012.02.002

35. Senekovic V, Poberaj B, Kovacic L, et al. The biodegradable spacer as a novel treatment modality for massive rotator cuff tears: a prospective study with 5-year follow-up. *Arch Orthop Trauma Surg*. 2017;137(1):95-103. doi:10.1007/s00402-016-2603-9

36. Senekovic V, Poberaj B, Kovacic L, Mikek M, Adar E, Dekel A. Prospective clinical study of a novel biodegradable sub-acromial spacer in treatment of massive irreparable rotator cuff tears. *Eur J Orthop Surg Traumatol*. 2013;23(3):311-316. doi:10.1007/s00590-012-0981-4

37. Singh S. *A Biomechanical Study Examining The Subacromial Balloon Spacer and Superior Capsular Reconstruction in the Treatment of Massive, Irreparable Rotator Cuff Tears*. Western University; 2017.

38. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The effect of the subacromial balloon spacer on humeral head translation in the treatment of massive, irreparable rotator cuff tears: a biomechanical assessment. *J Shoulder Elbow Surg*. 2019;28(10):1841-1847. doi:10.1016/j.jse.2019.03.036

39. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The Subacromial Balloon Spacer Versus Superior Capsular Reconstruction in the Treatment of Irreparable Rotator Cuff Tears: A Biomechanical Assessment. *Arthroscopy - Journal of Arthroscopic and Related Surgery*. 2019;35(2):382-389. doi:10.1016/j.arthro.2018.09.016

40. Sommer MC, Wagner E, Zhu S, et al. Complications of Superior Capsule Reconstruction for the Treatment of Functionally Irreparable Rotator Cuff Tears: A Systematic Review. *Arthroscopy*. 2021;37(9):2960-2972. doi:10.1016/j.arthro.2021.03.076

41. Tempelaere C, Pierrart J, Lefèvre-Colau MM, et al. Dynamic Three-Dimensional Shoulder Mri during Active Motion for Investigation of Rotator Cuff Diseases. *PLoS One*. 2016;11(7):e0158563. doi:10.1371/journal.pone.0158563

42. Terrier A, Reist A, Vogel A, Farron A. Effect of supraspinatus deficiency on humerus translation and glenohumeral contact force during abduction. *Clin Biomech (Bristol, Avon)*. 2007;22(6):645-651. doi:10.1016/j.clinbiomech.2007.01.015

43. Terry GC, Chopp TM. Functional anatomy of the shoulder. *J Athl Train*. 2000;35(3):248-255. www.journalofathletictraining.org

44. Tibone JE, Mansfield C, Kantor A, et al. Human Dermal Allograft Superior Capsule Reconstruction With Graft Length Determined at Glenohumeral Abduction Angles of 20° and 40° Decreases Joint Translation and Subacromial Pressure Without Compromising Range of Motion: A Cadaveric Biomechanical Study. *Arthroscopy*. 2022;38(5):1398-1407. doi:10.1016/j.arthro.2021.11.007

45. Yallapragada RK, Apostolopoulos A, Katsougrakis I, Selvan TP. The use of a subacromial spacer-inspace balloon in managing patients with irreparable rotator cuff tears. *J Orthop*. 2018;15(3):862-868. doi:10.1016/j.jor.2018.08.004

46. Yamaguchi K, Sher JS, Andersen WK, et al. Glenohumeral motion in patients with rotator cuff tears: a comparison of asymptomatic and symptomatic shoulders. *J Shoulder Elbow Surg*. 2000;9(1):6-11. doi:10.1016/s1058-2746(00)90002-8

Chapter 3

3 Mechanical Efficiency of the Shoulder and Functional Abduction Force in a Massive Rotator Cuff Deficiency Cadaveric Model: Comparing the Subacromial Balloon Spacer, Superior Capsule Reconstruction, and a Rigid Subacromial Implant

This chapter describes the testing conducted to compare the effectiveness of the subacromial balloon spacer, the superior capsular reconstruction, and a subacromial implant at restoring the mechanical efficiency of the shoulder by measuring the functional abduction force produced in a massive irreparable rotator cuff tear cadaveric model. Testing was conducted on all test states using a previously developed shoulder testing apparatus. Static muscle loading was employed at varying angles of glenohumeral abduction. Resistance to abduction (functional abduction force) was recorded in newtons using a six degree of freedom load cell.

(NB: Specimen preparation, simulator set-up, test states, and order of testing are similar to that which has been previously described in Chapter 2. However, the techniques to quantify the outcome variables related to load measurements were not employed in Chapter 2 and hence described herein.)

3.1 Introduction

As documented in Chapter 1, the shoulder is a complex joint with several planes of motion. Glenohumeral abduction and scapular plane abduction are critical to a patient's ability to perform basic activities of daily living. This requires the use of both large and small muscle groups that cross the glenohumeral joint to work in concert to position the arm in space. Maintaining the transverse and coronal force-couples of the shoulder as well as increasing the concavity-compression of the glenohumeral joint serves to stabilize the glenohumeral joint and maximize shoulder function during abduction. The rotator cuff, deltoid, latissimus dorsi, and pectoralis major are the primary contributors, although muscles such as the teres major and long heads of the both the biceps and triceps may also contribute to a lesser degree. The force components of the deltoid and the supraspinatus act superiorly about the glenohumeral joint center whereas the infraspinatus, teres minor, and subscapularis forces act inferiorly about the glenohumeral joint center. The synergistic relationship between the deltoid and the supraspinatus work to initiate abduction in a controlled manner and maintain joint stability. Previous work has demonstrated that the supraspinatus is the dominant contributor to abduction during the first 30 degrees of abduction, whereas the deltoid is more dominant beyond 30 degrees of abduction.[2,36] This is likely due to the difference in moment arms of the supraspinatus and deltoid about the center of rotation of the shoulder in different arm positions (Figure 3-1). At 0-degrees of abduction the supraspinatus moment arm is greater than the deltoid moment arm.[24,36] The anterior and middle deltoid moment arms increase from 0cm and 1.4cm at 0-degrees abduction to values of 1.5-2.0cm and 2.7-3.2cm, respectively at 60-degrees abduction.[24,36] However, the deltoid is significantly stronger than the supraspinatus with an ability to generate forces up to six times the body weight of the patient.[23] Therefore, at initiation of abduction the shear force exerted by the deltoid must be counteracted by the compressive force of the rotator cuff as well as the surrounding musculature such as the pectoralis major and latissimus dorsi to prevent excessive glenohumeral translation and maintain efficiency of the shoulder.[1,9,23]

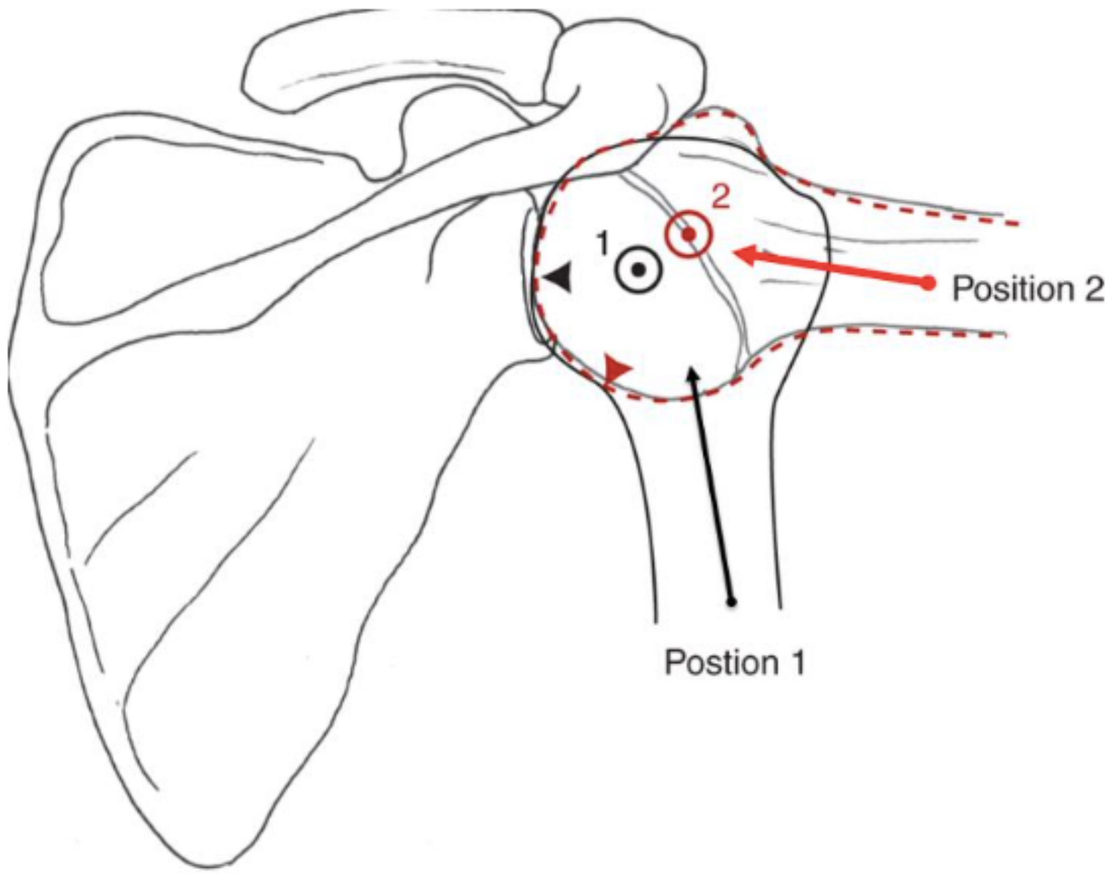

Figure 3-1: Change in force vectors of the deltoid muscle

Demonstration of the change in line of pull of the deltoid muscle as the arm abducts from 0 degrees (Position 1) up to 90 degrees (Position 2).

The supraspinatus tendon is the most common area for a degenerative full thickness rotator cuff tear to occur.[19] With deficiency of the supraspinatus, the deltoid muscle becomes solely responsible for the abduction capability of the shoulder. As previously discussed in Chapter 2, the presence of a rotator cuff tear also alters the kinematics of the glenohumeral joint with increased superior and posterior humeral head translation during abduction.[6,17,18,34,35,49,51,54] This can lead to a reduction in the abduction capability of the shoulder. This is believed to be a multifactorial process related to loss of function of the involved rotator cuff muscle and a reduction in the moment arm of the deltoid as the humeral head translates superiorly. This results in the deltoid requiring increased force production to provide the same degree of abduction as a healthy shoulder. Terrier et al.[51]

investigated the effects of supraspinatus deficiency on glenohumeral contact force and deltoid muscle force in a 3D finite element analysis based off a cadaveric shoulder. They demonstrated that with complete supraspinatus deficiency there was an 8% increase in the maximal force exerted on the glenohumeral articular surface and a 30% increase in the maximal deltoid muscle force required during shoulder abduction.

The mechanical efficiency of the shoulder refers to the force or effort required to move the shoulder. This is believed to be significantly impacted in the context of rotator cuff tears due to altered glenohumeral kinematics and loss of the force-couple and concavity-compression mechanisms of the shoulder. Several studies have quantified mechanical efficiency of the shoulder in the context of rotator cuff deficiency through a variety of different measures in the literature. With respect to glenohumeral abduction, these include total deltoid force exerted, abduction capability, abduction torque, deltoid abduction force, and functional abduction force.[5,6,11,16,25,34,35,39,40,47]

Halder et al.[16] utilized a supraspinatus deficient cadaveric model to examine the effects on glenohumeral abduction torque at zero degrees abduction using a load cell attached to the distal humerus. Complete full thickness defects caused a larger reduction in abduction torque than incomplete full thickness defects. Full thickness defects with complete tendon retraction resulted in a 58% reduction in measured glenohumeral abduction torque.[16] Similarly, Mura et al.[34] examined the impact of sequential sectioning of the rotator cuff in a stepwise fashion on abduction torque generation compared to the intact shoulder. Although there was a stepwise reduction in torque production, significant differences were not observed until the entire supraspinatus tendon, and more than half of the anterior infraspinatus was sectioned.[34] Similar results were reported by Rybalko et al.[39] with little difference between the intact shoulder and a partial supraspinatus tear. However, as tears progressed to involve the entire supraspinatus tendon there was significant reduction in deltoid abduction force. Oh et al.[35] also performed sequential sectioning of the rotator cuff in a cadaveric model but they measured abduction capability with ramp loading of the deltoid. They demonstrated that tears extending into at least half of the anterior infraspinatus tendon will lead to significant reduction in abduction capability of the shoulder at all deltoid loads when compared to the intact shoulder.

