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The Biomechanical Effects of Glenoid and Humeral Lateralization on the Rotator Cuff Muscles in Reverse Total Shoulder Arthroplasty

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Abstract

The utilization of reverse total shoulder arthroplasty (RTSA) has continued to increase as its clinical indications expand. The optimization of the rotator cuff function in the setting of RTSA is poorly understood and poor outcomes are associated with lack of external and internal rotation function. The purpose of this study is to evaluate the role of implant parameters on rotator cuff tendon excursion and moment arms in the setting of RTSA.

Using a cadaveric based model, a custom designed modular RTSA system was implanted that allowed for incremental changes to glenoid and humeral lateralization. Using a shoulder simulator and optical tracking, rotator cuff tendon excursion and moment arms were calculated at various arm positions and implant configurations.

Increased glenoid and humeral lateralization yielded overall increased tendon excursion. Despite lack of statistical significance, there was a trend towards increased rotator cuff moment arms as glenoid and humeral lateralization increased.

Keywords

Summary for Lay Audience

The use of reverse total shoulder arthroplasty (RTSA) has continued to increase as it has been found to be beneficial for an increasing number of glenohumeral problems. Despite great clinical outcomes, the consistency of internal and external rotation outcomes is poor. There have been a variety of implant designs studied and used in clinical practice that attempt to combat a variety of issues associated with RTSA. Some designs utilize a lateralized glenoid component while others prefer to lateralize the humeral component. There is a lack of literature that assesses the effect of lateralization of RTSA components on the rotator cuff tendons. The purpose of this study was to evaluate the effect of RTSA humeral and glenoid lateralization on the excursion and moment arms of the rotator cuff.

Using six cadaveric shoulder specimens, a modular RTSA implant was utilized that allowed incremental change to glenoid and humeral lateralization. These specimens were mounted onto a custom shoulder simulator that allowed for controlled abduction, internal rotation, and external rotation. Various implant configurations were tested at various arm positions. The excursion of supraspinatus, infraspinatus, teres minor, subscapularis superior and inferior were recorded at each trial. Excursion data was utilized to calculate respective moment arm data for each trial. The moment arms represent the effectiveness of a muscle on applying motion about a particular joint.

Results demonstrated statistically significant increase in tendon excursion as glenoid and humeral lateralization were increased, for all tendons tested. Despite lack of statistical significance, there was an overall trend towards increased rotator cuff moment arms as glenoid and humeral lateralization increased. Further research comparing these relationships to native rotator cuff excursion may further illustrate possible optimal implant positions that may restore native function.

Co-Authorship Statement

Chapter 1:   Yousif Atwan – sole author

Chapter 2:   Yousif Atwan – study design, data collection, statistical analysis, manuscript preparation

Jason Lockhart – study design, data collection, statistical analysis

Nicholas Van Osch – study design, data collection, statistical analysis

Dan Langohr – study design, statistical analysis, manuscript preparation

Jim Johnson – study design, reviewed manuscript preparation

George Athwal – study design, specimen preparation, manuscript preparation

Chapter 3:   Yousif Atwan – study design, data collection, statistical analysis, manuscript preparation

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Jim Johnson – study design, manuscript preparation

George Athwal – study design, specimen preparation, manuscript preparation

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Lastly, thank you to all my mentors, teachers, and supervisors at every step of my academic journey. I would have never had this opportunity without your guidance.

Dedication

To my mother and father.

My greatest mentors and supporters. I will never be able to thank you enough for the sacrifices you made in your life to provide my siblings and I with the opportunities we have. I hope to follow through with the only request you asked of me – Attempt to give back to my patients and those in need - daily, with the skills I have gained through the opportunities I've been blessed to have.

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Chapter 1

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1   Introduction

The purpose of this thesis is to biomechanically assess the effect of various reverse total shoulder arthroplasty parameters on the rotator cuff muscles. This chapter will highlight an overview of native shoulder anatomy and biomechanics. The development, rationale and biomechanics of reverse total shoulder arthroplasty will be introduced with a focus on potential implant variants. The objectives, hypotheses and overview of this thesis are also presented.

1.1   The Shoulder

The shoulder, or commonly referred to as the glenohumeral joint, is a synovial, diarthrodial ball-and-socket joint that provides the greatest range of motion of any joint in the human body. This vast range of motion includes flexion, extension, eternal rotation, internal rotation, abduction, and adduction. Developmental anatomy suggests our bipedal configuration allowed the sacrifice of significant articular congruity for increased soft tissue stability that allows this increased mobility.[1]

1.1.1   Osteology

The articulation of this joint is encompassed by a large humeral head and a relatively shallow cavity of the scapula, called the glenoid.

1.1.1.1   The Humerus

The humerus, shown in Figure 1-1, is the longest and largest bone in the upper extremity. It is composed of a shaft, proximal head, and distal condylar segments. The proximal segment consists of a humeral head, anatomic neck, greater tubercle, and lesser tubercle. The head is largely spheroid and has a radius of curvature of approximately 2.25 cm.[2] The anatomic neck of represents the junction between the humeral head and the tubercles and denotes the line of glenohumeral capsular attachment.[3] When the arm is at anatomic position (the humeral epicondyles are parallel with the coronal plane), the lesser tubercle is directly anterior, just beyond the anatomic neck and is the attachment site for

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subscapularis and the transverse ligament.[1] The greater tubercle is the most lateral and part of the proximal aspect of the humerus. It assumes attachment for infraspinatus, supraspinatus, and teres minor. The area between the tubercles is denoted the intertubercular groove and contains the long tendon of the biceps. In the coronal plane, the neck-shaft angle is approximately 135°.[4] The proximal half of the humeral shaft is cylindrical in shape and is home to the insertion of the three converging musculocutaneous units of the deltoid.[5]

Greater Tuberosity

Humeral Head

Bicipital Groove

Lesser Tuberosity

Humeral Neck (Anatomic)

Humeral Neck (Surgical)

Deltoid Tuberosity
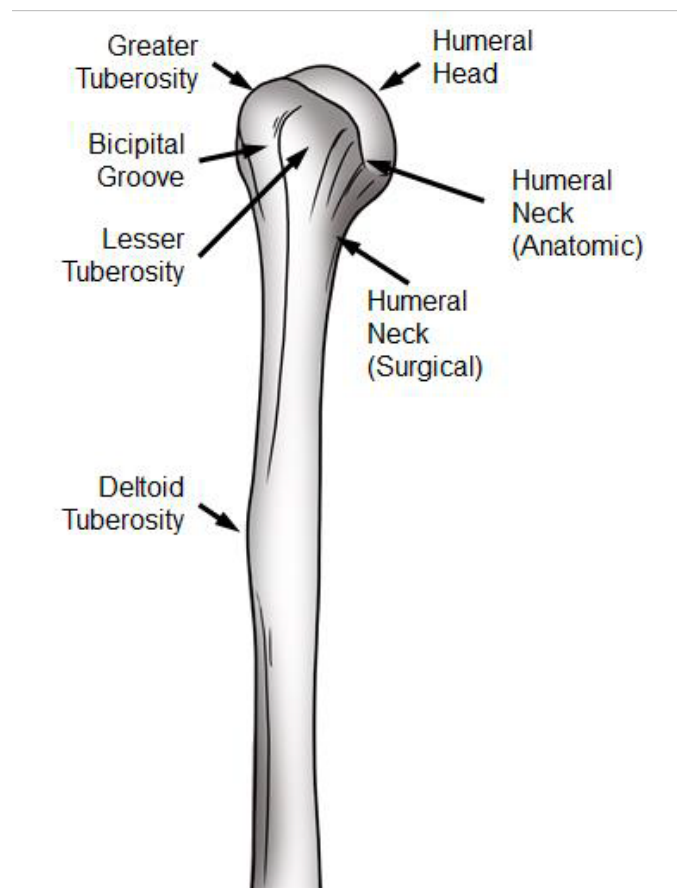
Figure 1-1: Bony Anatomy of Right Proximal Humerus

Illustration of the osseous anatomy of the proximal humerus.

1.1.1.2　The Scapula

The scapula is a large, broad, triangular bone that lies in the posterolateral aspect of the chest wall (Fig. 1-2 and Fig. 1-3). It is a predominately thin bone that spans the second to seventh ribs but has thicker prominences at the coracoid, spine and glenoid. The costal surface is concave and forms the subscapular fossa where it's predominately covered by the subscapularis muscle belly. The dorsal surface is divided by the scapular spine which separates the suprascapular fossa superiorly and infraspinous fossa inferiorly.

The superolateral surface of scapula is the glenoid, which articulates with the humeral head. The glenoid cavity has a surface area that is approximately three to four times small than that of the humeral head.[6] The glenoid cavity is retroverted approximately 4° to 12° in relation to the scapular plane. Meanwhile, the scapular plane is approximately 30° anterior to the coronal plane of the body.[7]
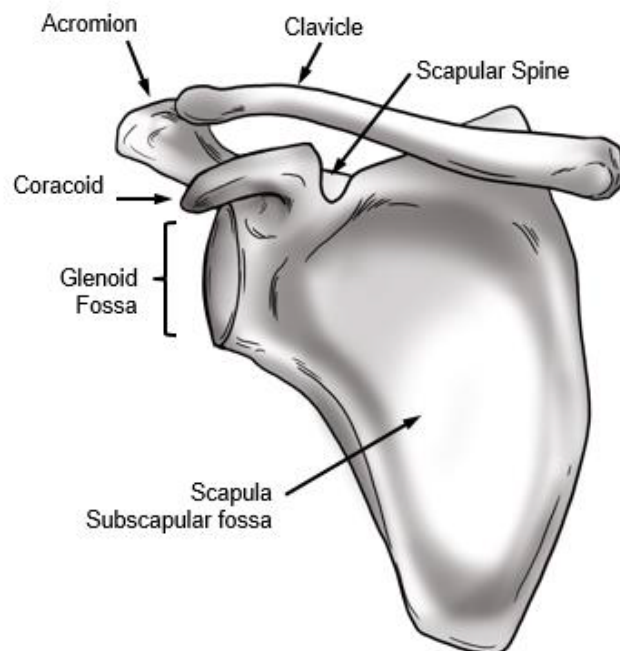
Figure 1-2: Bony Anatomy of Anterior Aspect of Scapula

Illustration of the osseous anatomy of the anterior aspect of the scapula. The clavicle is also depicted.
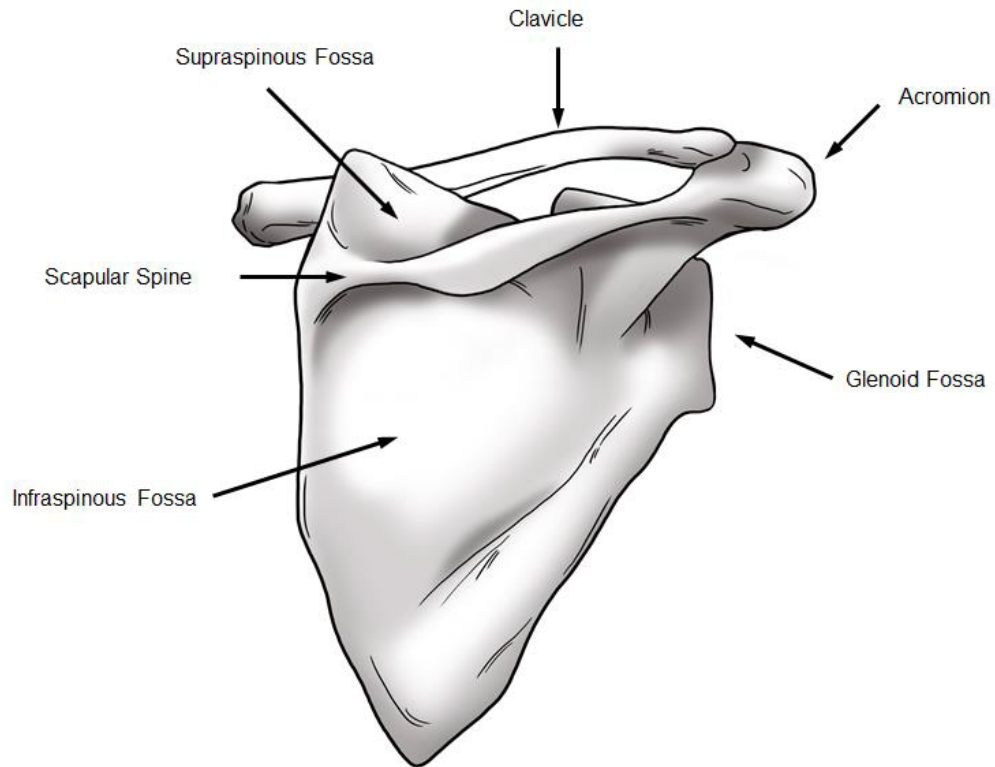
Figure 1-3: Bony Anatomy of Posterior Aspect of Scapula

Illustration of the osseous anatomy of the posterior aspect of the scapula. The clavicle is also depicted.

1.1.1.3　The Clavicle

The clavicle is a crane-like strut, with a double curve shape in the horizontal axis, that connects the trunk to the shoulder griddle. It is the first bone to ossify and often the last to fuse.[3] The medial aspect articulates with the sternum to form the sternoclavicular joint. The lateral third has a flat contour and serves as an attachment site for muscles and ligaments. Furthermore, the lateral aspect articulates with the acromion of the scapula to form the acromioclavicular joint.

1.1.2   Kinematics of the Shoulder

1.1.2.1   Static Stabilizers of the Shoulder

Since the glenohumeral joint is inherently unstable, it relies on the surrounding soft tissues to stabilize it at rest and during range of motion. The glenohumeral joint is predominantly stabilized statically by its joint capsule, ligaments, and labrum (Fig. 1-4). The glenoid capsule is a continuous fibrous structure that extends from the glenoid labrum to the neck of the humerus. In general, the capsule's surface area is twice that of the humeral head and thereby allowing up to 35 mL of fluid. The capsule tends to be lax in a resting state and tightens up at end range of motion.

The glenohumeral ligaments are extensions and reinforcements of the capsule and function to stabilize the glenohumeral joint at various positions. The superior glenohumeral ligament (SGHL) originated from the superior aspect of the glenoid and inserts to the fovea capitis and lies just superior to the lesser tubercle. It acts to resist inferior and posterior translation of the humerus at an adducted position.[8] The middle glenohumeral ligament most commonly originates from the labrum, just inferior to the SGHL and inserts just medial to the lesser tubercle. It is absent in up to 27% of specimens and acts as a secondary restraint to anterior translation of the humerus in an abducted position.[8,9] The inferior glenohumeral ligament is composed of anterior and posterior bands. It acts as the primary restraint to anterior and posterior translation in the abducted position.[8]

The glenoid labrum is composed of dense fibrous tissue and lays on the glenoid cavity.[9] It largely provides stability by increasing the depth of the glenoid cavity by 50% and thereby increasing the surface area available for contact the humeral head.[6,10,11]
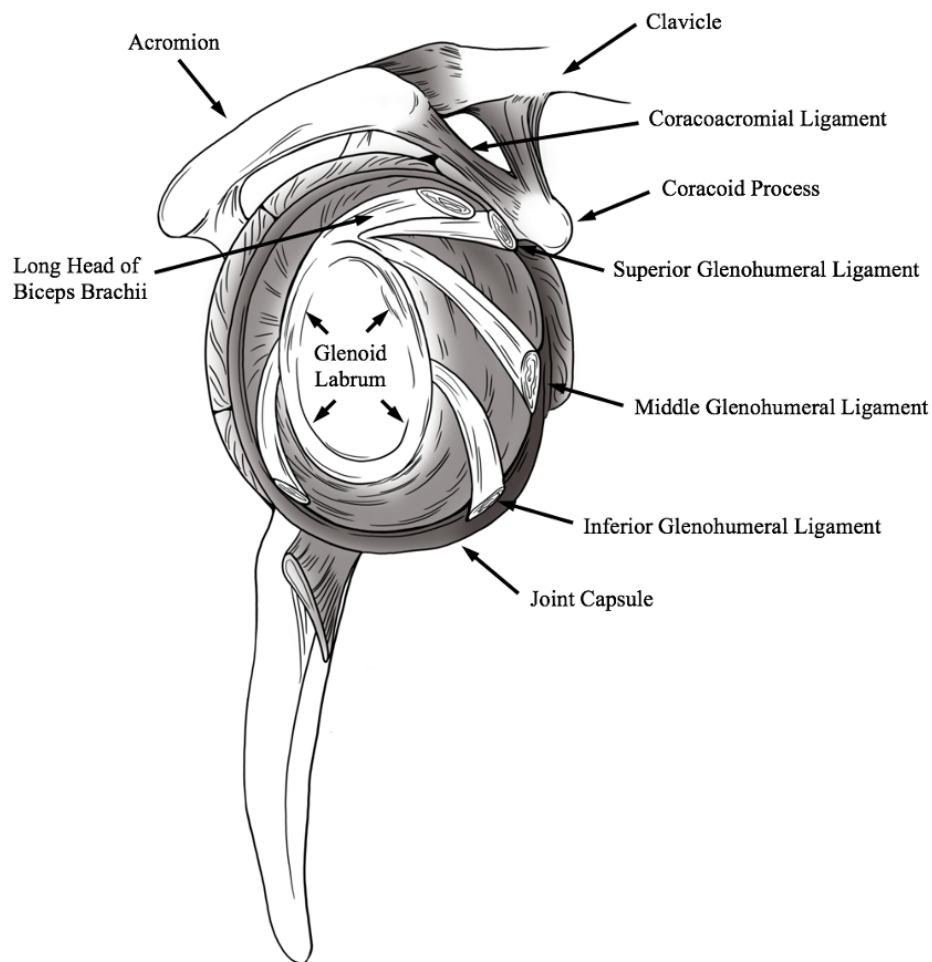
Figure 1-4: Soft Tissue Stabilizers of the Shoulder

Illustration of a sagittal view of the glenohumeral joint depicting associated stabilizers.

1.1.2.2   Rotator Cuff Muscles

1.1.2.2.1   Supraspinatus

The supraspinatus muscle originates from the supraspinatus fossa of the scapula and inserts into the greater tubercle of the humerus (Fig. 1-5B). Based on its length-tension curve, its maximal efficiency is at 30 of elevation. It's been demonstrated to have a shorter lever arm than the deltoid with an excursion approximately 66% of the deltoid.[12] The supraspinatus is innervated by the suprascapular nerve and its main blood supply is the suprascapular artery.

1.1.2.2.2   Infraspinatus

The infraspinatus muscle originates from the infraspinatus fossa of the scapula and inserts at the antero-superior aspect of the greater tubercle of the humerus (Fig. 1-5B). It accounts for up to 60% of the external rotation force applied on the humerus.[13] Furthermore, the muscle is an important stabilizer against posterior subluxation of the humerus.[14] The infraspinatus is innervated by the suprascapular nerve and its main blood supply is the suprascapular artery.

1.1.2.2.3   Teres Minor

The teres minor muscle originates from the middle portion of the lateral border of the scapula and inserts at the postero-inferior aspect of the greater tubercle of the humerus (Fig. 1-5B). The muscle provides up to 45% of the external rotation force applied on the proximal humerus.[13] Teres minor is innervated by the posterior branch of the axillary nerve and its main blood supply is the posterior humeral scapular circumflex artery.[15]

1.1.2.2.4   Subscapularis

The subscapularis muscle originates from the subscapularis fossa which encompasses most of the anterior aspect of the scapula (Fig. 1-5A). The upper 60% of the muscle inserts onto the lesser tuberosity of the humerus through a flattened tendinous structure. Meanwhile, the lower 40% of the muscle inserts below the lesser tubercle along the humeral neck through a fleshy insertion.[16] The subscapularis muscle functions as a large internal rotator of the proximal humerus. Due to its dense collagen distribution, the

muscle is also considered to be one of the passive stabilizers of the glenohumeral joint preventing anterior subluxation. The muscle is innervated by the upper and lower subscapular nerves. Its blood supply is derived from the axillary and subscapular arteries.
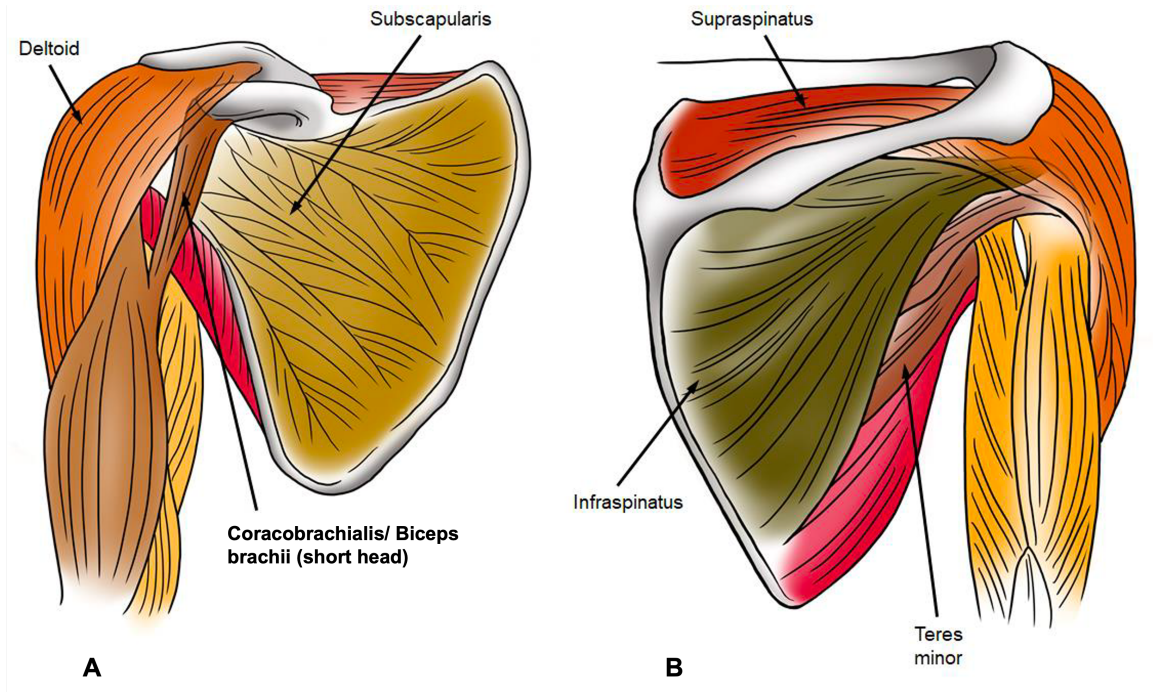
Figure 1-5: Dynamic Muscular Stabilizers

Illustration demonstrating the anterior (A) and posterior (B) muscular stabilizers around a scapula.

