10-26-2020 6:00 PM

Navigation and Patient Specific Instrumentation in Shoulder Arthroplasty

Joseph Cavanagh, *The University of Western Ontario*

Supervisor: Athwal, G, *The University of Western Ontario*
: Johnson, J, *The University of Western Ontario*
: Langohr, D, *The University of Western Ontario*

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

Recommended Citation

Cavanagh, Joseph, "Navigation and Patient Specific Instrumentation in Shoulder Arthroplasty" (2020). *Electronic Thesis and Dissertation Repository*. 7457.
https://ir.lib.uwo.ca/etd/7457

Abstract

The humeral head osteotomy influences shoulder arthroplasty component height, version and neck shaft angle and therefore outcomes. The purpose of this study is to develop and utilize navigation to execute the osteotomy.

3D printed models were used to develop a navigation technique, and then to execute planned osteotomies. Free hand, fixed angle guide, patient specific guides, and real time navigation osteotomies were completed. The height, neck shaft angle and version were recorded. Also collected, were the planes of the guides once they were placed.

Navigation had significantly less error from the planned osteotomy in neck shaft angle versus all other groups and for version compared to free hand and fixed angle guides. Patient specific guides had statistically less error from planned neck shaft compared to the fixed angle guides. There were no statistical differences in cut height across groups. There was no difference in planned, guide placement and completed osteotomy parameters.

Keywords

Anatomic total shoulder arthroplasty, reverse total shoulder arthroplasty, humeral head osteotomy, biomechanics, navigation, osteotomy guides, patient specific instrumentation, version, neck shaft angle.

Summary for Lay Audience

The rates of shoulder replacement are increasing, and projected to continue to do so. Both anatomic and reverse shoulder replacement rely on replacement of the proximal humerus. The humeral head cut influences the component height, its version and neck shaft angle. These parameters all influence outcomes of shoulder replacement. Little, however, has been done to evaluate these humeral head cuts. The purpose of this study is to develop navigation for the proximal humerus and use real time navigation to execute the cut.

3D printed models of 10 humeral specimen were created. These models were used to mark anatomic points and tracings in development of a proximal humerus navigation technique. These same models were then used to execute preoperatively planned head cuts. Four different cut methods were trialed; free hand, fixed angle guide, patient specific guides, and real time navigation. The cut height, neck shaft angle and version were recorded for all. Also collected, were the planes of the fixed angle and patient specific guides once they were placed. This was done to evaluate the accuracy in placing them, and their relation to the subsequent cut plane.

Our navigation error was minimized to 2.5 mm in estimating a superior point on the humerus. Navigation guided cuts had statistically significant less error from preoperatively planned cuts in neck shaft angle compared to all other groups. Navigated cuts also had statistically less error for achieving planned version compared to free hand and fixed angle guide cuts. Patient specific guides had statistically less error in achieving the preoperatively planned neck shaft angle compared to the fixed angle guides. There were no statistical differences in cut height across our four groups. There were no statistical differences in the version, neck shaft angle or cut height when comparing preoperatively planned osteotomy, guide placement and subsequent osteotomy with the use of guide, for both fixed angle and patient specific guides. Further research and utilization of navigation and patient specific guides may further improve shoulder arthroplasty.

Co-Authorship Statement

Chapter 1: Joseph Cavanagh – sole author

Chapter 2: Joseph Cavanagh – study design, data collection, statistical analysis, manuscript preparation
Jason Lockhart – study design, data collection, statistical analysis
Dan Langohr – study design, statistical analysis, reviewed manuscript
Jim Johnson – study design, reviewed manuscript
George Athwal – study design, reviewed manuscript

Chapter 3: Joseph Cavanagh – study design, data collection, statistical analysis, manuscript preparation
Jason Lockhart – study design, data collection, statistical analysis
Dan Langohr – study design, statistical analysis, reviewed manuscript
Jim Johnson – study design, reviewed manuscript
George Athwal – study design, specimen cuts, reviewed manuscript

Chapter 4: Joseph Cavanagh – sole author

Acknowledgments

Thanks to my supervisors, Dr. George Athwal, Dr. Jim Johnson and Dr. Dan Langohr. Thank you for your support, teaching and guidance. To Jason Lockhart for the countless hours in the lab. To Jacob Reeves for leaving his 3D printer on for days on end. To the team in the 'Tank'. To the Ortho boys. And lastly to my family, for your unwavering support.

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Chapter 1

1 Introduction

This thesis is focused on the use of navigation and patient specific instrumentation in total shoulder arthroplasty. This chapters covers anatomy and biomechanics of the shoulder. The development and indications for anatomic and reverse total shoulder arthroplasty are reviewed. Navigation and patient specific instrumentation in surgery, orthopaedics and shoulder arthroplasty are explored. Lastly, the rationale, objectives and hypothesis of this thesis will be discussed.

1.1 The Shoulder

The shoulder is the most mobile major joint in the human body. It forms the connection between the torso and the upper extremity. It is functionally imperative for many actions of daily living. It is a diarthrodial joint, consisting of articulation of the glenohumeral joint. This is surrounded by further osseous joints and a complex collection of soft tissue. The multiaxial nature of the joint allows great degrees of freedom, including forward flexion, extension, abduction, adduction, internal and external rotation as well as circumduction. To appreciate the complexity of achieving these significant range of motion, it is important to understand the osseous and soft tissue anatomy as well as kinematics of the shoulder.

1.1.1 Osteology

The shoulder, as osseous structures, consists of the clavicle, scapula and humerus (Figure 1-1). These three bones articulate between themselves; at the acromioclavicular joint between the clavicle and scapula and at the glenohumeral joint as an articulation of the humerus and scapula. Furthermore the sternoclavicular joint at the medial clavicle and sternum, and the scapulothoracic joint, between the anterior scapula and posterior thoracic rib cage, are included in the four joints of the shoulder girdle (Terry & Chopp, 2000).

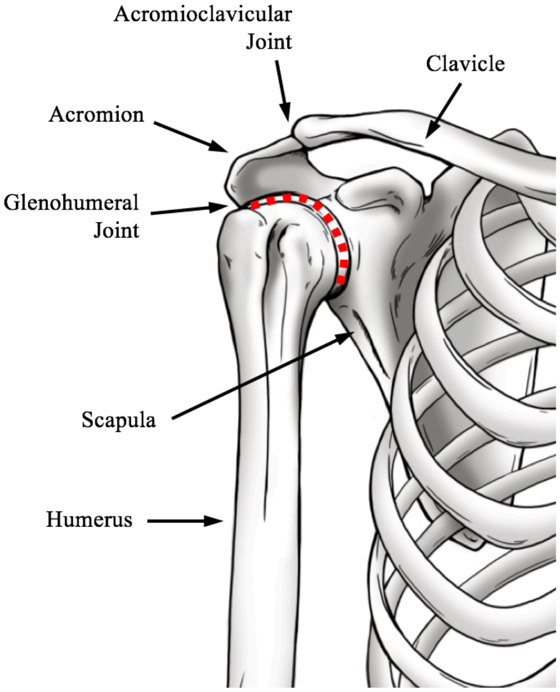

Figure 1-1: The Shoulder Joint

This illustration is of the osteology of the shoulder girdle. The red dashed line represents the glenohumeral joint.

1.1.1.1 The Humerus

The humerus is the long bone of the arm, spanning from the shoulder proximally to the elbow distally. The proximal aspect begins with the smooth convex articular surface; the humeral head. This articular surface comprises the humeral side of the glenohumeral joint. It is covered in articular cartilage and encompasses the bone. The three-dimensional geometry is complex. The head itself is slightly elliptical in shape, with a smaller anterior to posterior diameter than superior to inferior (Iannotti et al., 1992) The radius of the curve has some relationship to the thickness of the head, with an average curvature of forty six millimeters (P. Boileau & Walch, 1997). The head is angled superiorly, medially and posteriorly, as related to the long axis of the humeral shaft and transepidondylar axis at the elbow. (Figure 1-2) This is the combined version and neck shaft angle. Version is an axial plane measurement, as defined by the articular surface in relation to the epicondylar axis (P. Boileau & Walch, 1997). Other measurements for version utilize the transhumeral axis, or forearm. It poses a quite variable range, even side to side within individuals, but tends to be on average around twenty five to thirty degrees. (P. Boileau & Walch, 1997; Goldberg et al., 2020; Kronberg et al., 1990) Neck shaft angle is a coronal plane measurement, as defined by the articular surface in relation to the long axis of the humerus. It has an average of 135 degrees, and although variable, less so than version (P. Boileau & Walch, 1997; Goldberg et al., 2020; Keener et al., 2017; Robertson et al., 2000).

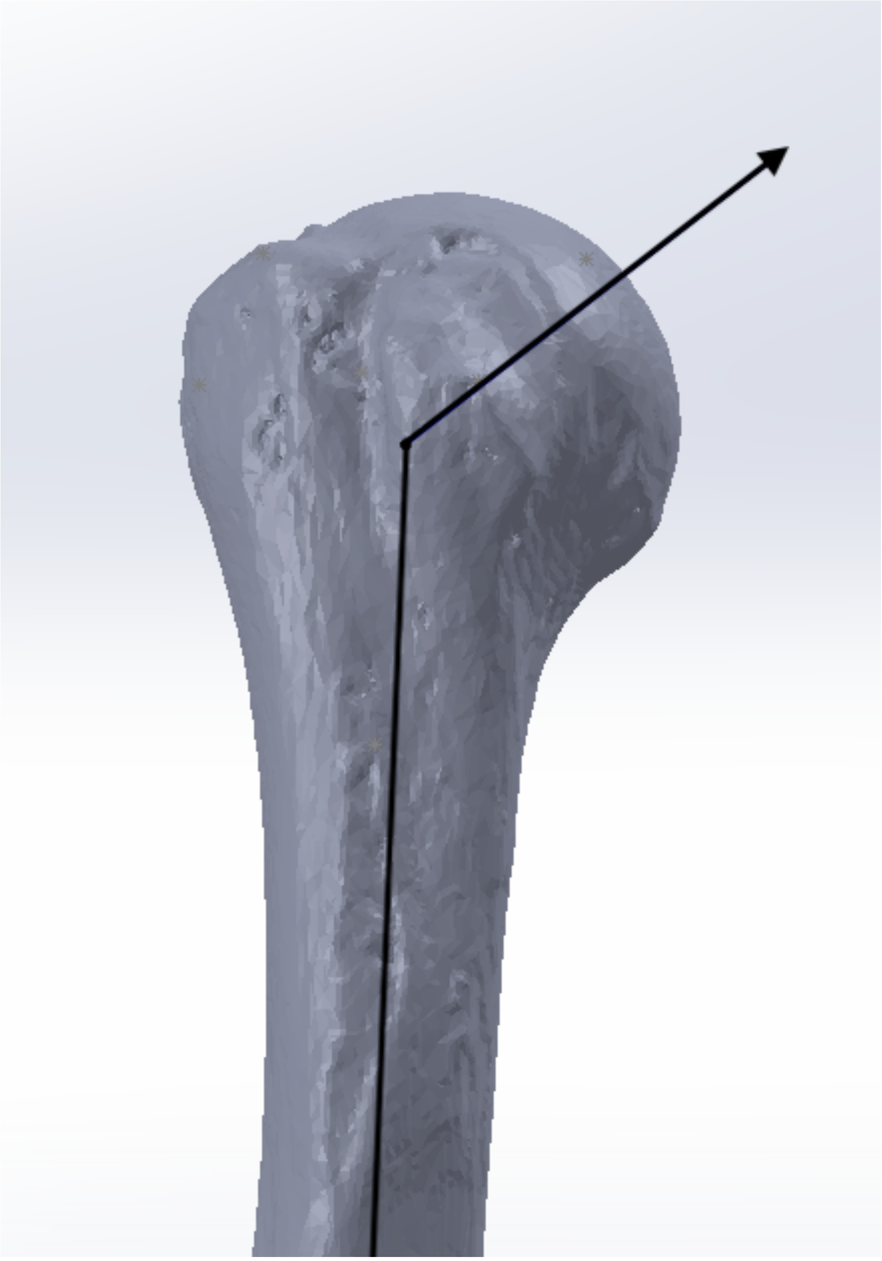

Figure 1-2: Humeral Head Orientation

Illustration of humerus, with long axis and humeral head orientation. The humeral head is superior, medial and posteriorly oriented.

The inferior border of the humeral head is the anatomic neck, where the smooth articular surface ceases and the uprising of bony tuberosities occur, both anteriorly and laterally. The lesser tuberosity sits anteriorly on the humerus, while the greater tuberosity sits anterolaterally. These two are split by the distinct bicipital groove. Laying further distal, yet also anterolaterally, is the deltoid tuberosity (Figure 1-3).

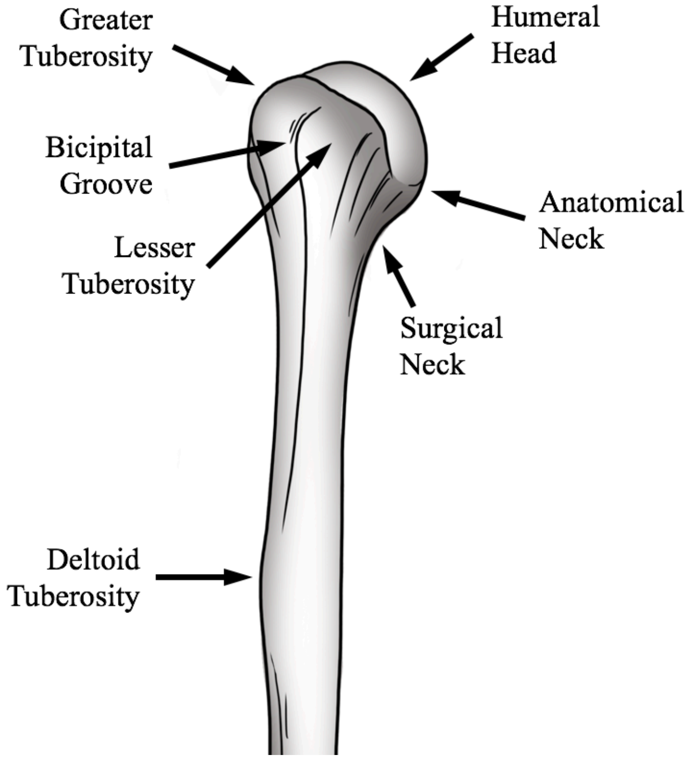

Figure 1-3: Osseous Anatomy of the Humerus

Illustration of osseous anatomy of the proximal humerus.

1.1.1.2 The Scapula

The scapula is the triangular posterior structure of the shoulder girdle. From its long medial border to one of its apexes superolateral, there is ample bony surface for muscle attachments. At the superolateral corner exists the coracoid, acromion and glenoid fossa. The first two provide further muscular attachment sites, and in the case of the acromion, an articular surface of the aforementioned acromioclavicular joint. The glenoid fossa too makes up a joint, with it articulating with our previously discussed humeral head. The glenoid itself is a concave surface, narrower proximally than distally in the sagittal plane, or as it is often described - pear shape in nature. It is also shallow with regards to its bony structure, with only thirty percent of the humeral head articular surface in contact at any given time. Axially the glenoid sits retroverted around seven degrees, and coronally superior of five degrees (Culham & Peat, 1993; Lugo et al., 2008; Terry & Chopp, 2000).

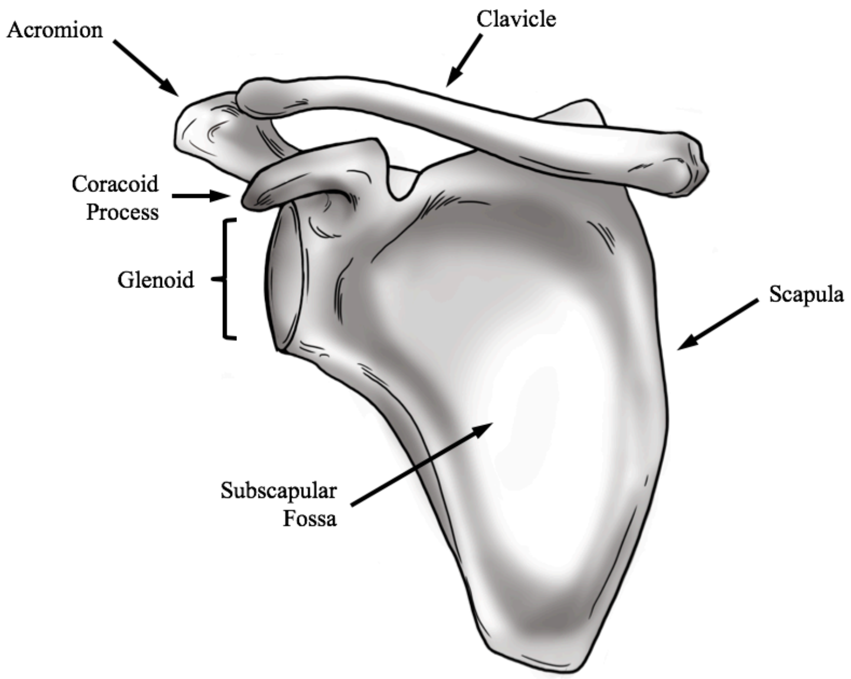

Figure 1-4: Anterior View of the Scapula

Illustration showing osseous anatomy of the anterior right scapula. Included is the clavicle.