Dyrna et al.[11] used total deltoid force and maximum abduction angle as their measures to represent mechanical efficiency of the shoulder. Both isolated supraspinatus tears and multiple tendon rotator cuff tears increased the total deltoid force required to reach maximal abduction and decreased maximum abduction angle achieved. Lastly, Berthold et al.[6] demonstrated that isolated non-retracted tendon tears require increased deltoid loads to reach maximal abduction angle. However, in massive rotator cuff tear and posterosuperior rotator cuff tear states they reported that there was significant reduction maximal abduction angle achieved with corresponding significant increases in deltoid force required to achieve these positions.[6] Collectively, these studies illustrate the importance of the rotator cuff to the normal function of the shoulder. In the context of rotator cuff deficiency, the mechanical efficiency of the shoulder falters with the deltoid being primarily responsible for compensating for the loss of rotator cuff function.

Few studies have examined the influence of a superior capsular reconstruction or a subacromial balloon spacer on the mechanical efficiency of the shoulder in the context of rotator cuff deficiency.[5,25,40,47] Lobao et al.[25] investigated deltoid abduction force in irreparable supraspinatus tendon tears with and without the use of the subacromial balloon spacer. There were significant increases in deltoid abduction force with the addition of the subacromial balloon at 0-, 30-, and 60- degrees of glenohumeral abduction. Values for the intact shoulder were not measured, therefore a comparison to the normal native environment could not be made. Rybalko et al.[40] compared a supraspinatus deficient cadaveric shoulder to that with a superior capsular reconstruction. There was a significant increase in abduction force at zero degrees abduction when compared to the supraspinatus deficient state. Abduction force values were like the intact shoulder a 0-, 30-, and 60-degrees of abduction. Conversely, Berthold et al.[5] reported that a superior capsular reconstruction using semi-tendinosus allograft with and without biceps tendon augmentation resulted in similar increases in mean deltoid force compared to a retracted posterosuperior rotator cuff defect. They report a significant improvement in glenohumeral abduction angle with the biceps augmented superior capsule reconstruction, however, the absolute difference compared to the rotator cuff deficient state was 3 degrees. Both states achieved significantly lower abduction angles than the intact state.[5] In a comparative study of the subacromial balloon spacer and superior capsular reconstruction in a massive irreparable rotator cuff tear model, Singh et al.[47] reported average functional abduction forces during various degrees of scapular plane abduction. The functional abduction force was significantly lower in the irreparable posterosuperior rotator cuff tear when compared to the intact shoulder. The subacromial balloon spacer and superior capsular reconstruction restored the functional abduction force comparable to the intact shoulder.[47] These were reported as mean values across all angles of abduction, and assessment of the effect of the balloon spacer or the superior capsular reconstruction at specific angles was not specified.

Another potential method is the use of a rigid subacromial implant as described and assessed for the effect on glenohumeral kinematics as summarized in Chapter 2. To date, no studies have been performed on the impact of this subacromial implant on the mechanical efficiency of the shoulder in the context of a massive irreparable rotator cuff tear. It is logical to postulate that this implant may produce improved mechanical efficiencies regarding abduction by lowering the deltoid forces required.

The gold standard for maximizing the mechanical efficiency of the rotator cuff deficient shoulder with respect to the deltoid is the reverse total shoulder arthroplasty.[4,23] The reverse shoulder arthroplasty moves the center of rotation of the shoulder joint distal and medial compared to the native shoulder. By medializing the center of rotation, the deltoid moment arm increases in length by 20-42% and some of the anterior and posterior muscles fibers of the deltoid are recruited to participate in abduction.[7,21,50] This enhanced torque-producing capacity of the deltoid may compensate for the loss of rotator cuff contribution to arm elevation. Rybalko et al.[40] demonstrated, deltoid abduction force is increased by 55%, 156%, and 76% when compared to the rotator cuff deficient shoulder state at 0-, 30-, and 60-degrees of abduction. Compared to the superior capsular reconstruction and the intact shoulder states, the reverse total shoulder arthroplasty increased deltoid abduction force at each angle tested as well. However, surgeons are hesitant to place a reverse total shoulder arthroplasty in a younger patient with rotator cuff deficiency and the absence of glenohumeral arthritis. It has been well documented that young patients treated with a reverse total shoulder arthroplasty are less satisfied, experience more complications, and have worse survivorship of their implants when compared to older aged patients.[3,10,13,33,41]

In light of the foregoing, the objective of this study was to perform a biomechanical comparison of a subacromial balloon spacer, a superior capsular reconstruction, and a rigid subacromial implant in a massive rotator cuff deficient cadaveric model. The effects on mechanical efficiency of the shoulder was quantified using functional abduction force as a surrogate measure. It was hypothesized that each surgical state would improve functional abduction force relative to the rotator cuff deficient test state, but not reach the values of the intact shoulder.

3.2 Methods

3.2.1 Cadaver & Simulator Preparation

Nine fresh-frozen male right cadaver shoulders with a mean age of 74 ± 15 years (age range: 49 – 101 years) were employed. Specimens were screened via computerized tomography (CT) scans and inspected to confirm the absence of joint and soft tissue pathology that could affect the outcome of interest. Specimens were transected at the mid-humeral level with the scapula, clavicle, and respective soft tissues preserved. The overlying skin, soft-tissue, muscle, ligaments, and joint capsules were maintained.

After thawing for 18 hours, each specimen was prepared for biomechanical testing. Rotator cuff muscles were identified and tagged at their tendon insertions with heavy, non-absorbable, braided suture (#5 Ethibond, Ethicon, Johnson & Johnson, New Jersey, USA). The supraspinatus, infraspinatus, and teres minor were accessed through a lateral deltoid split approach. The subscapularis was identified and tagged along the anterior surface of the exposed scapula with two sutures to represent the upper and lower aspects of the tendon. The anterior, middle, and posterior heads of the deltoid were tagged with three transosseous sutures through a single 2.0mm corticotomy located at the deltoid tuberosity on the lateral aspect of the transected humerus.

Full thickness dermis was harvested from the skin overlying the posteromedial border of the scapula at time of specimen preparation for later use as an autograft dermal superior capsular reconstruction.

Each specimen was affixed to a previously developed custom shoulder simulator via bolts affixed to plates attached to the base (Figure 3-2 & Figure 3-3).[14,15] This allowed the scapula to be rigidly fixed to the testing apparatus in a physiologic position with roughly 10-20 degrees of anterior tilt and roughly 10-20 degrees of external rotation. An intramedullary humeral rod assembly was cemented into the prepared humeral canal. Optical tracking markers (Certus, Northern Digital, Ontario, Canada) were secured to the superomedial scapular body and the intramedullary humeral rod assembly. This allowed tracking of the relative position of the scapula and humerus during testing. A six degree of freedom load cell (ATI, Apex, North Carolina, USA) was attached to the intramedullary humeral rod assembly and was used to quantify functional abduction force as described ahead.

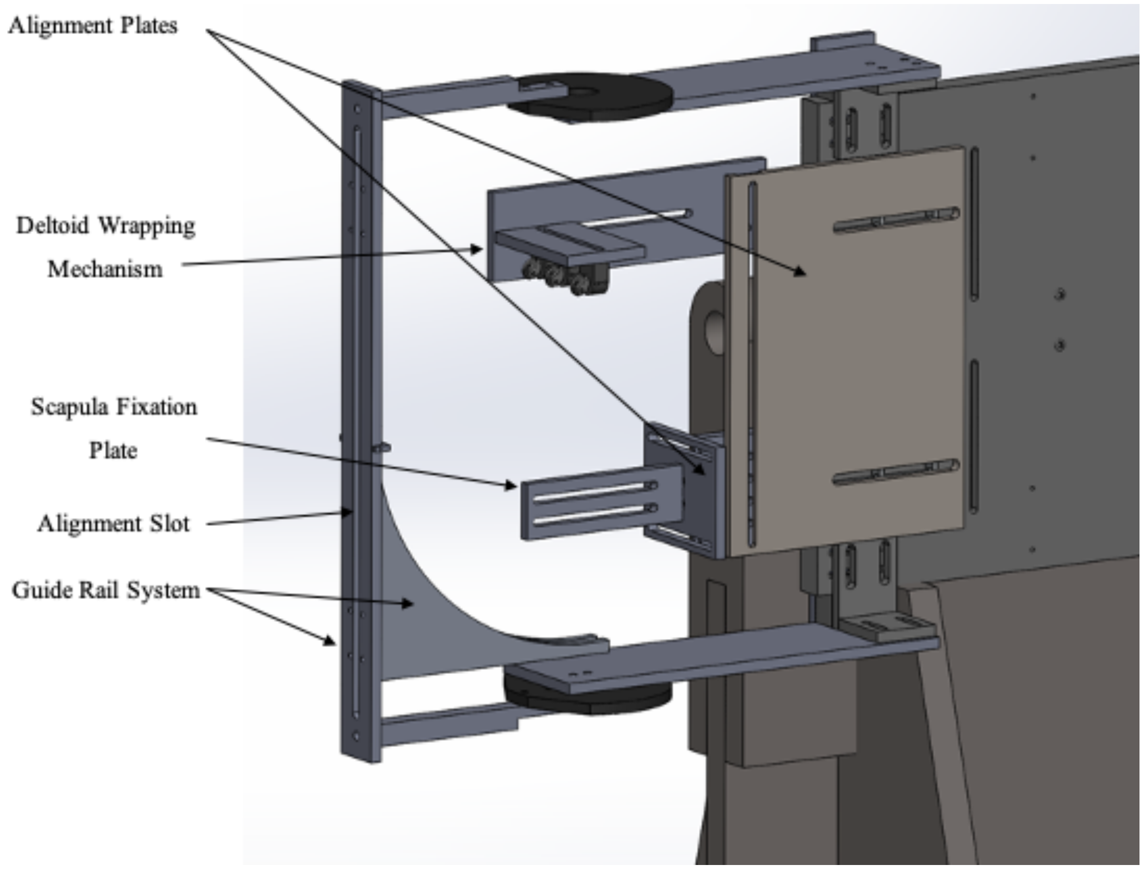

Figure 3-2: Shoulder simulator design for testing

The specimen is attached to the scapular fixation plate. The alignment plates allow medial-lateral and anterior-posterior translation of the specimen to centralize the glenohumeral joint. The guide rail system and alignment slot are positioned to permit abduction within the scapular plane. The deltoid wrapping mechanism allows precise positioning of the pulley system.

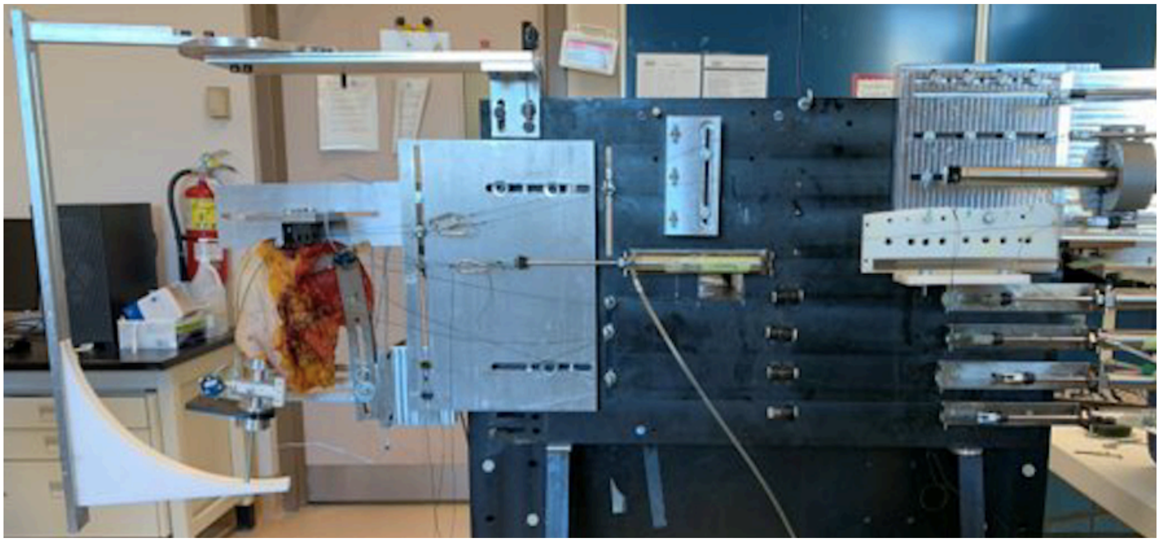

Figure 3-3: Specimen affixed to the shoulder simulator

Demonstration of a right shoulder specimen attached to the shoulder simulation with illustration of the component parts of the simulator. The pneumatic actuators are pictured to the far right of the image.