1.2 Reverse Total Shoulder Arthroplasty

1.2.1 History

Historically, the management of degenerative shoulder arthropathy in the setting massive and irreparable rotator cuff tears has been challenging and problematic. Charles S. Neer II was the first to introduce an anatomic shoulder prosthesis to combat this problem but the lack of constraint due to the absence of the rotator cuff led to failure of the implant.[17] In 1972, Neer designed the first "reversed" implant, the Mark I, whereby the ball and socket configuration was reversed.[17,18] This was a fixed fulcrum design with a large glenoid ball that aimed to provide stability and allow more motion. As the large ball did not allow for rotator cuff repair, Neer proceed to design the Mark II and Mark III with modifications including a smaller ball and introducing axial rotation to the humeral stem to improve motion. Despite these modifications, Neer abandoned these constrained designs as he continued to experience early failure of the glenoid component.[17-20]

Modern RTSA design is credited to the work of Paul-Marie Grammont and his design of the Delta prosthesis in 1985.[21-24] The differentiating principles of his design included a fixed center of rotation, medialized center of rotation and lowering of the humerus. To achieve this, he used a large ball that lacked the conventional neck used at that time. On the humeral side, he used a small cup with a non-anatomic neck-shaft angle of 155°.[21,22,24-26]

1.2.2 Biomechanics of Reverse Total Shoulder Arthroplasty

Unconstrained anatomic shoulder arthroplasty was abandoned for RTSA in the setting of shoulder arthritis and massive rotator cuff tears due to increased edge loading and rocking-horse phenomenon that led to increased failures.[27-29] Grammont proceeded to combat these issues by first improving the fixation of the glenoid component using a central peg and diverging screws to minimize micromotion at the prosthesis-bone interface.[21,30] Furthermore, he fixed the fulcrum of rotation, medialized the center of rotation and distalized the humerus.[21,31]

1.2.2.1   Fixation of Fulcrum of Rotation and Medialization of Center of Rotation

The initial designs of reverse total shoulder arthroplasty were adapted from total hip arthroplasty in which a fixed fulcrum for rotation was used.[31] Early RTSA designs utilized a glenoid neck which put the prosthesis at risk of increased shear forces that led to glenoid component loosening.[25,29-31] To combat this, Grammont eliminated the glenoid neck and used a spherical glenoid component that was directly fixed onto the bone.[25,29-31] This medialized the center of rotation and subsequently converted the torque forces at the glenoid component into compressive forces across the prosthesis-bone interface.[32,33] By medializing the center of rotation to the glenoid, this increased the distance away from the acromion and therefore increased the lever arm of the deltoid.[21,34] This improved the deltoid's abduction function by up to 42% through the recruitment of additional anterior and posterior deltoid fibers.[35] This contrasts with the posterior deltoid's physiologic role as an adductor in native shoulders.[35]

1.2.2.2   Distalization of the Humerus

While medialization of the center of rotation optimizes the deltoid, distalizing the humerus also increases the muscle's efficiency by lengthening and pre-tensioning. Based on length-tension relationship of muscles, the overall tension created by a muscle unit is the sum of its active and resting tension. Therefore, lengthening the muscle increases its resting tension and thereby allowing it to produce more torque. Studies have demonstrated a 30% increase in deltoid efficiency when 1 cm of humeral distalization is utilized.[34] Despite this advantage, care must be taken as over-lengthening the deltoid muscle may damage muscular fibers and decrease the resting tension resulting in inefficient motion.[36,37] Furthermore, in patients with increased risk of osteopenia, care must be taken as tensioning of the deltoid has resulted in acromial fracture post RTSA in approximately 3% of cases.[38]

1.2.3   Indications

Historically, the use of reverse total shoulder arthroplasty had been reserved for "cuff tear arthropathy in elderly patients as seen in Fig. 1-6.[39] This term was first coined by Neer to describe a massive rotator cuff tear that causes superior migration of the humeral head and subacromial impingement which leads to head collapse and erosion.[40] With improving technology and surgical experience, the incidence of reverse shoulder arthroplasty increased significantly based in registry data worldwide. In the United Kingdom, RTSA procedures increased 31.7% between 2012 and 2016.[41] Over the last 15 years, the incidence of RTSA in New Zealand and Norway increased from 2 to 56% and 12% to 52% respectively.[42,43] With its increased use, indications for RTSA have increased substantially to include acute proximal humerus fractures[24,44,45], cuff tear arthropathy[24,46-50], inflammatory arthropathy[48,51], tumor[24,52-54], nonunion or malunion[21,24,45], chronic shoulder dislocation[24], chronic pseudoparalysis[24,50,55,56] and revision arthroplasty.[21,24,57,58]

Figure 1-6: Example of End Stage Cuff Tear Arthropathy

Anteroposterior radiograph depicting end stage cuff tear arthropathy.

1.2.4   Implant Considerations

The design of RTSA has significantly evolved over time in search of optimizing function, range of motion and decreasing complications. Both surgical techniques and implant configurations have been developed and innovated for these purposes. To decrease the risk of scapular notching, in which impingement of the humeral component occurs on the inferior aspect of the scapular neck, surgeons have elected to place the glenoid baseplate at the inferior aspect of the glenoid. This technique has been found to decrease the risk of this phenomenon and thereby increase range of motion.[59]

Debate continues regarding the most optimal orientation and implant parameters of RTSA. Certain implant manufacturers allow for modification of parameters such as glenoid lateralization, humeral lateralization, polyethylene thickness, glenosphere diameter, neck-shaft angle, and cup constraint. In a computational based analysis, modification of these parameters has been shown to affect range of motion, stability and scapular notching.[60] For the purpose of this thesis, a focus will be placed on glenoid lateralization and humeral lateralization.

1.2.4.1   Glenoid Lateralization

Glenoid lateralization is defined is as the distance from the bone-baseplate interface to the center of rotation of the glenosphere (Fig. 1-7). Lateralization can be affected by the offset of the glenosphere relative to the baseplate as well as the geometry of the glenosphere itself. Furthermore, lateralization on the glenoid aspect can be configured by adjusting the amount of glenoid reaming or the utilization of bone grafts or augmented baseplates.[61]

Relative to Grammont's original design, novel RTSA designs have increased the use of lateral glenoid offset to improve stability and range of motion. Medialized designs have been shown to have decreased shear stress at the bone-baseplate interface and have decreased deltoid force required to elevate the arm. Nonetheless, they have higher rates of instability due to decreased rotator cuff tension and deltoid wrapping. Furthermore, as in Grammont's medialized design, there is an increased risk of scapular notching.[62] Subsequently, several computer-based models and biomechanical studies have suggested

increased glenoid lateralization may lead to increased implant stability and range of motion.[62-65] Meanwhile, Henninger et al. demonstrated that the lateralization of the center of rotation did not influence adduction or external rotation in a biomechanical based study. Albeit, they did demonstrate that this lateralization does decrease the mechanical advantage of the deltoid and increase the force required to dislocate the construct[66] Hettrich et al. further demonstrated that for every 1 mm of center of rotation lateralization, an additional 2.6% of deltoid force was required to elevate the arm.[67]

1.2.4.2   Humeral Lateralization

Humeral lateralization is defined as the distance between the deepest aspect of the humeral polyethylene and the vertical line passing through the center of the humeral stem (Fig. 1-8). Humeral lateralization can be configured through humeral tray geometry, inlay vs. on-lay design, polyethylene thickness and design. Several studies have demonstrated increased abductor lever arm of the deltoid with increased humeral lateralization due to the more lateral position of the greater tuberosity and effect of deltoid wrapping.[68-70] Using a biomechanical, cadaveric based model, Giles et al. demonstrated that increasing humeral lateralization from 0 mm to 10 mm decreased the deltoid force required to abduct the shoulder from 68% to 65% of bodyweight.[68]

In a biomechanical based model, Chan et al. studied the effect of humeral lateralization on the torque or the anterior and posterior rotator cuff. They demonstrated that increased humeral lateralization improved rotator cuff torque at various arm positions.[71] Meanwhile, computed tomography-based study by Lädermann et al. demonstrated that medialization through the humeral tray decreased abduction by 9 degrees while other range of motion was unchanged.[72] Furthermore, another computed tomography-based study by Keener et al. did not find humeral lateralization to have an effect of any aspect of range of motion.[63]
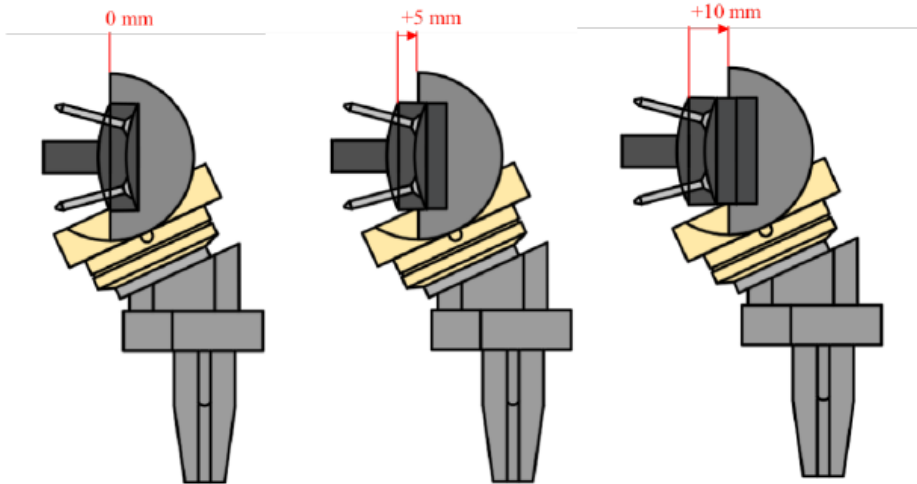
Figure 1-7: Glenoid Lateralization

Illustration depicting various glenoid lateralization positions in a custom modular RTSA model.
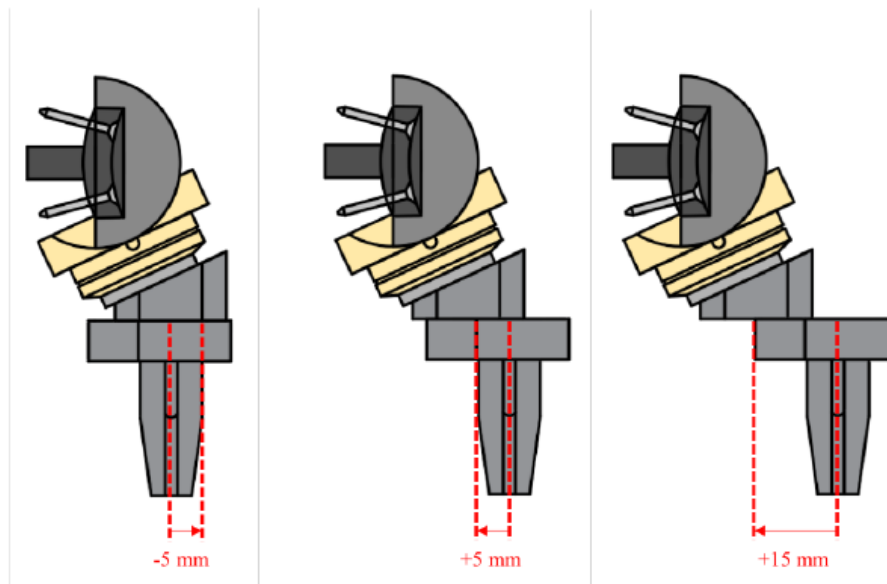
Figure 1-8: Humeral Lateralization

Illustration depicting various humeral lateralization positions in a custom modular RTSA model.

1.2.5   Classification of Reverse Total Shoulder Arthroplasty Implant Designs

Since Neer's development of the prototype RTSA, there has been an abundance of implants developed with a variety of designs. Roche et al. developed a classification system that enables the comparison of various prosthesis groups based on their distinguishing characteristics.[73] The two characteristics they used to classify designs were the position of the center of rotation relative to the native glenoid and the position of the humerus.[31,73] They defined three design categories (Fig. 1-9): Medial Glenoid/Medial Humerus (MGMH), Lateral Glenoid/Medial Humerus (LGMH) and Medial Glenoid/Lateral Humerus (MGLH).
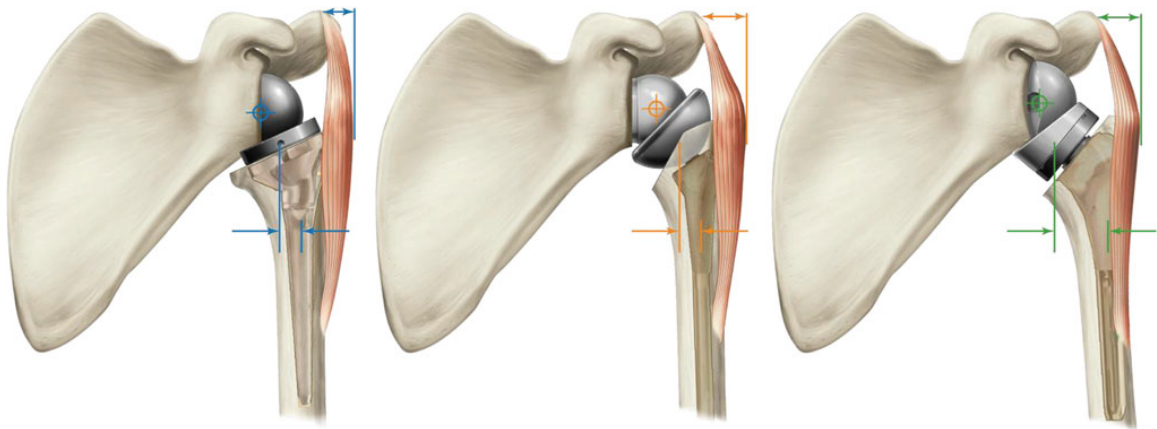
Figure 1-9: Reverse Total Shoulder Arthroplasty Design Classification System[60]

Left: medial glenoid/medial humerus (MGMH); Middle: lateral glenoid/medial humerus (LGMH); Right: medial glenoid/lateral humerus (MGLH)

1.2.5.1   Medial Glenoid/Medial Humerus (MGMH)

Within the MGMH design category, the center of rotation of the glenoid component is placed medially near the native glenoid and the humeral component is medial near the intramedullary axis. This is similar to Grammont's design and represented by the Delta III (DePuy International Ltd, Leeds, UK) prosthesis.[31,73] Due to the medial configuration, this design has been great at restoring abduction and forward elevation due to improved deltoid moment arm. Downsides to this medial configuration is the higher rate of scapular

notching due to the medial glenoid.[21,25,49,55,74] Furthermore, medialization leads to shortening of the rotator cuff muscles and subsequent poor internal and external rotation function.[21,25,49,55,74-77]

1.2.5.2   Lateral Glenoid/Medial Humerus (LGMH)

Within the LGMH design category, the center of rotation of the glenoid component is placed lateral to the native glenoid. This is achieved either by using a bone graft behind the baseplate or using a thicker glenoid component. The humeral component is unchanged relative to the humerus, but it is in a more lateral position compared to the acromion relative to the MGMH design due to the glenoid lateralization. Relative to the MGMH design, studies have shown improved internal and external rotation function and lower scapular notching rates. Due to the glenoid lateralization, this design does have a marginally higher glenoid component loosening rate.[73,78,79]

1.2.5.3   Medial Glenoid/Lateral Humerus (MGLH)

Within the MGLH design category, the center of rotation of the glenoid component is placed medial at the native glenoid, while the humeral component is placed in a lateral position. This design has been shown to have improved internal and external rotation function[75,80], decreased rate of scapular notching[60,73] and a relatively low glenoid component loosening rate.[81-83]

1.3 Thesis Rationale

The utilization of reverse total shoulder arthroplasty continues to increase as its indications broaden. Despite this, and accompanying innovations to improve function and longevity, several questions remain about optimal implant configuration to avoid complications. Range of motion deficits remain to be a challenging aspect to correct through implant design. While existing literature focuses on etiology, prevalence, and clinical outcomes of range of motion deficits, there is a deficiency in literature investigating the role of the rotator cuff as implant parameters are altered. To date, the optimal amount of lateralization within an implant design is not known. Currently available RTSA implants provide a wide range of lateralization options that result in theoretical benefits.

The purpose of this thesis is to evaluate the role of RTSA implant parameters on the rotator cuff using a cadaveric, biomechanical model. The thesis encompasses two main studies. The first focuses on the role of glenoid lateralization and humeral lateralization on rotator cuff excursion following RTSA implantation. The second study focuses on the effect of glenoid lateralization and humeral lateralization of the moment arms of the rotator cuff following RTSA implantation. These studies will yield important results that better delineate the effect of implant lateralization on the function and biomechanics of the rotator cuff following RTSA.

1.4 Thesis Objectives

The objectives of this thesis are to assess the role of commonly modifiable implant parameters on the excursion and biomechanics of the rotator cuff.

The primary objectives of this thesis are:

1. To evaluate the role of glenoid lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion (Chapter 2).

2. To evaluate the role of humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion (Chapter 2).

3. To evaluate the role of glenoid lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis moment arms (Chapter 3).

4. To evaluate the role of humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis moment arms (Chapter 3).

1.5 Thesis Hypothesis

The hypotheses of this thesis based on objectives are:

1. Increasing glenoid lateralization will result in increased excursion of supraspinatus, infraspinatus, teres minor, and subscapularis (Chapter 2).

2. Increasing humeral lateralization will result in increased excursion of supraspinatus, infraspinatus, teres minor, and subscapularis (Chapter 2).

3. Increasing glenoid lateralization will not result in a change in moment arms of supraspinatus, infraspinatus, teres minor, and subscapularis (Chapter 3).

4. Increasing humeral lateralization will result in increased moment arms of supraspinatus, infraspinatus, teres minor, and subscapularis (Chapter 3).

1.6   Thesis Overview

This thesis examines the biomechanics of the rotator cuff tendons in the setting of RTSA, focusing on component lateralization. The first chapter will focus on an overview of relevant anatomy, pathophysiology, and a review of RTSA design rationales. Chapter 2 is focused on the biomechanics of glenoid and humeral lateralization and their effect on rotator cuff tendon excursion. Chapter 3 is focused on the biomechanics of glenoid and humeral lateralization and their effect on rotator cuff tendon moment arms. Chapter 4 concludes the thesis and summarizes the findings and future areas of research within this field.

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Chapter 2

2 The Effect of Glenoid and Humeral Lateralization on the Excursion of the Rotator Cuff Muscles in Reverse Total Shoulder Arthroplasty

Overview

This chapter presents a study that examines the effect of incremental glenoid and humeral lateralization on the excursion of supraspinatus, infraspinatus, teres minor, and subscapularis. This study also examined the effect of glenohumeral abduction, internal rotation, and external rotation under various lateralization permutations.

2.1 Introduction

[NB: Parts of this material was presented in Chapter 1 and is also included here to ensure this chapter is in "article" format]

Historically, the use of reverse total shoulder arthroplasty (RTSA) had been reserved for "cuff tear arthropathy in elderly patients.[1] This term was first coined by Neer to describe a massive rotator cuff tear that causes superior migration of the humeral head and subacromial impingement which leads to head collapse and erosion.[2] With improving technology and surgical experience, the incidence of reverse shoulder arthroplasty increased significantly based in registry data worldwide. In the United Kingdom, RTSA procedures increased 31.7% between 2012 and 2016.[3] Over the last 15 years, the incidence of RTSA in New Zealand and Norway increased from 2% to 56% and 12% to 52% respectively.[4,5]

With its increased use, indications for RTSA have grown substantially to include acute proximal humerus fractures,[6-8] cuff tear arthropathy,[8-13] inflammatory arthropathy,[11,14] tumor,[8,15-17] nonunion or malunion,[7,8,18] chronic shoulder dislocation,[8] chronic pseudoparalysis,[8,13,19,20] and revision arthroplasty.[8,18,21,22]

RTSA design has significantly evolved over time in search of optimizing function, range of motion and decreasing complications. Both surgical techniques and implant configurations have been developed and innovated for these purposes. To decrease the risk of scapular notching, where impingement of the humeral component occurs on the inferior aspect of the scapular neck, surgeons have elected to place the glenoid baseplate at the inferior aspect of the glenoid. This technique has been found to decrease the risk of this phenomenon and thereby increase range of motion.[23]

Debate continues regarding the most optimal orientation and implant parameters of RTSA. Certain manufacturers allow for modification of parameters such as glenoid lateralization, humeral lateralization, polyethylene thickness, glenosphere diameter, neck-shaft angle, and cup constraint. In a computational based analysis, modification of these parameters has been shown to affect range of motion, stability and scapular notching.[24]

For the purpose of this study, focus is placed on glenoid lateralization and humeral lateralization.

Glenoid lateralization is defined as the distance from the bone-baseplate interface to the center of rotation of the glenosphere. Lateralization can be affected by the offset of the glenosphere relative to the baseplate as well as the geometry of the glenosphere itself. Furthermore, lateralization on the glenoid aspect can be configured by adjusting the amount of glenoid reaming or the utilization of bone grafts or augmented baseplates.[25]

Humeral lateralization is defined as the distance between the deepest aspect of the humeral polyethylene and the vertical line passing through the center of the humeral stem. Humeral lateralization can be configured through humeral tray geometry, inlay vs. on-lay design, polyethylene thickness and design. Various studies have demonstrated an increased abductor lever arm of the deltoid with increased humeral lateralization due to the more lateral position of the greater tuberosity, and also the effect of deltoid wrapping.[26-28] Using a biomechanical, cadaveric based model, Giles et al. demonstrated that increasing humeral lateralization from 0 mm to 10 mm decreased the deltoid force required to abduct the shoulder from 68% to 65% of bodyweight.[26]

Quantifying the excursion of a tendon allows for better understanding of the tendon's action and torque it applies around a joint. However, there remains a lack of information regarding the effect of incremental glenoid and humeral lateralization on the excursion of the rotator cuff in the setting of reverse total shoulder arthroplasty. The purpose of this in-vitro biomechanical cadaveric study was to evaluate the role of glenoid lateralization and humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion.