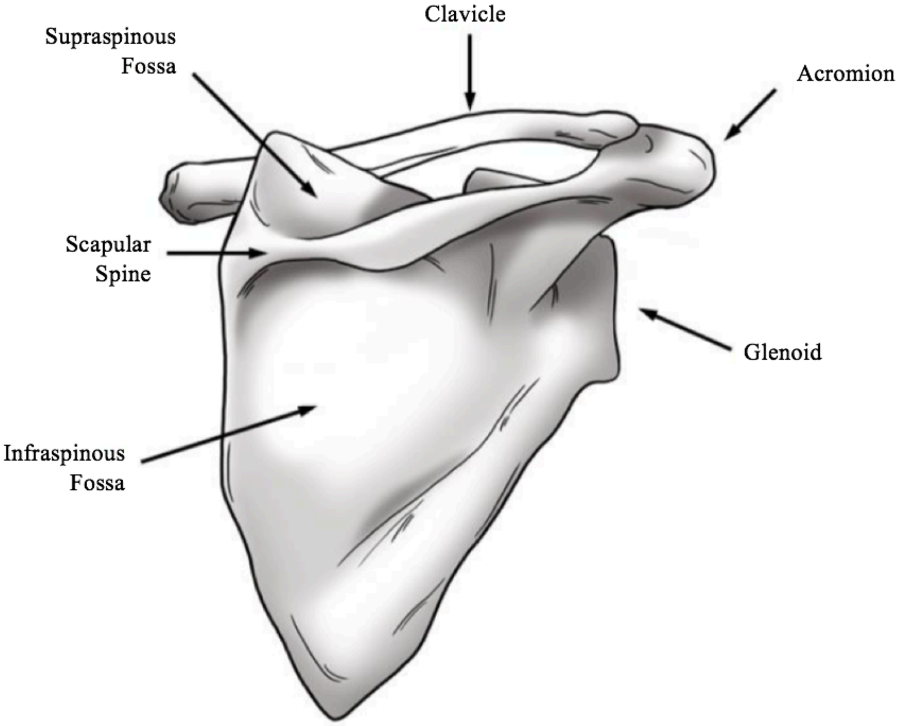

Figure 1-5: Posterior View of the Scapula

Illustration shows the osseous anatomy of the posterior right scapula. Included is the clavicle.

1.1.1.3 The Clavicle

The clavicle spans the anterior and superior portion of the thorax. It runs from its medial articulation with the proximal sternum at the sternoclavicular joint, to its lateral articulation with the acromion at the acromioclavicular joint. It is a thin bone, that allows muscle attachment along its length, while providing a support for the scapula (Terry & Chopp, 2000).

1.1.2 Soft Tissue and Motion of the Shoulder

The shoulder complex is fascinating anatomy, as an intricate balance between range of motion and stability. Alone the bony structures, notably the glenohumeral articulation, are shallow and unstable. The vast soft tissue structures surrounding the joint lends to more stability, with some of these same structures providing its wide range of motion. These can be both static and dynamic.

1.1.2.1 Static Stabilizers

The static structures include the labrum, joint capsule and surrounding ligaments. The labrum is a fibrocartilage structure that arises from the edges of the bony glenoid, coming to meet the long head of biceps at the supraglenoid tubercle. It can be up to fifty percent of the depth of the glenohumeral articulation, providing stability and a cupping effect for the joint (Howell & Galinat, 1989). It also provides attachment for the glenohumeral ligaments (Lugo et al., 2008).

The glenohumeral ligaments include the superior, middle and inferior ligaments. The inferior ligament is further divided into anterior and posterior. It runs from the inferior labrum and glenoid to the lesser tuberosity. The lesser is the insertion of both the middle and superior as well. The superior originates from the supraglenoid fossa and the middle from the supraglenoid tubercle. These three confer stability in various positions. When the arm is adducted, the superior ligament prevents inferior and posterior subluxation of the humeral head. The middle works in abduction, preventing both posterior and anterior subluxation. Lastly, the inferior works in abduction and external rotation. In this position it anterior movement of the humeral head (Terry & Chopp, 2000).

Lastly, the joint capsule itself is a static structure, running from the labrum onto the anatomic neck of the humerus. It is a fibrous structure. It is supported and reinforced by the previously mentioned ligaments, which run in close union with it (Huegel et al., 2014). It has no strain when the glenohumeral joint is completely centered, but aids in stability in when movement occurs (Abboud & Soslowsky, 2002).

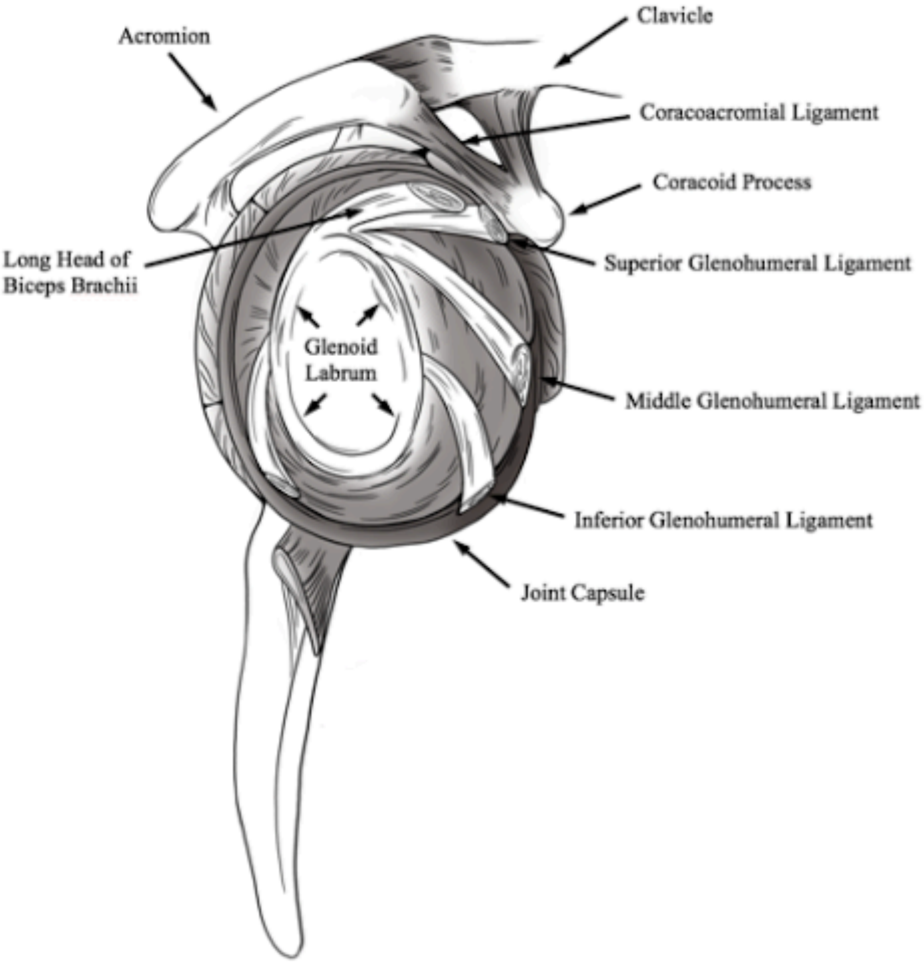

Figure 1-6: Soft Tissue Stabilizers of the Shoulder

Illustration shows a sagittal view of the right scapula and soft tissue stabilizers. Centered is the glenoid portion of the glenohumeral joint.

1.1.2.2 Dynamic Stabilisers

The dynamic stabilizers, as their name may imply, are active tissue under muscular control (Wuelker et al., 1998). They include the deltoid, rotator cuff and long head of biceps. As these structures contribute to range of motion of the glenohumeral joint, they too contribute to the stability of the joint (Wuelker et al., 1998). They can be seen in Figure 1-7.

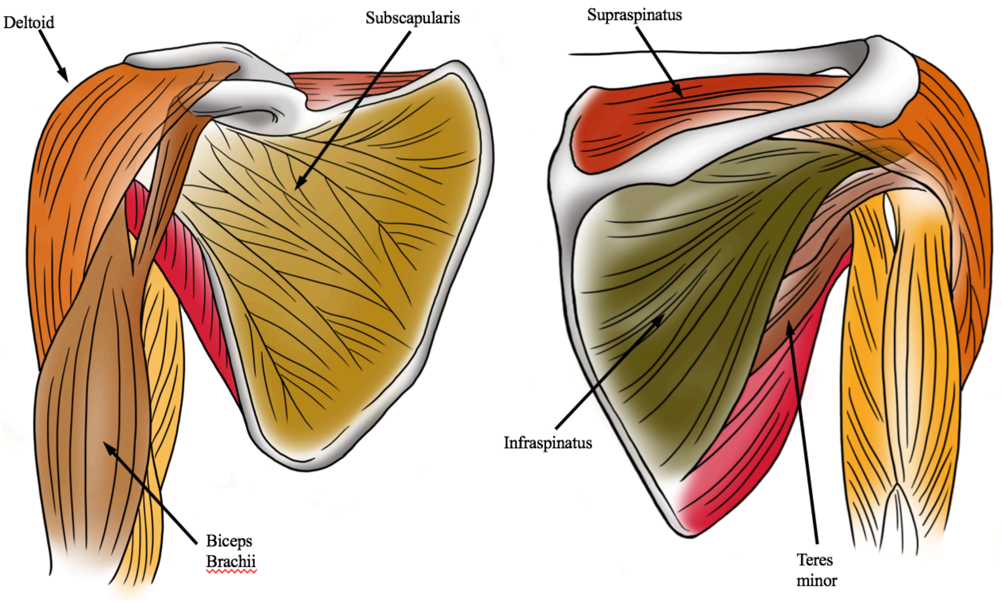

Figure 1-7: Dynamic Stabilizers of the Shoulder

Illustration depicting anterior (left) and posterior (right) views of the scapula with relevant dynamic soft tissue stabilizers of the shoulder.

1.1.2.3 Rotator Cuff Muscles

The rotator cuff is comprised of the supraspinatus, infraspinatus, teres minor and subscapularis muscles. The first three, the supraspinatus, infraspinatus and teres minor insert on the greater tuberosity in order from anterior superior to posterior inferior (Mochizuki et al., 2008). Their origins and innervations are distinct however. The supraspinatus arises from the aptly names supraspinatus fossa, above the spine on the scapula. Its innervation is from the suprascapular nerve. The infraspinatus and teres minor arise from below the scapular spine, on the posterior scapula. The infraspinatus is more proximal and innervated by the suprascapular nerve, while the more inferior teres minor is innervated by the axillary nerve. The subscapularis is the only rotator cuff muscle arising from the anterior surface of the scapular, in the subscapularis fossa. It is innervated by the upper and lower subscapularis nerves (Huegel et al., 2014).

Understanding the origin and insertions can lead one to better understand their actions. The subscapularis internally rotates the humerus. The supraspinatus is an abductor. The infraspinatus and teres minor provide external rotation. They also work in concert with each other, to allow for proper transferring of forces across the glenohumeral joint. Disruption or pathology of one of the muscles of the rotator cuff can alter this proper joint movement (Abboud & Soslowsky, 2002; Huegel et al., 2014). In addition to altered active joint mechanics, changes in the glenohumeral joint at rest can occur. This is because the rotator cuff is a mechanic block, notably for superior migration of the humeral head. Lack of superior rotator cuff integrity can allow for this superior displacement which is a hallmark feature of cuff tear arthropathy (C S Neer et al., 1983). Cuff tear arthropathy will be discussed in depth later in this chapter.

1.1.2.4 Long Head of Biceps Brachii

The biceps as its name suggests is composed of two parts, with a long head and short head. The short head arises from the coracoid process and does not cross the glenohumeral joint. The long head does, as it originates at the supraglenoid tubercle of the glenoid. It is an intraarticular structure, before becoming extra articular and running between the greater and lesser tuberosity. Its muscle belly and that of the short head run on the anterior arm to the radial tuberosity. It is supplied by the musculocutaneous nerve and is a forearm supinator and elbow flexor.

In addition to these actions, it is a stabilizer of the glenohumeral joint. Cadaveric studies have implicated it as a restraint of multidirectional displacement of the humeral head. Notably it inhibits anterior and inferior displacement, when the long head is activated (Alexander et al., 2013).

1.1.2.5 Deltoid

The deltoid is the most superficial muscle overlying the rotator cuff, and subsequently the shoulder. It is composed of 7 parts, that make up 3 functional units. The three units are anterior, middle and posterior. The anterior and posterior have 3 tendons within their functional group and the middle is a singular tendon (Wickham & Brown, 1998). They are all innervated by axillary nerve. They also all converge and insert at a common site, the deltoid tuberosity on the proximal lateral humerus. Despite some of their anatomic similarities their origins, and therefore actions are different. The anterior group originates on the clavicle and anterior acromion. The middle group arises from the middle portion of the lateral acromion. The posterior group is from the posterior acromion and scapular spine (Sakoma et al., 2011).

The anterior deltoid forward elevates the shoulder. The middle deltoid assists in this, with lesser force than the anterior generates. The middles prime movement is abduction of the shoulder. The posterior deltoid counters the anterior group, providing extension (Ackland, Pak, Richardson & Pandy, 2008).

1.1.2.6 Motion

From these aforementioned muscles come motion of the glenohumeral joint. These guide the shoulder movement, which happens in the sagittal, coronal, axial and scapular planes. Flexion and extension are in the sagittal, abduction and adduction in the coronal, and internal and external rotation in the axial (Gasbarro et al., 2017). The scapula plays an important part in these motions. In addition to being an articulating portion of the glenohumeral joint at its glenoid surface, the scapula also moves in relation to the thorax. This generates scapulothoracic motion. The combination of scapulothoracic motion, and the glenohumeral motion is collectively scapulohumeral rhythm (Inman et al., 1996).

1.2 Pathology of the Glenohumeral Joint

1.2.1 Osteoarthritis

Osteoarthritis may be commonly attributed to age but is a multifactorial process. In addition to age, other predispositions include obesity, joint malalignment, muscle weakness, neuropathy and genetics. (Goldring & Goldring, 2007). Change in the articular cartilage, however, is a constant across osteoarthritic joints. The articular surface provides a smooth surface to facilitate movement of the joint. Furthermore the articular surface is coated in lubricant, which also lowers the friction across the joint (Loeser et al., 2012). These are vital to a multiaxial mobile joint such as the glenohumeral joint. The bone surrounding the joint, as well as its regulatory pathways undergoes changes. The underlying bone becomes softer, and more susceptible to wear. Abnormal formation surrounding the joint in the form of osteophytes also occurs, which is hypothesized as a means to increase articular contact area to support a weakened joint (Loeser et al., 2012). The glenohumeral joint is not immune to these changes.

The glenohumeral joint has a wear pattern in osteoarthritis that was first described by Walch et al in 1999. (Walch et al., 1999). The classification is most commonly used clinically and based on distinct wear patterns of the glenoid in the axial plane. Further additions to the classification were made as seen (Bercik et al., 2016). The glenohumeral joint has also been classified with account for osteophyte formation and humeral head changes (Habermeyer et al., 2017).

1.2.2 Rheumatoid Arthritis

An autoimmune disorder, rheumatoid arthritis affects one in every hundred Canadians. This number increases to more than five in every hundred, if accounting for patients over seventy years old (A. L. Chen et al., 2003). It is an autoimmune condition, a chronic situation. It is manifested in the destruction of synovial joints (Guo et al., 2018). Three of the four joints of the shoulder girdle can be affected, the acromioclavicular, sternoclavicular and glenohumeral. The glenohumeral is affected by loss of motion, often insidious to begin, that becomes progressive in most cases. Furthermore if can affect the rotator cuff, in about three of four patients (A. L. Chen et al., 2003). Understandably this can have quite an impact on activities of daily living.