The intramedullary humeral rod assembly was positioned within the alignment slot of the abduction guide rail in the scapular plane. The rail permitted free internal and external rotation of the humerus during testing while promoting abduction within the scapular plane. Scapular abduction angles of interest (0, 15, 30, 45, and 60 degrees) were marked on the abduction guide rail with use of a digital goniometer. As the scapula was rigidly fixed to the simulator, all motion observed was through the glenohumeral joint and therefore represented 0-, 20-, 45-, 68-, and 90-degrees of combined abduction assuming the typical 2:1 ratio of glenohumeral to scapulothoracic motion. The humeral head was free to rotate and translate in all planes.

Braided, high-strength line was used to connect each sutured tendon to its dedicated pneumatic actuator. Each rotator cuff tendon line was positioned within the shoulder simulator to best replicate the physiologic line of action of the muscle-tendon unit. The deltoid tendon lines were routed through their own respective pulleys. The posterior pulley was positioned superior to the posterolateral corner of the acromion. The middle pulley was positioned superior to the middle of the acromion. The anterior pulley was positioned superior to the anterolateral corner of the acromion. Each pulley was medialized to the level of the scapular notch to simulate the deltoid wrapping effect over external soft tissues of the shoulder.

A custom LabVIEW (Texas Instruments, Austin, Texas, USA) code was developed to produce static muscle loading to each individual muscle using the pneumatic actuators. Muscle loads were based on previous cadaveric studies investigating superior humeral head translation in massive rotator cuff tear models.[32,38,47]

3.2.2 Testing Variables

3.2.2.1 Intact Rotator Cuff

The initial test state was that of a healthy shoulder with an intact rotator cuff. This test state was utilized to establish baseline values for functional abduction force during scapular plane abduction. The rotator cuff force-couples were in a balanced state as previously described in the literature.[12,30–32,38,45–47]

3.2.2.2 Massive Irreparable Rotator Cuff Tear

The lateral deltoid split was used to expose the rotator cuff tendon insertions. A massive irreparable rotator cuff tear was simulated by excising the supraspinatus and the upper infraspinatus tendon from its insertion (Figure 3-4). Beginning at the bicipital groove, the rotator interval was opened to identify the anterior edge of the supraspinatus tendon. The biceps tendon was transected at its labral attachment. The rotator cuff footprint was then elevated off the anterior greater tuberosity and the supraspinatus and anterior half of the infraspinatus tendons were excised with their superior capsule attachments as far as the glenoid rim medially.[12,35] The subscapularis and teres minor tendons were left intact. The actuator lines for the supraspinatus and infraspinatus were discarded.

Figure 3-4: Simulated massive irreparable rotator cuff tear

Lateral view of a right shoulder through a deltoid split. Demonstration of a simulated massive rotator cuff tear with resection of the supraspinatus and anterior half of the infraspinatus tendon.

3.2.2.3 Subacromial Balloon Spacer

The lateral shoulder incision was utilized again for exposure of the subacromial space and preparation of implantation of the subacromial balloon spacer. Following the surgical technique of the manufacturer, the distance was measured from 1cm medial to the glenoid rim to the greater tuberosity and an appropriate implant was selected.[42] Each specimen measured to fit the large subacromial balloon spacer.

The subacromial balloon was then inflated with normal saline to its maximal fill volume (40mL) before withdrawing fluid until the final recommended fill volume (25mL) was achieved.[42] The subacromial balloon was secured with a custom device to prevent back-flow of fluid and positioned within the subacromial space (Figure 3-5). Following completion of testing the final resting position of the subacromial balloon was noted relative to its initial implantation position.

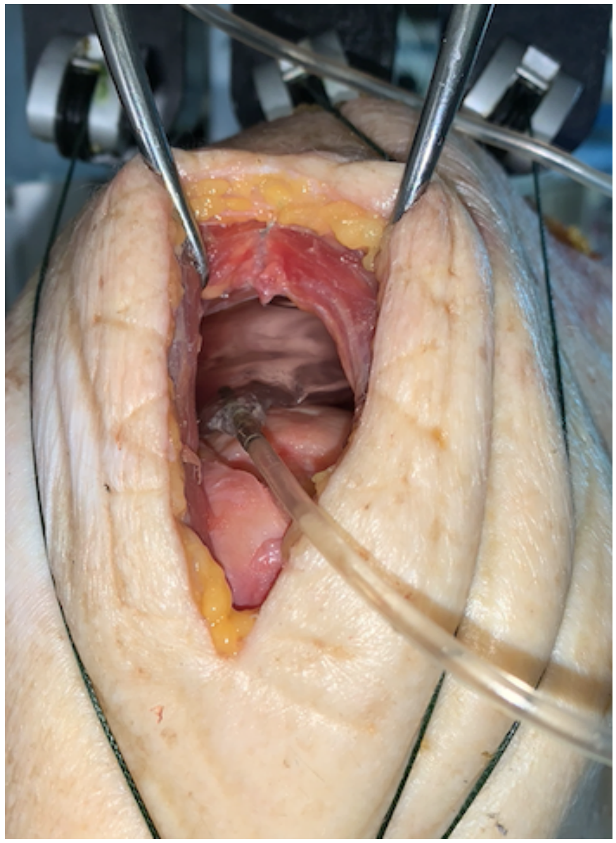

Figure 3-5: Inflated subacromial balloon spacer

Visualization of the right shoulder through a deltoid split approach. Inflated subacromial balloon spacer sits within the subacromial space. Custom tubing is seen exiting the lateral deltoid split.

3.2.2.4 Superior Capsular Reconstruction

Through the same lateral exposure, the subacromial balloon was deflated and retrieved from the subacromial space and a superior capsule reconstruction was completed through the deltoid split exposure. Glenoid measurements were taken from the remaining posterosuperior capsule to the level of the superior glenoid tubercle (12 o'clock position) as well as from the glenoid articular surface to the greater tuberosity.

Previously harvested autograft dermis was then prepared for implantation. Subcutaneous tissue was excised, leaving a full-thickness dermal graft. The graft was folded on itself to create a double thickness construct which was shaped to the appropriate dimensions.[12] A heavy braided suture (#1 Vicryl, Ethicon, Johnson & Johnson, New Brunswick, New Jersey, USA) was used to secure the graft circumferentially in its doubled position. Graft thickness was measured with digital calipers.

The graft was visualized within the joint to ensure sizing was correct. Once this was confirmed, two 2.8mm Q-FIX all-suture anchors (Smith & Nephew, London, UK) were placed in the glenoid. The first was in the posterosuperior glenoid near the edge of remaining infraspinatus and posterosuperior capsule. The second was placed in the superior glenoid tubercle at the 12 o'clock position. Each of these anchors allowed placement of mattress stitches within the medial aspect of the graft. The graft was then tied securely to the glenoid with a series of sliding, locking knots followed by alternating half-hitches. Laterally, two 5.5mm Healicoil suture anchors (Smith & Nephew, London, UK) were placed in the humerus medial to the greater tuberosity at the site of previous capsule insertion. The arm was maintained in 30 degrees of scaption, and the graft was tensioned with lateral traction. Mattress stitches were placed through the graft at the site of each medial anchor. A suture bridge construct was created with use of a lateral row 4.5mm knotless anchor (Footprint Ultra PK, Smith & Nephew, London, UK) that was placed laterally into the greater tuberosity. Excess lateral graft was excised to prevent impingement during motion. The graft was secured to the remaining posterosuperior capsule with interrupted figure-of-eight stitches (#2 FiberWire, Arthrex, Naples, Florida, USA) as described by Mihata et al.[31] (Figure 3-6).

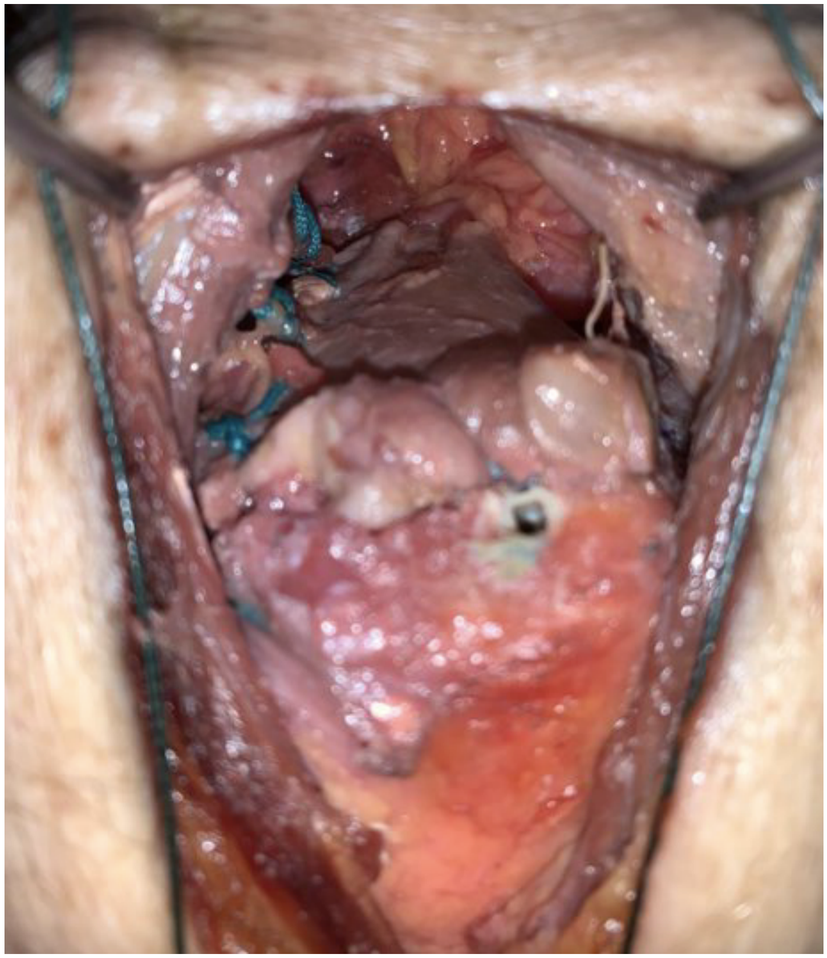

Figure 3-6: Superior capsular reconstruction with dermal autograft

Superior capsular reconstruction is visualized in the right shoulder through a deltoid split approach. The doubled dermal autograft is secured to the glenoid medially, the infraspinatus posteriorly, and the greater tuberosity laterally.

3.2.2.5 Rigid Subacromial Implant

Lastly, the rigid subacromial implant employed both the previous lateral incision as well as a posterior based incision. The superior capsule reconstruction was removed along with all suture material, ensuring no further damage to the rotator cuff or capsule.

The implant was introduced through the lateral incision such that the articular plate sat flush with the undersurface of the acromion with little to no extension beyond the lateral or anterior aspect of the acromion (Figure 3-7). Posteriorly, the implant's fixation arm was secured to the scapular spine superior to the suprascapular nerve (Figure 3-9). Fixation was obtained through multiple 3.5mm bicortical locking screws.