2.2   Materials and Methods

2.2.1   Cadaveric Specimen Preparation

Six fresh frozen left male cadaveric glenohumeral specimens were utilized (mean age 71, range 64 – 77). Specimens were pre-screened with CT scans to exclude those with underlying rotator cuff and/or glenohumeral pathology. They were thawed for 18 hours prior to testing. The humerus was transected at the midshaft region to accommodate for shoulder simulator testing. The overlying skin and subcutaneous fat were dissected, and the underlying musculature was exposed. The deltoid muscle was elevated at its origins and kept intact at its insertions. The underlying rotator cuff muscles were exposed. The subscapularis muscle was elevated from the subscapularis fossa and left intact at its insertion on the humerus. It was also divided and isolated into its superior and inferior portions. The supraspinatus was elevated from the supraspinatus fossa and kept intact as its humeral insertion. Likewise, infraspinatus and teres minor were also elevated at their origins and kept intact at their humeral insertions.

The five rotator cuff tendons were tagged with a heavy #5 non-absorbable braided suture (Ethibond, Ethicon, Johnson & Johnson, New Jersey, USA) as previously described by Kerrigan et al.[29] The three deltoid insertions were identified at the deltoid tuberosity by their anatomic description and also individually tagged with the Ethibond sutures.[30] The labrum was resected as well as the remaining glenoid articular cartilage. Fig. 2-1 demonstrates a specimen mounted onto the shoulder simulator with associated tendon cables to computer-controlled actuators.

Optical tracking sensor

Rotator cuff cables to pneumatic actuators

Scapular clamp

Silk sutures marking insertion and line of tendon
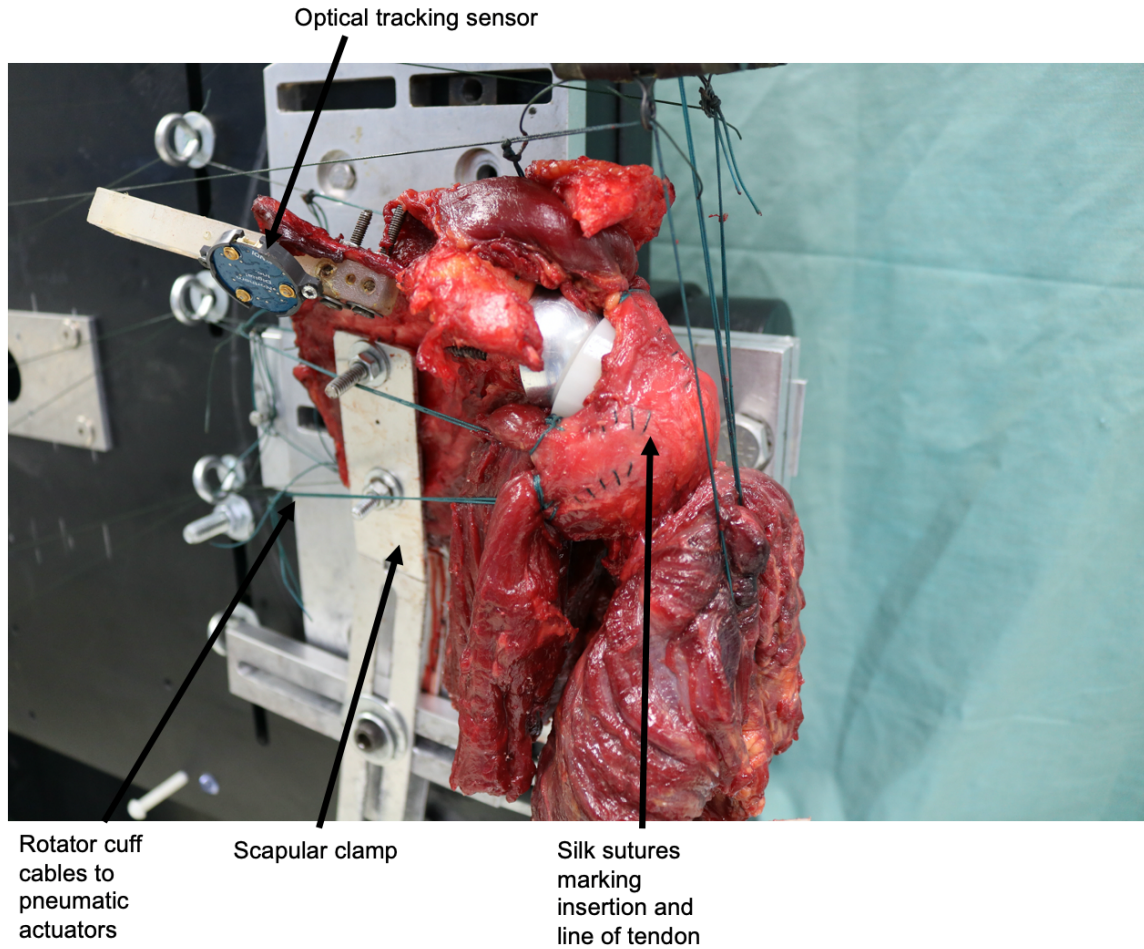
Figure 2-1: Implanted Custom Reverse Total Shoulder Arthroplasty Prosthesis

A specimen is shown mounted on the shoulder simulator using a scapular clamp. Ethibond sutures were used to tag the rotator cuff tendons and deltoid heads. The deltoid muscle was retracted for this image.

2.2.2 Custom Reverse Shoulder Arthroplasty Implantation

A custom modular implant (Fig. 2-2) was utilized for this study as previously described by Langohr et al.[26,31] The custom glenosphere allows for offset modularity in 5 mm increments. Furthermore, the custom humeral component also allows for offset modularity in 5 mm increments.
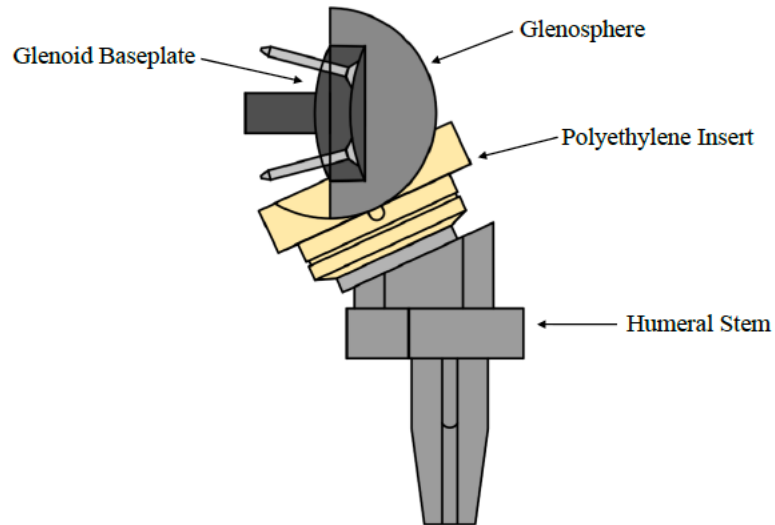
Figure 2-2: Sagittal View of Custom Modular Reverse Shoulder Arthroplasty Prosthesis

The custom designed modular reverse total shoulder arthroplasty implant features a glenoid base plate with lateralization option. The modular humeral stem also allows for incremental lateralization.

In order to prepare for implantation, a sagittal saw was utilized to complete the humeral cut at the anatomic neck. A powered reamer was then used to ream the proximal humerus and subsequently the humeral shaft. The glenoid was prepared using manual and powered reamers to remove any remaining cartilage. The RTSA was implanted using a technique from the Wright Medical Tornier Aequalis surgical technique manual (Wright Medical Technologies, Memphis, Tennessee) and as described by Kerrigan et al.[29] The custom

glenoid baseplate was secured by placing three screws into the glenoid. It was placed in neutral orientation and the inferior edge of the baseplate was aligned with the inferior aspect of the glenoid rim. The custom humeral component was cemented in neutral version relative to the native epicondylar axis. The inferior edge of the humeral cup was lined up with the superior aspect of the greater tuberosity to set humeral distalization. A metallic humeral rod was cemented at the distal aspect of the humeral shaft to facilitate connection to the shoulder simulator for testing.

2.2.3 Shoulder Simulator

A custom shoulder simulator was used for this experiment as described by Giles et al.[32] The scapula was fixed to the simulator in static position through a scapular clamp that was drilled through the scapular body (Fig. 2-3). The scapular was placed in a position that allowed for the glenoid face to be perpendicular to the horizontal as well as placing the glenoid center of rotation (COR) in a compatible position for the arc COR. The humeral rod was placed in the shoulder simulator assembly. This assembly allowed for abduction as well as internal and external rotation. The ethibond sutures used to tag the deltoid heads as well as rotator cuff muscles were individually tied to a long high strength cable (Sufix Performance Braid, 130lb strength). These cables were routed along their physiologic lines of action to pneumatic actuators that were computer controlled. These actuators applied loads to each tendon to mimic a physiologic glenohumeral joint. As previously described by Kerrigan et al, the deltoid muscle loading was split with 15% anterior, 70% middle and 15% posterior as abduction occurred. Furthermore, a 10 N load was applied in total for the rotator cuff muscles to stabilize the reverse total shoulder arthroplasty.[29]

Along the horizontal cable prior to connection to the pneumatic actuator, a knot was made for each rotator cuff tendon. This will subsequently be utilized as a measurement point within the experimental protocol. Furthermore, optical tracking sensors (OptoTrak™ Certus, NDI, Waterloo, ON) were fixed at a static point on the scapula and the humerus in order to determine their positions in space and relative to other digitized points as described within the protocol.
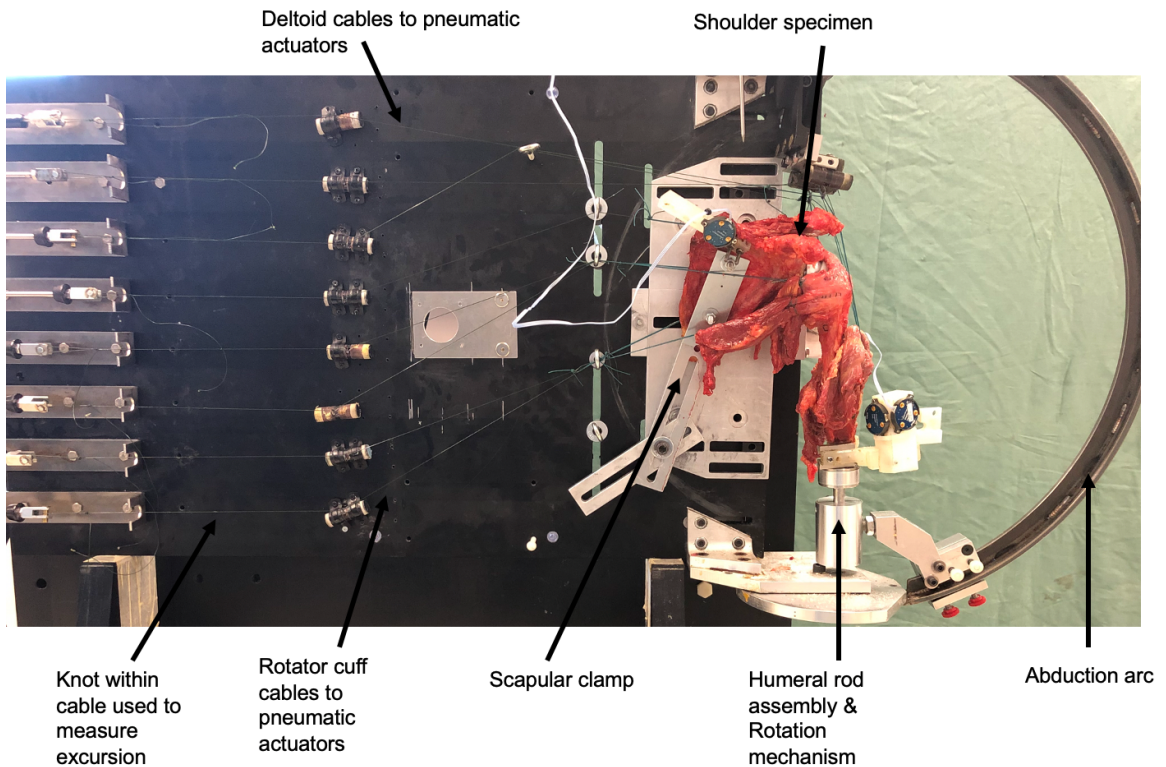
Figure 2-3: Experimental Shoulder Simulator

This image depicts the set up for the outlined experiment. The scapula is secured to the shoulder simulator via scapular clamp. The humerus is cemented into the humeral assembly which also allowed to incremental rotation. This assembly is attached to the abduction arc which allows for incremental abduction. The cables tagging the rotator cuff and deltoid tendons were passed through respective islets mimicking physiologic lines of action towards the actuators. A knot within each cable was used to measure relative excursion.

2.2.4   Testing Protocol

After the glenohumeral specimen with implanted reverse shoulder arthroplasty was
mounted on to the shoulder simulator, the cables were attached to the pneumatic actuator.
A 38 mm glenosphere and associated humeral polyethylene insert were utilized for the
duration of the case. Nine combinations of humeral and glenoid lateralization
configurations were tested. Glenoid lateralization parameters included: neutral, 5 mm and
10 mm. These were in the form of modular spacers placed between the glenoid baseplate
and the glenosphere. Humeral lateralization parameters included -5 mm, 5 mm, and 15
mm. For each implant configuration, the specimen was tested in multiple static positions.
Neutral rotation, 30° external rotation (ER), 60° ER, 30° internal rotation (IR) and 60° IR
were tested at both neutral and 90 degrees of abduction in the scapular plane. When
changing axial rotation, the abduction arc was locked into position to only permit axial
rotation. Table 2-1 summarizes the various implant configurations tested for this
experiment.

Implant Configuration	Glenoid Lateralization	Humeral Lateralization
1	0 mm	-5 mm
2	0 mm	-5 mm
3	0 mm	-5 mm
4	5 mm	5 mm
5	5 mm	5 mm
6	5 mm	5 mm
7	10 mm	15 mm
8	10 mm	15 mm
9	10 mm	15 mm

Table 2-1: List of Tested Implant Configurations

Table outlines the implant configurations tested within this experiment.

For each trial tested, the position of the humerus and the scapula were recorded in space. Using the optical tracking system, a stylus was utilized to digitize the knots on each rotator cuff tendon cable. This determines the excursion of each tendon after each configuration/position change.

2.2.5   Outcome Variables

The primary outcome measures of this experiment were the excursion of supraspinatus, infraspinatus, teres minor, subscapularis superior and subscapularis inferior. These excursion measurements were recorded for each implant configuration as lateralization was modified as well as rotation and abduction.

Using the optical tracking system, the position of the scapular marker was recorded as a static reference for each position. The knots on each cable for the respective tendons served as a marker that was digitized via the optical tracking system. This was compared relative to the scapular reference to determine the relative excursion in millimeters.

2.2.6   Statistical Analysis

Repeated measures of analysis of variance (RM-ANOVA) were utilized for statistical analysis through the Statistical Package for the Social Sciences software (IBM SPSS Statistics for Macintosh, Version 26.0.0.1; Armonk, NY; IBM Corp). Further pairwise comparisons of variables were completed. Statistical significance was defined as $p < 0.05$ for all analyses. Power analyses were completed and determined that six specimens were sufficient to obtain at least 80% power for each outcome variable for this study. The most medialized configuration of 0 mm glenoid lateralization and -5 mm humeral lateralization was utilized as baseline excursion in the neutral abduction and 0° rotation position for all other configurations assessed.

2.3　Results

2.3.1　Supraspinatus

Overall, a change in glenoid lateralization and humeral lateralization respectively produced a statistically significant change in supraspinatus tendon excursion ($p < 0.001$). Fig. 2-4(A) demonstrates overall results of lateral tendon excursion as glenoid lateralization is increased by 5 mm intervals. Fig. 2-4(B) demonstrates overall results of lateral tendon excursion as humeral lateralization is increased by 10 mm intervals. The lateral excursion of supraspinatus increased by 4.36 ± 0.40 mm when changing glenoid lateralization from 0 mm to 5 mm ($p < 0.001$). Meanwhile, lateral excursion increased by 8.10 ± 1.13 mm when changing glenoid lateralization from 5 mm to 10 mm ($p < 0.001$). Furthermore, lateral excursion increased by 4.10 ± 0.85 mm and 8.57 ± 0.53 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively ($p < 0.001$). These results include all implant configurations and positions.

2.3.1.1　Effect of Implant Configuration on Supraspinatus Excursion

Overall, each abduction and rotation angles had statistically significant effects on the excursion of supraspinatus ($p < 0.001$). As abduction increased from 0° to 90°, the supraspinatus tendon had increased medial excursion by 22.43 ± 3.26 mm ($p = 0.001$). In neutral abduction and all rotation states, increasing humeral lateralization, while maintaining the same glenoid lateralization, had a significant increase on supraspinatus lateral excursion ($p < 0.01$). The results at 90° of abduction are also summarized in Fig. 2-5.

Figure 2-4: Overall Supraspinatus Excursion

*The overall (inclusive of all testing parameters) mean excursion (+/- 1 SD) excursion of supraspinatus. Figure (A) demonstrates the effect of glenoid lateralization on lateral excursion. Figure (B) demonstrates the effect of humeral lateralization on lateral excursion. Significance (p <0.05) across multiple parameters is denoted with a "**".*

Figure 2-5: Excursion of Supraspinatus at Various Positions and Implant Configurations

*Mean excursion (+/- 1 SD) of supraspinatus as glenoid and humeral lateralization are varied at (A) 0° abduction/0° rotation, (B) 0° abduction/60° IR, (C) 0° abduction/60° ER, (D) 90° abduction/0° rotation, (E) 90° abduction/60° IR, and (F) 90° abduction/60°ER. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*

2.3.2   Infraspinatus

Overall, a change in glenoid lateralization and humeral lateralization respectively produced a statistically significant change in infraspinatus tendon excursion ($p < 0.001$). Fig. 2-6(A)demonstrates overall results of lateral tendon excursion as glenoid lateralization is increased by 5 mm intervals. Fig. 2-6(B) demonstrates overall results of lateral tendon excursion as humeral lateralization is increased by 10 mm intervals. The lateral excursion of infraspinatus increased by 2.89 ± 1.24 mm when changing glenoid lateralization from 0 mm to 5 mm ($p = 0.067$). Meanwhile, lateral excursion increased by 8.40 ± 1.29 mm when changing glenoid lateralization from 5 mm to 10 mm ($p = 0.001$). Furthermore, lateral excursion increased by 5.43 ± 0.49 mm and 6.10 ± 0.59 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively ($p < 0.001$). These results include all implant configurations and positions.

2.3.2.1   Effect of Implant Configuration on Infraspinatus Excursion

Overall, each abduction and rotation angles had statistically significant effects on the excursion of infraspinatus ($p < 0.001$). As abduction increased from 0° to 90°, the infraspinatus tendon had increased medial excursion by 3.58 ± 1.68 mm ($p = 0.086$). In neutral abduction and all rotation states, increasing humeral lateralization, while maintaining the same glenoid lateralization, had a significant increase on infraspinatus lateral excursion ($p < 0.01$). The results at 90° of abduction are also summarized in Fig. 2-7.
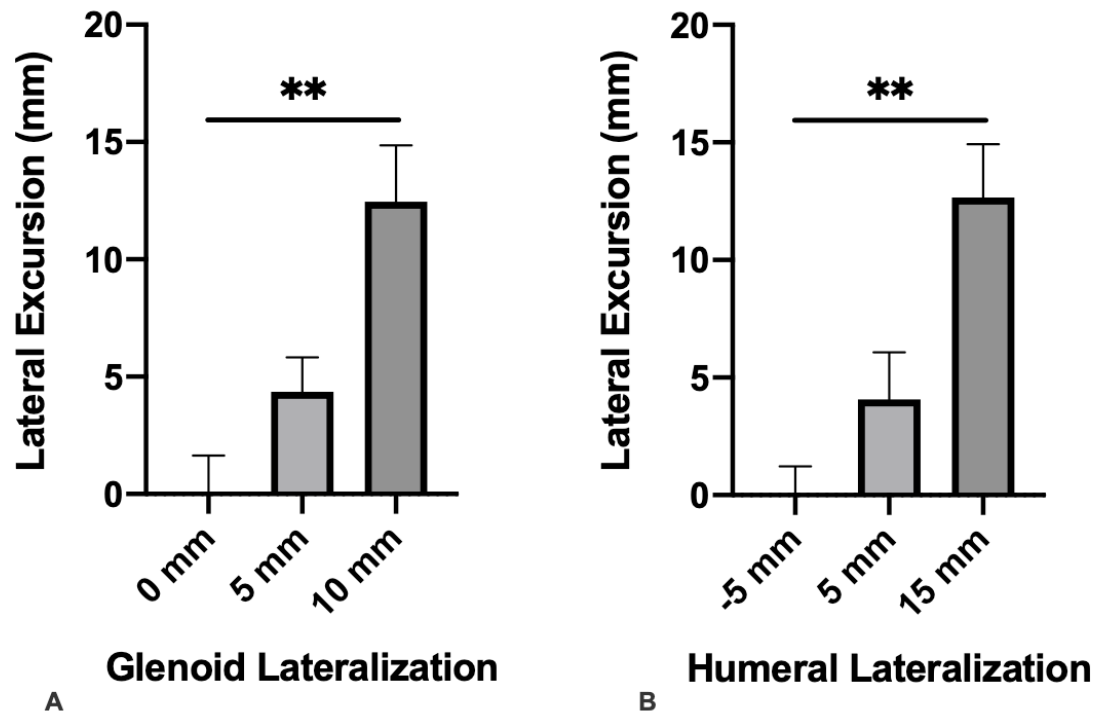
Figure 2-6: Overall infraspinatus excursion