1.2.3 Rotator Cuff Arthropathy

As aptly named, rotator cuff arthropathy is a disease process of the rotator cuff. Initially described by Dr Charles Neer in 1983, it was described as abnormal glenohumeral wear in patients experiencing progressive pain and loss of motion of the shoulder. His first group of reported patients consisted of twenty-six individuals. In these shoulders, all had complete supraspinatus tears and twenty-five possessed infraspinatus tears. From this a theory of humeral head exposure, and ensuing instability and abnormal motion at the glenohumeral joint was developed. More succinctly put, both nutritional and mechanical factors, were the causative factors behind rotator cuff arthropathy (C S Neer et al., 1983). Multiple different findings have

since been identified in different patients, including humeral head migration, acromion acetabulisation, or effusion. With or without these entities, however, patients share three findings in common; a degenerative glenohumeral joint, superior humeral head migration and rotator cuff insufficiency (Ecklund et al., 2007). Findings of calcium phosphate crystals in the cuff musculature lead to the theory this was the causative factor. A merging of the two ideas is as follows; cuff tear leads to migration and exposure of the humeral head, which is followed by wear, debris, inflammation and crystal formation. These crystals perpetuate wear, and the cycle continues. Even with these proposed mechanisms, one question remains unanswered: Why does every massive rotator cuff tear not becomes cuff tear arthropathy? (Ecklund et al., 2007)

1.3 Management

As with most orthopaedic manifestations, pathology of the shoulder is generally managed in two fashions – nonoperative and operative. Nonoperative is the first course and often exhausted before operative intervention occurs. Nonoperative measures include activity modification, oral analgesia, topical medications, injections, disease modifying agents, biologics, and physical therapy (Ansok & Muh, 2018; A. L. Chen et al., 2003; Chillemi & Franceschini, 2013; Mattei et al., 2015).

Operative management includes, but is not limited to, arthroscopic debridement, resurfacing, hemiarthroplasty, total shoulder arthroplasty, and reverse total shoulder arthroplasty (Chillemi & Franceschini, 2013). Arthroscopic debridement has no definitive impact on disease progression in osteoarthritis and rheumatoid arthritis. It however may serve as a temporizing measure for pain, or as the best operative intervention in patients who are not major surgery candidates from a medical or personal point of view (Weinstein et al., 2000). Debridement of the joint and alleviating mechanical symptoms via, loose body or osteophyte removal, synovectomy and capsular release may be amenable in some patients (A. L. Chen et al., 2003; Chillemi & Franceschini, 2013; Weinstein et al., 2000). Resurfacing is an option as well, but seemingly an option best served for avascular necrosis (Alizadehkhaiyat et al., 2013).

1.3.1 Shoulder Arthroplasty

Arthroplasty is the gold standard of surgical interventions. It includes the aforementioned resurfacing arthroplasty, hemiarthroplasty, anatomic total shoulder arthroplasty and reverse total shoulder arthroplasty. Hemiarthroplasty and total shoulder arthroplasty may be used in both osteoarthritic as well as rheumatologic shoulders. A review of three hundred and three patients by Sperling et al suggest for improvement in pain, motion and need for revision surgeries, total shoulders were superior to hemiarthroplasty (Sperling et al., 2007). For osteoarthritic shoulders, a recent systematic review showed total shoulders have lower revision rates, but counter with a trend towards higher complications (Van Den Bekerom et al., 2013). Reverse total shoulder arthroplasty is used in the setting of rotator cuff arthropathy, osteoarthritis, and revision scenarios – for resurfacing, hemiarthroplasty, anatomic and reverse alike (Ackland et al., 2015; Familiari et al., 2018). Fracture, albeit outside the scope of our work, can be managed by hemiarthroplasty, anatomic or reverse total shoulder arthroplasty (Dillon et al., 2019). Overall both anatomic and reverse total shoulder arthroplasty exhibits success, with good long term outcomes (Simovitch et al., 2017).

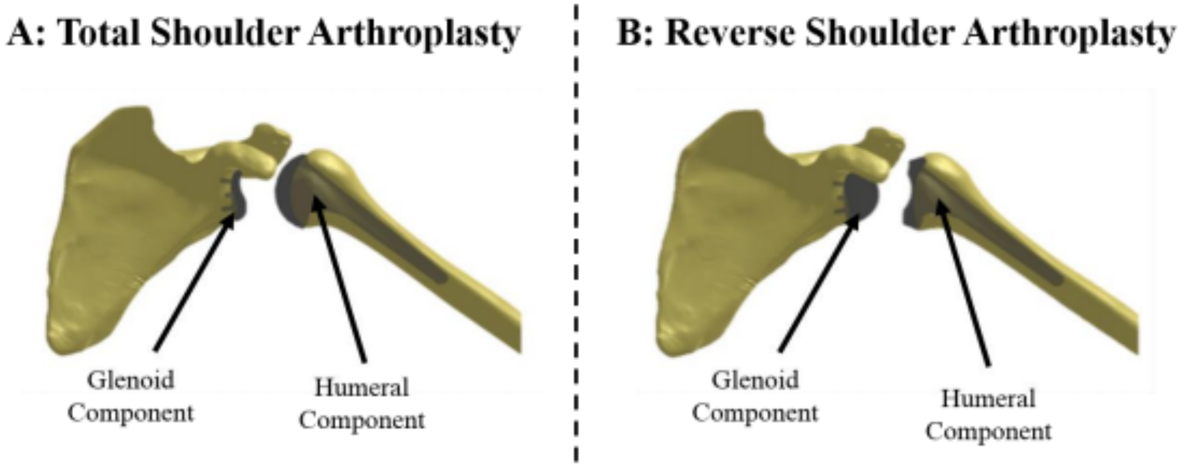

Figure 1-8: Anatomic and Reverse Total Shoulder Arthroplasty

Image depicts a rendition of a (A) Total Shoulder Arthroplasty and (B) Reverse Total Shoulder Arthroplasty

The first shoulder arthroplasty can be traced back to 19th century France from the hands of Dr. Jules Emile Péan with the insertion of rubber and metal into a tuberculous affected shoulder (Lugli, 1978). The patients reported success of range of motion improvement was disappointingly short lived, with the return of infection necessitating implant removal (Flatow & Harrison, 2011). The modern founding father of shoulder arthroplasty is attributed to Dr. Charles Neer, an American surgeon (Brand & Bigliani, 2011). His work began with the use of a hemiarthroplasty in the 1950s, adding a glenoid component in 1972 to create the index case of the modern shoulder arthroplasty (P. Boileau et al., 2006; Charles S Neer, 1974).

The early desires to recreate the glenohumeral anatomy was limited by the humeral side, with an inability to truly recreate anatomic head size and positioning. These both factored into error in mimicking the center of rotation, which carried over into wear and functionality issues (P. Boileau et al., 2006). Adaptations and progressive 'generations' of implants were made to try and accommodate for these issues. This included the creation of modular heads in an effort to address the humeral heads posterior medial positioning, comparatively to the humeral canal. Positioning is important for the integrity of the musculature (Nyffeler et al., 2004) as well as component interface. Humeral head to glenoid mismatching can lead to eccentric loading which can lead to loosening (Favre et al., 2008; Nyffeler et al., 2004).

A monumental change in shoulder arthroplasty followed shortly after. This was the introduction of Grammont's reverse total shoulder arthroplasty in 1985. Prior to, a short lineage of constrained prosthesis, standard ball and socket, reverse ball and socket, and other designs were trialed through the 1970s with minimal success (Baulot et al., 2011; Pascal Boileau et al., 2005). The success in Grammont's reverse design was in the two significant changes implemented- fixing the medialized center of rotation and distalising the humerus. This reduced the moment at the implant-bone interface, and further recruited and tensioned the deltoid as it is the dominant muscle for action (Sheth & Saltzman, 2019).

This great innovation of the Grammont reverse total shoulder was by no means the end to the anatomic design. This continues to be utilized extensively (Schairer et al., 2015). Grammont's original design was born out of his desire to improve outcomes in rotator cuff deficient shoulders, as these were noted to have poorer outcomes with the anatomic design (Flatow & Harrison, 2011). While much innovation has continued to be developed for these designs, of most relevance to this thesis is the humeral cut.

Anatomic total shoulder arthroplasties are designed to recreate normal shoulder anatomy. This very much applies to the humeral aspect of the joint replacement. The osteotomy of the humeral head is done at the level of the anatomic neck (Keener et al., 2017). The goal is recreation of the articular surface, and with it the positioning and tensioning of the anatomic joint that preceded replacement (Iannotti et al., 2005; Michael L. Pearl, 2005).

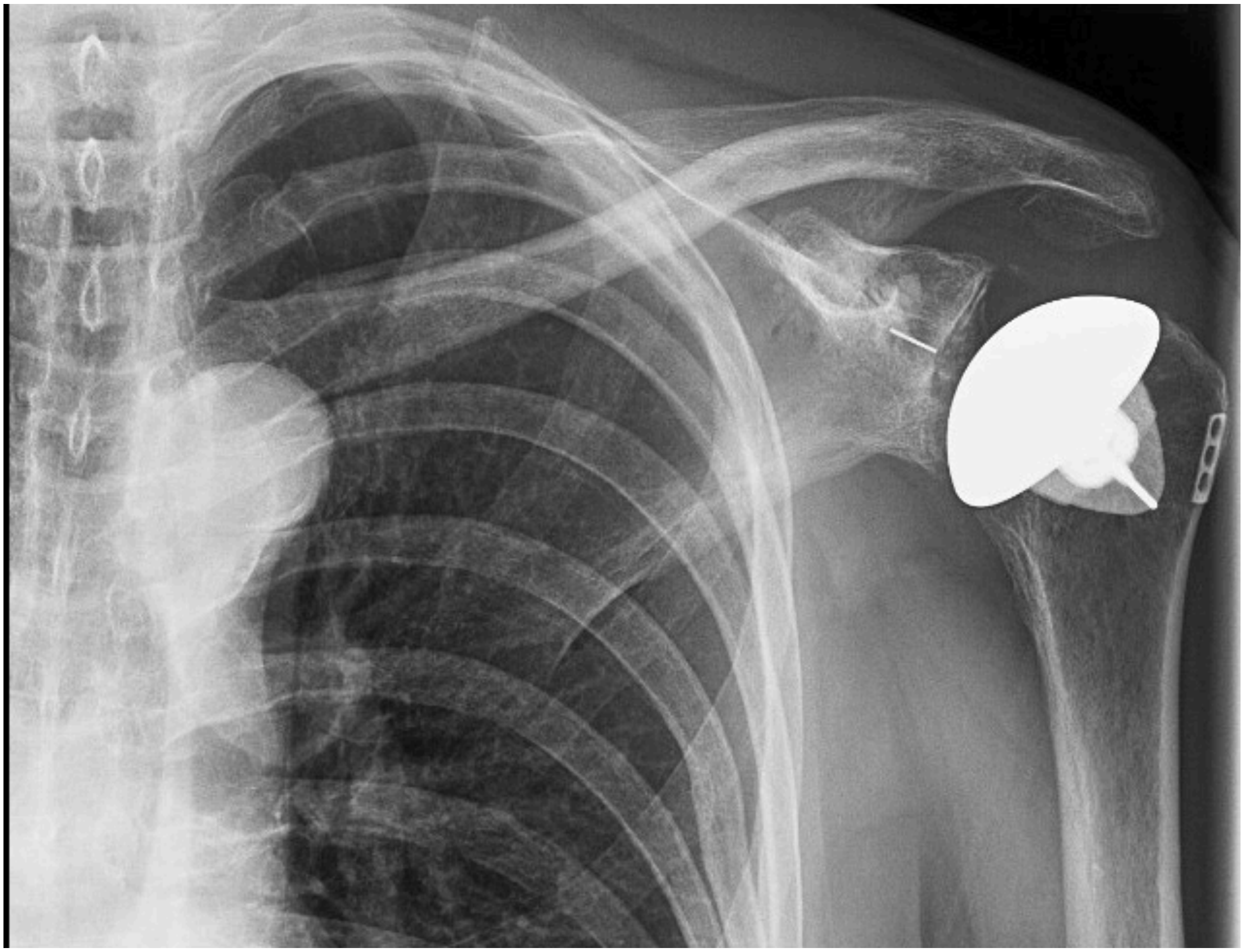

Figure 1-9: Anatomic Shoulder Arthroplasty

Anteroposterior (AP) radiograph of an anatomic total shoulder arthroplasty of the left shoulder. A stemless humeral component is shown.

Reverse total shoulder arthroplasty does not aim to recreate the anatomic joint. It reverses it, placing a concave surface on the humerus and a hemisphere on the glenoid. Although an anatomic joint is not being created, the humeral cut may still be aimed as an anatomic resection of the humeral head (Gerber, Pennington, et al., 2009). The original design by Grammont was a cut at 155 degrees of neck shaft angle. This was done to lengthen and therefore optimise the deltoid moment arm (Pascal Boileau et al., 2005; Sheth & Saltzman, 2019). The average anatomic neck shaft angle is 135, meaning the reverse was cut at a more steep angle (Keener et al., 2017). While some have transitioned back to a more anatomic 135 angle, some still employ the traditional 155 degree cut (Werthel et al., 2019).

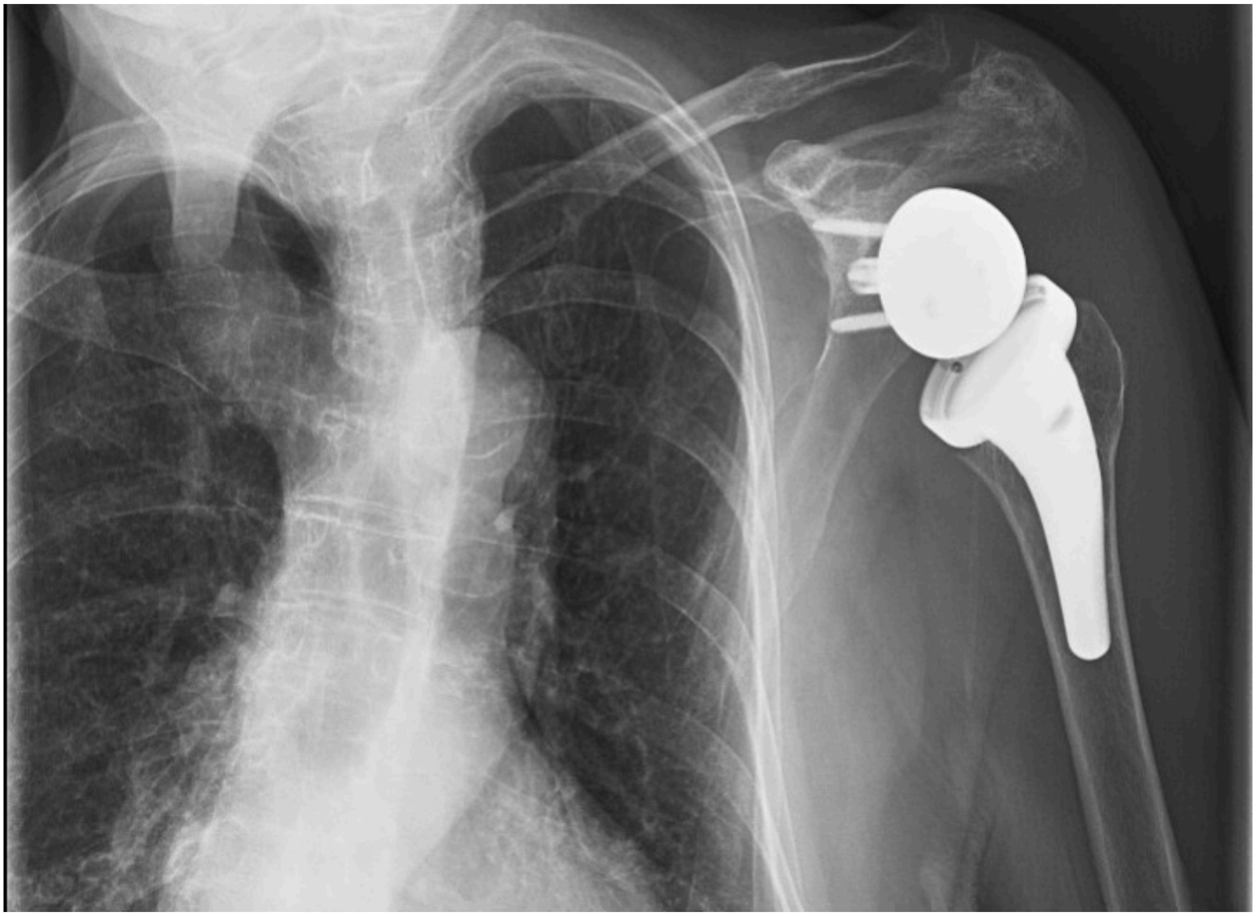

Figure 1-10: Reverse Total Shoulder Arthroplasty

Anteroposterior (AP) radiograph of a reverse total shoulder arthroplasty of the left shoulder.

1.3.1.1 Humeral Head Osteotomies

In shoulder arthroplasty, the humerus is prepared with a cut to remove its anatomic head or articular surface. The goal of the humeral head osteotomy in anatomic shoulder arthroplasty is to create a cut through the anatomic neck (Keener et al., 2017; Lädermann et al., 2015; Walch & Boileau, 1999). The vast variability in patients anatomy in the region make this patient specific anatomical cut optimal (Walch & Boileau, 1999). With variable anatomy, degenerative changes and osteophytes, this cut can be difficult to achieve. The same difficulties can be encountered in the humeral head osteotomy for reverse total shoulder arthroplasty. For both, neck shaft angle (inclination), version and cut height are all impacted by where the cut starts and finishes (Harrold et al., 2014; Suter et al., 2017).