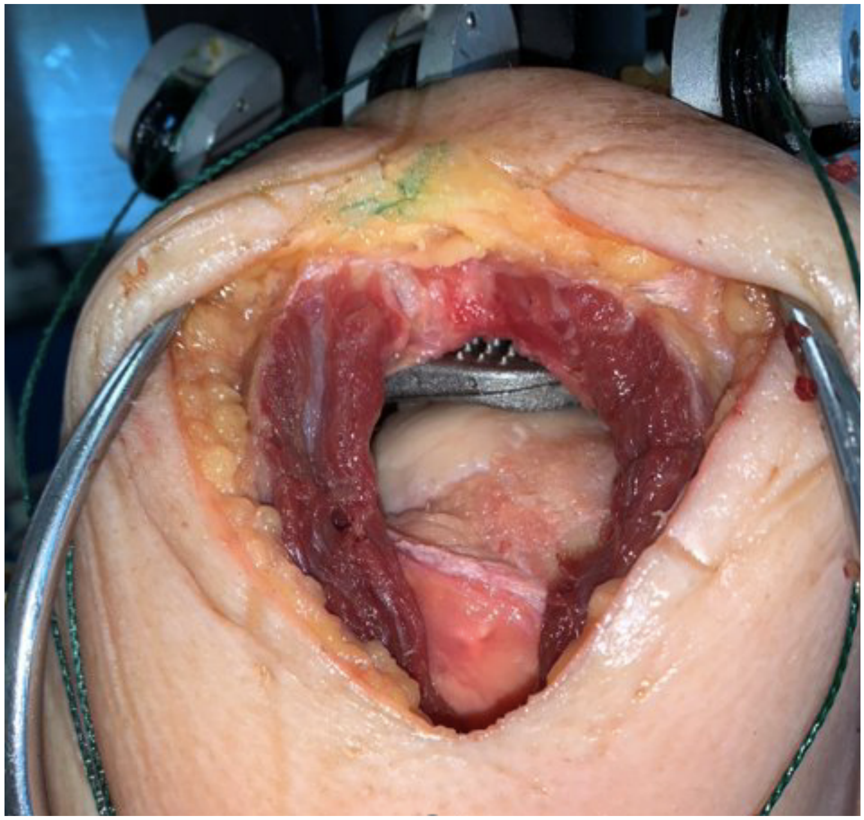

Figure 3-7: Lateral view of rigid subacromial implant

The metallic subacromial implant is positioned in the subacromial space of the right shoulder through a deltoid split approach. The articular component of the device is seen extending from the undersurface of the acromion.

Figure 3-8: Posterior view of rigid subacromial implant

Demonstration of the fixation of the metallic subacromial implant to the posterior scapular spine. Also visualized is the fixation screw for the modular articular components which were inserted posteriorly.

The 5mm low constraint and 5mm high constraint modular articular inserts were then placed from the posterior based incision and secured to the implant with a posterior fixation screw (Figure 3-9).

A B

Figure 3-9: Metallic subacromial implants

Lateral view of the subacromial implant illustrating the difference in the articular radius of curvature. (A) 5mm high constraint and (B) 5mm low constraint models.

The shoulder was passively taken through a full range of motion to identify regions of greater tuberosity impingement on the undersurface of the implant. A tuberoplasty was then performed on the portion of the greater tuberosity that was devoid of rotator cuff attachment to prevent impingement as previously described in our lab (Figure 3-10).[14]

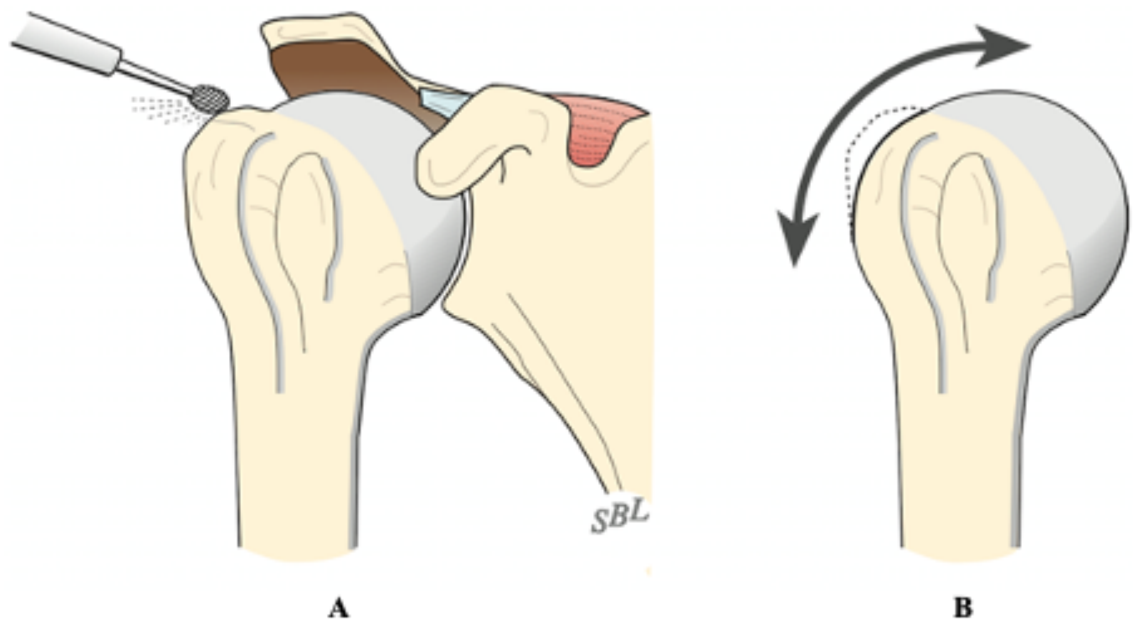

Figure 3-10: Depiction of tuberoplasty procedure

(A) Demonstration of the tuberoplasty procedure being performed with a burr. (B) Completed tuberoplasty procedure demonstrating the smooth transition between the humeral head and the lateral proximal humerus.[26]

3.2.3 Testing Protocol

Prior to each test state, the surgical incisions were closed in a layered fashion. The muscle splits and subcutaneous tissues were closed with 2-0 Vicryl (Ethicon, Johnson & Johnson, New Brunswick, New Jersey, USA) and the skin was closed with a non-absorbable stitch to maintain specimen integrity. The shoulder was taken through full passive range of motion in flexion, extension, abduction, adduction, internal rotation, and external rotation to eliminate any residual stiffness within the tissues. Normal saline was utilized to keep the overlying soft-tissues and articular surfaces well hydrated.

Muscle loads of 10N were applied through the supraspinatus, infraspinatus, teres minor, superior subscapularis, and inferior subscapularis. An 80N load was spread equally across each head of the deltoid through a custom pulley system. This protocol has been established in several biomechanical studies investigating glenohumeral kinematics in rotator cuff deficiency.[12,30–32,38,45–47] This muscle loading scenario was utilized so that superior humeral head translation would be promoted in subsequent test states. Following the introduction of a massive irreparable rotator cuff tear, rotator cuff force-couples were restored maintaining a 10N load in the teres minor muscle and decreasing the load to 5N in the superior subscapularis and 5N in the inferior subscapularis. Deltoid loading remained the same for all test states.

The load cell was zeroed at the beginning of each test prior to the actuation of the muscle loading. Once the actuators were active, the arm was positioned within the alignment slot of the abduction guiderail first at 0-degrees of glenohumeral abduction and subsequently at each arm position moving in 15-degree increments. Resistance to abduction was maintained using a surgical instrument just distal to the load cell at each arm position for a minimum of 5 seconds to allow for force data collection. The surgical instrument was carefully placed on the same location of the humeral rod assembly throughout testing to ensure the resultant force vector was in line with the scapular plane.

3.2.4 Outcome Variables

The outcome variable of interest was the functional abduction force of the shoulder produced at the load cell which was located at a fixed distance relative to the deltoid tuberosity. This value has been previously used as a surrogate measure of abduction strength or mechanical efficiency of the shoulder.[47] Over the 5 second data collection period, the average force value from each recording was calculated and reported in Newtons at each of the five arm positions for each test state. The intact rotator cuff state was considered the baseline value for each arm position.

3.2.5 Statistical Analysis

Statistical analysis was carried out using a two-way repeated measures analysis of variance (RM-ANOVA) in SPSS (IBM, Armonk, NY, USA). The independent variables were the abduction angle and test state, and the dependent variable was functional abduction force. A Bonferroni correction was used to correct for the multiple statistical analyses performed, with the significance value set as $p<0.05$.

3.3 Results

3.3.1 Functional Abduction Force

The general trends averaged across all angles tested are indicated in Figure 3-11. The intact shoulder produced a mean functional abduction force of 14.0 ± 9.4N across all angles of abduction. Following the simulated massive irreparable rotator cuff tear involving the supraspinatus and half of the infraspinatus, the functional abduction force decreased to 9.1 ± 4.0N (P = 0.016). This represents a 4.9N decrease from the intact state.

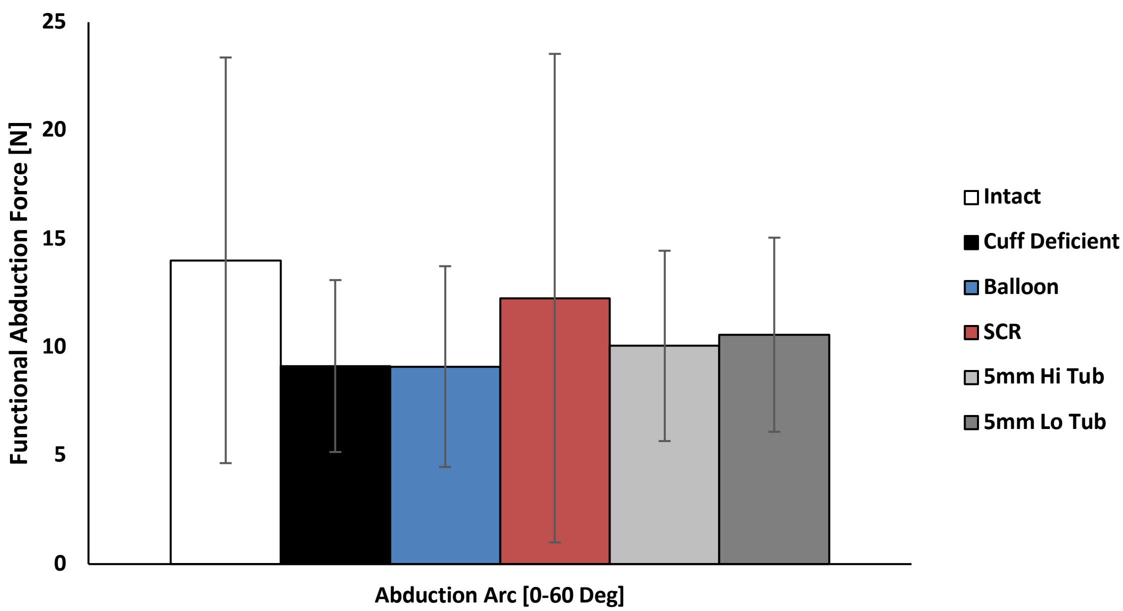

Figure 3-11: Functional abduction force (mean ± 1 SD) generation

Values are averaged across each angle of abduction to show general trends between test states. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint with tuberoplasty. 5mm Lo Tub = 5mm low constraint with tuberoplasty.

No surgical test state reached the functional abduction force values of the intact shoulder. The subacromial balloon spacer generated 9.1 ± 4.6N of functional abduction force, a value that was identical to the rotator cuff deficient test state ($P > 0.05$) and 4.9N lower than the intact rotator cuff ($P = 0.023$). The superior capsular reconstruction averaged 12.3 ± 11.3N of functional abduction force generation, this was 1.7N lower than the intact state ($P > 0.05$) and 3.1N higher than the rotator cuff deficient state ($P > 0.05$). The 5mm high constraint implant produced 10.1 ± 4.4N of functional abduction force. This value is 3.9N lower than the intact rotator cuff tear state ($P = 0.012$) and 0.9N higher than the rotator cuff deficient state ($P > 0.05$). Similarly, the 5mm low constraint implant generated 10.6 ± 4.5N of functional abduction force, a 3.4N reduction compared to the intact shoulder ($P = 0.049$) and a 1.4N increase relative to the rotator cuff deficient test state ($P > 0.05$). There were no statistically significant differences observed between the surgical test states for average functional abduction force production.