*Figure outlining the overall (inclusive of all testing parameters) mean excursion (+/- 1 SD) excursion of infraspinatus. Figure (A) demonstrates the effect of glenoid lateralization on lateral excursion. Figure (B) demonstrates the effect of humeral lateralization on lateral excursion. Significance (p <0.05) across multiple parameters is denoted with a "**".*
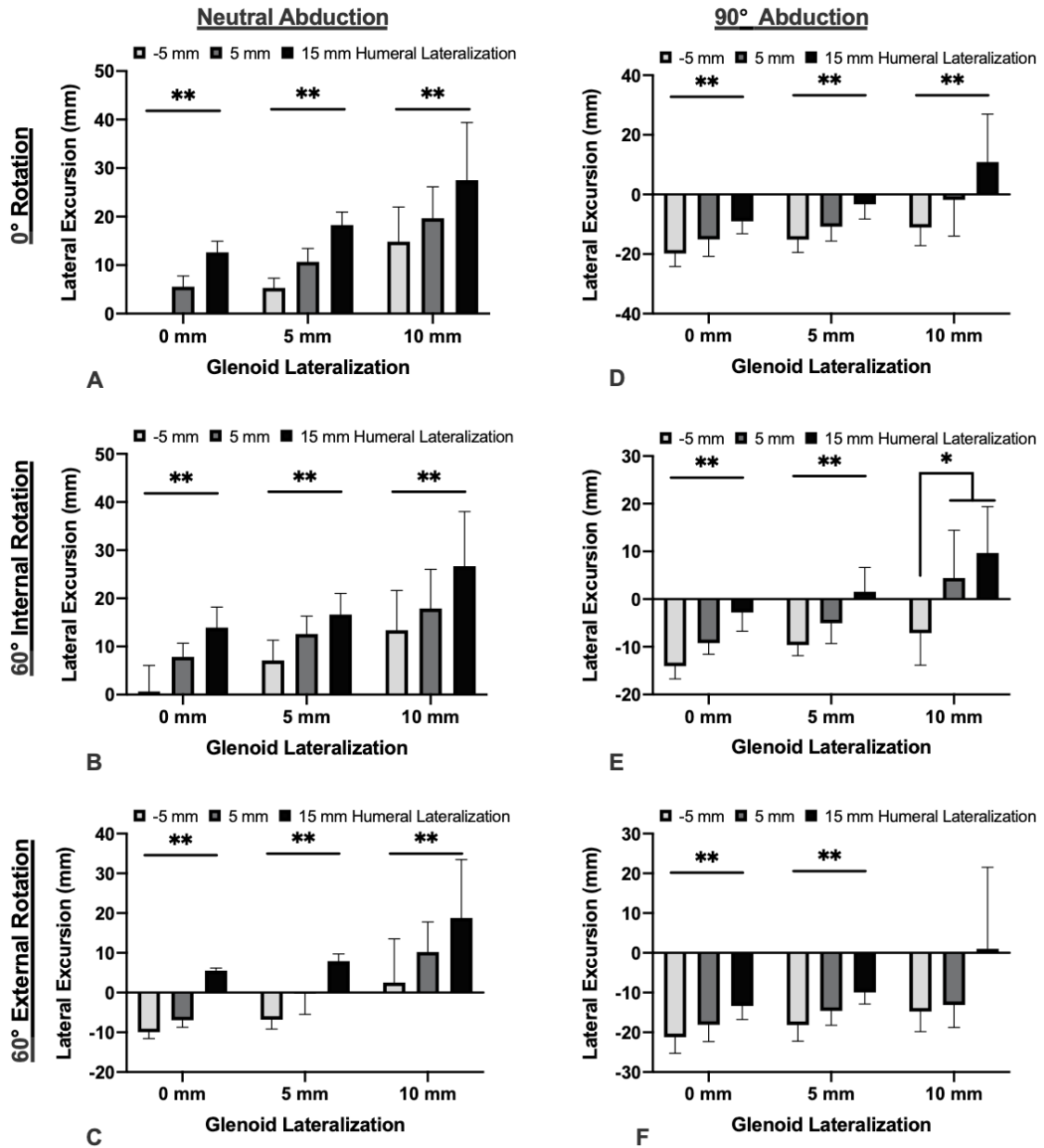
Figure 2-7: Excursion of Infraspinatus Under Various Positions and Implant Configurations

*Mean excursion (+/- 1 SD) of infraspinatus as glenoid and humeral lateralization are varied at (A) 0° abduction/0° rotation, (B) 0° abduction/60° IR, (C) 0° abduction/60° ER, (D) 90° abduction/0° rotation, (E) 90° abduction/60° IR, and (F) 90° abduction/60°ER. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*

2.3.3   Teres Minor

Overall, a change in glenoid lateralization and humeral lateralization respectively produced a statistically significant change in teres minor tendon excursion ($p < 0.001$). Fig. 2-8(A) demonstrates overall results of lateral tendon excursion as glenoid lateralization is increased by 5 mm intervals. Fig. 2-8(B) demonstrates overall results of lateral tendon excursion as humeral lateralization is increased by 10 mm intervals. The lateral excursion of teres minor increased by 1.35 ± 2.53 mm when changing glenoid lateralization from 0 mm to 5 mm ($p = 0.62$). Meanwhile, lateral excursion increased by 7.09 ± 1.29 mm when changing glenoid lateralization from 5 mm to 10 mm ($p = 0.006$). Furthermore, lateral excursion increased by 5.33 ± 0.50 mm and 5.32 ± 1.26 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively ($p < 0.001$). These results include all implant configurations and positions.

2.3.3.1   Effect of Implant Configuration on Teres Minor Excursion

Overall, each abduction and rotation angles had statistically significant effects on the excursion of teres minor ($p < 0.001$). As abduction increased from 0° to 90°, the teres minor tendon had increased lateral excursion by 22.70 ± 2.90 mm ($p = 0.001$). In neutral abduction and all rotation states, increasing humeral lateralization, while maintaining the same glenoid lateralization, had a significant increase on teres minor lateral excursion ($p < 0.01$). The results at 90° of abduction are also summarized in Fig. 2-9.
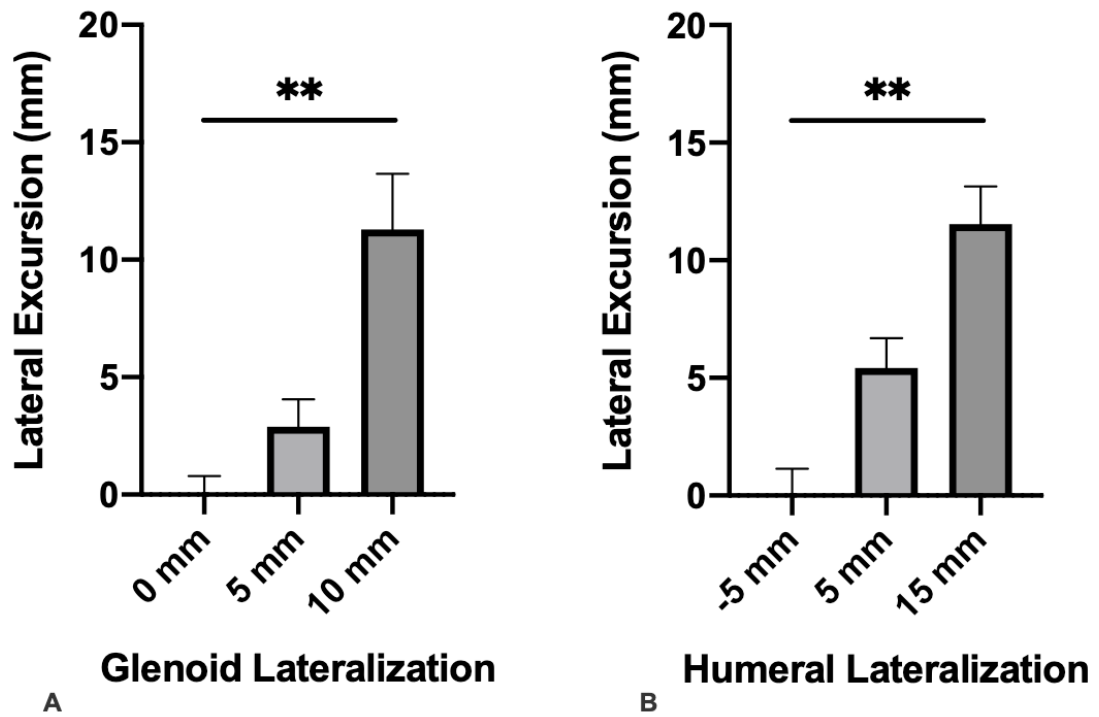
Figure 2-8: Overall Teres Minor Excursion

*Figure outlining the overall (inclusive of all testing parameters) mean excursion (+/- 1 SD) excursion of teres minor. Figure (A) demonstrates the effect of glenoid lateralization on lateral excursion. Figure (B) demonstrates the effect of humeral lateralization on lateral excursion. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*
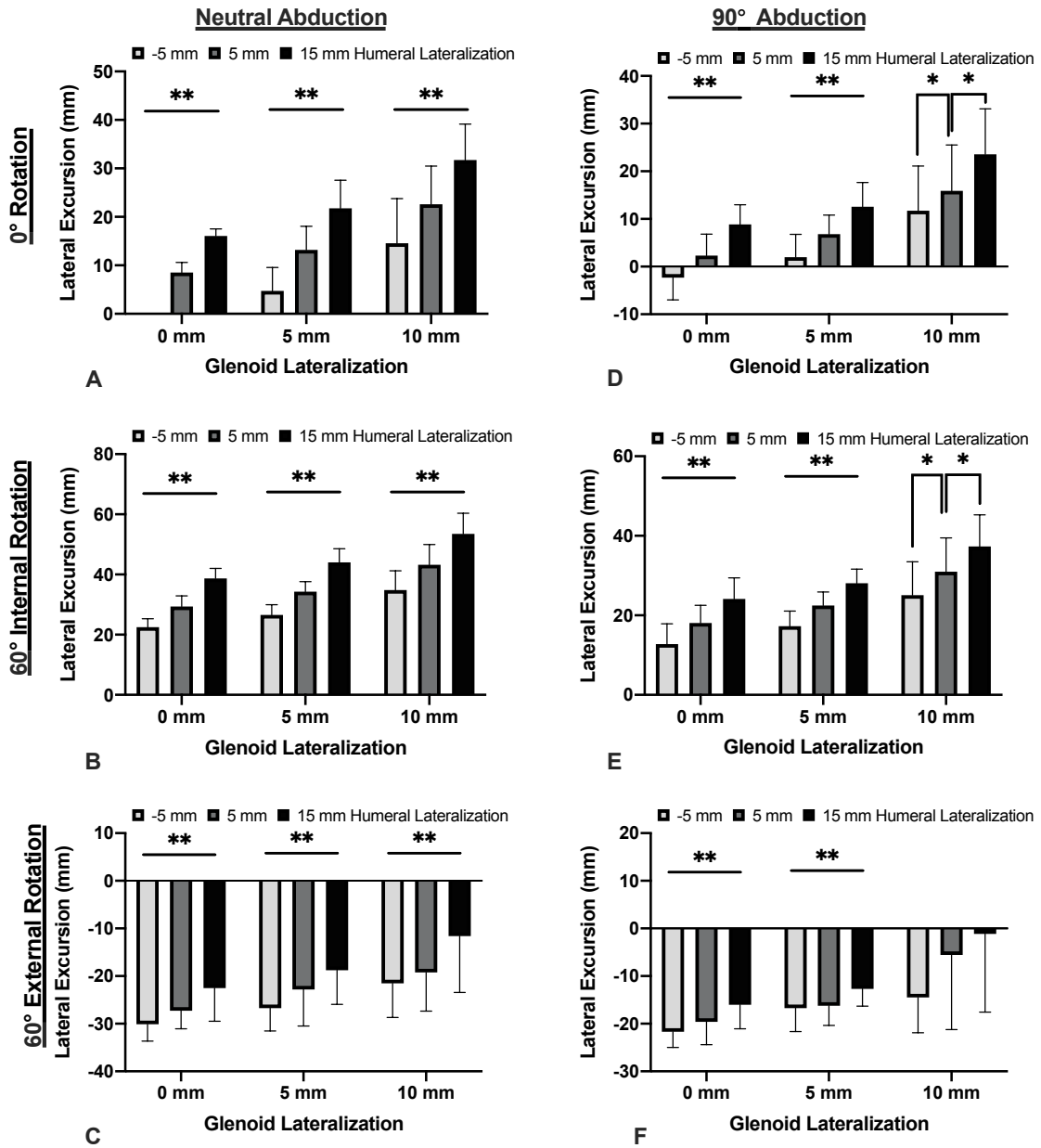
Figure 2-9: Excursion of Teres Minor Under Various Positions and Implant Configurations

*Mean excursion (+/- 1 SD) of teres minor as glenoid and humeral lateralization are varied at (A) 0° abduction/0° rotation, (B) 0° abduction/60° IR, (C) 0° abduction/60° ER, (D) 90° abduction/0° rotation, (E) 90° abduction/60° IR, and (F) 90° abduction/60°ER. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*

2.3.4   Subscapularis Superior

Overall, a change in glenoid lateralization and humeral lateralization respectively produced a statistically significant change in subscapularis superior tendon excursion ($p < 0.05$). Fig. 2-10(A) demonstrates overall results of lateral tendon excursion as glenoid lateralization is increased by 5 mm intervals. Fig. 2-10(B) demonstrates overall results of lateral tendon excursion as humeral lateralization is increased by 10 mm intervals. The lateral excursion of subscapularis superior decreased by 0.80 ± 4.54 mm when changing glenoid lateralization from 0 mm to 5 mm ($p = 0.87$). Meanwhile, lateral excursion increased by 8.78 ± 1.21 mm when changing glenoid lateralization from 5 mm to 10 mm ($p = 0.001$). Furthermore, lateral excursion increased by 6.56 ± 0.51 mm ($p < 0.001$) and 4.73 ± 2.14 mm ($p = 0.08$) when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. These results include all implant configurations and positions.

2.3.4.1   Effect of Implant Configuration on Subscapularis Superior Excursion

Overall, rotation had a statistically significant effect on the excursion of subscapularis superior ($p < 0.001$). As abduction increased from 0° to 90°, the subscapularis superior tendon had increased lateral excursion by 4.03 ± 1.58 mm ($p = 0.05$). In neutral abduction and all rotation states, increasing humeral lateralization, while maintaining the same glenoid lateralization, had a significant increase on subscapularis superior lateral excursion ($p < 0.01$). The results at 90° of abduction are also summarized in Fig. 2-11.
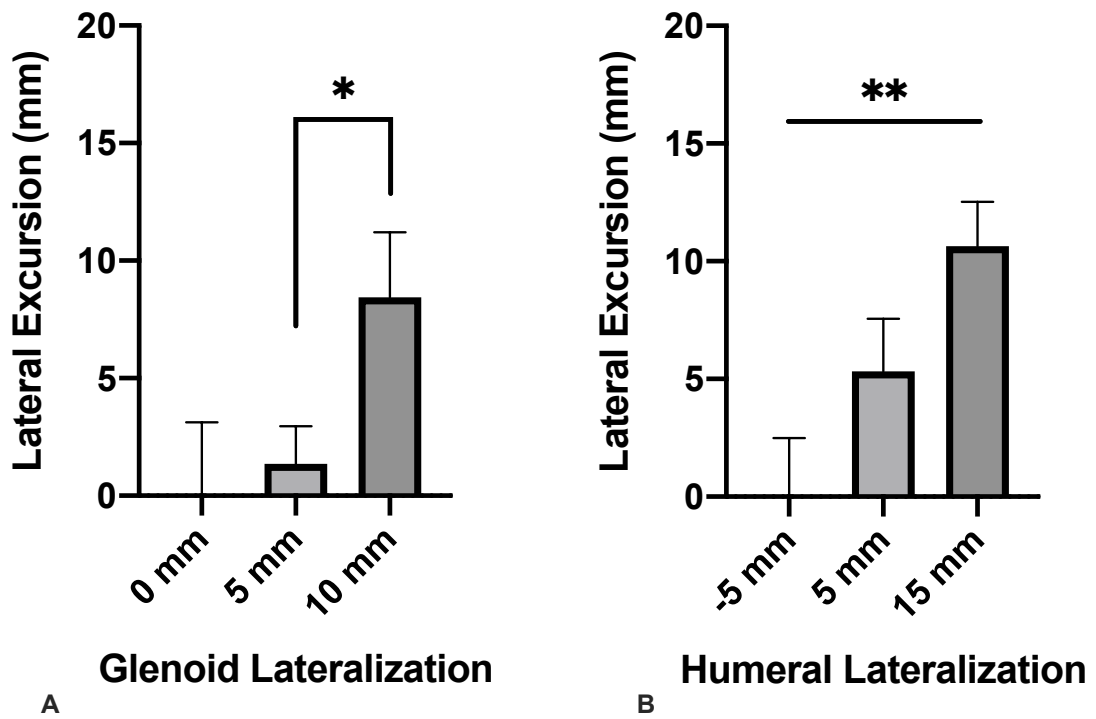
Figure 2-10: Overall Subscapularis Superior Excursion

Figure outlining the overall (inclusive of all testing parameters) mean excursion (+/- 1 SD) excursion of subscapularis superior. Figure (A) demonstrates the effect of glenoid lateralization on lateral excursion. Figure (B) demonstrates the effect of humeral lateralization on lateral excursion. Significance (p <0.05) is denoted with a "".*

Figure 2-11: Excursion of Subscapularis Superior Under Various Positions and Implant Configurations

*Mean excursion (+/- 1 SD) of subscapularis superior as glenoid and humeral lateralization are varied at (A) 0° abduction/0° rotation, (B) 0° abduction/60° IR, (C) 0° abduction/60° ER, (D) 90° abduction/0° rotation, (E) 90° abduction/60° IR, and (F) 90° abduction/60°ER. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*
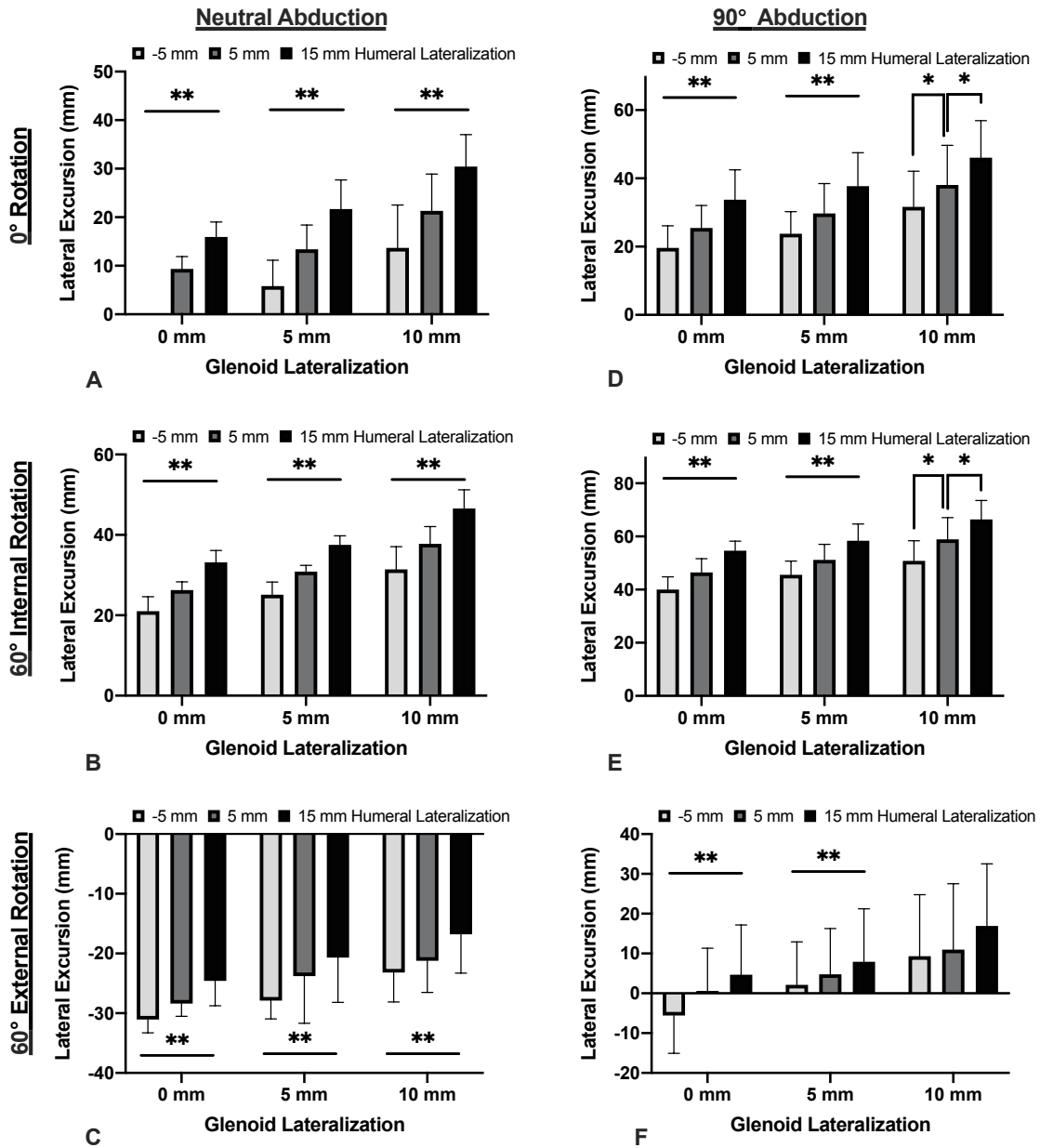
2.3.5 Subscapularis Inferior

Overall, a change in glenoid lateralization and humeral lateralization respectively produced a statistically significant change in subscapularis inferior tendon excursion ($p < 0.05$). Fig. 2-12(A) demonstrates overall results of lateral tendon excursion as glenoid lateralization is increased by 5 mm intervals. Fig. 2-12(B) demonstrates overall results of lateral tendon excursion as humeral lateralization is increased by 10 mm intervals. The lateral excursion of subscapularis inferior decreased by 0.33 ± 3.46 mm when changing glenoid lateralization from 0 mm to 5 mm ($p = 0.93$). Meanwhile, lateral excursion increased by 8 ± 1.03 mm when changing glenoid lateralization from 5 mm to 10 mm ($p = 0.001$). Furthermore, lateral excursion increased by 7.31 ± 0.23 mm ($p < 0.001$) and 5.67 ± 2.13 mm ($p = 0.04$) when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. These results include all implant configurations and positions.