1.3.1.2 Neck Shaft Angle

As visualised in the coronal plane, the neck shaft angle is a measurement of the long axis of the humerus and the orientation of the articular surface of the humeral head. There is unsurprisingly variability in this angle. Keener et al placing the mean from 135 – 140, in keeping with what was previously mentioned. The range encompasses angles from 123 degrees upwards to 150 degrees from various cadaveric studies (Goldberg et al., 2020; Keener et al., 2017; M. L. Pearl & Volk, 1996; Michael L. Pearl, 2005; Robertson et al., 2000).

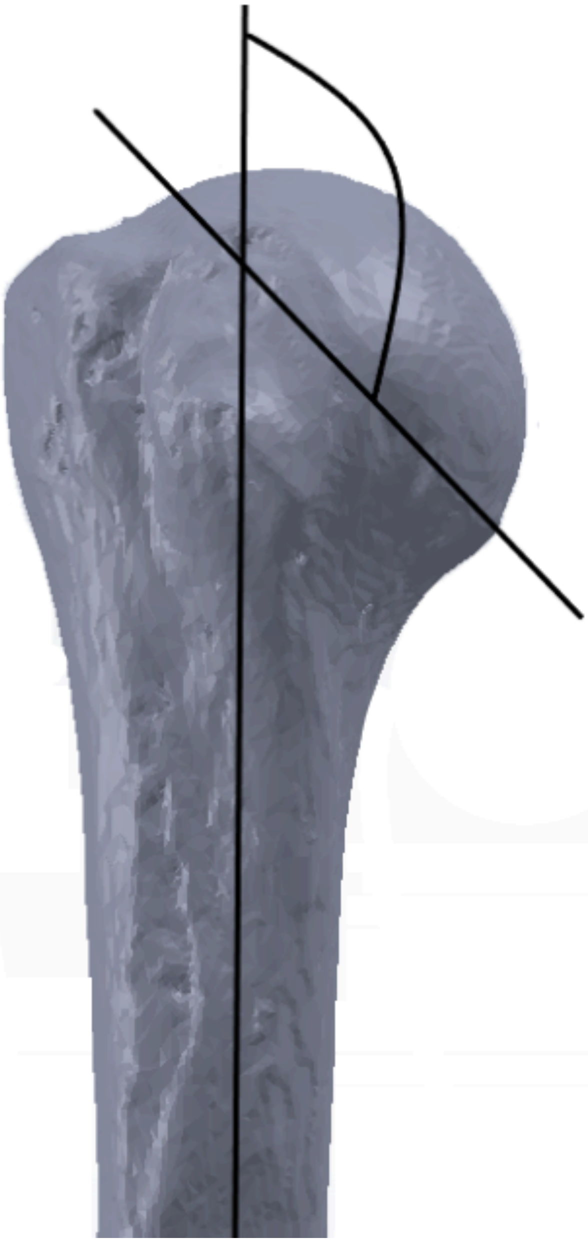

Figure 1-11: Neck Shaft Angle

Illustration of coronal view of humerus. Neck shaft angle is measured from the long axis and the osteotomy plane as shown.

Desired neck shaft angle or inclination for the anatomic total shoulder is patient specific (Iannotti et al., 2005; Michael L. Pearl, 2005; Walch & Boileau, 1999). Anatomic total shoulder humeral prosthesis can be both fixed and variable angle, with the angle being the neck shaft measurement. Although exceptions exists, with fixed angled guide for fixed angle prosthesis, patient specific cuts with variable prosthesis to match the patient is recommended (Jeong et al., 2009).

Range of motion is also affected by a nonanatomic humeral head reconstruction. Increase in diameter, superior or inferiorly positioned head or an oversized head can effect range of motion, cause impingement and alter muscle tensioning (Favre et al., 2008; Franta et al., 2007; Harryman et al., 1995; Nyffeler et al., 2004; Terrier et al., 2010). Alteration in the humeral anatomy has shown to eccentrically load the glenoid and may be a causative factor in a rocking horse type phenomena leading to loosening and early failure (Büchler & Farron, 2004). Even with current measures, such as osteotomy guides, Lädermann et al. showed over forty percent of stems were placed in greater of five degrees of varus or valgus malalignment compared to their desired angle (Lädermann et al., 2020). This can partly be reflective of the cut, but also implantation of the humerus. The latter indicating even more the need to minimising error in the initial osteotomy.

The reverse total shoulder, as its design has progressed and changed, has not surprisingly encountered controversy with the neck shaft angle (Rugg et al., 2019; Sheth & Saltzman, 2019). It was originally designed at a non-anatomic angle of 155 degrees (Pascal Boileau et al., 2005; Gerber, Pennington, et al., 2009). Much research has been done on the influence of this angle. It affects stability, range of motion, contact stress and scapular notching in reverse total shoulder arthroplasty whether at the original 155 angle design, a more anatomic 135 degrees or in between (Ferle et al., 2019; Gobezie et al., 2019; Gutiérrez et al., 2008; Langohr et al., 2016; Werner et al., 2017). Differences in technique and instrumentation still exist with ranges of 127.5 to 155 degrees present commercially (Werthel et al., 2019). Although these exist, whether an anatomic cut or a set angle cut is designed, the same still holds true - precision of this cut is desired.

1.3.1.3 Humeral Head Version

Humeral head version may be the most variable of the parameters of shoulder replacement. It has been long established that there is significant variability in the version or retrotorsion of the humerus. Cadaveric-based work by Boileau and Walch found variability of -6.7 to 47.5 degrees of retroversion within sixty five humeri. (P. Boileau & Walch, 1997) Side to side difference has even been exhibited in individuals (Kronberg et al., 1990). Current literature would quote the angle at 18-25 degrees, with patients outside that window (Keener et al., 2017). The variability of this angle seems to be found both in non-arthritic and arthritic populations. Recent work showing a potential correlation of version to glenoid morphology in osteoarthritic shoulders may provide further patient specific correction (Raniga et al., 2019). Again, as with the previous cut parameters, the near proximity of the soft tissues of the shoulder can mean a misguided cut with too much version can impact the integrity of the posterior cuff. This violation of the posterior cuff theoretically causes detriment to range of motion (Harrold & Wigderowitz, 2012).

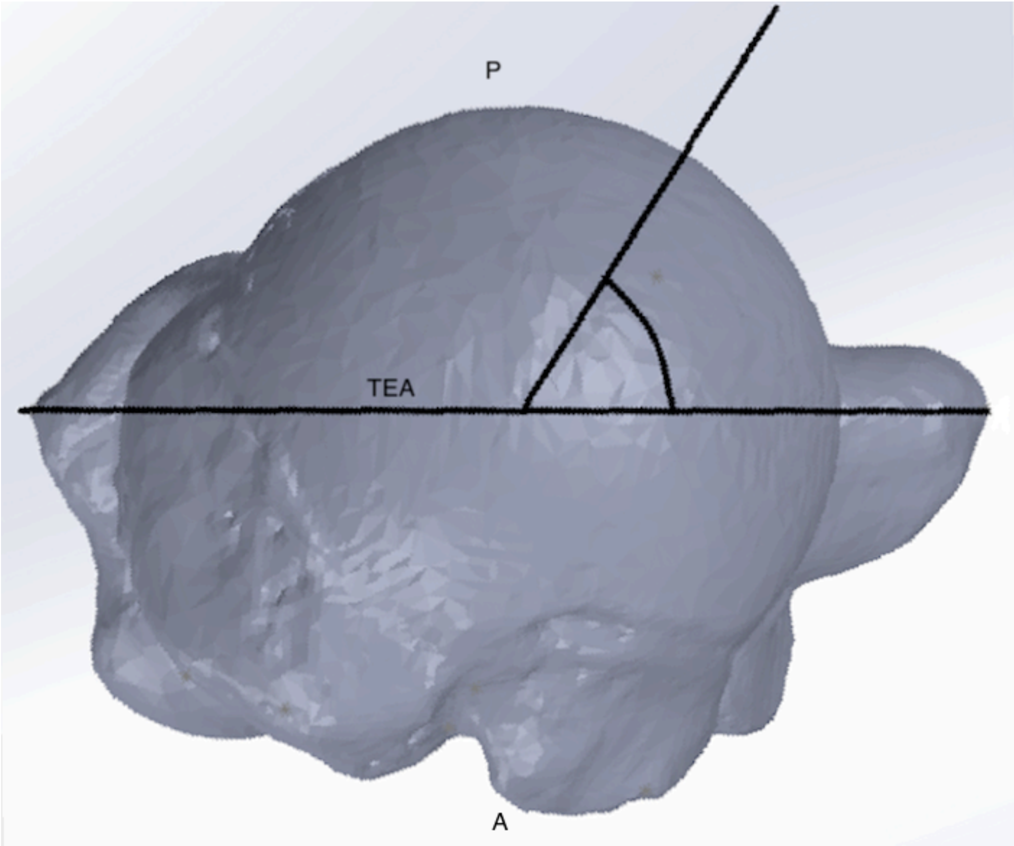

Figure 1-12: Humeral Head Version

Axial plane view of humerus. The transepicondylar axis is labelled (TEA). The angle shown between the transepicondylar axis and humeral head orientation is version. Bottom of image is anterior (A), and top is posterior (P).

Version of the cut is also a factor in the outcome of the shoulder replacement. Extensive literature covers the versions of the glenoid, but less with regards to the humerus. Overtly increasing the retroversion may violate the posterior cuff muscles as they exit the osteotomy plane (Suter et al., 2017). The proper balance of soft tissue with a patient specific version cut is also argued as better for outcomes (P. Boileau et al., 2008; P. Boileau & Walch, 1997; Michael L. Pearl & Volk, 1995). For functional outcomes, this balancing may be more important in an anatomic shoulder arthroplasty, which is more reliant on the rotator cuff muscles (Walch & Boileau, 1999). The soft tissue however is also a major contributor to stability in both types of shoulder arthroplasty (Gerber, Costouros, et al., 2009; Kany et al., 2017). Improvement of the soft tissue stability may be manipulated by altering the version of the humeral component (Favre et al., 2010).

In conjunction with stability comes range of motion, another major outcome in shoulder arthroplasty. Computer modelling has shown changes in retroversion can change muscle length, and cause mismatch of anterior and posterior structures (Roche et al., 2013). Changes and alterations of humeral head version have been shown to affect range of motion in shoulder arthroplasty (Berhouet et al., 2013; Kontaxis et al., 2017; Stephenson et al., 2011).

However, others have not shown the correlation of version and muscle activation forces (Gulotta et al., 2012). It has been theorized that the humeral version may not change the gross overall motion arc, but the field in which this arc occurs (Ackland et al., 2015).

Very recently, 2 year outcome data showed matching patient specific retroversion leads to improved range of motion and other clinical outcomes (Oh et al., 2019). Exact version, and ultimately affect, may still be debated in the literature. It is evident, however, it plays a role in shoulder arthroplasty outcomes, and will likely continue to be studied moving forward.

1.3.1.4 Cut Height

Small margins of error in implant positioning are accepted in the shoulder. Overstuffing of the joint is established as a risk factor for early failure. Overstuffing can occur in both an adequate neck cut with varus malalignment or a high head cut which can alter the center of rotation

(Iannotti et al., 2005). Distancing from the anatomic center of rotation has been linked to problems with impingement and range of motion (Iannotti et al., 2005; Williams et al., 2001).

Figure 1-13: Cut Height

Image depicts multiple humeral head cut heights. Line B represents an anatomic osteotomy. Line A represents a high cut, and Line C represents a low cut.

1.4 Navigation

Intraoperative navigation is within the umbrella of computer assisted surgery. It melds preoperative imaging with technology during the surgical case with the inherent goal of the improvement of outcomes. This can further be defined as either passive or active navigation.

Active navigation provides physical guidance to the actions of the surgeon. An example of this would include preprinted surgical guides, which limit the actions of the surgeon, providing active guidance for screw fixation, for example. The contrast of passive navigation is there is no constraint on the surgeon (Qureshi et al., 2014). It is based on intraoperative imaging that is based on the patient anatomy as well as imaging acquired preoperatively. Intraoperative registration of predetermined anatomical landmarks with optical trackers creates a relationship between the operative field and the preexisting imaging. With this link, visual navigation can be utilized by the surgeon. Equipment with optical trackers can be visualized in relationship to the preexisting imaging to provide the surgeon with a guide for cuts, angles or positioning of components. Navigation is used in a wide variety of surgical disciplines. Its first use can be traced back to the early 20th century where the use of skull frames and coordinate systems were trailed for intracranial lesion targeting (Karkenny et al., 2019). It has since made advancements to where it stands today. Using various imaging modalities such as ultrasound, magnetic resonance imaging and computed tomography it has been developed and used, in cardiac surgery, neurosurgery, urology and orthopaedic surgery (Karkenny et al., 2019; Li et al., 2011; Peoples et al., 2019; Rassweiler et al., 2014).

1.4.1 Navigation in Orthopaedics

Orthopaedics and its many subspecialties have varying degrees of incorporation of navigation in day-to-day work. Most predominantly has been the field of spine surgery and lower extremity arthroplasty. Pedicle screws provide the bone-implant interface in spinal surgery stabilization. Navigated screws showed improved positioning with decreased cut out of bone compared to non-navigated techniques. (Luther et al., 2015; Verma et al., 2016; Zhang et al., 2017) The effect of this on complication rates and clinical significance is not yet proven in the short term (Wagner et al., 2018). The utilization in the knee dates back to the late 1990s. The interest and implementation of navigation was to improve cuts and component positioning in total knee arthroplasty. The rationale is that malalignment of the femoral and tibial components is associated with limited range of motion and earlier failure rates. (Berend et al., 2004; Delp et al., 1998; Ritter et al., 1994). Studies have shown significant improvement with navigation as evident by the work of Anderson et al and Bäthis et al, however the translation of this to survivorship or improved outcomes has yet to be clearly exhibited (Anderson et al., 2005; Bäthis et al., 2004; Jones & Jerabek, 2018). Navigation of total hip arthroplasty shows similarities to its use in total knee arthroplasty. Although navigation can provide improved cup positioning, the clinical significance of this is yet to be fully understood (Hohmann et al., 2011; Lass et al., 2014; Wasterlain et al., 2017).

1.4.2 Navigation in Shoulder Arthroplasty

Navigation within the shoulder has been utilized before, more often with regards to the glenoid as opposed to the humerus. Early adoption of computer assisted surgery in the shoulder was based on hemiarthroplasty for fractures. Bicknell et al simulated proximal humerus fractures, and utilized navigated and non-navigated hemiarthroplasty for repair (Bicknell et al., 2007). They showed trends towards significantly more accurate recreation of the proximal humeral anatomy. The optical trackers used however, were placed in the humeral shaft requiring further incisions outside the operative field (Bicknell et al., 2007). Further progression has fortunately been made which tracker positioning, moving it within the standard deltopectoral approach operative field for intraoperative navigation of the humerus (Edwards et al., 2008). The navigation of the humeral head was based off the intraoperative points taken representing the medial and lateral epicondyles and six points representing the circumference of the humeral head. The actual cuts however were not navigated intraoperatively, but rather by the surgeon to recreate pre-operative templated cuts or desired cuts. A navigated plate was placed on the humeral head osteotomy plane which allowed real time feedback on the neck shaft angle and the retroversion of the cut. This provided room for correction. To our knowledge, utilization of real time humeral navigation has yet to be discussed in the literature.

Included in Edwards et al. work was the use of a real time navigation glenoid reamer, which provided live feedback of neck shaft angle and version of the glenoid reaming (Edwards et al., 2008). Multiple studies on glenoid navigation have been carried out. The early literature showed improved version but no significant neck shaft angle changes by Nguyen et al, with later studies finding improvements in both version and neck shaft angle with navigated glenoid implantation (Nguyen et al., 2009; Stübig et al., 2013; Verborgt et al., 2011, 2014). This, albeit, is with evidence of improvement in positioning, but with the downside of significant increase in operative time (Kircher et al., 2009). An argument lies in the unknown clinical significance of these improvements (Sadoghi et al., 2015). This has not been further discussed in the literature.

1.5 Patient Specific Instrumentation

Again, as with navigation, patient specific guides have been used in lower extremity arthroplasty and spinal surgery more than other orthopaedic realms. Specifically, in spinal surgery, it is used to created patient specific instrumentation for the insertion of pedicle screws. The relatively small bone stock of pedicles provides little room for error in their insertion. Errors can mean violation of the neighboring anatomic structures, which include the spinal cord. Traditionally the screws were inserted with the use of fluoroscopy, or freehanded with cortical ball tip guidewire checks for cortical perforation. Merc et al exhibited a significant decrease in pedicle screws with cortical perforation for the patient guided insertion compared to free hand insertion (Merc et al., 2014). Follow-up work confirmed the lower rate of cortical perforation, but had no clinical significance on disability scoring or patient reported pain (Merc et al., 2017). The focus on total knee arthroplasty indicated the alignment and outcomes do not show any difference in patient specific instrumentation contrasted to the standard of care (Kosse et al., 2018; Lachiewicz & Henderson, 2013).