The largest functional abduction force value was generated in the 0-degree abduction arm position for all test states (Figure 3-12). There were significant reductions noted in the functional abduction force values when comparing 0-degrees abduction to 15-degress abduction (16.3N, $P = 0.008$, intact; 7.3N, $P < 0.001$, massive irreparable rotator cuff tear; 7.6N, $P < 0.001$, subacromial balloon; 22.9N, $P < 0.001$, superior capsular reconstruction; 7.7N, $P < 0.001$, 5mm high constraint implant; 6.8N, $P < 0.001$, 5mm low constraint implant). The superior capsular reconstruction and the intact shoulder states experienced the largest reductions in functional abduction force from 0-degrees to 15-degrees abduction. At 0-degrees of abduction, the intact shoulder produced significantly more functional abduction force than the rotator cuff deficient state (13.2N, $P = 0.027$), the 5mm high constraint implant (12.4N, $P = 0.014$), and the 5mm low constraint implant (12.8, $P = 0.013$). Interestingly, the superior capsular reconstruction produced 3.3N more functional abduction force than the intact shoulder at 0-degrees abduction ($P > 0.05$). As a result, the superior capsular reconstruction generated significantly more functional abduction force than the rotator cuff deficient state (16.5N, P = 0.004), the subacromial balloon (15.6N, P = 0.008), the 5mm high constraint implant (15.7N, P = 0.002), and the 5mm low constraint implant (16.0N, P = 0.002) at 0-degrees abduction. At 15-degrees of abduction, the intact rotator cuff state produced significantly more functional abduction force than all other test states. There was a 4.3N difference with the rotator cuff deficient state (P = 0.015), a 3.6N difference with the subacromial balloon state (P = 0.006), a 3.4N difference with the superior capsular reconstruction (P = 0.011), a 3.8N difference with the 5mm high constraint implant (P = 0.003), and a 3.3N difference compared to the 5mm low constraint implant (P < 0.001). At 30-degrees, the intact rotator cuff state generated significantly more functional abduction force than the rotator cuff deficient state (3.5N, P = 0.019), the subacromial balloon spacer state (3.5N, P = 0.034), and the superior capsular reconstruction (3.1N, P = 0.040). However, there were no significant differences between either the 5mm high constraint implant (3.0N, P > 0.05) or the 5mm low constraint implant (2.1N, P > 0.05) when compared to the intact state. At 45-degrees abduction there were no significant differences between any test state. At 60-degrees of abduction, the 5mm high constraint implant demonstrated significantly more functional abduction force than the subacromial balloon spacer (3.2N, P = 0.011). Similarly, the 5mm low constraint implant demonstrated significantly more functional abduction force than the superior capsular reconstruction (5.4N, P = 0.002). No test state demonstrated any significant differences compared to the intact shoulder or rotator cuff deficient shoulder at 60-degrees abduction.

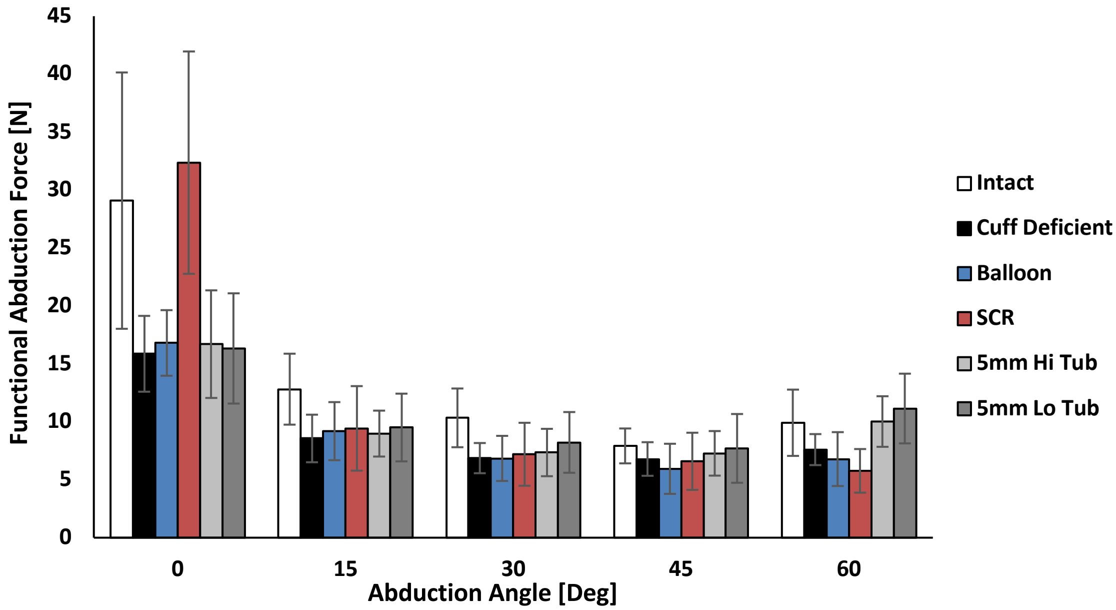

Figure 3-12: Functional abduction force (mean ± 1 SD) production

Values are reported for each arm position tested. SCR = Superior capsular reconstruction. 5mm Hi Tub = 5mm high constraint with tuberoplasty. 5mm Lo Tub = 5mm low constraint with tuberoplasty.

When considering functional abduction force through the abduction arc of 15-60 degrees the overall relationships change. The intact shoulder produced a mean functional abduction force of 10.2 ± 3.0N. The simulated massive irreparable rotator cuff tear generated a 7.5 ± 1.7N functional abduction force. The subacromial balloon spacer and superior capsular reconstruction produced lower functional abduction force values than both the intact rotator cuff tear state and the rotator cuff deficient state. The subacromial balloon produced 7.2 ± 2.5N of functional abduction force, and the superior capsular reconstruction generated 7.2 ± 3.0N of functional abduction force. In contrast, the 5mm high constraint implant produced 8.4 ± 2.3N of functional abduction force. Likewise, the 5mm low constraint implant produced 9.1 ± 3.1N of functional abduction force. The two subacromial implants were the only surgical test states to improve upon the rotator cuff deficient state.

3.4 Discussion

This study utilized a cadaveric model with a simulated massive irreparable rotator cuff tear to compare the impact of a subacromial balloon spacer, superior capsular reconstruction, and two subacromial implants on the mechanical efficiency of the shoulder using functional abduction force production as the surrogate measure. The functional abduction force analysis revealed that the creation of a massive irreparable rotator cuff tear resulted in significantly lower abduction force production than the intact shoulder. This was most noticeable at 0-, 15-, and 30-degrees of abduction. Our findings with respect to loss of abduction force generation in the context of a massive irreparable rotator cuff tear are well supported by the previous literature on this topic.[6,11,16,34,35,39,45]

Our study revealed that the insertion of a subacromial balloon spacer in a cadaveric model with a massive irreparable rotator cuff tear resulted in less functional abduction force generation than the intact rotator cuff test state. There were also no significant differences noted between the subacromial balloon spacer and the rotator cuff deficient test state at any arm position. In fact, the subacromial balloon spacer generated lower functional abduction force values than the rotator cuff deficient shoulder at 45-degrees and 60-degrees of abduction. As mentioned in Chapter 2 (Section 2.4), instability of the subacromial balloon was again appreciated during testing which may have impacted the data recorded during testing. However, these results do not fully align with previous literature on mechanical efficiency of the shoulder in the context of the subacromial balloon being used in a rotator cuff deficient shoulder.[25,47] Singh et al.[47] utilized a similar testing protocol for measuring functional abduction force of the shoulder during scapular plane abduction in a massive irreparable rotator cuff tear cadaveric model. They reported significant reductions in functional abduction force in the rotator cuff deficient shoulder compared to intact shoulder. The subacromial balloon spacer was comparable to the intact shoulder. The absolute values reported for functional abduction force were at or below 1N. These values are small in comparison to the current study (9.1 – 14.0N). Both studies also used similar loading protocols of the surrounding musculature. Possible explanations for the differences could include the variability that is seen in cadaveric *in-vitro* testing as well as the positioning of the subacromial balloon spacer as it is an unconstrained implant. Additionally, functional abduction force was presented as mean values averaged across all angles of abduction, therefore, it cannot be determined if there were significant differences between the test states at specific positions of abduction. Conversely, the values reported in a study by Lobao et al.[25] are much larger than those reported in the current study. They utilized an irreparable supraspinatus cadaveric model with both balanced and unbalanced loading through the deltoid. With insertion of the subacromial balloon they identified significant increases in deltoid load at 0-, 30-, and 60-degrees of glenohumeral abduction. However, as the infraspinatus remained intact in this study, it would be expected that glenohumeral compressive forces, glenohumeral kinematics, and abduction force would be improved compared to a posterosuperior irreparable rotator cuff tear.[18,35] Additionally, the deltoid loading protocol was not reported making direct comparisons difficult.

From a clinical standpoint, two randomized controlled trials have shown conflicting results with respect to shoulder function following a subacromial balloon spacer.[27,52] Despite identical postoperative rehabilitation protocols, Metcalfe et al.[27] reported a 50-degree improvement and a 1.9kg improvement in abduction range of motion and abduction strength, respectively, when looking at the shoulder debridement only group. Whereas in the shoulder debridement and subacromial balloon group, the abduction range of motion only improved 23.2 degrees with no improvement in abduction strength. These findings would be consistent with the biomechanical results of our study as the insertion of the subacromial balloon spacer did not improve functional abduction force compared to the massive irreparable rotator cuff tear state. Conversely, Verma et al.[52] observed a significant improvement in forward elevation range of motion in the subacromial balloon spacer group when compared to the partial rotator cuff repair group, however, there were several concomitant procedures in this study that may have confounded the results and led to improvement in shoulder function. Otherwise, no differences were noted between the groups.

The superior capsular reconstruction produced a higher functional abduction force than the rotator cuff deficient, subacromial balloon spacer, and both subacromial implant test states across all angles. It was the only surgical test state that did not result in a statistically significant difference when compared to the intact shoulder state at 0-degrees of abduction. However, when assessing the 15-60 degree abduction range, the superior capsular reconstruction produced less functional abduction force than both the intact shoulder and rotator cuff deficient states. All test states produced more functional abduction force at 0-degrees than at 15-degrees glenohumeral abduction. The intact shoulder and superior capsular reconstruction seemed to be most affected, with substantial reductions in functional abduction force values when comparing 0-degrees to 15-degrees abduction. For the intact shoulder, this has a logical explanation. As all rotator cuff muscles are in continuity, the force-couple and concavity-compression mechanisms are intact. In the intact shoulder state, the supraspinatus and infraspinatus are in continuity, and have 10N loads applied through their actuators. Additionally, the subscapularis has a total of 20N (10N superior subscapularis and 10N inferior subscapularis) of force applied through its actuators. Whereas in each subsequent test state the supraspinatus and infraspinatus are removed, and the subscapularis has a total of 10N (5N superior subscapularis and 5N inferior subscapularis) of force applied through its actuators to balance the force couples with the remaining teres minor. Therefore, the intact shoulder should have an advantage through early abduction range due to the contributions of the rotator cuff musculature. Interestingly, the superior capsular reconstruction produced more functional abduction force than the intact shoulder at 0-degrees despite the loss of rotator cuff contribution. Since the superior capsular reconstruction is tensioned at 30-degrees glenohumeral abduction, it is under increased tension when lowered to 0-degrees glenohumeral abduction. This allows the graft to act as a spring-loaded pseudo muscle. This contributes to the initiation of abduction and could explain the significant differences between the superior capsular reconstruction and all other experimental test states at this arm position. Once the arm is in 15-degrees of glenohumeral abduction and beyond, however, the superior capsular reconstruction loses this advantage and functions similar to a biological spacer. It generates much less functional abduction force than the intact shoulder across the 15-60 degree glenohumeral abduction range. Our study is the first biomechanical cadaveric investigation to show these findings with respect to the superior capsular reconstruction. Both Singh et al.[47] and Berthold et al.[5] reported that the superior capsular reconstruction improved functional abduction force and cumulative deltoid force, respectively, when compared to massive posterosuperior rotator cuff tears, however, these differences were not found to be significant. Additionally, these values were reported as mean values across all angles of abduction tested. Rybalko et al.[40] reported on deltoid abduction force in a supraspinatus deficient cadaveric model treated with a superior capsular reconstruction. Contrary to our findings, they demonstrated that the superior capsular reconstruction produced significantly more deltoid abduction force than the supraspinatus deficient state at 0-, 30-, and 60-degrees glenohumeral abduction. Additionally, the absolute values of the deltoid abduction force increased with increasing glenohumeral abduction, whereas in our study the values dramatically decreased from 0-15 degrees abduction. In clinical follow up studies, the superior capsular reconstruction appears to lead to improvements in patient shoulder function and strength at two years.[8,22] However, as previously demonstrated in the subacromial balloon spacer randomized-controlled trial, caution must be taken interpreting clinical outcome measures after shoulder surgery as there were significant improvements in all clinical measures in the debridement only surgical group after a dedicated physiotherapy program despite an untreated irreparable rotator cuff tear.[27]