2.3.5.1 Effect of Implant Configuration on Subscapularis Inferior Excursion

Overall, each abduction and rotation angles had statistically significant effects on the excursion of subscapularis inferior ($p < 0.001$). As abduction increased from 0° to 90°, the subscapularis inferior tendon had increased lateral excursion by 23.16 ± 1.59 mm ($p < 0.001$). In neutral abduction and all rotation states, increasing humeral lateralization, while maintaining the same glenoid lateralization, had a significant increase on subscapularis inferior lateral excursion ($p < 0.01$). The results at 90° of abduction are also summarized in Fig. 2-13.
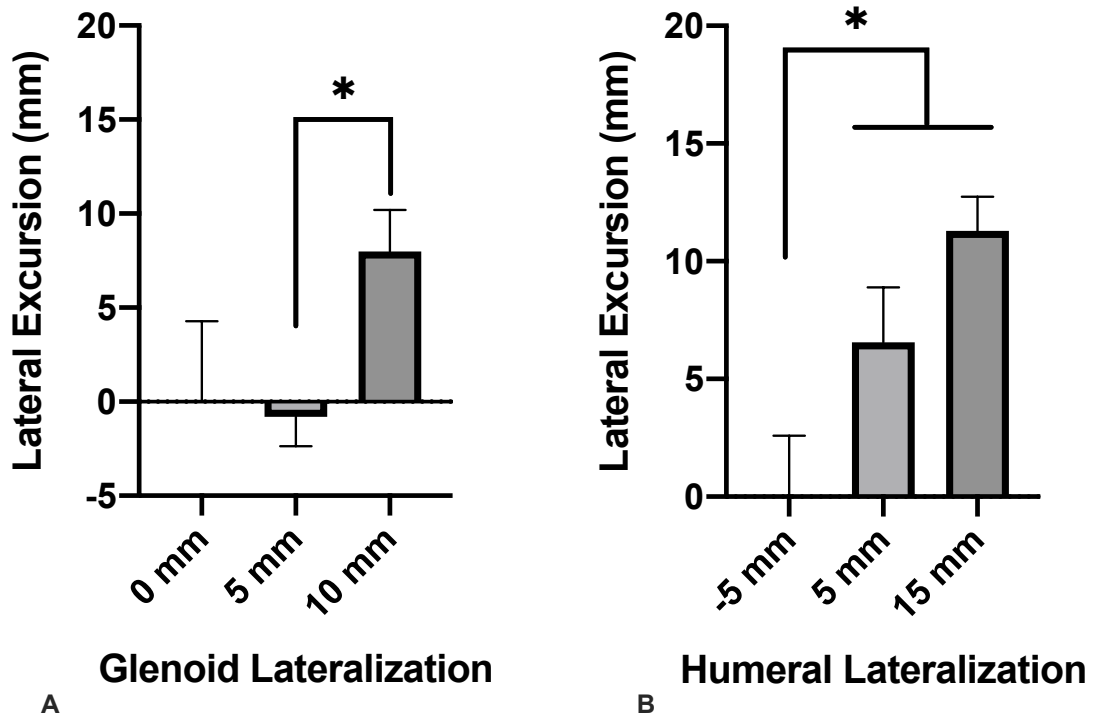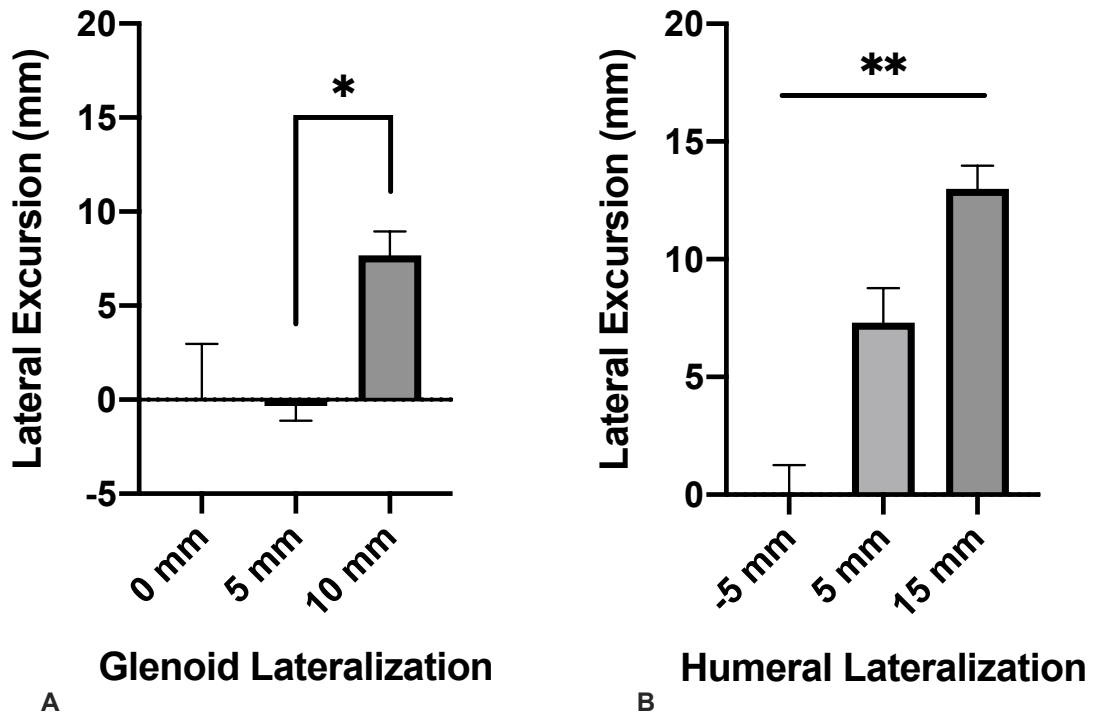
Figure 2-12: Overall Subscapularis Inferior Excursion

*Figure outlining the overall (inclusive of all testing parameters) mean excursion (+/- 1 SD) excursion of subscapularis inferior. Figure (A) demonstrates the effect of glenoid lateralization on lateral excursion. Figure (B) demonstrates the effect of humeral lateralization on lateral excursion. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*
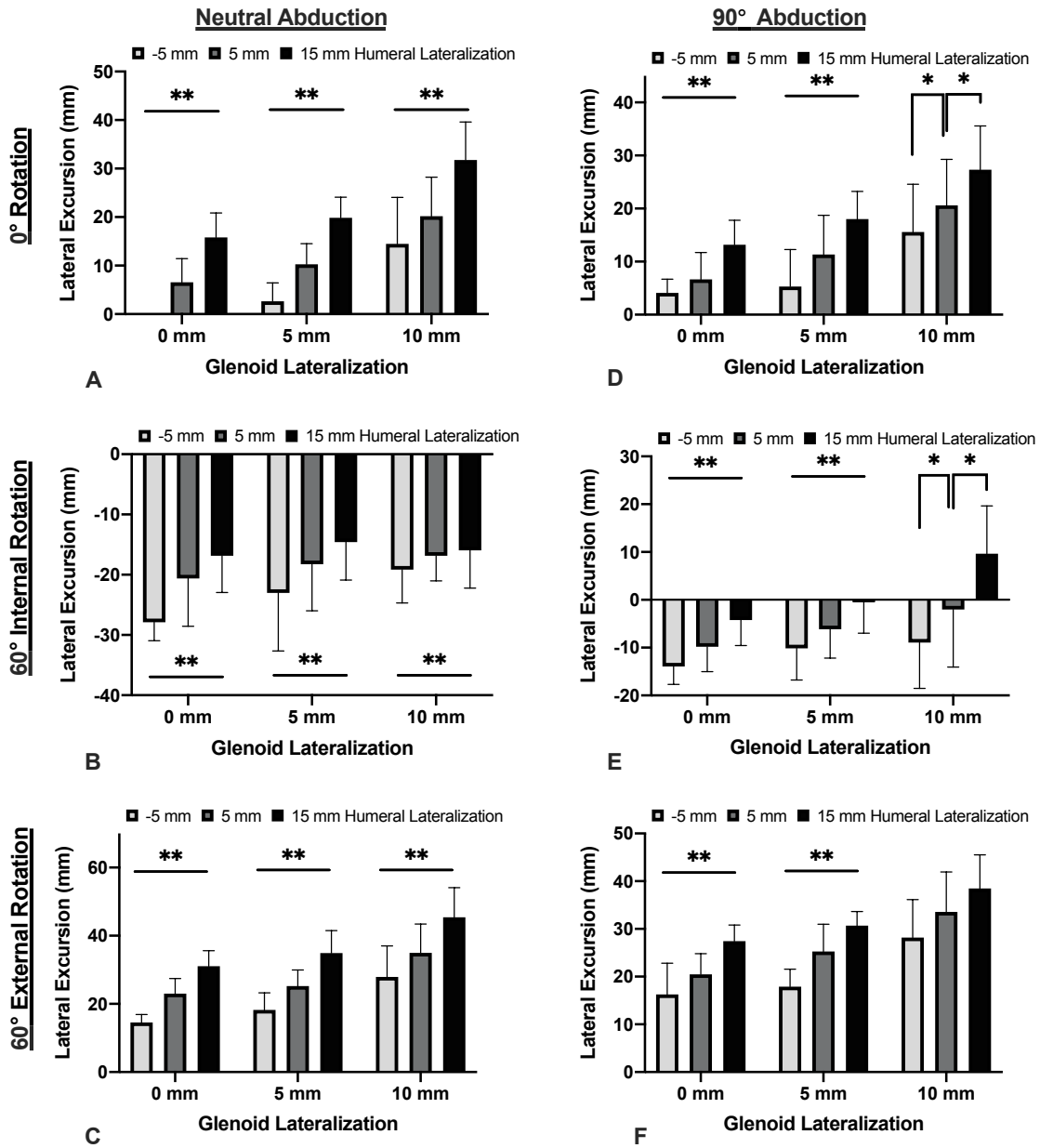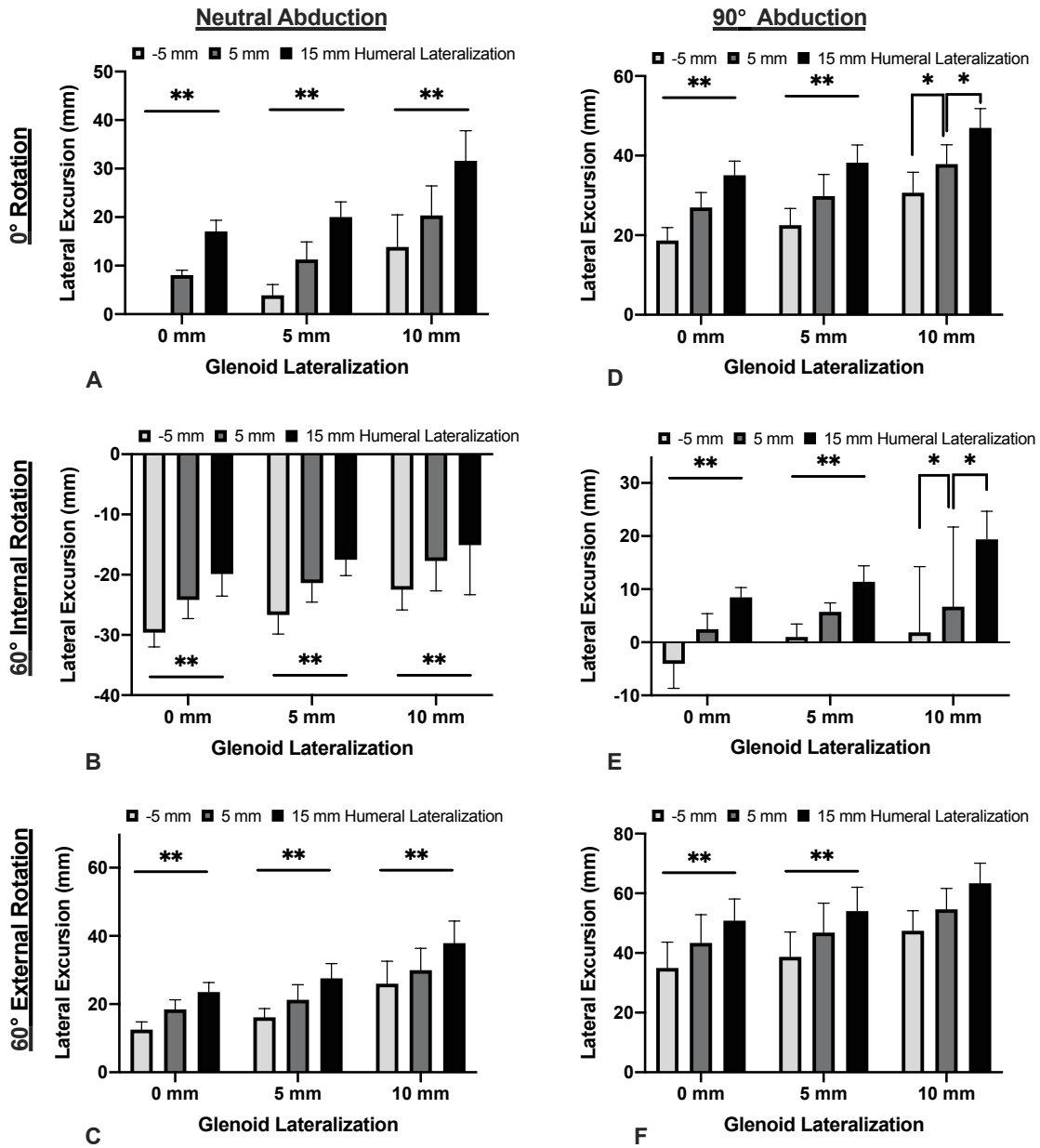
Figure 2-13: Excursion of Subscapularis Inferior Under Various Positions and Implant Configurations

*Mean excursion (+/- 1 SD) of subscapularis inferior as glenoid and humeral lateralization are varied at (A) 0° abduction/0° rotation, (B) 0° abduction/60° IR, (C) 0° abduction/60° ER, (D) 90° abduction/0° rotation, (E) 90° abduction/60° IR, and (F) 90° abduction/60°ER. Significance (p <0.05) across multiple parameters is denoted with a "**" and with a "*" for individual comparisons.*

2.4 Discussion

The primary objective of this study was to evaluate the role of RTSA implant lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis tendon excursions. This study focused on varying glenoid lateralization (0, 5 and 10 mm) and humeral lateralization (-5, 5 and 15 mm) while keeping all other implant parameters constant. Each implant configuration was assessed at five rotation states (60° IR, 30° IR, 0°, 30° ER and 60° ER) for each abduction position (0° and 90°). Excursion was measured in millimeters and values were reported relative to the most medialized configuration (0 mm glenoid lateralization and -5 mm humeral lateralization).

Based on the results outlined above, there was a general trend of increased lateral excursion of the rotator cuff as the glenoid or humeral components were lateralized. Interestingly, humeral lateralization from 5 mm to 15 mm yielded larger incremental excursion of the tendons when compared to humeral lateralization from -5 mm to 5 mm. For example, the change in supraspinatus excursion from 5 mm to 15 mm of humeral lateralization was 12.7 mm while only 4.1 mm when changing humeral lateralization from -5 mm to 5 mm. This could be attributed to increased wrapping of the tendon around the glenosphere in a medialized humeral state. This results in a non-linear correlation of tendon excursion at the more medialized humeral positions. Meanwhile, as the humeral component was further lateralized, the interval excursion of supraspinatus from 5 mm to 15 mm was similar to altering the glenoid component from 0 mm to 10 mm of lateralization. Since glenoid lateralization does not alter the wrapping of the tendons on the glenosphere, its incremental change was predominantly uniform.

As abduction increased from 0° to 90°, there was significant medial excursion of the supraspinatus tendon and lateral excursion of teres minor and subscapularis inferior. Meanwhile, there was minimal (<5 mm) excursion of infraspinatus and subscapularis superior. These findings correlate with the known insertional anatomy of these tendons. A cadaveric study demonstrated that teres minor and subscapularis inferior insert up to 10 mm and 18 mm distal to the articular surface, respectively.[33] Furthermore, the subscapularis tendon complex inserts along the medial aspect of the bicipital groove and therefore at an anterior anatomic position; while teres minor inserts at the posterior aspect

of the greater tuberosity and assumed a posterior anatomic position.[33] In contrast, the supraspinatus tendon insertion assumed a superior and lateral position on the greater tuberosity and therefore in similar line to the abduction motion.[33,34] These anatomic locations of the respective tendon insertions account for the contrasting excursion findings as the arm is abducted.

With respect to the effect of rotation on tendon excursion, the anterior tendons (subscapularis superior and subscapularis inferior) trended towards lateral excursion as internal rotation increased while the posterior tendons (infraspinatus and teres minor) trended towards lateral excursion as external rotation increased. Lateral excursion also further increased for the most inferior tendons (subscapularis inferior and teres minor) during abduction relative to their neutral abduction rotational states. This correlates with their anatomic actions and insertional anatomy outlined above.[33,35]

A cadaveric based biomechanical study investigated the effect of two RTSA implant designs relative to native glenohumeral anatomy and discovered that both designs shifted the center of rotation medially and inferiorly relative to native glenohumeral anatomy.[36] Furthermore, this study noted that the humerus shifts inferiorly by approximately 22 mm.[36] In native glenohumeral anatomy, the insertional anatomy of infraspinatus and teres minor are aligned with the center of rotation. Although lowering of the humerus has been found to improve elevation in the setting of RTSA due to increasing deltoid tension, it may have unintended biomechanical consequences of altering the position of rotator cuff insertions with respect to the center of rotation of the joint.[37,38] In normal glenohumeral anatomy, the insertion of infraspinatus and teres minor are approximately in line with the center of rotation of the joint. This inferior and medial shift of the humerus may further explain the findings of lower lateral excursion from -5 mm to 5 mm of humeral lateralization compared to 5 mm to 15 mm. Tendon wrapping around a glenosphere that has altered the relative position of the insertional anatomy and center of rotation leads to a non-linear path relative to native glenohumeral anatomy.

2.4.1   Strengths and Limitations

To our knowledge, this is the first cadaveric biomechanical study examining the role of glenoid and humeral lateralization at various intervals on rotator cuff excursion. The utilization of a modular RTSA implant allowed for multiple implant configurations to be tested. This allowed the testing parameters to include most RTSA implant options available on the market. Furthermore, the glenohumeral simulator used in this study allowed for controlled range motion and computer-controlled tension on the rotator cuff. The utilization of an optical tracking system with six degrees of freedom allowed for highly accurate data acquisition. The use of a custom shoulder simulator allowed for reproducible motion while maintaining specimen integrity by ensuring the tissues remained moist.

There are fundamental limitations to cadaveric based biomechanical studies. First, the shoulder simulator did not allow for scapulothoracic motion. Therefore, to simulate 90° of humerothoracic abduction, 60° of glenohumeral abduction was used for this experiment.[39,40] Furthermore, these results are based on time-zero and do not consider potential soft tissue stretch or dynamic compensation over time. Similarly, while preparing specimens for this experiment, some soft tissue was removed to accommodate implantation that may exactly mimic in-vivo characteristics such as tissue stretch, soft tissue elongation over time and potential dynamic change of muscle lines of action. Furthermore, this testing model did not account for elements of rotator cuff arthropathy as only non-arthritic specimens with intact rotator cuffs were used for testing.

2.5 Conclusions

This study provided detailed insight into the role of incremental glenoid and humeral lateralization on the excursion of supraspinatus, infraspinatus, teres minor, subscapularis superior and subscapularis inferior in the setting of reverse total shoulder arthroplasty. This study outlined the relative excursion patterns of the rotator cuff tendons in various arm positions. Compared to native glenohumeral anatomy, the inferior position of the humerus alters the line of action of the rotator cuff tendons and thereby the effect of humeral and glenoid lateralization on their respective excursion. As the inferior tendons (teres minor and subscapularis inferior) insert further away from the center of rotation, they exhibit increased lateral excursion with increased abduction. Furthermore, the wrapping of tendons around the glenosphere in an extremely medialized humerus influence the incremental excursion of the tendons with humeral lateralization compared to glenoid lateralization.

The findings of this study have clinical and biomechanical implications on the design of future research examining implant configurations for optimal rotator cuff function in the setting of reverse total shoulder arthroplasty. The use of these results will allow for the calculation of moment arms in a subsequent study.

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Chapter 3

3   The Effect of Glenoid and Humeral Lateralization on the Moment Arms of the Rotator Cuff Muscles in Reverse Total Shoulder Arthroplasty

Overview

This chapter presents a study that examines the effect of incremental glenoid and humeral lateralization on the moment arms of supraspinatus, infraspinatus, teres minor, and subscapularis. This study also examined the effect of glenohumeral abduction, internal rotation, and external rotation under various lateralization permutations.

3.1   Introduction

[NB: Parts of this material was presented in earlier chapters and is also included here to ensure this chapter is in "article" format]

Historically, the use of reverse total shoulder arthroplasty (RTSA) had been reserved for "cuff tear arthropathy in elderly patients.[1] This term was first coined by Neer to describe a massive rotator cuff tear that causes superior migration of the humeral head and subacromial impingement which leads to head collapse and erosion.[2] With improving technology and surgical experience, the incidence of reverse shoulder arthroplasty increased significantly based in registry data worldwide. In the United Kingdom, RTSA procedures increased 31.7% between 2012 and 2016.[3] Over the last 15 years, the incidence of RTSA in New Zealand and Norway increased from 2% to 56% and 12% to 52% respectively.[4,5] With its increased use, indications for RTSA have increased substantially to include acute proximal humerus fractures,[6-8] cuff tear arthropathy,[8-13] inflammatory arthropathy,[11,14] tumor,[8,15-17] nonunion or malunion,[7,8,18] chronic shoulder dislocation,[8] chronic pseudoparalysis,[8,13,19,20] and revision arthroplasty.[8,18,21,22]

The design of RTSA has significantly evolved over time in search of optimizing function, range of motion and decreasing complications. Both surgical techniques and implant configurations have been developed and innovated for these purposes. To decrease the risk of scapular notching, in which impingement of the humeral component occurs on the inferior aspect of the scapular neck, surgeons have elected to place the glenoid baseplate at the inferior aspect of the glenoid. This technique has been found to decrease the risk of this phenomenon and thereby increase range of motion.[23]

Debate continues regarding the most optimal orientation and implant parameters of RTSA. Certain implant manufacturers allow for modification of parameters such as glenoid lateralization, humeral lateralization, polyethylene thickness, glenosphere diameter, neck-shaft angle, and cup constraint. In a computational based analysis, modification of these parameters has been shown to affect range of motion, stability and scapular notching.[24] For the purpose of this chapter, a focus will be placed on humeral lateralization and glenoid lateralization.