1.5.1 Patient Specific Instrumentation in Shoulder Arthroplasty

There does exist a growing amount of literature on the patient specific guides in shoulder arthroplasty. A relatively new introduction in the field, the focus has been glenoid based. This is likely because this half of the procedure has smaller bone stock, often more deformed anatomy and argued the culprit in revision necessity (Villatte et al., 2018). By utilizing patient three-dimensional imaging and industry software, a surgeon can create a customized guide for glenoid component positioning. These most commonly consist of a 3D printed central drill guide, with peripheral limbs to match the deformed glenoid anatomy. Further improvement has added a superior drill hole guide in addition to the central hole, to control for rotation of the final glenoid component (Dallalana et al., 2016; Hendel et al., 2012; Throckmorton et al., 2015). The use of these guides progressed from showing improvement in cadaveric models by Throckmorton et al and Walch et al. in surgeons of varying degrees of experience to in vivo studies. Hendel et al showed significant improvement in patient specific guide use in neck shaft angle as well as medial and lateral offset comparative to the non-guided group in a forty-four patient randomized trial. They also showed significant decrease in the malpositioning of the definitive glenoid component (Hendel et al., 2012; Throckmorton et al., 2015; Walch et al., 2015).

1.6 Thesis Rationale

There does exist a growing amount of literature on the patient specific guides in shoulder arthroplasty. A relatively new introduction in the field, the focus has been glenoid based. This is likely because this half of the procedure has smaller bone stock, often more deformed anatomy and argued the culprit in revision necessity (Villatte et al., 2018). By utilizing patient three-dimensional imaging and industry software, a surgeon can create a customized guides for glenoid component positioning. These most commonly consist of a 3D printed central drill guide, with peripheral limbs to match the deformed glenoid anatomy. Further improvement has added a superior drill hole guide in addition to the central hole, to control for rotation of the final glenoid component (Dallalana et al., 2016; Hendel et al., 2012; Throckmorton et al., 2015). The use of these guides progressed from showing improvement in cadaveric models by Throckmorton et al and Walch et al. in surgeons of varying degrees of experience to in vivo studies. Hendel et al showed significant improvement in patient specific guide use in neck shaft angle as well as medial and lateral offset comparative to the non-guided group in a forty-four patient randomized trial. They also showed significant decrease in the malpositioning of the definitive glenoid component (Hendel et al., 2012; Throckmorton et al., 2015; Walch et al., 2015).

Some interesting work has been performed for guides used for corrective osteotomies for malunions of the humerus. They created pre-osteotomy pin guides to control for rotation of the proximal and distal segments post cut (Vlachopoulos, Lüthi, et al., 2018). Notably however, distinct guides for humeral head osteotomies for the purpose of shoulder arthroplasty have not been published. This, according to our knowledge, represents a new area of research.

1.7 Thesis Objectives

The objectives of this thesis were to evaluate the importance of humeral component positioning in shoulder arthroplasty, develop navigation of the proximal humerus and evaluate and compare the different methods of executing the humeral head osteotomy.

The primary objectives of this thesis are:

1. To review the anatomy of the proximal humerus and develop a registration technique applicable for intraoperative use. (Chapter 2).
2. To evaluate the accuracy and repeatability of proximal humerus registration techniques and validate these techniques (Chapter 2).
3. To evaluate the accuracy of different methods of humeral head osteotomies (Chapter 3).
4. To evaluate the accuracy of guide placement, and accuracy of guide based humeral head osteotomies (Chapter 3).

1.8 Thesis Hypothesis

The hypotheses of this thesis based on the objectives are:

1. We will be able to register anatomic landmark of the humerus with 2 millimetres of error over multiple iterations (Chapter 2).

2. We will be able to develop a registration technique for the proximal humerus with target registration error within 2 millimetres (Chapter 2).

3. Navigation and patient specific guides will produce more accurate humeral head osteotomies measured by degrees of version and neck shaft angle relative to fixed angle guide and free hand osteotomy methods (Chapter 3).

4. There will be no significant difference in cut height of humeral head osteotomies across testing groups (Chapter 3).

5. There will be no significant difference in guide placement and osteotomy planes with the use of cutting guides, both fixed angle and patient specific (Chapter 3).

1.9 Thesis Overview

The focus of this thesis is the anatomic neck cut for shoulder arthroplasty. This chapter begins with a review of the humeral anatomy, and importance of component positioning. It continues with evaluating navigation and patient specific instrumentation in orthopaedics and more specifically in shoulder arthroplasty. Chapter 2 revolves around previous means of proximal humeral anatomy mapping, and the development of a navigation technique for the proximal humerus. This navigation technique is utilized in Chapter 3, comparing it to other cutting techniques including patient specific guides. Chapter 4 concludes the thesis, with findings, summary and future areas of research in the domain.

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Chapter 2

2 Humeral Navigation

Shoulder arthroplasty involves the reconstruction of the glenohumeral joint. Both the glenoid and proximal humerus undergo implantation of components in shoulder arthroplasty. Proper positioning of these components is critical to the success and longevity of the shoulder arthroplasty. Surgical navigation has been studied and used for the glenoid, but it has not yet been fully studied and applied for the proximal humerus. This chapter focuses on the anatomy of the humerus, and development of a navigation technique for the proximal humerus based on this anatomy.

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2.1 Introduction

Shoulder arthroplasty, both anatomic and reverse, are widely used surgeries for management of shoulder pathology. The indications can include arthroplasty for fracture, necrosis, rheumatoid arthritis, osteoarthritis, and rotator cuff disease (Ackland et al., 2015; Sanchez-Sotelo, 2011; Sperling et al., 2007; Van Den Bekerom et al., 2013). There is long term success shown in shoulder arthroplasty for both the anatomic and the reverse design in function and longevity (Ernstbrunner et al., 2019; Flurin et al., 2013; Norris & Iannotti, 2002; Simovitch et al., 2017; Torchia et al., 1995; Wright et al., 2020). Rates of shoulder arthroplasties performed continue to rise worldwide and are projected to only increase even further (Day et al., 2010; Lübbeke et al., 2017).

Humeral head osteotomies are carried out in hemiarthroplasty, anatomic, and reverse total shoulder arthroplasty. The desired humeral osteotomy is to be at the anatomic neck for both anatomic and in some cases reverse total shoulder arthroplasty (Keener et al., 2017; Lädermann et al., 2015; Walch & Boileau, 1999; Wall et al., 2007). The proximal humerus has a unique and complex bony structure, which can be further complicated by distorted anatomy in pathologic processes, such as osteoarthritis, rotator cuff arthropathy, necrosis, or fracture. The osteotomy of the humeral head also plays a large role in component sizing and positioning on the humeral side

(Chalmers et al., 2018; Michael L. Pearl, 2005; Suter et al., 2017). Component positioning has a large role in outcomes of shoulder arthroplasty, including altered range of motion, impingement, and early failure rates (Blevins et al., 1998; Harryman et al., 1995; Iannotti et al., 2005; Jeon et al., 2016; Nyffeler et al., 2004; Williams et al., 2001).

Personalized medicine has been utilized in surgical specialties, including orthopaedics, both in the form of intraoperative navigation as well as patient specific guides. These methods have been used with successful outcomes and significant improvement in implant positioning across multiple subspecialties. Notably, these have been used more extensively in lower extremity arthroplasty and spinal surgery (Anderson et al., 2005; Bäthis et al., 2004; Luther et al., 2015; Verma et al., 2016). Glenoid navigation, as well as patient specific guides, for glenoid reaming have been developed and used for shoulder arthroplasty. Navigation of guidewire placement has shown improvement in positioning of the glenoid baseplate (Kircher et al., 2009; Stübig et al., 2013). Patient specific guides for the glenoid use pre-operative imaging to create a single-use custom fit guide for positioning. Multiple studies have also shown statistical improvement with the use of these guides, both in cadaveric work, as well as intraoperatively (Gauci et al., 2016; Hendel et al., 2012; Throckmorton et al., 2015; Walch et al., 2015). Navigation has been used for the humerus before. It was utilized with palpation around the humeral head, and a navigated humeral canal rod. This allowed for reference of the angle and version, both of which were measured after a non-navigated cut had been made (Edwards et al., 2008).

To date, there exist limited real time navigation or patient specific instrumentation to guide the humeral head osteotomy for shoulder arthroplasty. This presents an opportunity for potential improvement in a widely utilized and continually growing surgical intervention. The goal of this study is to develop a novel technique for intraoperative navigation. We will apply and evaluate this technique in vitro with the use of our custom humerus models. It is hypothesized that we will be able create a novel workflow based on anatomic landmarks to allow us to estimate humeral head points within 2 millimeters and humeral cut angles within 2 degrees of error, in agreement with other commercially available systems for other joints. These findings could potentially help further advance improvement in shoulder arthroplasty.

2.2 Selection of Models

5 non-osteoarthritic and 5 osteoarthritic shoulder computed tomography (CT) scans were selected at random from our database at the Hand and Upper Limb Centre Bio-Engineering Research Lab (Western University, London, Canada). The control normal database included 112 CT scans (32 Female, 80 Male). The osteoarthritic database included 88 CT scans (35 Female, 53 Male). Scans included the proximal humerus as well as the epicondylar region done in a single session, without collection of the mid portion of the humerus so as to decrease patient radiation exposure. These were all taken under the same protocol at our single institution, St Joseph's Hospital, London, Ontario, Canada, using a Discovery CT750HD scanner (General Electric, Boston, MA, USA). Of the selected models, there were 3 right and 2 left for the osteoarthritic and 4 right and 1 left humeri for the control group.

2.3 Creation of 3D Models

The CT scans were digitized in to 3D models from the Digital Imaging and Communications in Medicine (DICOM) data using Mimics software (Materialise, Leuven, Belgium). Once in Mimics, the scans underwent digitization and masking to determine points of best fit for any gaps in the cortical surfaces. Extra data points within the humeral canal were removed to facilitate later filling with cancellous surrogate. The thickness of the cortical bone was monitored for the specimens to ensure accuracy. Various measurements pre- and post-masking were done to make print compatible models. They were on average four millimeters in cortical thickness, which is in agreement with the range of previous literature on humeral head thickness (Majed et al., 2019; Tingart et al., 2003).

Once the masking of the models within Mimics was completed, the specimen CT DICOM files were uploaded to SolidWorks (Dassault Systèms, Vélizy-Villacoubay, France). The models were evaluated within SolidWorks to ensure adequate transfer of data points, with models representing their original non osteoarthritic and osteoarthritic CT scans (Figure 2-1).

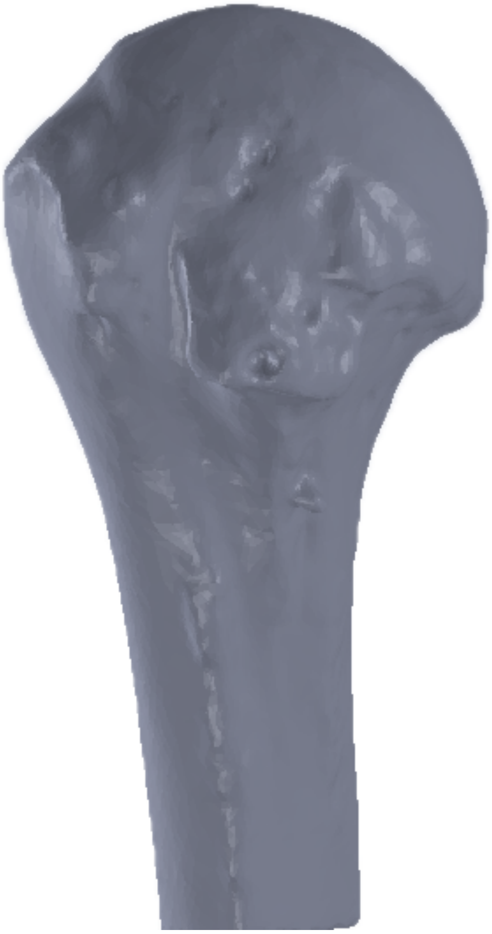


Figure 2-1: SolidWorks Model

Model of Proximal Humerus in SolidWorks after transfer from DICOM data

Within the SolidWorks program, the specimen scans were prepared to allow for the production of the experimental testing models using additive manufacturing. The clinical CT scans taken at our institution were segmental, with the mid-section of the diaphyseal humerus absent to decrease radiation exposure for patients. This necessitated spanning the diaphyseal deletion and controlling for rotation when creating our final models. To account for the diaphyseal deletion within specimens, 3 mm colinear slots on the proximal humerus and distal epicondyle segments were added to the digital model to ensure correct rotation. An additive manufacturing printer

(MakerBot Replicator 5th Generation, NY, USA) was used to print the proximal humerus and distal epicondyle models using polylactic acid as material.

Once the hollow models had been printed, spray foam was used to recreate cancellous bone within the 3D proximal humerus hollow models. To select the type of spray foam that best replicated the qualities of cancellous bone, an experiment was conducted. We tested four types of spray foam, and subjectively concluded that LePage TiteFoam (Henkel Corporation, Mississauga, Canada) had similar characteristics to cancellous bone when clinically cut with an oscillating surgical saw. As such, to create clinically similar bone models, the hollow 3D printed proximal humerus of polylactic acid was filled with this spray foam.

Cold rolled steel rod of 3/8” diameter was acquired and measured and cut to size. The diaphyseal deletion for each specimen between the printed humeral head and epicondyles, was measured and marked accordingly on the steel rods. A straight line was marked on the rods. A drill press was used to created holes in the rod near the proximal and distal ends. The proximal and distal printed pieces were aligned and secured to the steel rods with bolts to ensure proper rotational alignment and length of the specimen (Figure 2-2).

Figure 2-2: 3D Printed Humeral Model

Image shows the 3D polylactic acid printed humerus with cold rolled steel humeral diaphysis

2.4 Selection of Navigation Landmarks

The complex anatomy of the proximal humerus can lead to some difficulty in producing consistent anatomic landmarks for registration. This is only amplified when osteoarthritic changes are involved with the shoulder joint. We desired to take this into account during the selection of our points to be able to establish readily reproducible landmarks which were also readily accessible intraoperatively. We reviewed the literature to determine the best proximal humerus anatomic landmarks to assist with surgical navigation.

The standard working field, or approach, for shoulder arthroplasty is the deltopectoral approach. The anterosuperior approach may be used (Molé et al., 2011) but the deltopectoral is the approach of use at our institution, and again is the more frequently used of the two (Sager & Khazzam, 2018). The approach extends within the deltopectoral groove, at its greatest length from the coracoid extending distally (to the deltoid tuberosity). In this field is exposed the humeral head, the greater and lesser tuberosities, as well as the proximal portion of the bicipital groove (Hoppenfeld et al., 2016; Sager & Khazzam, 2018).

The anatomy of the biceps groove has long been understood to be unique, possessing a curved course (Krahl, 1948). In the findings of Johnson et al, they found a correlation of the relationship of humeral head retroversion and biceps groove retroversion. They did so by identifying the different version of the groove at the surgical and anatomical neck levels. This indicates a role for a tracing of the groove. Incorporating this anatomy, and being able to capture the grooves rotation, can subsequently be a potential marker for humeral head retroversion. (P. Boileau et al., 2008; Johnson et al., 2013)

Statistical shape modelling has also been undertaken in attempts to model the proximal humerus. Statistical shape modelling utilizes homologous landmarks to accurately recreate anatomy. It has been used with wide success and validity in other fields, such as forensics, anthropology and evolutionary biology (Audenaert et al., 2019). Vlachopoulos et al exhibited a trend in improvement in restoration of anatomy with a statistical shape modelling algorithm compared to contralateral humerus templating in paired cadavers (Vlachopoulos, Carrillo, et al., 2018). A study by Poltaretskyi et al looked at the application of this method in osteoarthritic proximal humerus CT scans. They evaluated the performance of statistical shape modelling in terms of accuracy versus other previously used techniques such as the use of fixed guides and the contralateral limb. Their measured outcomes were retroversion, humeral head height, offset, curvature, and neck shaft angle. Their results showed statistical improvement with statistical shape modelling in retroversion and neck shaft angle, comparative to controls. In their modelling, they had a high concentration of landmarks on the greater and lesser tuberosities, humeral head surface and notably the bicipital groove (Poltaretskyi et al., 2017). This supports the biceps groove as being a valuable anatomic landmark in mapping the complex proximal humeral anatomy.