Both variations of the subacromial implant were unable to achieve the functional abduction force values of the intact shoulder when considering the 0–60 degree abduction range. However, both implants generated more functional abduction force than the rotator cuff deficient test state. When considering the 15-60 degree abduction range, the 5mm high constraint and 5mm low constraint implant improve upon the rotator cuff deficient test state and the other surgical test states as well. As previously discussed, the superior capsular reconstruction and the intact shoulder have a significant advantage at initiation of abduction from the resting 0-degree position. Conversely, at low angles of abduction, the subacromial implant appears to act primarily as a rigid mechanical spacer with absolute functional abduction force values similar to the subacromial balloon spacer. However, at mid-to-high range abduction values (i.e., more than 30 degrees), the subacromial implants demonstrate an improvement upon the rotator cuff deficient shoulder, subacromial balloon spacer, and superior capsular reconstruction. At 30-degrees glenohumeral abduction the two subacromial implants show no statistically significant differences compared to the intact shoulder state. Whereas the rotator cuff deficient, subacromial balloon spacer, and the superior capsular reconstruction all produce significantly less functional abduction force at this arm position. As mentioned, the subacromial balloon spacer is subject to compression (i.e., loss of thickness) and displacement, thus the impact of the balloon may be variable. Additionally, the superior capsular reconstruction performs best when under tension. However, when that tension dissipates, the superior capsular reconstruction becomes a biological spacer subject to stretching, tearing, and compression.[12,28,29,48] Thus, its impact on functional abduction force is lost. As the subacromial implant is a rigid metallic structure, changes in the structure of the implant throughout glenohumeral abduction are not an issue. This could explain the differences through the middle range of glenohumeral abduction. At maximal glenohumeral abduction (60-degrees), the 5mm high constraint implant produced significantly more functional abduction force than the subacromial balloon. Whereas the 5mm low constraint implant produced significantly more functional abduction force than the superior capsular reconstruction. Both the subacromial balloon spacer and superior capsular reconstruction generated less functional abduction force than the rotator cuff deficient state in this arm position. These statistically significant differences likely represent the change in deltoid moment arm in this arm position. As discussed in Chapter 2, both subacromial implants led to inferior translation relative to the intact unbalanced rotator cuff tear state. Although the inferior translation of the center of rotation of the humeral head is not at the magnitude of the reverse shoulder arthroplasty, this relative inferior translation could explain the significant differences between the 5mm high constraint implant and the subacromial balloon, and the 5mm low constraint implant and the superior capsular reconstruction at 60-degrees glenohumeral abduction.

This study has limitations. Cadaveric specimens may not replicate the clinical scenario seen *in-vivo*. However, measures were taken to reduce the discrepancies. Soft-tissue structures including skin, fat, muscle, tendon, ligament, and capsule were left intact to replicate the normal shoulder environment. All tissues were kept hydrated with normal saline throughout testing to maintain their integrity. Total test time was kept under the previously documented critical time threshold for maintenance of mechanical properties of soft-tissues *in-vitro*.[20] Additionally, this testing protocol was based off previous work on massive irreparable rotator cuff tears in cadaveric shoulders.[30–32,38,46,47] Another limitation of the study is that the shoulder simulator applied static muscle loads which may not reflect the true dynamic loading of the muscles of the shoulder girdle. Although this has been accomplished in the past, several biomechanics studies utilize static muscle loads when assessing functional abduction force.[5,6,11,16,25,34,39,40,47] Lastly, our shoulder simulator did not permit scapulohumeral rhythm as the scapula was rigidly fixed to the simulator. Mixed protocols exist within the literature with respect to scapulohumeral rhythm, however, this omission could impact the functional abduction force generation as scapulothoracic motion may contribute to early abduction. With respect to the test states following the intact shoulder, the subscapularis loading was reduced to maintain the transverse force-couple between the subscapularis and the teres minor to reflect the loss of the supraspinatus and infraspinatus. This could result in less glenohumeral compression and may impact the amount of functional abduction force produced for each subsequent test state. Additionally, the surgical test states represent time zero. The effects of cyclical loading, creep, and attritional wear are not apparent in our study. This could impact the performance of the surgical implants over time as there are reports and biomechanical studies demonstrating graft failure, graft tearing, graft stretching, balloon displacement, and balloon resorption.[12,28,37,42–44,48,53] Lastly, the optimal design and positioning of the subacromial implant is not known. Additionally, the use of a tuberoplasty requires the disruption of normal patient anatomy and indicates that the geometry acromial component of the implant could be optimized to mitigate this requirement.

3.5 Conclusion

A comparative study was performed on a cadaveric shoulder simulation of a massive irreparable rotator cuff tear assessing the mechanical efficiency of the shoulder. The simulation of a massive irreparable rotator cuff tear led to significant reductions in functional abduction force compared to the intact shoulder. The addition of a subacromial balloon did not significantly improve the functional abduction force values from the rotator cuff deficient state, also resulting in significantly lower values than the intact shoulder during 0-30 degrees of abduction. The superior capsular reconstruction demonstrates a significant improvement upon the rotator cuff deficient test state, and each of the surgical test states at 0-degrees abduction. This effect is lost at all other angles of abduction. The subacromial implants produced less functional abduction force than the intact shoulder at low angles of abduction (i.e., 0-15 degrees). However, from 30-60 degrees of abduction, the implants improve upon the rotator cuff deficiency, subacromial balloon spacer, and superior capsular reconstruction test states. When comparing the subacromial implants, the 5mm low constraint implant appears to be more effective at generating functional abduction force than the 5mm high constraint implant, although no statistically significant differences were appreciated at any angle of abduction. However, as mentioned in Chapter 2, the 5mm low constraint implant may produce this benefit at the cost of additional anterior and inferior humeral head translation relative to the 5mm high constraint implant.

3.6 References

1. Ackland DC, Pandy MG. Lines of action and stabilizing potential of the shoulder musculature. *J Anat*. 2009;215(2):184-197. doi:10.1111/j.1469-7580.2009.01090.x

2. Alpert SW, Pink MM, Jobe FW, McMahon PJ, Mathiyakom W. Electromyographic analysis of deltoid and rotator cuff function under varying loads and speeds. *J Shoulder Elbow Surg*. 2000;9(1):47-58. doi:10.1016/s1058-2746(00)90009-0

3. Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR). *Hip, Knee & Shoulder Arthroplasty Annual Report 2022*.; 2022.

4. Berliner JL, Regalado-Magdos A, Ma CB, Feeley BT. Biomechanics of reverse total shoulder arthroplasty. *J Shoulder Elbow Surg*. 2015;24(1):150-160. doi:10.1016/j.jse.2014.08.003

5. Berthold DP, Bell R, Muench LN, et al. A new approach to superior capsular reconstruction with hamstring allograft for irreparable posterosuperior rotator cuff tears: a dynamic biomechanical evaluation. *J Shoulder Elbow Surg*. 2021;30(7S):S38-S47. doi:10.1016/j.jse.2021.04.002

6. Berthold DP, Muench LN, Dyrna F, Beitzel K. Biomechanical Consequences of Rotator Cuff Tears on the Glenohumeral Joint. In: *The Failed Rotator Cuff*. Springer International Publishing; 2021:15-22. doi:10.1007/978-3-030-79481-1_3

7. Boileau P, Gonzalez JF, Chuinard C, Bicknell R, Walch G. Reverse total shoulder arthroplasty after failed rotator cuff surgery. *J Shoulder Elbow Surg*. 2009;18(4):600-606. doi:10.1016/j.jse.2009.03.011

8. Burkhart SS, Pranckun JJ, Hartzler RU. Superior Capsular Reconstruction for the Operatively Irreparable Rotator Cuff Tear: Clinical Outcomes Are Maintained 2 Years After Surgery. *Arthroscopy*. 2020;36(2):373-380. doi:10.1016/j.arthro.2019.08.035

9. Campbell ST, Ecklund KJ, Chu EH, McGarry MH, Gupta R, Lee TQ. The role of pectoralis major and latissimus dorsi muscles in a biomechanical model of massive rotator cuff tear. *J Shoulder Elbow Surg*. 2014;23(8):1136-1142. doi:10.1016/j.jse.2013.11.030

10. Chelli M, Boileau P, Domos P, et al. Survivorship of Reverse Shoulder Arthroplasty According to Indication, Age and Gender. *J Clin Med*. 2022;11(10). doi:10.3390/jcm11102677

11. Dyrna F, Kumar NS, Obopilwe E, et al. Relationship Between Deltoid and Rotator Cuff Muscles During Dynamic Shoulder Abduction: A Biomechanical Study of Rotator Cuff Tear Progression. *Am J Sports Med*. 2018;46(8):1919-1926. doi:10.1177/0363546518768276

12. E Cline K, Tibone JE, Ihn H, et al. Superior Capsule Reconstruction Using Fascia Lata Allograft Compared With Double- and Single-Layer Dermal Allograft: A Biomechanical Study. *Arthroscopy*. 2021;37(4):1117-1125. doi:10.1016/j.arthro.2020.11.054

13. Ernstbrunner L, Suter A, Catanzaro S, Rahm S, Gerber C. Reverse Total Shoulder Arthroplasty for Massive, Irreparable Rotator Cuff Tears Before the Age of 60 Years: Long-Term Results. *J Bone Joint Surg Am*. 2017;99(20):1721-1729. doi:10.2106/JBJS.17.00095

14. Fleet C. *The Design and Evaluation of a Subacromial Implant in Restoring Normal Glenohumeral Joint Stability in the Presence of a Massive Irreparable Rotator Cuff Tear*. Western University; 2022.

15. Giles JW, Ferreira LM, Athwal GS, Johnson JA. Development and performance evaluation of a multi-PID muscle loading driven in vitro active-motion shoulder simulator and application to assessing reverse total shoulder arthroplasty. *J Biomech Eng*. 2014;136(12):121007. doi:10.1115/1.4028820

16. Halder AM, O'Driscoll SW, Heers G, et al. Biomechanical comparison of effects of supraspinatus tendon detachments, tendon defects, and muscle retractions. *J Bone Joint Surg Am*. 2002;84(5):780-785. doi:10.2106/00004623-200205000-00013

17. Itami Y, Park MC, Lin CC, et al. Biomechanical analysis of progressive rotator cuff tendon tears on superior stability of the shoulder. *J Shoulder Elbow Surg*. 2021;30(11):2611-2619. doi:10.1016/j.jse.2021.04.012

18. Keener JD, Wei AS, Kim HM, Steger-May K, Yamaguchi K. Proximal humeral migration in shoulders with symptomatic and asymptomatic rotator cuff tears. *J Bone Joint Surg Am*. 2009;91(6):1405-1413. doi:10.2106/JBJS.H.00854

19. Kim HM, Dahiya N, Teefey SA, et al. Location and initiation of degenerative rotator cuff tears: an analysis of three hundred and sixty shoulders. *J Bone Joint Surg Am*. 2010;92(5):1088-1096. doi:10.2106/JBJS.I.00686

20. King GJ, Pillon CL, Johnson JA. Effect of in vitro testing over extended periods on the low-load mechanical behaviour of dense connective tissues. *J Orthop Res*. 2000;18(4):678-681. doi:10.1002/jor.1100180422

21. Kontaxis A, Johnson GR. The biomechanics of reverse anatomy shoulder replacement--a modelling study. *Clin Biomech (Bristol, Avon)*. 2009;24(3):254-260. doi:10.1016/j.clinbiomech.2008.12.004