Humeral lateralization is defined as the distance between the deepest aspect of the humeral polyethylene and the vertical line passing through the center of the humeral stem. Humeral lateralization can be configured through humeral tray geometry, inlay vs. on-lay design, polyethylene thickness and design. Several studies have demonstrated an increased abductor lever arm of the deltoid with increased humeral lateralization due to the more lateral position of the greater tuberosity and effect of deltoid wrapping.[25-27] Using a biomechanical, cadaveric based model, Giles et al. demonstrated that increasing humeral lateralization from 0 mm to 10 mm decreased the deltoid force required to abduct the shoulder from 68% to 65% of bodyweight.[25]

Meanwhile, glenoid lateralization is defined is as the distance from the bone-baseplate interface to the center of rotation of the glenosphere. The offset of the glenosphere relative to the baseplate as well as the geometry of the glenosphere itself can alter the glenoid lateralization. Furthermore, the amount of glenoid reaming, utilization of bone graft and use of metal augments during implantation of the glenoid baseplate can also alter the amount of lateralization on the glenoid aspect.[28]

The moment arm of a muscle represents its ability to exert torque to a joint and is defined by the distance from its force line of action to the center of rotation.[29-31] Therefore, the larger the magnitude of the moment arm, the more leverage the muscle has on that joint.[29] In glenohumeral literature, the most common method of deriving the moment arm is by using the tendon-excursion method. By using this method, each muscle's moment arms are found by evaluating the instantaneous slope of its tendon excursion relative to the joint angle curve over various joint movements.[29,31-33] As modern RTSA has shifted the center of rotation inferiorly and medially, the moment arm of the deltoid muscle has increased and allowed for increased efficiency of arm elevation.[18,34-36] Conversely, the effect of this design on the optimization of the rotator cuff moment arms continues to be studied. There remains a lack of information regarding the effect of incremental glenoid and humeral lateralization on the moment arms of the rotator cuff tendons in the setting of reverse total shoulder arthroplasty. In light of the foregoing, the purpose of this in-vitro biomechanical cadaveric study is to evaluate the role of glenoid lateralization and

humeral lateralization on the moment arms produced by the supraspinatus, infraspinatus, teres minor, and subscapularis.

3.2 Materials and Methods

3.2.1   Cadaveric Specimen Preparation

[NB: Cadaveric specimen preparation is similar to that described in Chapter 2].

Six fresh frozen left male cadaveric glenohumeral specimens were utilized (mean age 71, range 64 – 77). Specimens were pre-screened with CT scans to exclude those with underlying rotator cuff and/or glenohumeral pathology. They were thawed for 18 hours prior to testing. The humerus was cute at the midshaft level to accommodate fitting within the shoulder simulator. Skin and subcutaneous fat were dissected and removed in order to expose the underlying muscles. The deltoid muscle was elevated from its origins and kept intact at its insertions. The subscapularis muscle was elevated from its origin, left intact at its insertion on the humerus and was divided into its superior and inferior portions. Similarly, supraspinatus, infraspinatus and teres minor were also elevated at their origins and kept intact at their humeral insertions. A heavy #5 non-absorbable braided suture (Ethibond, Ethicon, Johnson & Johnson, New Jersey, USA) was used to tag each rotator cuff tendon as previously described by Kerrigan et al.[37] The three deltoid insertions were identified at the deltoid tuberosity by their anatomic description and also individually tagged with the Ethibond sutures.[38] The labrum and remaining glenoid articular cartilage were resected.

Six simple sutures were used in sequential manner proximally; starting at the tendinous insertion of each rotator cuff tendon and separated by approx. 5 mm in line with the tendon to delineate it appropriate anatomic path (0, PERMA-HAND Silk, Ethicon, Johnson & Johnson, New Jersey, USA). Fig. 3-1 demonstrates a specimen mounted onto the shoulder simulator with associated tendon cables to computer-controlled actuators.
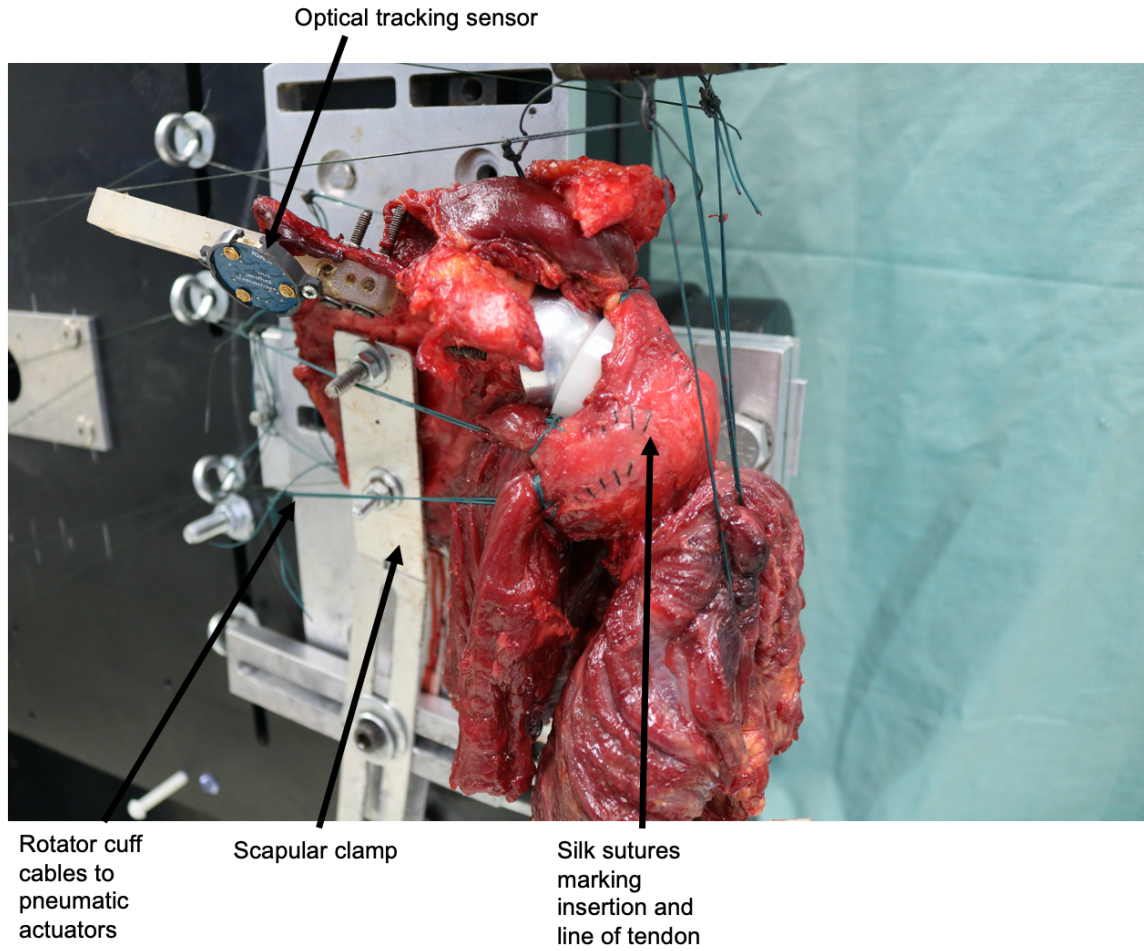
Figure 3-1: Implanted Custom Reverse Total Shoulder Arthroplasty Prosthesis

The specimen is shown mounted on the shoulder simulator using a scapular clamp. Ethibond sutures were used to tag the rotator cuff tendons and deltoid heads. The deltoid muscle was retracted for this image.

3.2.2 Custom Reverse Shoulder Arthroplasty Implantation

Similar to Chapter 2, a custom modular implant was utilized for this study as previously described by Langohr et al.[25,39] The custom glenosphere allows for offset modularity in 5 mm increments. Furthermore, the custom humeral component also allows for offset modularity in 5 mm increments.

A sagittal saw was used to complete the humeral cut at the anatomic neck. A powered reamer was then used to ream the proximal humerus and subsequently the humeral shaft. The glenoid was prepared using manual and powered reamers to remove any remaining cartilage. The RTSA was implanted using a technique from the Wright Medical Tornier Aequalis surgical technique manual (Wright Medical Technologies, Memphis, Tennessee) and as described by Kerrigan et al.[37] The custom glenoid baseplate was secured with three screws into the glenoid vault. The baseplate was placed in neutral orientation and its inferior edge was aligned with the inferior edge of the glenoid. The custom humeral component was cemented in neutral version relative to the native epicondylar axis. The inferior edge of the humeral cup was lined up with the superior aspect of the greater tuberosity to set humeral distalization. A metallic humeral rod was cemented at the distal aspect of the humeral shaft to facilitate connection to the shoulder simulator for testing.

3.2.3 Shoulder Simulator

The shoulder simulator used was the same as described in chapter 2. As a review, the scapula was fixed to the simulator in static position using a clamp through the scapular body. Its position was adjusted to allow the glenoid face to be perpendicular to the horizontal and match the COR of the arc simulator. The humeral rod was placed in the shoulder simulator assembly which allowed for abduction as well as internal and external rotation. The ethibond sutures used to tag the deltoid heads as well as rotator cuff muscles were individually tied to a long high strength cable (Sufix Performance Braid, 130lb strength). These cables were routed along their physiologic lines of action to computer-controlled pneumatic actuators that applied loads to each tendon to mimic a physiologic

glenohumeral joint. As previously described by Kerrigan et al, the deltoid muscle loading was split with 15% anterior, 70% middle and 15% posterior as abduction occurred. Furthermore, a 10 N load was applied in total for the rotator cuff muscles to stabilize the reverse total shoulder arthroplasty.[37]

Along the horizontal cable prior to connection to the pneumatic actuator, a knot was made for each rotator cuff tendon. This was used as a measurement point within the experimental protocol. Lastly, optical tracking sensors (OptoTrak™ Certus, NDI, Waterloo, ON) were fixed at a static point on the scapula and the humerus in order to determine their positions in space and relative to other digitized points as described within the protocol.

3.2.4   Testing Protocol

For the duration of the protocol, a 38 mm glenosphere and associated humeral polyethylene insert were utilized. Similar to the protocol in chapter 2, nine combinations of humeral and glenoid lateralization configurations were tested (Table 3-1). Humeral lateralization parameters included -5 mm, 5 mm, and 15 mm. Glenoid lateralization parameters included: neutral, 5 mm and 10 mm; and were in the form of modular spacers placed between the glenoid baseplate and the glenosphere. For each implant configuration, the specimen was tested in multiple static positions: Neutral rotation, 30° external rotation (ER), 60° ER, 30° internal rotation (IR) and 60° IR. These positions were tested for both neutral and 90 degrees of abduction in the scapular plane. When changing axial rotation, the abduction arc was locked into position to only permit axial rotation. For each trial, the position of the humerus and the scapula were recorded in space as were the silk sutures along each rotator cuff tendon. Using the optical tracking system, a stylus was utilized to digitize the knots on each rotator cuff tendon cable. This determines the excursion of each tendon after each configuration/position change.

Implant Configuration	Glenoid Lateralization	Humeral Lateralization
1	0 mm	-5 mm
2	0 mm	-5 mm
3	0 mm	-5 mm
4	5 mm	5 mm
5	5 mm	5 mm
6	5 mm	5 mm
7	10 mm	15 mm
8	10 mm	15 mm
9	10 mm	15 mm

Table 3-1: List of Tested Implant Configurations

Table outlines the implant configurations tested within this experiment.

3.2.5   Outcome Variables

The main outcome measures of this experiment were the moment arms of supraspinatus, infraspinatus, teres minor, subscapularis superior and subscapularis inferior. Tendon excursion measurements were recorded for each implant configuration as lateralization was modified as well as rotation and abduction as outlined in Chapter 2. Using the optical tracking system, the position of the scapular marker was recorded as a static reference for each position. The knots on each cable for the respective tendons served as a marker that was digitized via the optical tracking system. This was compared relative to the scapular reference to determine the relative excursion in millimeters. The silk sutures along each tendon were digitized to record the location of each tendon throughout the various arm positions. Further optical digitization included the glenoid baseplate, glenosphere, bicipital groove, greater tuberosity, lesser tuberosity, acromion, and coracoid for coordination.

Using the tendon excursion method, the moment arm (r) was related to joint rotation (θ) tendon excursion (E) by $r = dE/d\theta$. The excursion was calculated by optical digitization.

Tendon motion was captured by digitization of the respective tendons at specified joint positions. Matlab software (Mathworks, Inc, Natick, MA, USA) was used to run custom calculations that fit the plotted data into a polynomial computing moment arms.

3.2.6　Statistical Analysis

Repeated measures of analysis of variance (RM-ANOVA) were utilized for statistical analysis through the Statistical Package for the Social Sciences software (IBM SPSS Statistics for Macintosh, Version 26.0.0.1; Armonk, NY; IBM Corp). Further pairwise comparisons of variables were completed. Statistical significance was defined as $p < 0.05$ for all analyses. Power analyses were completed and determined that six specimens were sufficient to obtain at least 80% power for each outcome variable for this study.

3.3   Results

3.3.1   Supraspinatus

Overall, a change in glenoid lateralization (p = 0.40) and humeral lateralization (p = 0.27) did not result in statistically significant changes in the moment arm of supraspinatus. Fig. 3-2(A) demonstrates overall moment arm changes as glenoid lateralization is increased by 5 mm intervals. Fig. 3-2(B) demonstrates overall moment arm changes as humeral lateralization is increased by 10 mm intervals. The moment arm of supraspinatus increased by 7.31 ± 8.3 mm when changing glenoid lateralization from 0 mm to 10 mm. Meanwhile, the moment arm increased by 0.86 ± 0.67 mm and 10.19 ± 7.68 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. Overall, a change in rotation did not yield a statistically significant change in the moment arm of supraspinatus (p = 0.33). The moment arm at 0° of abduction was 50.29 ± 5.19 mm compared to 33.94 ± 2.23 mm at 90° of abduction (p = 0.03). These results include all implant configurations and positions.

As a general trend, peak moment arms were found in the 60° internally rotated position in both abduction positions (Fig. 3-3). Furthermore, as humeral lateralization increased (while glenoid lateralization remained constant), there was an increase in the peak moment arm throughout all tested positions. The largest supraspinatus moment arm at 0° of abduction was at 60° of internal rotation and using a combination of 10 mm glenoid and 15 mm humeral lateralization (58.21 ± 1.64 mm). At 90° of abduction, the peak moment arm was also noted in the same arm position and implant configuration to be 44.27 ± 1.80 mm. Fig. 3-3 summarizes all calculated moment arms for respective arm positions and implant configurations.
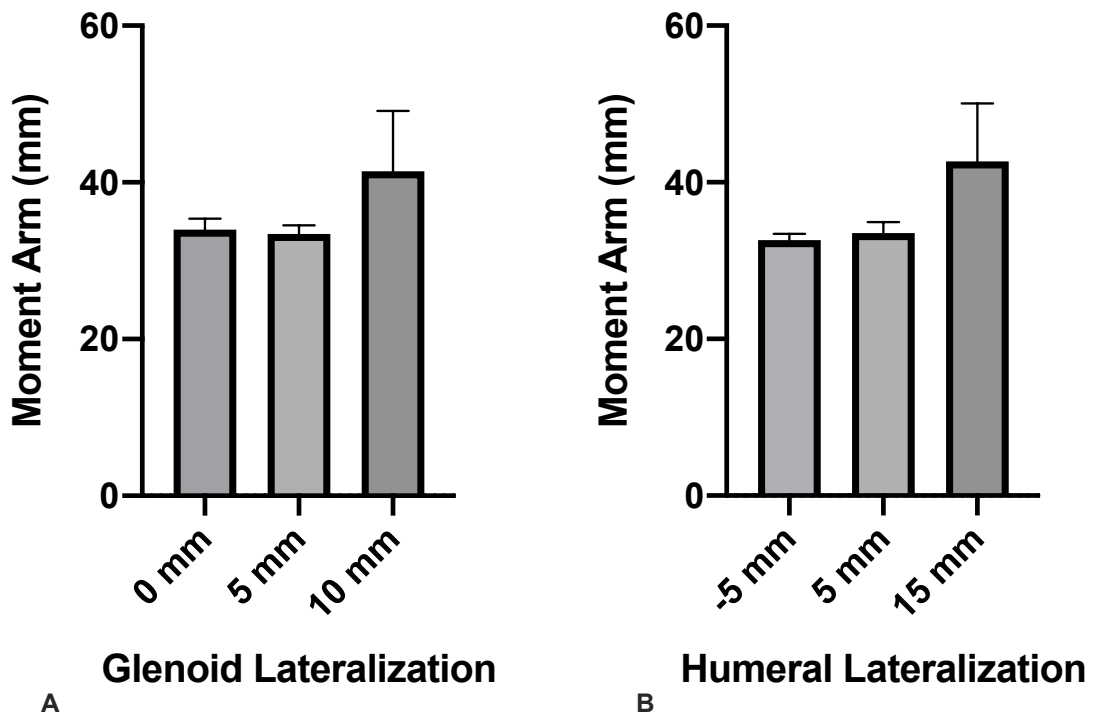
Figure 3-2: Overall Supraspinatus Moment Arm

Figure outlining the overall (inclusive of all testing parameters) mean moment arm (+/- 1 SD) of supraspinatus. Figure (A) demonstrates the effect of glenoid lateralization on moment arm. Figure (B) demonstrates the effect of humeral lateralization on moment arm.

Neutral Abduction

0 mm Glenoid Lateralization

A

Rotation (°)

5 mm Glenoid Lateralization

B

Rotation (°)

10 mm Glenoid Lateralization

C

Rotation (°)

90° Abduction

0 mm Glenoid Lateralization

D

Rotation (°)

5 mm Glenoid Lateralization

E

Rotation (°)

10 mm Glenoid Lateralization

F

Rotation (°)

Legend:
— -5 mm Humeral Lateralization
--- 5 mm Humeral Lateralization
···· 15 mm Humeral Lateralization

Figure 3-3: Moment Arms of Supraspinatus Under Various Positions and Implant Configurations

Moment arm (+/- 1 SD) of supraspinatus as rotation and humeral lateralization are varied at (A) 0° abduction/0 mm Glenoid, (B) 0° abduction/5 mm Glenoid, (C) 0° abduction/10 mm Glenoid, (D) 90° abduction/0 mm Glenoid, (E) 90° abduction/5 mm Glenoid, and (F) 90° abduction/10 mm Glenoid. Negative rotation equates to internal rotation, while positive rotation denotes external rotation.

3.3.2   Infraspinatus

Overall, a change in glenoid lateralization (p = 0.39) and humeral lateralization (p = 0.26) did not result in statistically significant changes in the moment arm of infraspinatus. Fig. 3-4(A) demonstrates overall moment arm changes as glenoid lateralization is increased by 5 mm intervals. Fig. 3-4(B) demonstrates overall moment arm changes as humeral lateralization is increased by 10 mm intervals. The moment arm of infraspinatus increased by 7.44 ± 8.08 mm when changing glenoid lateralization from 0 mm to 10 mm. Meanwhile, the moment arm increased by 0.90 ± 0.65 mm and 9.16 ± 7.50 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. Overall, a change in rotation did not yield a statistically significant change in the moment arm of infraspinatus (p = 0.33). The moment arm at 0° of abduction was 40.48 ± 5.34 mm compared to 32.09 ± 1.16 mm at 90° of abduction (p = 0.22). These results include all implant configurations and positions.

As a general trend, peak moment arms were found in the 60° internally rotated position in both abduction positions (Fig. 3-5). Furthermore, as humeral lateralization increased (while glenoid lateralization remained constant), there was an increase in the peak moment arm throughout all tested positions. The largest infraspinatus moment arm at 0° of abduction was at 60° of internal rotation and using a combination of 10 mm glenoid and 15 mm humeral lateralization (49.12 ± 5.30 mm). At 90° of abduction, the peak moment arm was also noted in the same arm position and implant configuration to be 42.40 ± 2.27 mm. Fig. 3-5 summarizes all calculated moment arms for respective arm positions and implant configurations.