The distal humerus and proximal forearm have been used in various ways in the estimation of humeral torsion (P. Boileau et al., 2008). Included in these estimations are the medial and lateral epicondyle, and their associated epicondylar axis. Given their prior use, and their predictable and distinct anatomy, they were chosen as landmarks. Our final group of landmarks to assist with surgical navigation consisted of the humeral head center, superolateral ridge of the greater tuberosity, the biceps groove at the articular surface and surgical neck, pectoralis major insertion, greater and lesser tuberosities and the medial and lateral epicondyles (Figure 2-3).

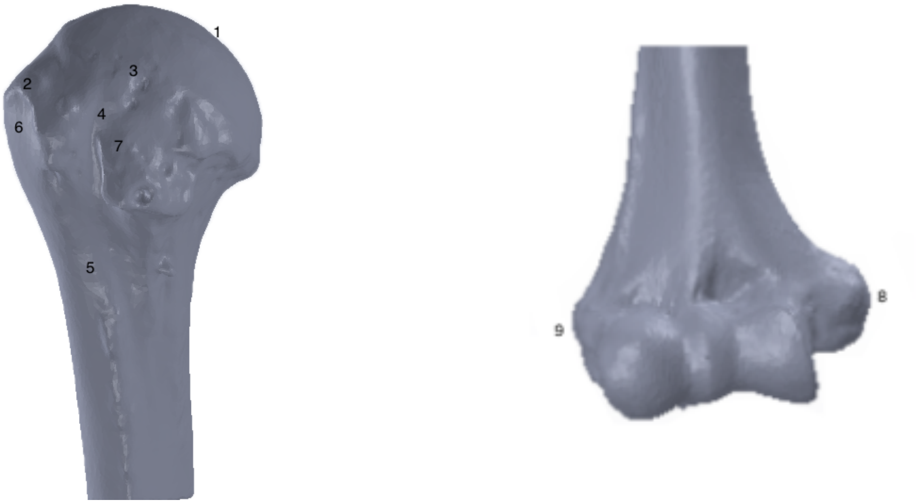


Figure 2-3: Anatomic Landmarks

Images show the nine landmarks selected for development of navigation. The image on the left depicts the proximal landmark 1 – Humeral Head Center, 2 – Superolateral ridge Greater Tuberosity, 3 – Biceps groove at articular surface, 4 – Biceps groove at surgical neck, 5 – Pec Major insertion, 6 – Greater Tuberosity and 7 – Lesser Tuberosity. The image on the right depicts the distal landmarks 8 – Medial Epicondyle and 9 – Lateral Epicondyle.

2.5 Validation of Navigation Landmarks

2.5.1 Data Collection

The nine anatomic points were selected on the models in SolidWorks. This was done with a point selection tool within the program to replicate the utilization of a stylus point in vivo. The nine points were selected on all ten models. Following a five-day period, these were again recollected. This same method was followed one last time for three data collections on all ten models by author JTC, each separated by five days. Three collections were performed to permit statistical analysis.

2.5.2 Outcome Variables

The main outcome variable was registration error, in millimeters, over our three iterations of point selections. We measured the error between selections for each of the nine anatomic locations. With each point selection in SolidWorks, we had raw position data (x,y,z) of the point coordinates, the difference between points was then calculated to represent the resultant error in repeated point selection in mm.

2.5.3 Statistical Analysis

A two-way (point, iteration) repeated measures multivariate (healthy, OA) analysis of variance (RM-MANOVA) with least significant difference were used for statistical analysis (SPSS Version 26.0; SPSS Inc, Chicago, IL, USA). Statistical significance was defined as $p < 0.05$.

2.5.4 Results

The selected point was found to have a significant effect on relative resultant selection error ($p<0.001$). The relative resultant error for the proximal points were typically between 2 to 2.5 mm (Figure 2-1), with the tuberosities having mean errors of 3.1 ± 0.59 and 5.4 ± 1.4 millimeters, respectively. The relative resultant error over iterations was below 2 mm in only the epicondylar landmarks, with mean errors of 1.49 ± 0.66 and 1.73 ± 0.60 mm for the medial and lateral epicondyles, respectively.

The greater tuberosity landmark consistently had significantly higher error than all other points ($p<0.008$) (Figure 2-1), and the lesser tuberosity had significantly higher error than the bicipital groove and both epicondyles ($p<0.01$). There were no other statistically significant differences among the points. The resultant errors of each landmark are plotted to scale on a humerus in Figure 2-4.

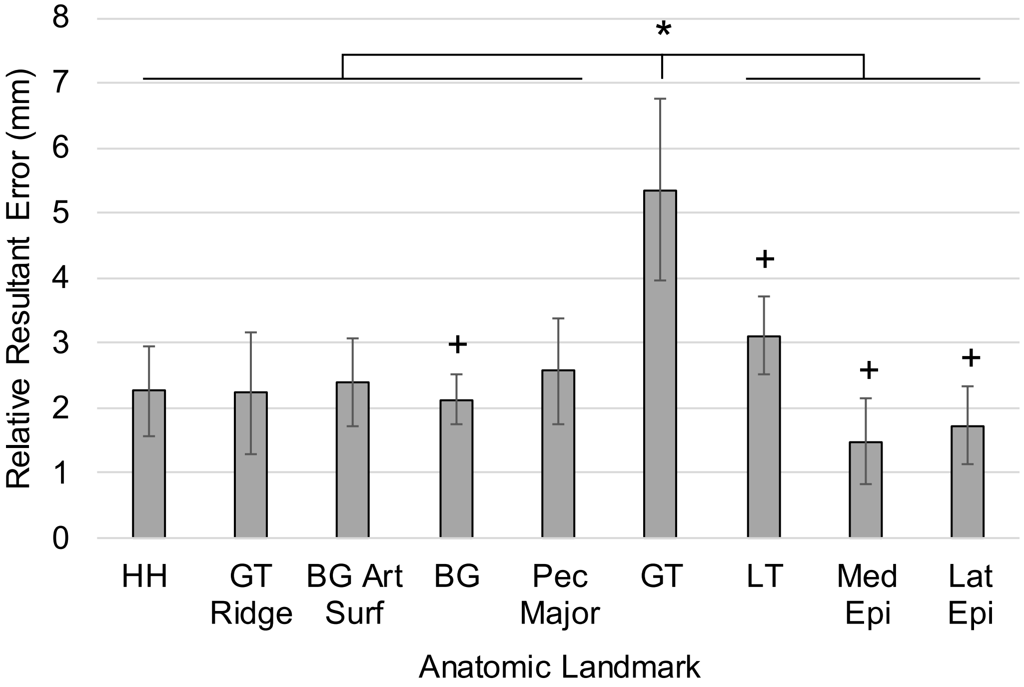


Figure 2-4: Relative Resultant Error for Humeral Landmarks Investigated

Error of point selection over multiple iterations. The greater tuberosity was significantly higher error comparative to all points as shown by '' and the lesser tuberosity had significantly higher error comparative to the biceps groove, medial and lateral epicondyles as shown by '+'*

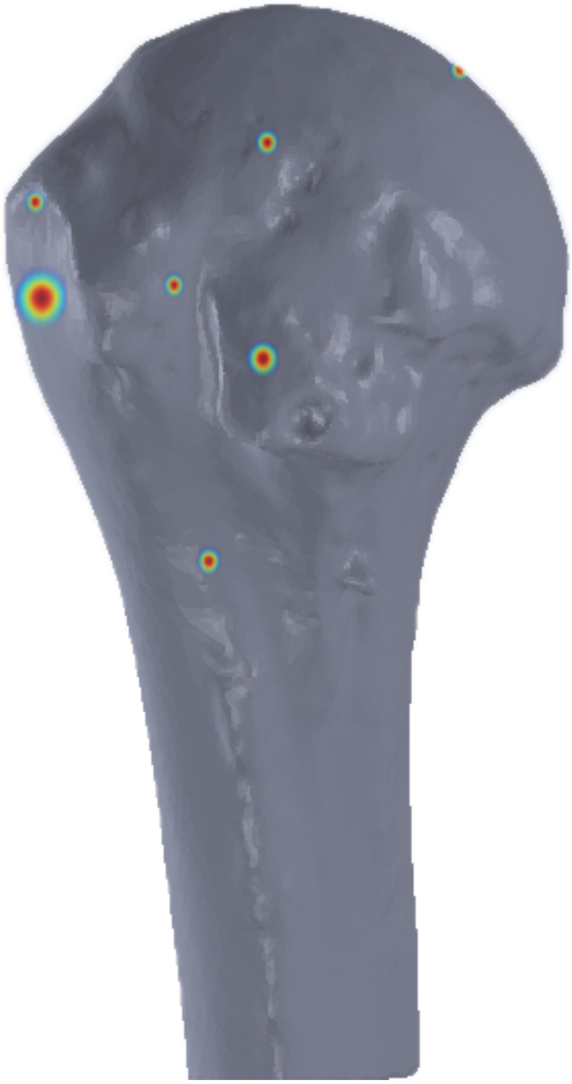


Figure 2-5: Proximal Humeral Landmarks

Image depicts the points of selection in the proximal humerus. Radius of points represents error in each point selection over multiple iterations.

2.5.5 Discussion

The results of this section yield insight into the error associated with the repeated selection of the humeral head landmarks investigated in this study. It was found that there were two landmarks, the greater tuberosity and the lesser tuberosity, with significantly higher error compared to the others, with the remainder of the proximal points having errors in the 2 mm range, and the epicondyles below 2 mm.

It was also found that the lesser and greater tuberosity had higher errors between selection iterations, which indicates that these points are more difficult to select repeatedly. Its postulated that this is due to the larger area of these anatomic landmarks, and their varying surface anatomy. The larger the area the more room for error. Although the humeral head too possess a large area it is suspected the hemispherical nature of it provides more regular reference for point selection.

No significant difference was detected between the healthy and OA groups, which indicates that humeral head disease state may not affect the repeatability of selection of humeral landmarks. This is important since many patients undergoing humeral head reconstruction have some degree of degeneration

2.6 Analysis of Selection points – Creation of Workflow and Index

2.6.1 Methods

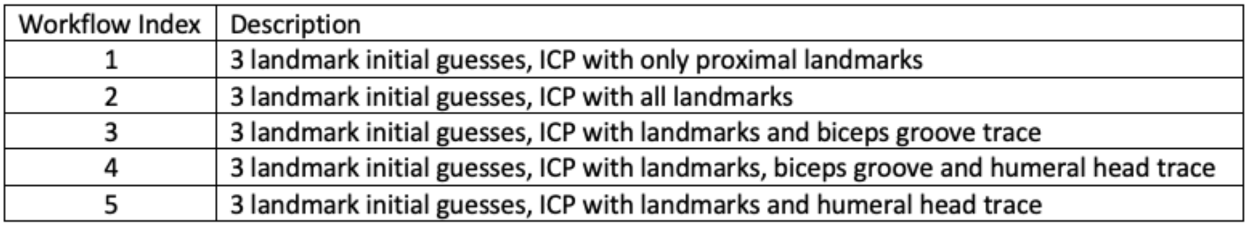
Using our novel 3D printed humeral models, we collected our previously defined nine anatomic landmark points using a stylus connected to an optical tracker equipped with four tracking markers. An infrared camera provided by Intellijoint Surgical Inc. (Waterloo, Ontario, Canada) was mounted and provide live feedback of the collection. Each of the nine points were individually collected, on all ten specimens. Prior to collection the stylus was placed on a proximal reference point. This reference point was in all SolidWorks models and included in the 3D printed models as a raised point. This created a reference point between the SolidWorks files and the 3D printed models from which we could analyze error.

These data points were then input into custom MATLAB code and proprietary registration code provided by Intellijoint (Waterloo, Ontario, Canada) that was used to co-register the in-vitro humerus to the 3D model of the humerus. This process was repeated four times, with continued algorithmic changes to ensure accuracy. Custom written MATLAB code then calculated the resulting registration error using a reference point located at the superior aspect of the humerus which was artificially created such that it was distinctly present in both the SolidWorks 3D models as well as on the physical 3D printed models and could be repeatably selected to minimize and potential error associated with the identification of this point.

2.6.2 Outcome Variable

The two outcomes measured were landmark index and workflow sequence. These were both assessed in terms of the resulting registration error of the reference point.

A workflow sequence represents the process by which the registration was accomplished, and could include a combination of points, a combination of points and a trace, or combination of points and traces. We defined 5 independent workflows to be assessed (Table 2-3). All possible combinations of 3 landmark points were fed in our 5 different workflows. This outcome was measured to see if there was any type of point and tracing combination in the different workflows that would be statistically significantly better than the other.



Workflow Index	Description
1	3 landmark initial guesses, ICP with only proximal landmarks
2	3 landmark initial guesses, ICP with all landmarks
3	3 landmark initial guesses, ICP with landmarks and biceps groove trace
4	3 landmark initial guesses, ICP with landmarks, biceps groove and humeral head trace
5	3 landmark initial guesses, ICP with landmarks and humeral head trace

Table 2-1: List of Workflows

Figure describes the workflows used. ICP is iterative closest point, a method of registration

A landmark index was any combination of 3 of the 9 anatomic points used to perform registration. Given that we had collected all 9 points on each specimen, it was possible to look at any combination of 3 points (for a total of 84 combinations), to evaluate the associated registration error.

2.6.3 Statistics

A repeated measure of analysis of variance (RM-ANOVA) was used for statistical analysis (SPSS Version 26.0; SPSS Inc, Chicago, IL, USA). Evaluation was done by pairwise comparison. Statistical significance was defined as $p < 0.05$. Comparisons were made on the workflow and landmarks, as well as differences in these parameters in healthy versus osteoarthritic models. Ten specimen sample size was selected upon evaluation of similar prior cadaveric studies in the literature (Bicknell et al., 2007; Chan et al., 2017; Levy et al., 2014; Nguyen et al., 2009).

2.6.4 Results

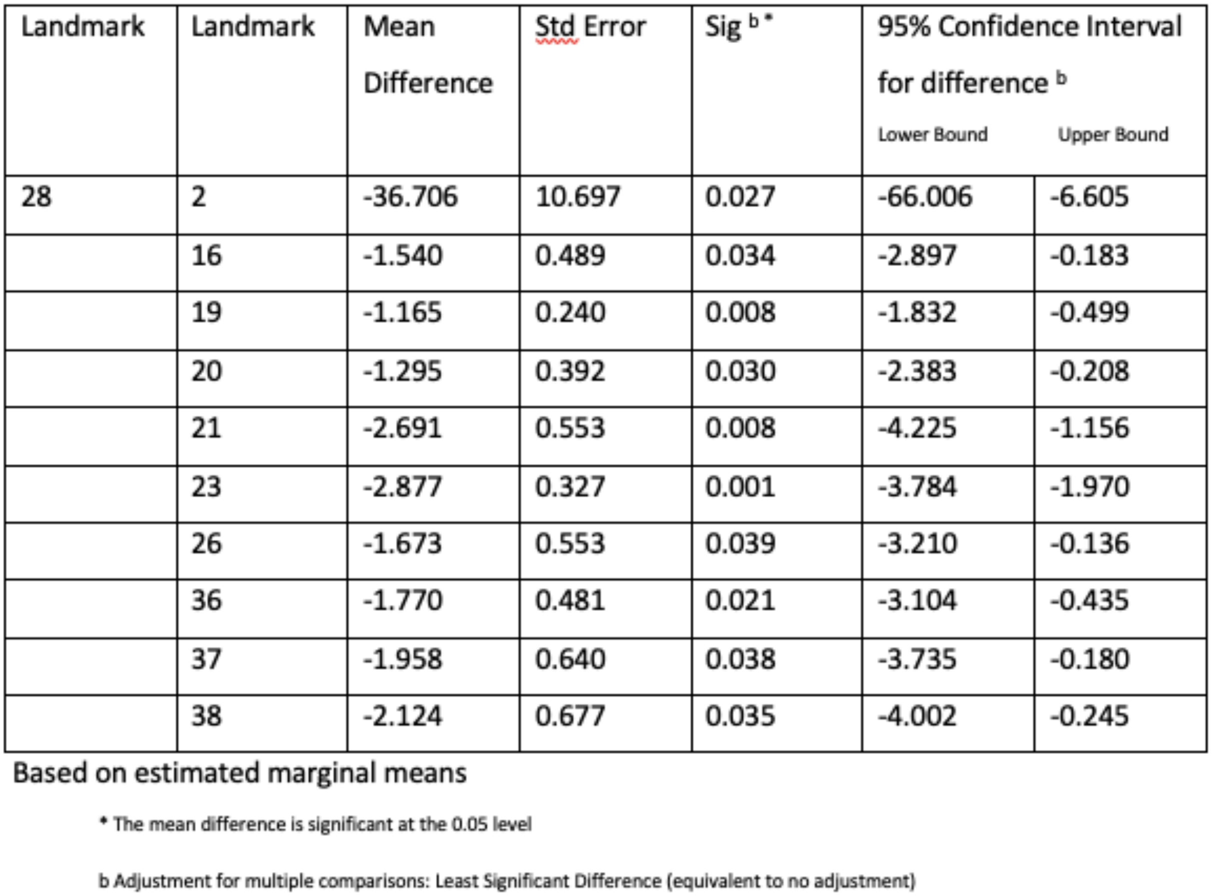
2.6.4.1 Workflow

No workflows were statistically significant from the others on pairwise comparison. A p value of 0.055 was exhibited for Workflow 4, comparative to Workflow 1.