22. Lacheta L, Horan MP, Goldenberg BT, Dornan GJ, Higgins B, Millett PJ. Minimum 2-year clinical outcomes after superior capsule reconstruction compared with reverse total

shoulder arthroplasty for the treatment of irreparable posterosuperior rotator cuff tears in patients younger than 70 years. *J Shoulder Elbow Surg*. 2020;29(12):2514-2522. doi:10.1016/j.jse.2020.04.002

23. Lam F, Bhatia DN, Mostofi SB, van Rooyen K, de Beer JF. Biomechanical considerations of the normal and rotator cuff deficient shoulders and the reverse shoulder prosthesis. *Curr Orthop*. 2007;21(1):40-46. doi:10.1016/j.cuor.2006.10.004

24. Liu J, Hughes RE, Smutz WP, Niebur G, Nan-An K. Roles of deltoid and rotator cuff muscles in shoulder elevation. *Clin Biomech (Bristol, Avon)*. 1997;12(1):32-38. doi:10.1016/s0268-0033(96)00047-2

25. Lobao MH, Canham RB, Melvani RT, Abboud JA, Parks BG, Murthi AM. Biomechanics of Biodegradable Subacromial Balloon Spacer for Irreparable Superior Rotator Cuff Tears. *Journal of Bone and Joint Surgery*. 2019;101(11):e49. doi:10.2106/JBJS.18.00850

26. Matsen III FA. www.shoulderarthritis.blogspot.com. Rotator cuff tears - what to do if they are irreparable?

27. Metcalfe A, Parsons H, Parsons N, et al. Subacromial balloon spacer for irreparable rotator cuff tears of the shoulder (START:REACTS): a group-sequential, double-blind, multicentre randomised controlled trial. *The Lancet*. 2022;399(10339):1954-1963. doi:10.1016/S0140-6736(22)00652-3

28. Mihata T, Bui CNH, Akeda M, et al. A biomechanical cadaveric study comparing superior capsule reconstruction using fascia lata allograft with human dermal allograft for irreparable rotator cuff tear. *J Shoulder Elbow Surg*. 2017;26(12):2158-2166. doi:10.1016/j.jse.2017.07.019

29. Mihata T, Lee TQ, Hasegawa A, et al. Five-Year Follow-up of Arthroscopic Superior Capsule Reconstruction for Irreparable Rotator Cuff Tears. *Journal of Bone and Joint Surgery - American Volume*. 2019;101(21):1921-1930. doi:10.2106/JBJS.19.00135

30. Mihata T, McGarry MH, Kahn T, Goldberg I, Neo M, Lee TQ. Biomechanical Effect of Thickness and Tension of Fascia Lata Graft on Glenohumeral Stability for Superior

Capsule Reconstruction in Irreparable Supraspinatus Tears. *Arthroscopy*. 2016;32(3):418-426. doi:10.1016/j.arthro.2015.08.024

31. Mihata T, McGarry MH, Kahn T, Goldberg I, Neo M, Lee TQ. Biomechanical role of capsular continuity in superior capsule reconstruction for irreparable tears of the supraspinatus tendon. *American Journal of Sports Medicine*. 2016;44(6):1423-1430. doi:10.1177/0363546516631751

32. Mihata T, McGarry MH, Pirolo JM, Kinoshita M, Lee TQ. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: A biomechanical cadaveric study. *American Journal of Sports Medicine*. 2012;40(10):2248-2255. doi:10.1177/0363546512456195

33. Muh SJ, Streit JJ, Wanner JP, et al. Early follow-up of reverse total shoulder arthroplasty in patients sixty years of age or younger. *J Bone Joint Surg Am*. 2013;95(20):1877-1883. doi:10.2106/JBJS.L.10005

34. Mura N, O'Driscoll SW, Zobitz ME, et al. The effect of infraspinatus disruption on glenohumeral torque and superior migration of the humeral head: a biomechanical study. *J Shoulder Elbow Surg*. 2003;12(2):179-184. doi:10.1067/mse.2003.9

35. Oh JH, Jun BJ, McGarry MH, Lee TQ. Does a critical rotator cuff tear stage exist?: a biomechanical study of rotator cuff tear progression in human cadaver shoulders. *J Bone Joint Surg Am*. 2011;93(22):2100-2109. doi:10.2106/JBJS.J.00032

36. Otis JC, Jiang CC, Wickiewicz TL, Peterson MG, Warren RF, Santner TJ. Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. *J Bone Joint Surg Am*. 1994;76(5):667-676. doi:10.2106/00004623-199405000-00007

37. Prat D, Tenenbaum S, Pritsch M, Oran A, Vogel G. Sub-acromial balloon spacer for irreparable rotator cuff tears: Is it an appropriate salvage procedure? *J Orthop Surg (Hong Kong)*. 2018;26(2):2309499018770887. doi:10.1177/2309499018770887

38. Reeves JM, Singh S, Langohr GDG, Athwal GS, Johnson JA. An in-vitro biomechanical assessment of humeral head migration following irreparable rotator cuff tear and

subacromial balloon reconstruction. *Shoulder Elbow*. 2020;12(4):265-271. doi:10.1177/1758573219865479

39. Rybalko D, Bobko A, Amirouche F, et al. Biomechanics in an Incomplete Versus Complete Supraspinatus Tear: A Cadaveric Study. *Orthop J Sports Med*. 2020;8(12):2325967120964476. doi:10.1177/2325967120964476

40. Rybalko D, Bobko A, Amirouche F, et al. The biomechanics of the supraspinatus-deficient shoulder treated with superior capsular reconstruction vs. reverse total shoulder arthroplasty-experimental study. *Int Orthop*. 2020;44(11):2371-2377. doi:10.1007/s00264-020-04674-y

41. Samuelsen BT, Wagner ER, Houdek MT, et al. Primary reverse shoulder arthroplasty in patients aged 65 years or younger. *J Shoulder Elbow Surg*. 2017;26(1):e13-e17. doi:10.1016/j.jse.2016.05.026

42. Savarese E, Romeo R. New Solution for Massive, Irreparable Rotator Cuff Tears: The Subacromial "Biodegradable Spacer." *Arthrosc Tech*. 2012;1(1). doi:10.1016/j.eats.2012.02.002

43. Senekovic V, Poberaj B, Kovacic L, et al. The biodegradable spacer as a novel treatment modality for massive rotator cuff tears: a prospective study with 5-year follow-up. *Arch Orthop Trauma Surg*. 2017;137(1):95-103. doi:10.1007/s00402-016-2603-9

44. Senekovic V, Poberaj B, Kovacic L, Mikek M, Adar E, Dekel A. Prospective clinical study of a novel biodegradable sub-acromial spacer in treatment of massive irreparable rotator cuff tears. *Eur J Orthop Surg Traumatol*. 2013;23(3):311-316. doi:10.1007/s00590-012-0981-4

45. Singh S. *A Biomechanical Study Examining The Subacromial Balloon Spacer and Superior Capsular Reconstruction in the Treatment of Massive, Irreparable Rotator Cuff Tears*. Western University; 2017.

46. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The effect of the subacromial balloon spacer on humeral head translation in the treatment of massive, irreparable

rotator cuff tears: a biomechanical assessment. *J Shoulder Elbow Surg*. 2019;28(10):1841-1847. doi:10.1016/j.jse.2019.03.036

47. Singh S, Reeves J, Langohr GDG, Johnson JA, Athwal GS. The Subacromial Balloon Spacer Versus Superior Capsular Reconstruction in the Treatment of Irreparable Rotator Cuff Tears: A Biomechanical Assessment. *Arthroscopy - Journal of Arthroscopic and Related Surgery*. 2019;35(2):382-389. doi:10.1016/j.arthro.2018.09.016

48. Sommer MC, Wagner E, Zhu S, et al. Complications of Superior Capsule Reconstruction for the Treatment of Functionally Irreparable Rotator Cuff Tears: A Systematic Review. *Arthroscopy*. 2021;37(9):2960-2972. doi:10.1016/j.arthro.2021.03.076

49. Tempelaere C, Pierrart J, Lefèvre-Colau MM, et al. Dynamic Three-Dimensional Shoulder Mri during Active Motion for Investigation of Rotator Cuff Diseases. *PLoS One*. 2016;11(7):e0158563. doi:10.1371/journal.pone.0158563

50. Terrier A, Reist A, Merlini F, Farron A. Simulated joint and muscle forces in reversed and anatomic shoulder prostheses. *J Bone Joint Surg Br*. 2008;90(6):751-756. doi:10.1302/0301-620X.90B6.19708

51. Terrier A, Reist A, Vogel A, Farron A. Effect of supraspinatus deficiency on humerus translation and glenohumeral contact force during abduction. *Clin Biomech (Bristol, Avon)*. 2007;22(6):645-651. doi:10.1016/j.clinbiomech.2007.01.015

52. Verma N, Srikumaran U, Roden CM, et al. InSpace Implant Compared with Partial Repair for the Treatment of Full-Thickness Massive Rotator Cuff Tears: A Multicenter, Single-Blinded, Randomized Controlled Trial. *J Bone Joint Surg Am*. 2022;104(14):1250-1262. doi:10.2106/JBJS.21.00667

53. Yallapragada RK, Apostolopoulos A, Katsougrakis I, Selvan TP. The use of a subacromial spacer-inspace balloon in managing patients with irreparable rotator cuff tears. *J Orthop*. 2018;15(3):862-868. doi:10.1016/j.jor.2018.08.004

54. Yamaguchi K, Sher JS, Andersen WK, et al. Glenohumeral motion in patients with rotator cuff tears: a comparison of asymptomatic and symptomatic shoulders. *J Shoulder Elbow Surg*. 2000;9(1):6-11. doi:10.1016/s1058-2746(00)90002-8

Chapter 4

4 Thesis Summary and Conclusions

This chapter revisits the objectives and hypotheses from Chapters 2 and 3. The results are also revisited and assessed relative to the original objectives and hypotheses. The strengths and weaknesses of this work are discussed, followed by suggestions for future work in this field. This chapter concludes by discussing the significance of this work from a clinical perspective.

4.1 Summary of Findings

Massive irreparable rotator cuff tears that occur in younger, higher demand patients without glenohumeral arthritis continue to pose a challenge to the treating surgeon. There is no clear joint sparing surgical treatment that is favoured in this patient population. A reverse shoulder arthroplasty is designed to function in the absence of an intact rotator cuff, however, the success of this operation in younger patients without glenohumeral arthritis is hindered by worse outcomes, shorter implant survival, and the need for revision operations during the lifetime of the patient.

Some of the joint sparing surgical procedures rely on a biological or synthetic spacer to prevent contact between the humeral head and the undersurface of the acromion and correct the altered glenohumeral kinematics seen in rotator cuff deficiency. These surgical procedures do not appear to consistently provide a lasting effect and have a risk of displacement, resorption, tearing of the graft, stretching of the graft, and progression to rotator cuff tear arthropathy. Recently, a novel metallic subacromial implant was developed to treat this patient population, however, this has not been assessed clinically. Early biomechanical results presented herein demonstrated that it was effective in reducing the posterior and superior translation of the humeral head seen in the context of massive rotator cuff deficiency in a cadaveric model. However, it did require the use of a tuberoplasty to prevent impingement and improve overall range of motion of the shoulder.