Figure 3-4: Overall infraspinatus Moment Arm

Figure outlining the overall (inclusive of all testing parameters) mean moment arm (+/- 1 SD) of infraspinatus. Figure (A) demonstrates the effect of glenoid lateralization on moment arm. Figure (B) demonstrates the effect of humeral lateralization on moment arm.
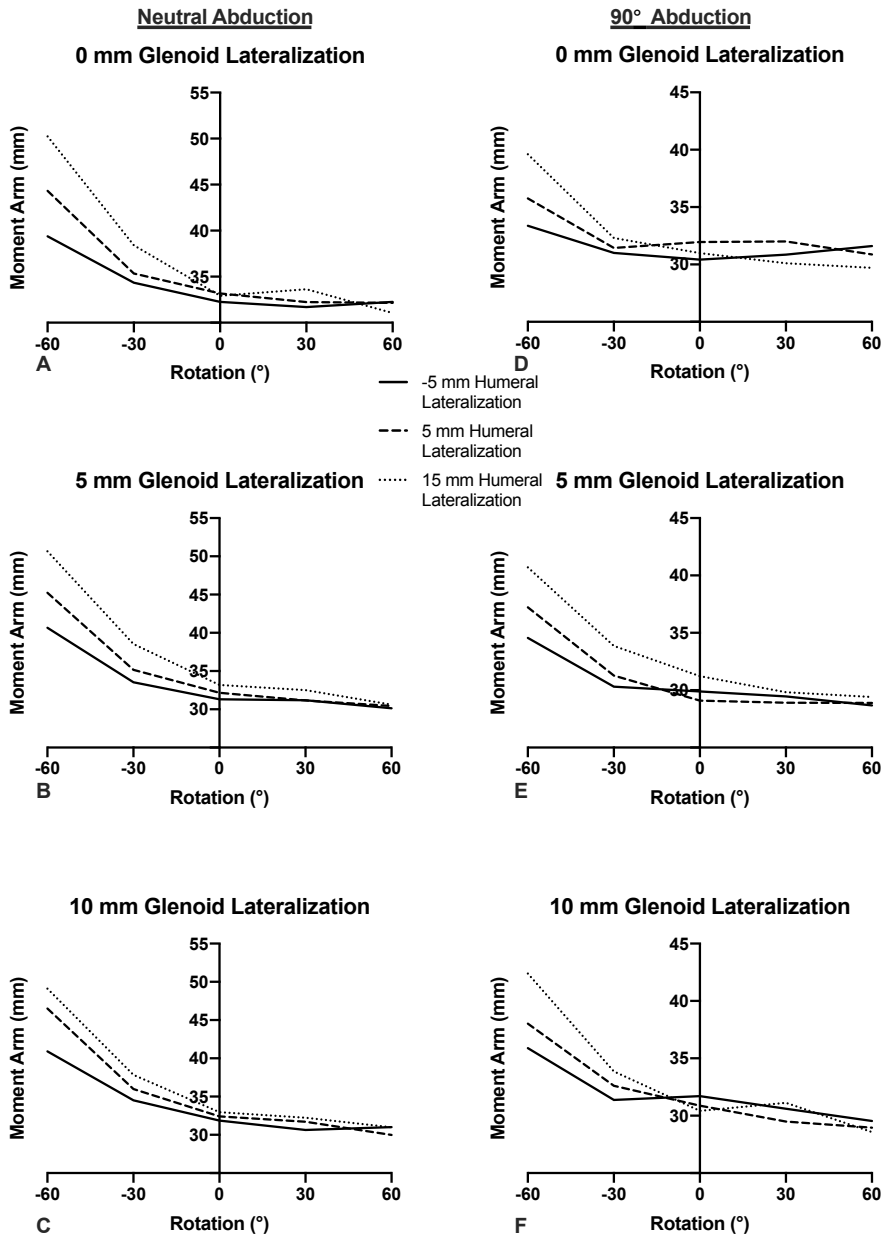
Figure 3-5: Moment Arm of Infraspinatus Under Various Positions and Implant Configurations

Moment arm (+/- 1 SD) of infraspinatus as rotation and humeral lateralization are varied at (A) 0° abduction/0 mm Glenoid, (B) 0° abduction/5 mm Glenoid, (C) 0° abduction/10 mm Glenoid, (D) 90° abduction/0 mm Glenoid, (E) 90° abduction/5 mm Glenoid, and (F) 90° abduction/10 mm Glenoid. Negative rotation equates to internal rotation, while positive rotation denotes external rotation.

3.3.3   Teres Minor

Overall, a change in glenoid lateralization (p = 0.31) and humeral lateralization (p = 0.27) did not result in statistically significant changes in the moment arm of teres minor. Fig. 3-6(A) demonstrates overall moment arm changes as glenoid lateralization is increased by 5 mm intervals. Fig. 3-6(B) demonstrates overall moment arm changes as humeral lateralization is increased by 10 mm intervals. The moment arm of teres minor increased by 8.97 ± 7.4 mm when changing glenoid lateralization from 0 mm to 10 mm. Meanwhile, the moment arm increased by 1.65 ± 0.14 mm and 9.10 ± 7.82 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. Overall, a change in rotation did not yield a statistically significant change in the moment arm of teres minor (p = 0.29). The moment arm at 0° of abduction was 53.66 ± 6.30 mm compared to 40.65 ± 1.16 mm at 90° of abduction (p = 0.08). These results include all implant configurations and positions.

As a general trend, peak moment arms were found in the 60° externally rotated position in both abduction positions (Fig. 3-7); with exception to 0 mm and 5 mm of glenoid lateralization in neutral abduction where the peak moment arm was at 30° of external rotation (Fig 3-7(A-B)). Furthermore, as humeral lateralization increased (while glenoid lateralization remained constant), there was an increase in the peak moment arm throughout all tested positions. The largest teres minor moment arm at 0° of abduction was at 60° of external rotation and using a combination of 10 mm glenoid and 15 mm humeral lateralization (62.90 ± 1.55 mm). At 90° of abduction, the peak moment arm was also noted in the same arm position and implant configuration to be 49.46 ± 6.41 mm. Fig. 3-7 summarizes all calculated moment arms for respective arm positions and implant configurations.
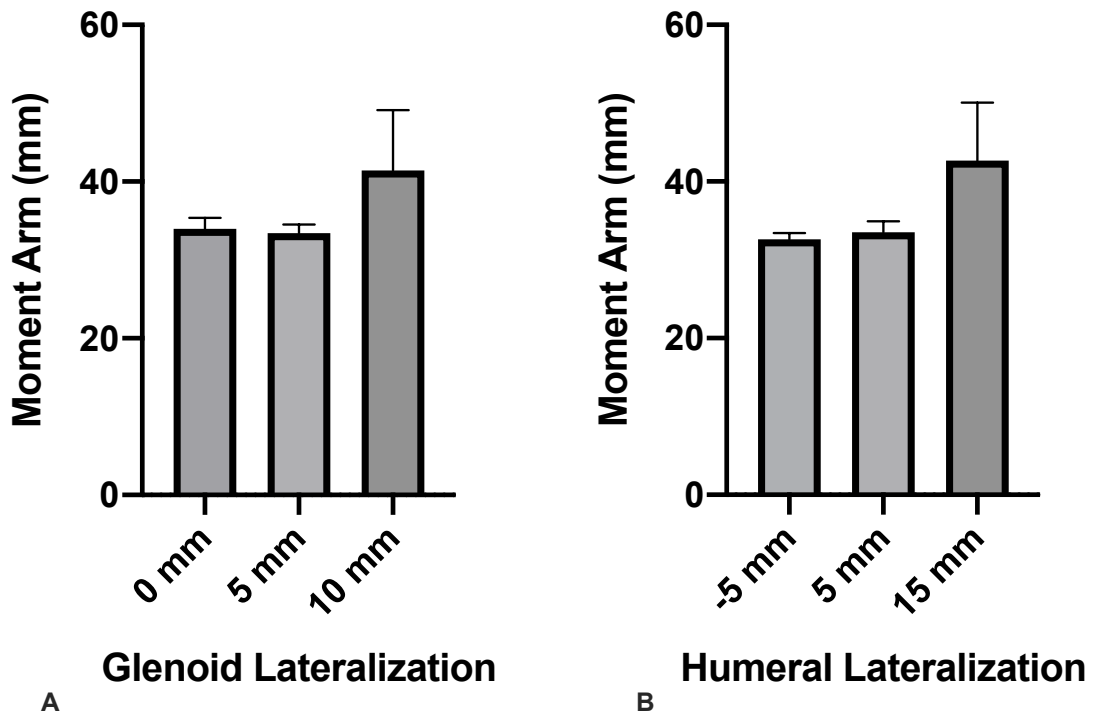
Figure 3-6: Overall Teres Minor Moment Arm

Figure outlining the overall (inclusive of all testing parameters) mean moment arm (+/- 1 SD) of teres minor. Figure (A) demonstrates the effect of glenoid lateralization on moment arm. Figure (B) demonstrates the effect of humeral lateralization on moment arm.
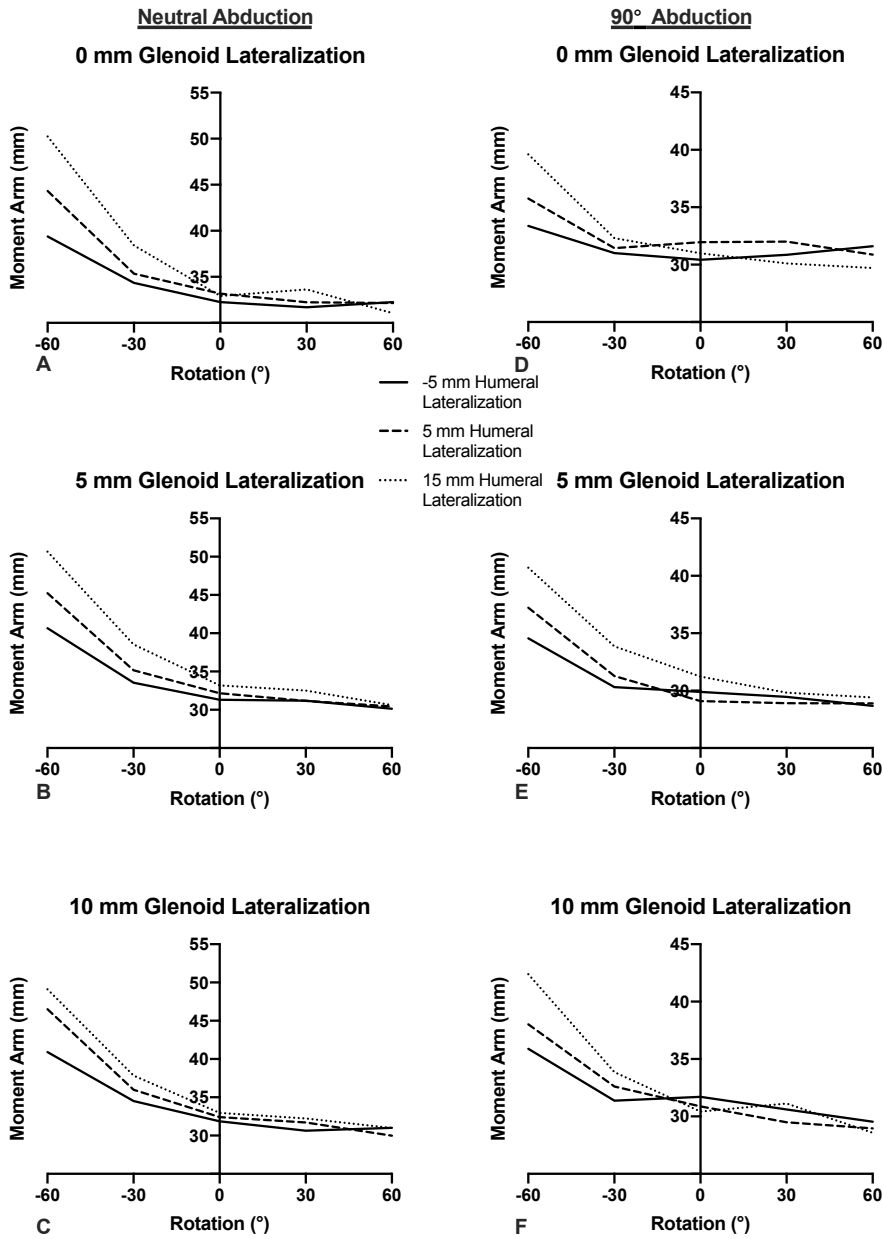
Figure 3-7: Moment Arm of Teres Minor Under Various Positions and Implant Configurations

Moment arm (+/- 1 SD) of teres minor as rotation and humeral lateralization are varied at (A) 0° abduction/0 mm Glenoid, (B) 0° abduction/5 mm Glenoid, (C) 0° abduction/10 mm Glenoid, (D) 90° abduction/0 mm Glenoid, (E) 90° abduction/5 mm Glenoid, and (F) 90° abduction/10 mm Glenoid. Negative rotation equates to internal rotation, while positive rotation denotes external rotation.

3.3.4   Subscapularis Superior

Overall, a change in glenoid lateralization (p = 0.34) and humeral lateralization (p = 0.18) did not result in statistically significant changes in the moment arm of subscapularis superior. Fig. 3-8(A) demonstrates overall moment arm changes as glenoid lateralization is increased by 5 mm intervals. Fig. 3-8(B) demonstrates overall moment arm changes as humeral lateralization is increased by 10 mm intervals. The moment arm of subscapularis superior increased by 8.32 ± 7.61 mm when changing glenoid lateralization from 0 mm to 10 mm. Meanwhile, the moment arm increased by 0.81 ± 0.82 mm and 11.29 ± 7.38 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. Overall, a change in rotation did not yield a statistically significant change in the moment arm of subscapularis superior (p = 0.39). The moment arm at 0° of abduction was 35.36 ± 3.91 mm compared to 35.36 ± 1.85 mm at 90° of abduction (p = 0.99). These results include all implant configurations and positions.

As a general trend, moment arms followed a more uniform trend across range of motion in both abduction positions compared to other muscles (Fig. 3-9). Furthermore, as humeral lateralization increased (while glenoid lateralization remained constant), there was an increase in the peak moment arm throughout all tested positions. The largest subscapularis superior moment arm at 0° of abduction was at 60° of external rotation and using a combination of 10 mm glenoid and 15 mm humeral lateralization (33.84 ± 8.71 mm). At 90° of abduction, the peak moment arm was also noted in 60° of internal rotation and the same implant configuration to be 41.526 ± 6.49 mm. Fig. 3-9 summarizes all calculated moment arms for respective arm positions and implant configurations.
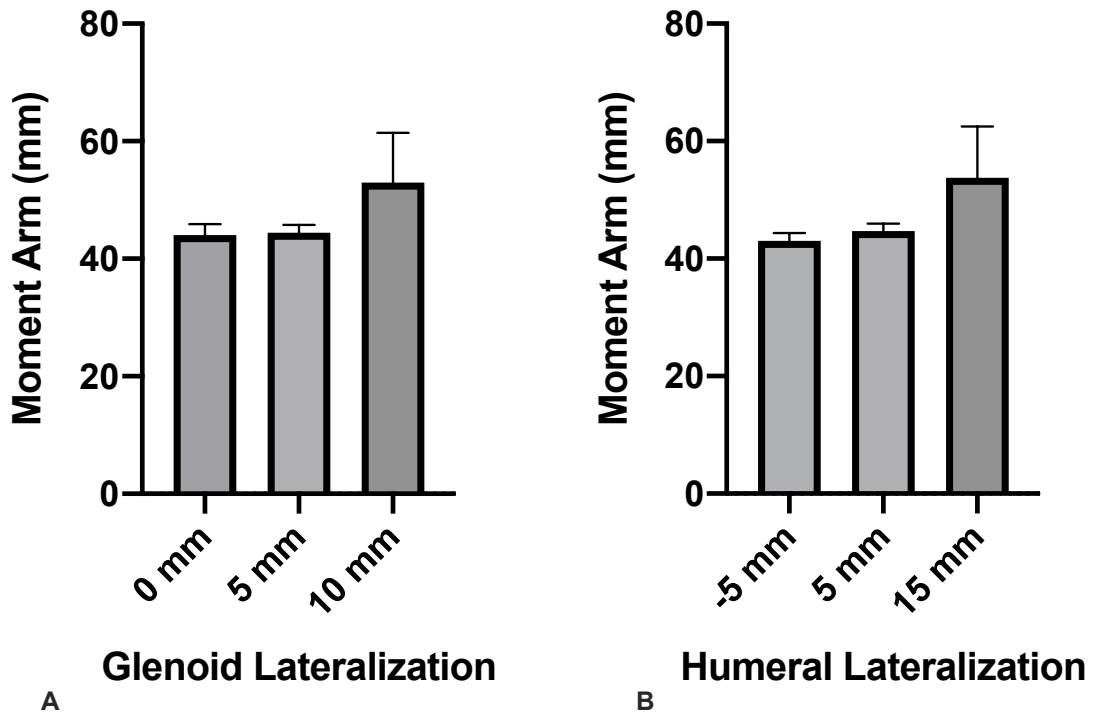
Figure 3-8: Overall Subscapularis Superior Moment Arm

Figure outlining the overall (inclusive of all testing parameters) mean moment arm (+/- 1 SD) of subscapularis superior. Figure (A) demonstrates the effect of glenoid lateralization on moment arm. Figure (B) demonstrates the effect of humeral lateralization on moment arm.
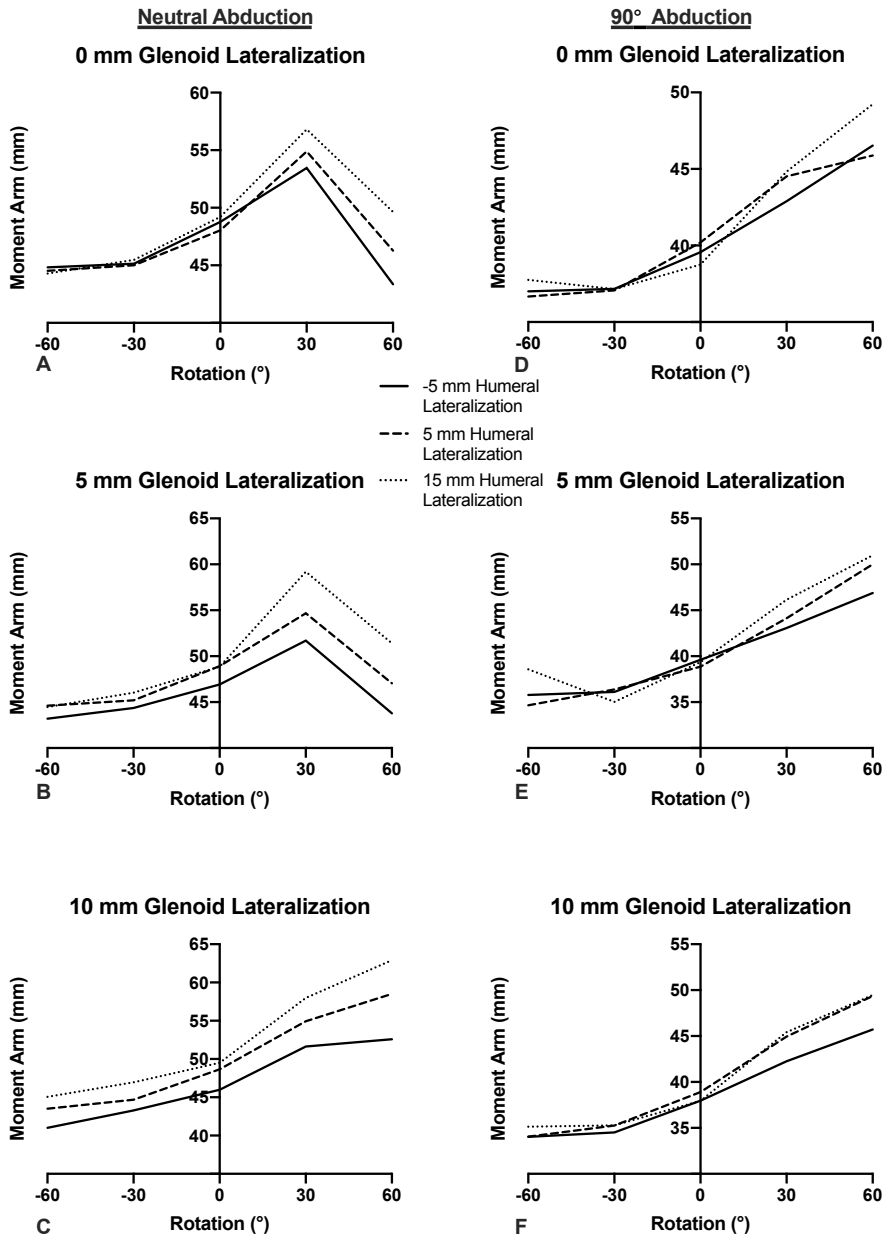
Figure 3-9: Moment Arm of Subscapularis Superior Under Various Positions and Implant Configurations

Moment arm (+/- 1 SD) of subscapularis superior as rotation and humeral lateralization are varied at (A) 0° abduction/0 mm Glenoid, (B) 0° abduction/5 mm Glenoid, (C) 0° abduction/10 mm Glenoid, (D) 90° abduction/0 mm Glenoid, (E) 90° abduction/5 mm Glenoid, and (F) 90° abduction/10 mm Glenoid. Negative rotation equates to internal rotation, while positive rotation denotes external rotation.

3.3.5   Subscapularis Inferior

Overall, a change in glenoid lateralization (p = 0.31) and humeral lateralization (p = 0.20) did not result in statistically significant changes in the moment arm of subscapularis inferior. Fig. 3-10(A) demonstrates overall moment arm changes as glenoid lateralization is increased by 5 mm intervals. Fig. 3-10(B) demonstrates overall moment arm changes as humeral lateralization is increased by 10 mm intervals. The moment arm of subscapularis inferior increased by 8.65 ± 7.07 mm when changing glenoid lateralization from 0 mm to 10 mm. Meanwhile, the moment arm increased by 2.25 ± 0.57 mm and 9.86 ± 7.23 mm when changing humeral lateralization from -5 mm to 5 mm and 5 mm to 15 mm, respectively. Overall, a change in rotation did not yield a statistically significant change in the moment arm of subscapularis inferior (p = 0.32). The moment arm at 0° of abduction was 40.99 ± 4.39 mm compared to 36.81 ± 0.54 mm at 90° of abduction (p = 0.42). These results include all implant configurations and positions.