2.6.4.2 Landmarks

No landmark index alone showed statistical significance. Evaluating pairwise comparisons, there were eleven workflow models that exhibited mean errors that has less than a 1 mm difference between each other. The lowest mean difference on comparison was recorded for landmark index 28, which was significantly better than ten other landmark indexes (Table 2-2).

The landmarks listed in Table 2-3 are statistically significant comparative to Landmark index 28. Landmark 28 is Pectoralis Major Insertion, Biceps Groove and Humeral Head Center.



Landmark	Landmark	Mean Difference	Std Error	Sig ^{b*}	95% Confidence Interval for difference ^{b}	
					Lower Bound	Upper Bound
28	2	-36.706	10.697	0.027	-66.006	-6.605
	16	-1.540	0.489	0.034	-2.897	-0.183
	19	-1.165	0.240	0.008	-1.832	-0.499
	20	-1.295	0.392	0.030	-2.383	-0.208
	21	-2.691	0.553	0.008	-4.225	-1.156
	23	-2.877	0.327	0.001	-3.784	-1.970
	26	-1.673	0.553	0.039	-3.210	-0.136
	36	-1.770	0.481	0.021	-3.104	-0.435
	37	-1.958	0.640	0.038	-3.735	-0.180
	38	-2.124	0.677	0.035	-4.002	-0.245

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

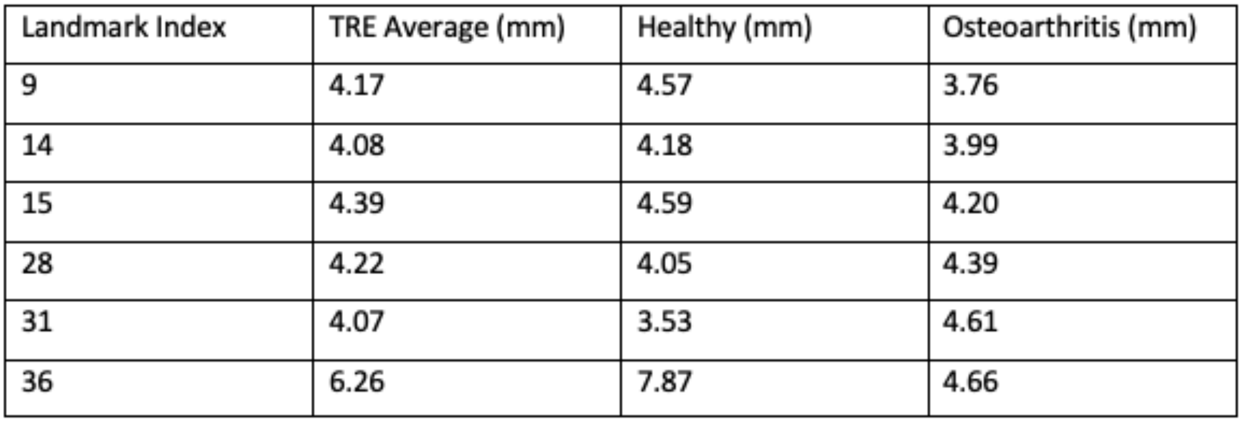
b Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustment)

Table 2-2: Landmark Index 28 and statistically significant other landmarks indexes

In terms of points included in the landmark indices, the lesser tuberosity and superolateral ridge of the greater tuberosity both commonly present in the top five performing landmark indexes.

There were also multiple landmark indexes that were statistically significantly poor performing, of which, it was common for the medial and/or lateral epicondyle to be present, which indicated that the inclusion of these landmarks did not result in optimal registration error.

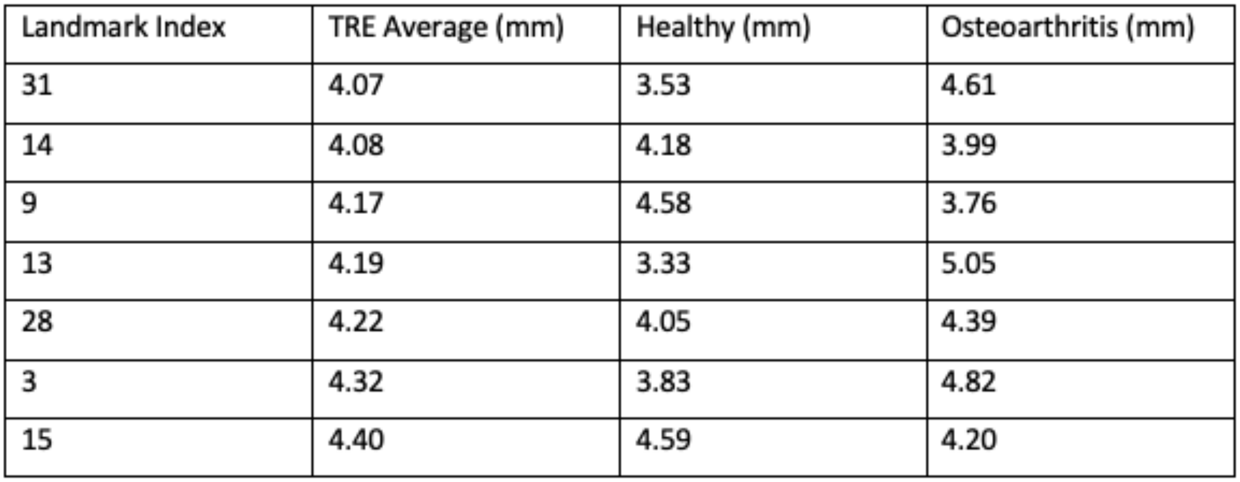
Looking at only the result of workflow #4 since it used both tracings, the utilization of the lesser tuberosity, superolateral ridge of greater tuberosity, and the humeral head landmarks produced a registration error of 4.21 and 4.40 mm within the non-osteoarthritic and osteoarthritic models, respectively, which were among the smallest errors observed. This showed that these landmarks may be advantageous in terms of minimizing registration. The lesser tuberosity, superolateral ridge of greater tuberosity and humeral head is index 15 in Table 2-3 and Table 2-4.



Landmark Index	TRE Average (mm)	Healthy (mm)	Osteoarthritis (mm)
9	4.17	4.57	3.76
14	4.08	4.18	3.99
15	4.39	4.59	4.20
28	4.22	4.05	4.39
31	4.07	3.53	4.61
36	6.26	7.87	4.66

Table 2-3: Target Registration Error (TRE) of Landmark Indexes using Workflow 4

Measurement in millimeters. Ordered by Osteoarthritic Models, smallest error to largest.



Landmark Index	TRE Average (mm)	Healthy (mm)	Osteoarthritis (mm)
31	4.07	3.53	4.61
14	4.08	4.18	3.99
9	4.17	4.58	3.76
13	4.19	3.33	5.05
28	4.22	4.05	4.39
3	4.32	3.83	4.82
15	4.40	4.59	4.20

Table 2-4: Target Registration Error (TRE) of Landmark Indexes using Workflow 4

Measurement in millimeters. Ordered by all models error, smallest to largest.

2.7 Discussion

The desired humeral head osteotomy plane in anatomic and some reverse shoulder arthroplasties is at the anatomic neck. This is reliant to a degree on the appreciation of the native anatomy, which may be distorted in pathological processes (Ansok & Muh, 2018). The purpose of our study was to develop a novel, reproducible landmark registration technique within the operative field for navigated shoulder arthroplasty. Secondly, we aimed to create a novel workflow with landmark registration to allow for real time navigation of the proximal humeral.

Various workflow models were proposed and assessed using all possible combinations of anatomic points, traces, or a combination of the two. There was no significant effect detected for workflow selection in terms of registration error. Workflow #4 approached significance compared to Workflow #1 (p = 0.055) and included the humeral head and the bicipital groove tracings, as well as three anatomic landmarks. Overall, it was observed that as the number of anatomic points increased, the error decreased.

It was also found that there were ten landmark indexes that were statistically significantly worse in terms of registration error.

The selection of the workflow and landmarks is two-fold. The workflow model, although not significant, includes traces which as described above is supported by the literature. The biceps groove has been shown to have a torsional path, related to the humeral head version (Burks, 1998; Johnson et al., 2013). Poltaretskyi et al exhibited a high concentration of points within the biceps groove on statistical shape modelling as well as on the ridge of the greater and lesser tuberosity (Poltaretskyi et al., 2017). Of the best performing landmark indexes was a combination of the lesser tuberosity, superolateral ridge of the greater tuberosity, and the humeral head center. These had some of the smallest target registration errors among the landmark indexes, most notably when used in conjunction with Workflow #4. These three anatomic points were also individually represented in high frequency among the best performing landmark indexes, likely as a result of the combination of the ease of intraoperative availability and reproducibility.

The utilization of the lesser tuberosity, superolateral ridge of the greater tuberosity, and the humeral head, also provides for greater triangulation avoiding the points being near collinear. When points are, or near collinear, it may lead to failure of resolving the trackers position and orientation (Rao, 2000; J. B. West & Fitzpatrick, 1999).

The poor performance of the epicondyles is likely related to the distance from the reference point selected as well as the fact that we were trying to estimate the torsion of the humerus. There is a wide variety in the degree of torsion the humerus has from proximal to distal, and the corresponding relationship of the transepicondylar axis and humeral head (Raniga et al., 2019). This variability may have been why the indexes utilizing the epicondyles were some of the worst indexes collected. These points are also under, in some cases substantial, soft tissue in patients and not within field of the approach to the humerus. The soft tissue may further error with these points and collecting the points outside of the main surgical field may increase infection risk.

The greater tuberosity had the widest range of error of all landmarks chosen and tested. This may be accounted for as the greater tuberosity has one of the larger surface areas of the points selected, with variable surface anatomy. This may lead to the variation in points selected at each iteration, and the large mean shown.

2.8 Strengths and Limitations

This is a novel study of an anatomic navigation technique for the proximal humerus. Statistical shape modelling has been done in this field identifying consistent anatomic landmarks and furthering this research we have created both a workflow and index of points to estimate proximal humeral anatomic points.

This study does possess some weaknesses. We did not achieve statistical significance for one individual workflow, nor did we for any one individual landmark index. We had some trends towards significance, and a collection of indexes that we were able to rule out. The models that were printed used best attempts at creation of the anatomic surfaces based on the CTs of the native patient anatomy. However, these models may not represent completely the accurate surface anatomy desired, as reproduction of these models during printing of the models may have introduced a small amount of error. This also does not take into account any soft tissue encountered during the operative procedure, as these models were made based solely of bony anatomy of the CT scans. We also note the potential error associated with collecting, and creation of models with an absent mid-shaft. The CT collection protocol takes a segment of proximal humerus, and then the epicondyles. These two segments alignment are reliant on no patient movement during the scan, which we cannot ensure, although any associated error would be present in both the CT and physical models, and as such was not expected to significantly impact our results.

2.9 Conclusions

This study represents a novel implementation of the registration of the proximal humerus. We were able to reproduce anatomic landmarks and tracings within the surgical field of a standard shoulder arthroplasty. Using these, we developed a workflow to allow navigation of the proximal humerus. These landmarks and workflow had strong correlation with previously identified anatomy in previous anatomic studies, statistical shape modelling and fracture work. This study provides a framework to build upon for further developing mapping and navigation of the proximal humerus. We see this as a base for future direction of study and advancement in this discipline. We hope to further improve shoulder arthroplasty, in preparation of osteotomies and component positioning.

2.10 References

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Chapter 3

3 Navigation and Patient Specific Guides for Humeral Head Osteotomy in Shoulder Arthroplasty

Shoulder arthroplasty involves the reconstruction of the glenohumeral joint. Both the glenoid and proximal humerus undergo implantation of components. Proper positioning of these components is critical to the success and longevity of the shoulder arthroplasty. Surgical navigation has been studied and used for the glenoid, but it has not yet been fully studied and applied for the proximal humerus. Patient specific guides have been developed and implemented for the glenoid. Currently, the humeral head anatomic neck cut is via a free-hand technique or utilizes generic guides. These guides can be intramedullary or extramedullary referencing. This chapter focuses on the use of navigation and patient specific instrumentation in orthopaedics, and shoulder arthroplasty. Lastly, it examines methods of executing the humeral neck cut, including patient specific instrumentation and a novel navigation technique.

3.1 Introduction

Shoulder arthroplasty is one of the great orthopaedic innovations of the last century. Between its two mainstays, anatomic and reverse total shoulder arthroplasty, the rates have risen and are projected to continue to rise (Day et al., 2010; Padegimas et al., 2015). Between these two shoulder implant types, treatment for osteoarthritis, cuff tear arthropathy, fracture, rheumatoid arthritis and revision arthroplasty can be done with good outcomes. Outcomes for shoulder arthroplasty include longevity, pain relief and range of motion (Wright et al., 2020).

For these outcomes, proper positioning of components is imperative. Component positioning is in turn tied to the intra-operative bony resection. The humeral head osteotomy impacts version, neck shaft angle (inclination) and head height (Harrold et al., 2014; Suter et al., 2017). Humeral height, if reconstructed too high, can cause overstuffing (Iannotti et al., 2005) which is an established risk of early failure (Bohsali et al., 2006; Geervliet et al., 2019). Too low a osteotomy can result in damage to the rotator cuff, resection of part of the greater or lesser tuberosity and potentially joint laxity (Suter et al., 2017).

Version is important to reconstitute to patient anatomic shoulder. It is done so to reconstitute patient anatomy, provide adequate range of motion, correct tensioning of soft tissue, stability and implant survival (P. Boileau et al., 2008; P. Boileau & Walch, 1997; Keener et al., 2017; Michael L. Pearl & Volk, 1995). The reverse total shoulder humeral version may be less reliant on patient specific version, as it is less influenced by the rotator cuff. The anatomic positioning of the reverse humeral component influences range of motion (Kontaxis et al., 2017; Stephenson et al., 2011) but not the actual muscle forces needed for range of motion (Gulotta et al., 2012). Recent literature is supportive of improved outcomes and range of motion for retroversion matched to patient anatomy (Oh et al., 2019). This may indicate that like anatomic total shoulders, retroversion of the reverse humeral component should match patient anatomy. However, while the debate is yet to be settled, achieving accurate humeral version during osteotomy evidently influences shoulder arthroplasty.

Anatomic total shoulder arthroplasty aims for a patient specific neck shaft angle (Iannotti et al., 2005; Keener et al., 2017; Michael L. Pearl, 2005) which is a mean of 135 degrees, but ranging from 123 degree to 150 degrees (Keener et al., 2017; M. L. Pearl & Volk, 1996; Michael L. Pearl, 2005; Robertson et al., 2000). Neck shaft angle for the reverse total shoulder is variable based on implant design, with ranges from 127.5 to 155 degrees. (Werthel et al., 2019). The neck shaft angle in reverse total shoulder arthroplasty has been widely studied. It influences stability, range of motion, contact stress and scapular notching, whether at the original 155 angle design, a more anatomic 135 degrees or in between (Ferle et al., 2019; Gobezie et al., 2019; Gutiérrez et al., 2008; Langohr et al., 2016; Werner et al., 2017).

Both patient specific instrumentation and navigation have been used in shoulder arthroplasty. This advanced techniques have predominantly been developed for the glenoid side. Navigation has shown both improvement in version and neck shaft angle for glenoid component positioning (Nguyen et al., 2009; Stübig et al., 2013; Verborgt et al., 2011, 2014). Patient specific instrumentation has also been used to successfully improve positioning of the glenoid component (Dallalana et al., 2016; Hendel et al., 2012; Throckmorton et al., 2015; Walch et al., 2015).

While the use of patient specific instrumentation and navigation for the glenoid is established, the study of these in humeral head osteotomies is limited. What work has been done with the humerus included utilizing navigation intraoperatively to establish an osteotomy plane. Using anatomic landmarks to identify the desired plane, a non-navigated osteotomy was done to best match this defined plane. A navigated plate was then used to place on the humeral head osteotomy plane which allowed real time feedback on the neck shaft angle and the retroversion of the cut, which provided room for further free hand correction (Edwards et al., 2008).

The purpose of this study was to evaluate patient specific instrumentation and navigation, as well as industry standard guides and free hand cuts on the humeral head osteotomy. Specifically, this study quantified the version, neck shaft angle and osteotomy height for each method compared to a preoperatively planned desired osteotomy plane. It was hypothesized that patient specific instruments and surgically navigated osteotomies would have no significant differences between them in obtaining the preoperatively selected ideal osteotomy plane. Additionally, that both the patient specific instrumentation and the navigation would be significantly superior to generic guides and the free hand technique for version and neck shaft angle.