The first objective of this thesis (Chapter 2) was to perform a biomechanical comparison of the subacromial balloon spacer, the superior capsular reconstruction, and the rigid subacromial implant in a massive rotator cuff deficient cadaveric model. The primary outcome measure of interest in this segment of the thesis was humeral head translation on the glenoid in the anterior-posterior and superior-inferior directions. It was hypothesized that the subacromial balloon spacer, superior capsular reconstruction, and both subacromial implants would restore the humeral head position in both anterior-posterior and superior-inferior directions such that it would not be significantly different than the translation observed in the intact shoulder. Furthermore, it was postulated that the subacromial balloon spacer would lead to further anterior humeral head translation when compared to the superior capsular reconstruction and the subacromial implants. A custom shoulder simulator was utilized for the purposes of the biomechanical comparison. This simulator applied physiologic static loads to the rotator cuff musculature as well as the deltoid during glenohumeral abduction in the scapular plane. Each test state was compared to the intact rotator cuff state and the massive irreparable rotator cuff tear state. The results of this study indicated that the subacromial balloon spacer, superior capsular reconstruction, and both the 5mm high constraint and 5mm low constraint implants were successful in reducing the posterior and superior humeral head translation observed in massive irreparable rotator cuff tears. Each surgical state reduced the superior and posterior humeral head translation to values that were not significantly different than the intact shoulder. Therefore, the first hypothesis was accepted. It should be noted, however, that the subacromial balloon spacer was unable to demonstrate significant differences compared to the massive irreparable rotator cuff tear state. It is believed that the variability in the balloon's positioning as well as its occasional displacement contributed to significant variance in its data. Similarly, the second hypothesis was accepted. The subacromial balloon spacer resulted in additional anterior translation relative to the intact shoulder, superior capsular reconstruction, and 5mm high constraint implant. An unexpected finding was that the 5mm low constraint implant also led to additional anterior translation of the humeral head compared to the intact shoulder, superior capsular reconstruction, and 5mm high constraint implant. Although both subacromial implants restored humeral head position in the context of a massive irreparable rotator cuff tear, the 5mm high constraint implant resulted in less anterior and inferior humeral head translation relative to the intact shoulder state. This may demonstrate the impact of the constraint of the articular surface with a lower radius of curvature resulting in more conformity with the humeral head and less overall observed translation.

The second objective of this thesis (Chapter 3) was to perform a biomechanical comparison of the subacromial balloon spacer, the superior capsular reconstruction, and the rigid subacromial implant in a massive rotator cuff deficient cadaveric model. The outcome measure of interest in this study was the mechanical efficiency of the shoulder as measured by the functional abduction force. It was hypothesized that the subacromial balloon spacer, superior capsular reconstruction, and both subacromial implants would improve the functional abduction force compared to the massive irreparable rotator cuff tear state. It was also hypothesized that the surgical states would not restore functional abduction force to the levels of the intact shoulder. A custom shoulder simulator was utilized for the purposes of the biomechanical comparison. This simulator applied physiologic static loads to the rotator cuff musculature as well as the deltoid during glenohumeral abduction in the scapular plane. Each test state was compared to the intact rotator cuff state and the massive irreparable rotator cuff tear state. The results demonstrated that the superior capsular reconstruction was the only surgical state to significantly improve functional abduction force compared to the massive irreparable rotator cuff tear state. Additionally, it was the only surgical state that was not significantly different than the intact rotator cuff tear state. This would result in a rejection of our first hypothesis. These findings are driven by the functional abduction force generation at 0-degrees of abduction for both the intact shoulder state and the superior capsular reconstruction. Beyond this, the superior capsular reconstruction produces significantly less functional abduction force than the intact shoulder at 15-degrees and 30-degrees abduction. Similarly, the superior capsular reconstruction shows no statistical improvement upon the rotator cuff deficient test state between 15-60 degrees of glenohumeral abduction, with values less than the rotator cuff deficient test state on average. The subacromial balloon produced less functional abduction force than the intact shoulder and an identical amount compared to the rotator cuff deficient shoulder. Whereas the 5mm high constraint and 5mm low constraint subacromial implants produced functional abduction force values that were not significantly different than the intact shoulder. When considering 60-degrees of abduction, the 5mm high constraint and 5mm low constraint implants produced significantly more functional abduction force than the subacromial balloon spacer and superior capsular reconstruction, respectively. Our second hypothesis was also rejected as the superior capsular reconstruction generated functional abduction force values above the level of the intact shoulder at 0-degrees abduction, and both the 5mm high constraint and 5mm low constraint subacromial implants produced functional abduction force values larger than the intact shoulder state at 60-degrees of abduction.

4.2 Strengths and Limitations

This thesis utilized a well-established cadaveric testing protocol and built upon previous work completed on massive irreparable rotator cuff tears. The current study is one of two comparative biomechanical studies investigating the subacromial balloon spacer and superior capsular reconstruction in the context of a massive irreparable rotator cuff tear. The addition of a novel rigid subacromial implant further differentiates our work from previous studies, and the inclusion of the subacromial balloon spacer and superior capsular reconstruction allows the results to be directly compared to two of the leading joint-sparing surgical techniques for massive irreparable rotator cuff tears. Additionally, this study conducted testing using repeated measures methodology. This resulted in each test state being evaluated on each individual specimen, permitting fair comparison of test states.

The development of the implant itself is a particular strength of the study. To our knowledge, this implant is the only permanent metallic subacromial device proposed to treat patients with massive irreparable rotator cuff tears. The aim of the implant is to improve upon the subacromial balloon spacer and superior capsular reconstruction by providing a lasting improvement in glenohumeral kinematics and mechanical efficiency of the shoulder in the context of a massive irreparable rotator cuff tear.

As mentioned in both Chapters 2 & 3, there are several limitations to this thesis that are inherent to cadaveric biomechanical studies. *In-vitro* testing on a cadaveric specimen can at best simulate the *in-vivo* environment of the shoulder, however, exact replication of the dynamic nature of the shoulder joint is challenging. This was mitigated by following a well-established testing protocol used in several previous cadaveric studies. Our study focused on scapular plane abduction, and therefore the complex movements of the shoulder such as flexion, extension, rotation, and adduction were not assessed. However, the focus of this study was assessing both glenohumeral kinematics and mechanical efficiency of the shoulder in rotator cuff deficiency, specifically superior and posterior humeral head migration. This is commonly assessed in the literature in both abduction and scapular plane abduction as the deltoid uniformly contracts, thus promoting translation of the humeral head. Another limitation is the order of testing. Ideally, the testing protocol would have been randomized such the impact of repetitive testing on the compliance of the tissues would have been minimized. However, due to the increasing invasiveness of each subsequent surgical state, randomization would not have been possible. Lastly, the subacromial implants remain in the early design stages. Results from previous studies and this thesis suggest that modifications to the implant's articular surface may improve contact with the humeral head as well as alleviate the requirement for a tuberoplasty. Should the implant's design change substantially, the impact on glenohumeral kinematics and mechanical efficiency of the shoulder may require further investigation.

4.3 Directions for Future Research

The results of this study indicate that at the recommended fill volume for the large subacromial balloon spacer, the humeral head translates anterior and inferior relative to the intact shoulder state at high angles of abduction. This corroborates the findings of previous work on this implant. Moving forward, extensive study on optimal fill volumes of the subacromial balloon spacer shoulder be completed to limit over-correction of humeral head translation in the context of a massive irreparable rotator cuff tear. Additionally, the current surgical technique for insertion of the subacromial balloon spacer recommends placement through a deltoid split or a lateral arthroscopic portal. As the balloon has asymmetric dimensions for length and width, insertion through a posterior arthroscopic portal should be considered. This may have effects on the glenohumeral kinematics of the shoulder in the context of a massive irreparable rotator cuff tear. Lastly, displacement of the subacromial balloon has proven to be an issue in biomechanical studies with similar incidents being reported in clinical studies. From a design perspective, there should be consideration for methods of early fixation in the subacromial space to limit this complication without compromising the effect of the balloon.

The superior capsular reconstruction and its impact on the biomechanics of the shoulder in rotator cuff deficiency have been extensively studied in the laboratory. However, current clinical concerns of the procedure include reductions in range of motion, graft failure, graft stretching, and loss of fixation. Several graft types have been previously investigated, however, due to cyclic loading, dermal grafts tend to stretch (i.e., creep). Alternative graft materials should be investigated to determine if there are more durable options for this surgical procedure.

With respect to the metallic subacromial implants, this thesis built upon the early research in the laboratory that focused on its design and development. Various changes were made to the original design; however, the implant's design has room for optimization. Therefore, shape optimization, material selection, articular thickness, use of constraint, and other design changes are likely to occur in the future. Specifically, changes in the articular surface of the implant to try to mitigate the need for the tuberoplasty procedure would be of particular importance.

As demonstrated in Chapters 2 & 3, the subacromial implant paired with a tuberoplasty partially restored functional abduction force while preventing the superior and posterior humeral head translation observed in massive rotator cuff deficiency. This led to slight overcorrection of humeral head translation such that there was anterior and inferior humeral head translation relative to the intact shoulder state. These results suggest that the 5mm thick implants may in fact be too thick at the point of contact with the humeral head and that design changes should occur to prevent the necessity of a tuberoplasty. Observations during testing revealed that the humeral head would occasionally contact the subacromial implant eccentrically, favoring the anterolateral corner. Design changes to the radius of curvature of this portion of the articular plate may in fact slightly decrease the thickness and disperse the contact forces with the humeral head. Likewise, the subacromial implant was designed to fit the lateral and anterior edges of the acromion. A converging lateral edge or reduction in the width of the implant in the medial-lateral dimension may alleviate the need for a tuberoplasty by reducing impingement with the greater tuberosity. Additional design modifications to decrease the overall anterior-posterior dimensions may also be beneficial in preventing the anterolateral impingement, although this may be more prominent in forward flexion of the shoulder. Lastly, another important research question would be the impact of the subacromial implant on the glenohumeral and subacromial contact pressures in comparison to the intact and rotator cuff deficient states.

Several other studies should be considered with respect to the use of a new surgical implant. Once final materials are selected for the implant, cyclical loading in non-destructive conditions should be investigated to determine the impact of the implant on the structural integrity of the scapula. It is critical to assess for areas of stress-concentration in the acromion and scapular spine as these are areas that are often subject to insufficiency fracture in this patient population. Additionally, this would allow for assessment of micromotion of the implant at its fixation points on the scapular spine and undersurface of the acromion. The next logical step would be destructive loading conditions to determine the location and patterns of periprosthetic fractures should they occur, as well as assessing modes of failure of the implant. As the reverse shoulder arthroplasty is the common endpoint for this patient population, studies that investigate the compatibility of this subacromial implant and the reverse shoulder arthroplasty would be of interest, particularly determining if the implant could remain in situ as a preventative measure for scapular spine and acromial insufficiency fractures. Ultimately, limited clinical studies will be required to determine the safety and efficacy of this implant in treating massive irreparable rotator cuff tears in a young patient population without glenohumeral arthritis.

4.4 Significance

This thesis presented a biomechanical comparison of two recognized surgical treatments (subacromial balloon spacer and superior capsular reconstruction) and a novel rigid subacromial implant in a massive rotator cuff deficient cadaveric model. The results of this thesis add to the breadth of literature on rotator cuff deficiency and the effect of a subacromial balloon spacer and superior capsular reconstruction. This thesis is unique, however, in that it investigates a new surgical implant designed to treat the patient population with a massive irreparable rotator cuff tear and no glenohumeral arthritis. Several interesting findings were observed, some with particular importance to this patient population. Each surgical state was effective in reducing the altered glenohumeral kinematics observed in massive rotator cuff deficiency, specifically the posterior and superior humeral head translation. With respect to the mechanical efficiency of the shoulder, the superior capsular reconstruction demonstrated superiority in initiation of abduction from a resting position compared to other surgical states. This is critically important to the rotator cuff deficient patient and is a key distinguishing factor for this surgical intervention. However, the superior capsular reconstruction was unable to provide any significant benefit at higher abduction angles, mostly acting as a biological spacer when no longer under tension. The subacromial implants improved upon the rotator cuff deficient state by preventing posterior and superior translation of the humeral head and partially restoring the mechanical efficiency of the arm during abduction. There was slight overcorrection with anterior and inferior humeral head translation compared to the intact shoulder, however, the impact of this is unknown at this time. The unique design of this implant could lead to a permanent implantable solution to the altered glenohumeral kinematics of the shoulder in rotator cuff deficiency, with a modest improvement in shoulder function. This could improve upon the previous recognized surgical treatments as the metallic device would not be subject to degradation over time or be at risk of stretching and tearing during repetitive use.

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Ferguson Devin P, Stevens Madison, Stewart Samuel, Oxner William, Dunning Cynthia, Glennie R Andrew. Describing the spine surgery learning curve during the first two years of independent practice. Medicine. (2021); 100(41): e27515. DOI:10.1097/MD.0000000000027515.

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Ferguson Devin P & Wong Ivan H. Arthroscopic anatomic glenoid reconstruction hardware removal. *Arthroscopy Techniques.* (2023) DOI:10.1016/j.eats.2022.10.011