As a general trend, peak moment arms were found in the 60° externally rotated position in both abduction positions (Fig. 3-11); with exception to 0 mm and 5 mm of glenoid lateralization in neutral abduction where the peak moment arm was at 30° of external rotation (Fig. 3-11(A-B)). Furthermore, as humeral lateralization increased (while glenoid lateralization remained constant), there was an increase in the peak moment arm throughout all tested positions. The largest subscapularis inferior moment arm at 0° of abduction was at 60° of external rotation and using a combination of 10 mm glenoid and 15 mm humeral lateralization (51.17 ± 7.02 mm). At 90° of abduction, the peak moment arm was also noted in the same arm position and implant configuration to be 49.79 ± 4.63 mm. Fig. 3-11 summarizes all calculated moment arms for respective arm positions and implant configurations.
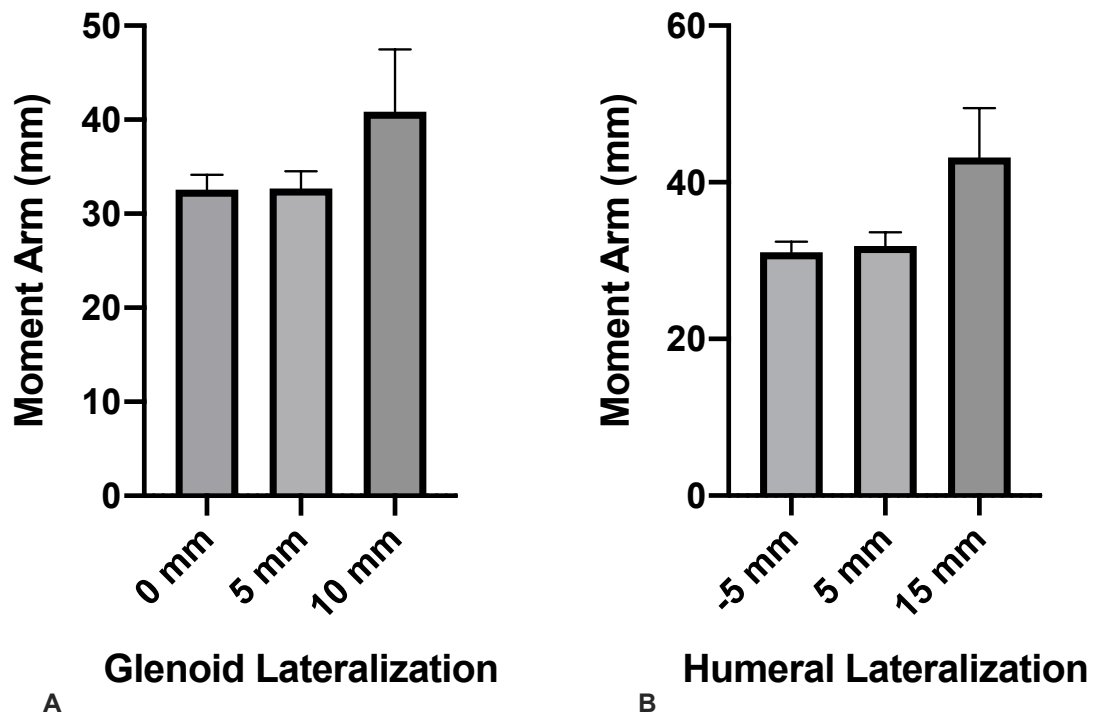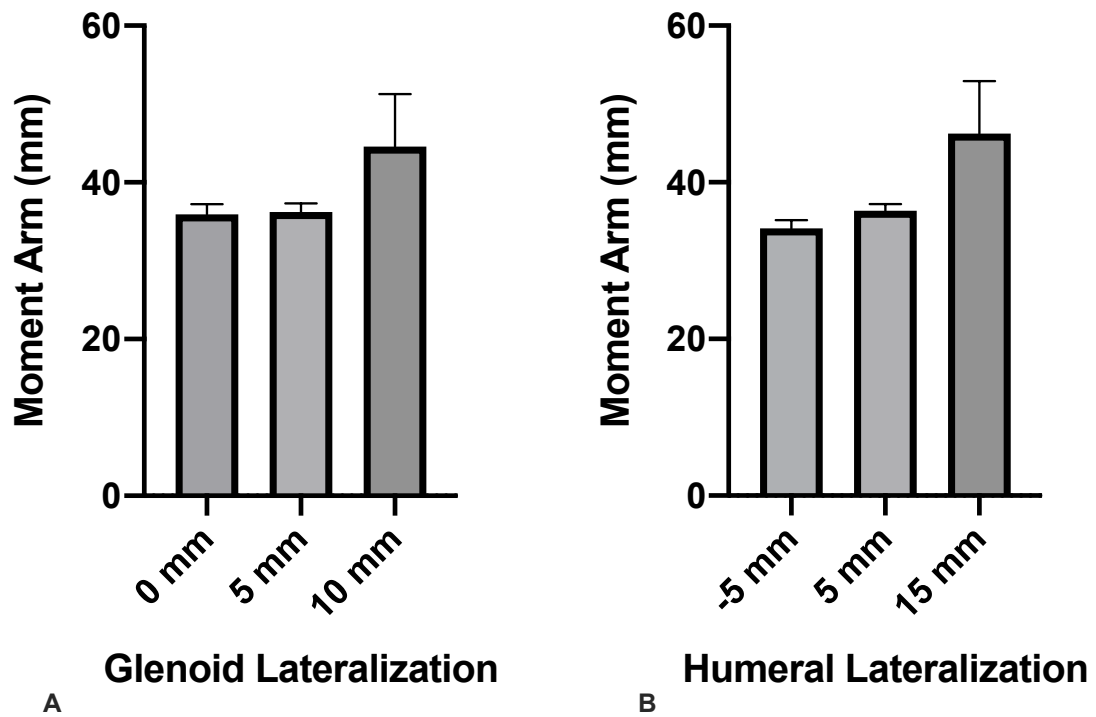
Figure 3-10: Overall Subscapularis Inferior Moment Arm

Figure outlining the overall (inclusive of all testing parameters) mean moment arm (+/- 1 SD) of subscapularis inferior. Figure (A) demonstrates the effect of glenoid lateralization on moment arm. Figure (B) demonstrates the effect of humeral lateralization on moment arm.
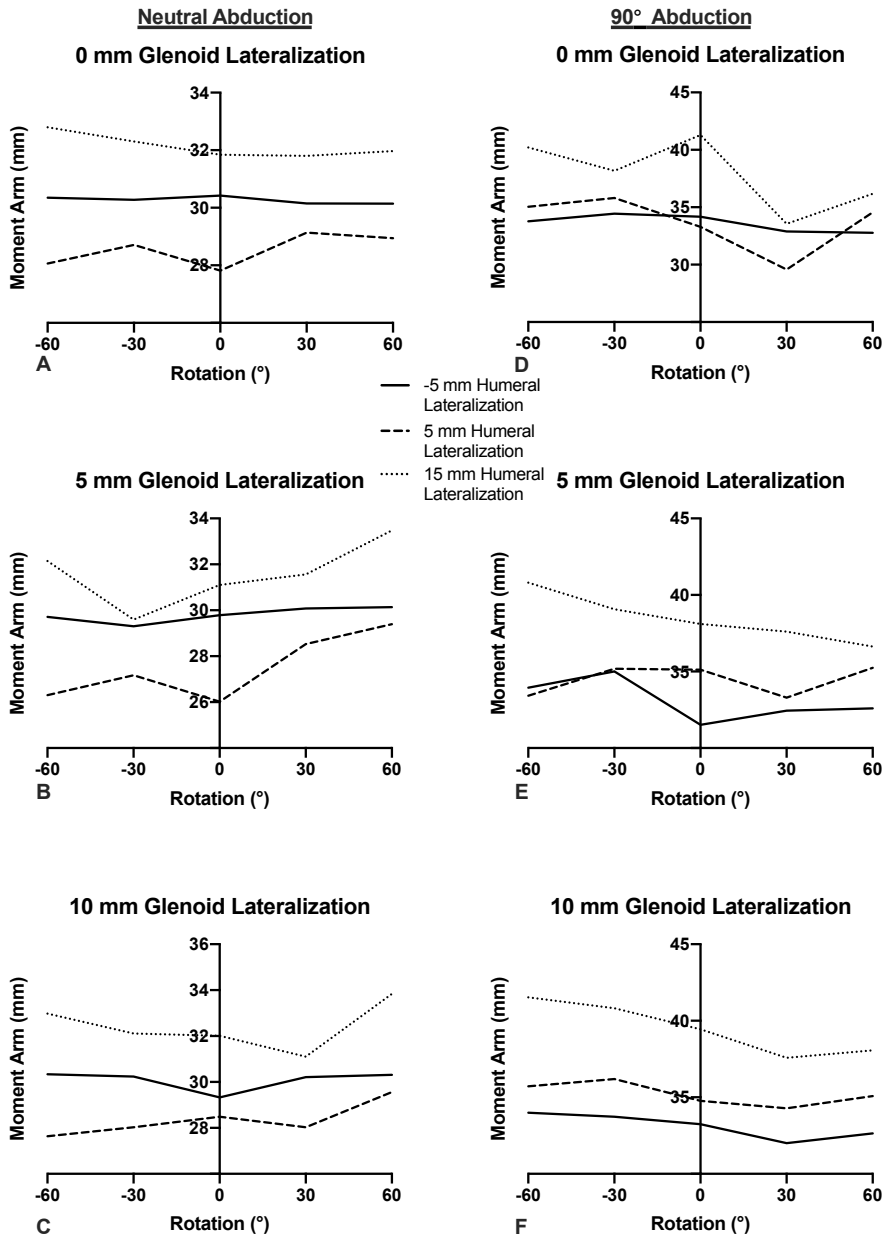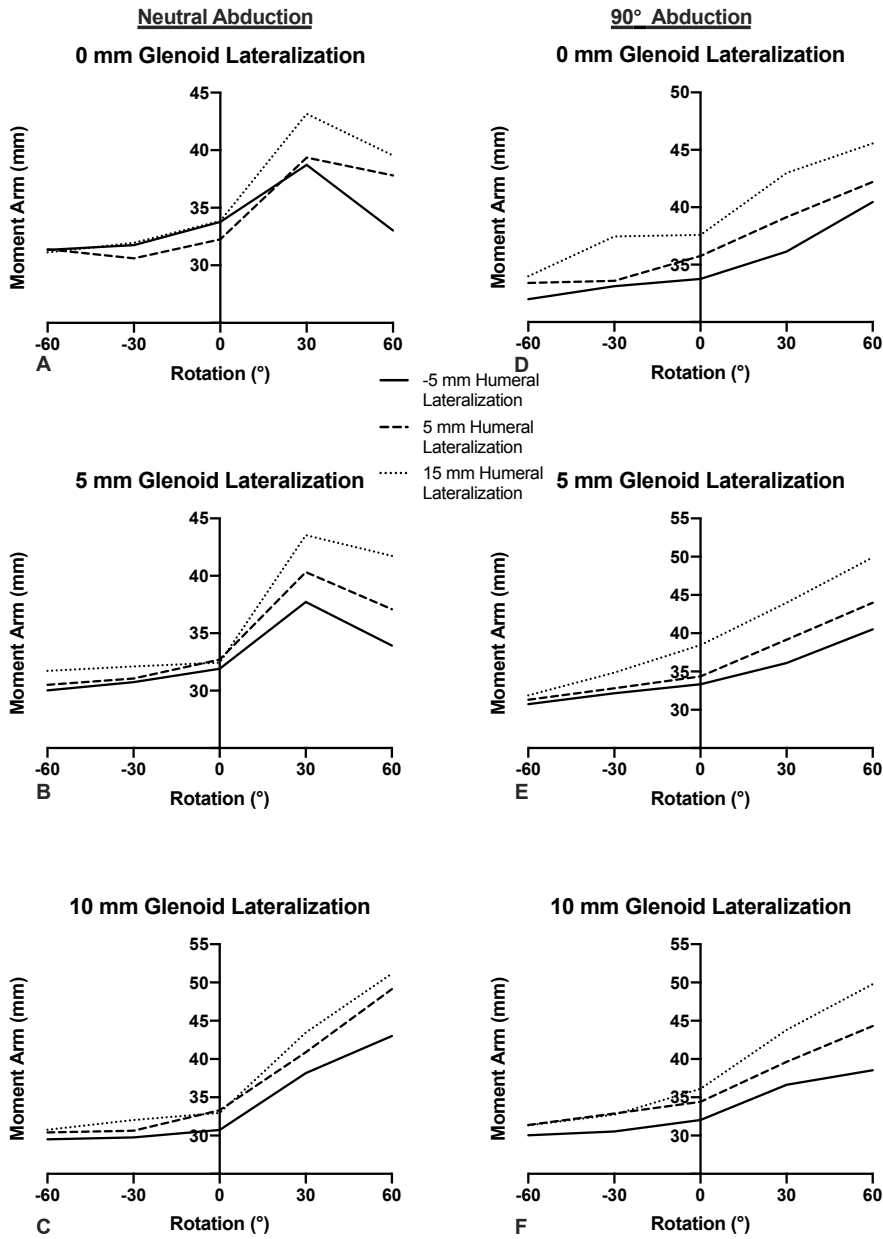
Figure 3-11: Moment Arm of Subscapularis Inferior Under Various Positions and Implant Configurations

Moment arm (+/- 1 SD) of subscapularis inferior as rotation and humeral lateralization are varied at (A) 0° abduction/0 mm Glenoid, (B) 0° abduction/5 mm Glenoid, (C) 0° abduction/10 mm Glenoid, (D) 90° abduction/0 mm Glenoid, (E) 90° abduction/5 mm Glenoid, and (F) 90° abduction/10 mm Glenoid. Negative rotation equates to internal rotation, while positive rotation denotes external rotation.

3.4 Discussion

The primary objective of this study was to evaluate the role of RTSA implant lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis tendons moment arms. This study focused on varying glenoid lateralization (0, 5 and 10 mm) and humeral lateralization (-5, 5 and 15 mm) while keeping all other implant parameters constant. Each implant configuration was assessed at five rotation states (60° IR, 30° IR, 0°, 30° ER and 60° ER) for each abduction position (0° and 90°). Overall moment arms were measured in millimeters.

Based on the results outlined, increasing glenoid or humeral lateralization did not yield a statistically significant change in the moment arms of supraspinatus, infraspinatus, teres minor, subscapularis superior and subscapularis inferior. Although not significant, a trend towards increased peak moment arm as lateralization increased was observed for all muscles tested. This trend is supported by other studies that evaluated lateralized RTSA designs. A CT based range of motion analysis had previously demonstrated increased range of motion as glenoid lateralization increased.[40] Meanwhile, a computational based study found that lateralized RTSA designs increased the external rotators moment arms relative to a medialized RTSA design.[27] Furthermore, Chan et al. demonstrated improved anterior and posterior rotator cuff torque as humeral lateralization was increased in neutral abduction.[41]

Abduction was found to have a significant effect on the overall moment arm of supraspinatus. This is likely due its dominant function within the plane of that motion.[42-45] The peak moment arms of supraspinatus were found to be at the most internally rotated position within out study. This finding correlates with a biomechanical study evaluating moment arms of muscles around the shoulder after RTSA.[34] Although this study only evaluated a single implant configuration, they determined that at neutral abduction, supraspinatus is likely to behave as an external rotator.[34] Although we did not find a statistically significant difference in the overall moment arm of subscapularis superior between the two abduction positions, the peak moment arm was larger in the further abducted position when the implant configuration was most lateralized. This is also consistent with the study described earlier.[34]

Aside from moment arms, there are many factors to take into account when considering modifying glenoid or humeral lateralization in RTSA. Biomechanically, studies have demonstrated increased impingement free range of motion that decreases notching as glenoid lateralization is incrementally increased.[46,47] Studies have demonstrated that scapular spine strain is increased with increased glenoid lateralization but decreased with further humeral lateralization.[37,48] Furthermore, increased lateralization may have a negative impact on other aspects of RTSA. Further lateralization may hinder the possibility of a subscapularis repair or result in a tethered repair which limits external rotation. Furthermore, biomechanical studies demonstrated that as glenoid lateralization was incrementally increased, there was an increase in joint load and decrease in the mechanical advantage of the deltoid muscle.[25,47]

3.4.1   Strengths and Limitations

To our knowledge, this is the first cadaveric biomechanical study examining the role of glenoid and humeral lateralization at various intervals on rotator cuff excursion and moment arms. While other studies have evaluated a limited number of implant designs, the use of a modular RTSA within this study allowed for various implant configurations to be tested. Therefore, most implant configurations available on the market were able to be replicated within this study. Furthermore, the glenohumeral simulator used in this study allowed for controlled range motion and computer-controlled tension on the rotator cuff. While implanted and secured under the glenohumeral simulator, the quality of the specimen was maintained by ensuring it remained moist throughout the testing protocol. The utilization of an optical tracking system with six degrees of freedom allowed for highly accurate data acquisition.

Cadaveric based studies do have inherent limitations. First, the shoulder simulator did not allow for scapulothoracic motion. However, to simulate 90° of humerothoracic abduction, 60° of glenohumeral abduction was used for this experiment as previously described.[49,50] Furthermore, this study outlined outcomes at a single time point and did not account for soft tissue accommodation or stretching over an extended period of time. Similarly, while preparing specimens for this experiment, some soft tissue was removed to accommodate implantation that may exactly mimic in-vivo characteristics such as tissue stretch, soft tissue elongation over time and potential dynamic change of muscle lines of action. Furthermore, this testing model assumed an intact rotator cuff. Therefore, the moment arms presented within this study may not fully represent those of patients with rotator cuff disease. Lastly, out of plane rotation/translation differences may induce error when using the tendon excursion method to calculate moment arms.

3.5 Conclusions

This study provided detailed insight into the role of incremental glenoid and humeral lateralization on the excursion of supraspinatus, infraspinatus, teres minor, subscapularis superior and subscapularis inferior in the setting of reverse total shoulder arthroplasty. This study outlined the relative moment arm patterns of the rotator cuff tendons in various arm positions. Abduction was found to have a statistically significant effect on the overall moment arm of the supraspinatus. Although not statistically significant, there was a trend towards increased moment arms as glenoid and humeral lateralization was increased for all muscles studied.

The findings of this study have clinical and biomechanical implications on the design of future research examining implant configurations for optimal rotator cuff function in the setting of reverse total shoulder arthroplasty. They may also be used to aid in developing and validating upper extremity models such as those used to assess the contribution of individual muscles to the stability and motion of the glenohumeral joint. Furthermore, these results can also be used to evaluate the biomechanical role and optimization of tendon transfers in the setting of RTSA.

3.6   References

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Chapter 4

4   Thesis Conclusions

The utilization of reverse total shoulder arthroplasty (RTSA) continues to increase as its indications broaden. Range of motion deficits remain to be a challenging aspect to correct through implant design. While existing literature focuses on etiology, prevalence, and clinical outcomes of range of motion deficits, there is a deficiency in literature investigating the role of the rotator cuff as implant parameters are altered. The purpose of this thesis was to utilize a cadaveric, biomechanical model to evaluate the effect of glenoid and humeral lateralization on the excursion and moment arms of the rotator cuff tendons in the setting of RTSA.

The primary objectives of this thesis were:

5. To evaluate the role of glenoid lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion (Chapter 2).

6. To evaluate the role of humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion (Chapter 2).

7. To evaluate the role of glenoid lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis moment arms (Chapter 3).

8. To evaluate the role of humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis moment arms (Chapter 3).

4.1   Summary of Chapter 2: The Effect of Glenoid and Humeral Lateralization on the Excursion of the Rotator Cuff Muscles in Reverse Total Shoulder Arthroplasty

The purpose of this study was to evaluate the role of glenoid and humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis excursion. The main outcome measure was excursion for each tendon under various implant configurations and arm positions.

Regarding glenoid lateralization, the hypothesis of this study was that increasing glenoid lateralization would result increased lateral excursion of each rotator cuff tendon. The rationale was that with increased glenoid lateralization, the center of rotation is lateralized and thereby lateralizes the insertions of the rotator cuff tendons. The results of this study demonstrated a general trend of uniform increase in lateral excursion of the rotator cuff as glenoid lateralization was increased.

With respect to humeral lateralization, the hypothesis of this study was that increasing humeral lateralization would result in increased lateral excursion of each rotator cuff tendon. The rationale was like the above in that as the humerus lateralizes, so does the insertional anatomy and thereby increases excursion. The results of this study also demonstrated a general trend of increased lateral excursion of the rotator cuff tendons as humeral lateralization was increased. Interestingly, the excursion increase was not uniform as seen with humeral lateralization. Early humeral lateralization (-5 mm to 5mm) yielded lower excursion change compared to lateralization from 5 mm to 15 mm. This difference was likely due to the wrapping of the tendons around the glenosphere in a medialized state compared to a linear orientation in a more lateralized (humeral) state.

Furthermore, as abduction increased from 0° to 90°, the supraspinatus, teres minor and subscapularis inferior were found to have medial excursion. Meanwhile, subscapularis superior and infraspinatus had lateral excursion with increased abduction.

4.2 Summary of Chapter 3: The Effect of Glenoid and Humeral Lateralization on the Moment Arms of the Rotator Cuff Muscles in Reverse Total Shoulder Arthroplasty

The purpose of this study was to evaluate the role of glenoid and humeral lateralization on supraspinatus, infraspinatus, teres minor, and subscapularis moment arms. The main outcome measure was the moment arm for each tendon under various implant configurations and arm positions.

Regarding glenoid lateralization, the hypothesis of this study was that increasing glenoid lateralization would not alter the moment arm of each rotator cuff tendon. The rationale was that with increased glenoid lateralization, the center of rotation is lateralized as is the insertional anatomy of the rotator cuff and thereby the distance between these two points remain the same. The results of this study did not demonstrate a statistically significant change in moment arms of the rotator cuff tendons as glenoid lateralization was increased.

With respect to humeral lateralization, the hypothesis of this study was that increasing humeral lateralization would result in increased moment arms of each rotator cuff tendon. The rationale was that as the humerus lateralizes, the distance between the insertion of the tendons on the humerus and the center of rotation will increase. The results of this study also did not demonstrate statistically significant change in moment arms as the humerus was lateralized but there was a trend towards increased moment arms. Interestingly, the excursion increase was not uniform as seen with humeral lateralization.

Abduction had a statistically significant effect on the moment arm of supraspinatus and not the other tendons studied. This is the first cadaveric biomechanical study to examine the effect of incremental humeral and glenoid lateralization on the moment arms of the rotator cuff.

4.3 Future Direction

This current thesis evaluated the role of glenoid and humeral lateralization on the excursion and moment arms of various RTSA configurations. Future opportunities may include three-dimensional mapping of the rotator cuff tendons throughout range of motion at various implant configurations. This may have a role in pre-operative planning to estimate post-operative range of motion. Furthermore, this analysis may be compared to native glenohumeral anatomy. Lastly, other surgical parameters such as polyethylene thickness, glenosphere size, and baseplate position may also be tested to assess their effects on the excursion and moment arms of the rotator cuff tendons.

4.4 Significance

The utilization of RTSA has continued to increase in clinical settings as the clinical indications continue to expand. Despite initially used for rotator cuff deficient patients, its use in rotator cuff intact scenarios has increased. Despite significant research assessing optimal implant configurations to improve forward elevation, decrease acromial stress, and improve stability, there was a paucity in literature assessing the effects on the rotator cuff tendons. The findings of this thesis have clinical and biomechanical implicants on the design of future research assessing optimal RTSA implant configurations that optimizes rotator cuff function. The digitization of the rotator cuff tendons in three-dimensional space as motion occurs at various implant configurations provides valuable information to develop and validate future glenohumeral models.

Curriculum Vitae

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