3.2 Material and Methods

3.2.1 Specimen Preparation

3.2.1.1 Creation of 3D printed models

5 non-osteoarthritic and 5 osteoarthritic shoulder computed tomography (CT) scans were selected at random from our database at the Hand and Upper Limb Centre Bio-Engineering Research Lab (Western University, London, Canada). The control normal database included 112 CT scans (32 Female, 80 Male). The osteoarthritic database included 88 CT scans (35 Female, 53 Male). CT models of the humerus were taken from DICOM images, and transferred into Mimics software. Masking edges and creating points of best fit to make congruent, continuous surfaces on the models was then done. The geometry within the canal was removed to facilitate later filling with a cancellous bone surrogate. The thickness of the cortical bone was monitored for the specimens to ensure accuracy. Various measurements pre masking as well as post masking were done. These were an average of four millimeters of cortical thickness in agreement with the range of previous literature on humeral head cortical thickness (Majed et al., 2019;

Tingart et al., 2003). These prepared models were then transferred into SolidWorks computer aided design software for further modifications.

Within the SolidWorks program, the specimen scans were prepared to allow for the production of the experimental testing models using additive manufacturing. The clinical CT scans taken at our institution were segmental, with the mid-section of the diaphyseal humerus absent to decrease radiation exposure for patients. This necessitated spanning the diaphyseal deletion and controlling for rotation when creating our final models. To account for the gap within the scans we created 3 mm wide colinear slots on the proximal humerus and distal epicondyle segments. These segments also had features to allow for the creation a 3/8" circular hole. On the proximal segment we filled with our central hole only to below the surgical neck, so as to ensure no interference with the later osteotomy cuts. The humeral shaft height was measured for each specimen, as well as the segment gap on the CT scans. Utilizing a three-dimensional printer (MakerBot Replicator 5th Gen, NY, USA), the proximal humerus and distal epicondyle models were printed using polylactic acid as material. Steel rods with 3/8" diameter were acquired, and each rod was measured and cut to size. The gap was for each specimen was measured and marked accordingly on the steel rods. A straight line was marked on the rods. A drill press was used to created holes in the rod. The proximal and distal printed pieces were aligned and secured to the steel rods to ensure proper rotation and length of the specimen.

3.2.1.2 Creation of 3D printed guides

Neck shaft angle and retroversion were determined using the preoperative planned osteotomy. These planes were virtually created in Mimics at the junction of the head and anatomic neck, which has been previously described (Knowles et al., 2016; E. A. West et al., 2018). Osteotomies were created by two authors (GSA and JTC). This method has previously shown intraclass correlation coefficient of 0.87 (Y. Chen et al., 2018). These were the osteotomy planes that were defined as desired for our printed guides.

Using the SolidWorks models of the ten humeri, inversion of selected surface area of the proximal humerus was done. This was designed to take into consideration the surgical exposure field, and incorporate both unique individual surface anatomy, as well as consistent bony landmarks. The focus was on the tuberosities, more notably the lesser tuberosity, and the bicipital groove. The proximal portion of the guide was aligned to our preoperatively planned osteotomy. The thickness of the guide was designed to maximize the length of the cut surface, but not inhibit the saw blade from completing the cut. Estimates of the guide length needed was based on the difference between the average of head diameter and the length of the saw utilized in our lab. Two pin holes were placed to create stability to our cutting guide.

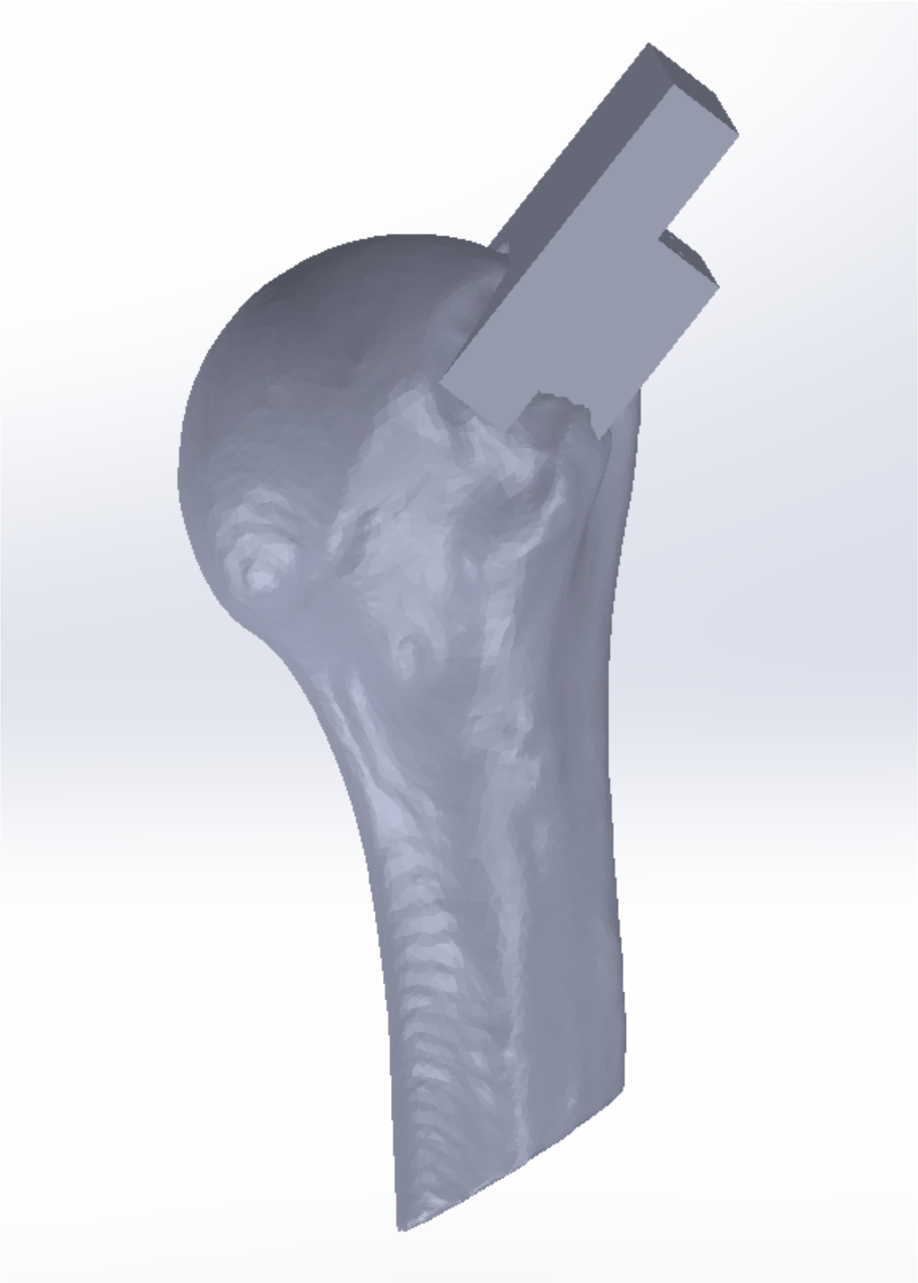

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Figure 3-1: Patient Specific Guide

Rendering of SolidWorks model of a patient specific guide. Template was used to 3D print guides used for osteotomies.

3.2.2 Testing Protocol

Randomization was done prior to testing. Four identical models had been created for each of the ten specimens. Of these four models, one was assigned to each testing group. The four testing groups were free hand osteotomy, fixed angle guide, patient specific guide and navigated. Once all 40 specimens had been assigned to their cut groups we generated a random list of unique specimen identifiers for each specimen. This was done to aid in blinding of the models. These unique identifiers were then randomized to an order set, which we would follow for our cutting order.

Each specimen preparation was done identically, no matter the testing group. The humeral model was mounted securely to a stand. This was within field of view of our Intellijoint infrared camera (Intellijoint Surgical Inc. Waterloo, Canada) which was also secured to a separate stand. We created an adjustable clamp for another optical tracking device. This was mounted on the humerus, in view of the camera and operative field, and fastened in place.

Digitization of the humeral models was then performed with the optical tracker mounted stylus, by selecting anatomic landmarks on the proximal humerus. As defined in Chapter 2, the selected points of the landmark index – superolateral ridge of greater tuberosity, lesser tuberosity and humeral head center – were made visible on a monitor for referencing. Visualizing these before selection was done to minimize any error. The traces, of the biceps groove and humeral head, were then taken on each model. The target registration error (TRE) was then calculated for each model. For any outliers in the TRE, reassessment of the equipment was done and recollection of points to see if improvement could be made to an acceptable level of 3mm or less.

Following digitization of the humerus, the osteotomies were performed. This was done in the aforementioned blinded, randomized order. The same protocol listed above was done prior to each specimen osteotomy. Following each osteotomy, digitization of the cut surface was done with the optical tracker stylus. The optical tracking stylus has a flat surface on the end opposite to the stylus point. Placing this flush to the cut surface, enabled capturing the osteotomy plane. This provided the resulting resected humeral surface for digitization for calculation of version, neck shaft angle and height of the cut. As well, data points were collected for these same three parameters on any guides used, both the patient specific and fixed angle guides. All cuts, in all four groups, were done by a senior shoulder surgeon (GSA).

3.2.2.1 Free Hand

Each model was registered as previously outlined in Section 3.2.2. Once mounted and the humerus model registered, the preoperative planned osteotomy were displayed onto the monitor. This was done to visualize the desired osteotomy plane as would be done preoperatively and intraoperatively with surgical planning software. The osteotomy was made, and the plane captured with the flat stylus surface.

3.2.2.2 Industry Guide

We utilized a 135-degree standard commercially available industry guide (Wright Medical, Memphis, TN, USA) to guide the head neck osteotomy as recommended in many shoulder arthroplasty technical manuals. The preoperative plan highlighting the templated osteotomy plan was brought up on the monitor for reference by the surgeon. The guide was placed at the neck shaft angle, version and height of the osteotomy. It was then fixed by two pins. The cut was made with the plane of the guide. The flat portion of the stylus was placed on the osteotomy plane and this plane was captured. The stylus was then moved onto the industry guide, and ensured it was flush across the guide surface. The parameters of this resulting resection plane we recorded.

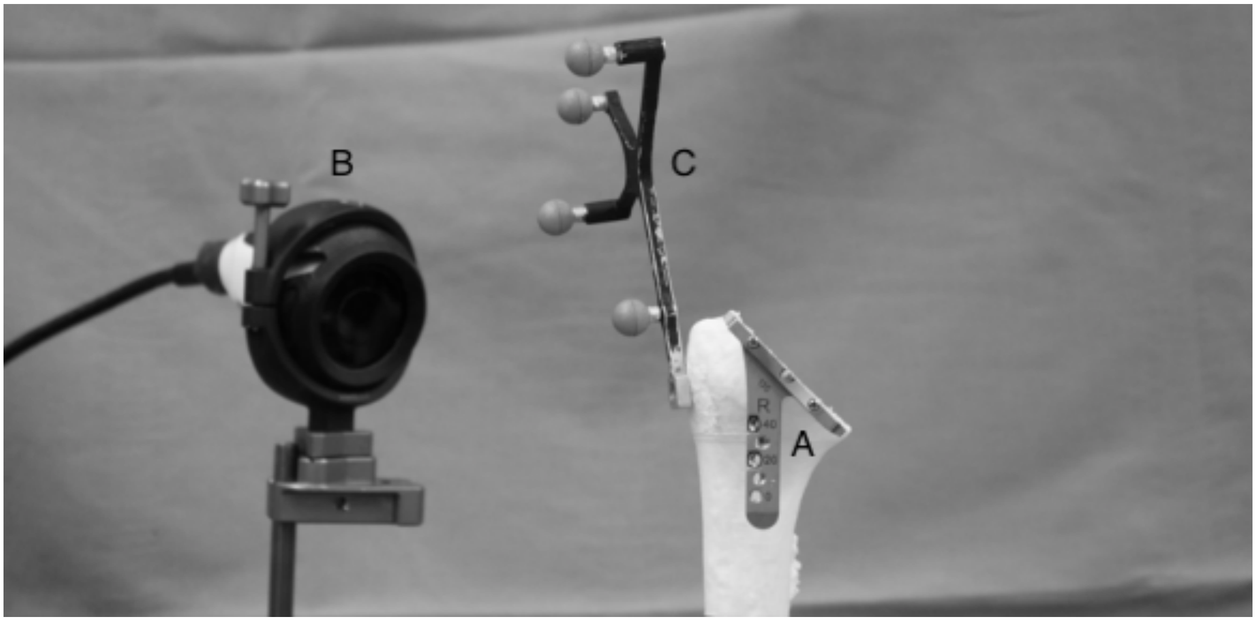


Figure 3-2: Industry Cutting Guide

Image shows an Industry fixed angle cutting guide (A) (Wright Medical, Memphis, TN, USA). The osteotomy has been completed. Also shown is the infrared camera (B) and the optical tracker (C) attached to the proximal humerus.

3.2.2.3 Patient Specific Guide

Patient specific guides were individually made based off the inversion of the surface anatomy of each humerus. The guides were centered on the lesser tuberosity and biceps groove. The placement was done base on the fit of the guide to the existing anatomy. This was confirmed with cross referencing to its desired position, as displayed on the screen by showing the planned guide in SolidWorks. Two guide pins secured the guide in place.

Once the cut had been complete we utilized the flat surface of the stylus for measurement. We placed it flush to the cut plane and took our measurements. We then placed it flush on surface of the guide to take the same measurements, allowing for comparison between the pre templated osteotomy, the plane of our guide positioning, and the plane of our cut.

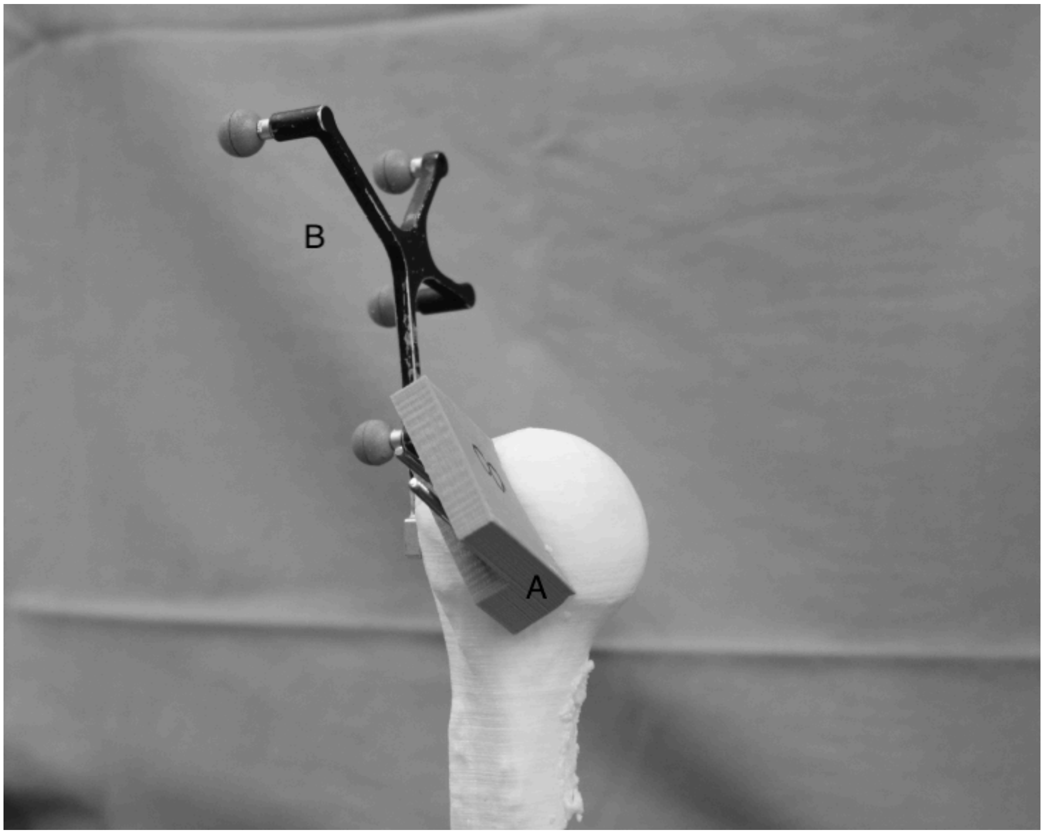


Figure 3-3: Patient Specific Guide

Image shows a 3D printed patient specific cutting guide (A) mounted to the humerus. Also in view is the optical tracker (B), attached to the proximal humerus.

3.2.2.4 Navigation

In addition to registration of the humerus, in the navigation group, we needed to register the bone saw to allow for real time feedback while doing our osteotomy. For our cuts we used a 0.8mm thickness oscillating blade (ConMed, Utica, New York, USA). The saw blade was registered with the flat stylus surface on the undersurface of the blade. The optical tracker was mounted on the saw, creating a navigated saw blade (Figure 3-4).

The live navigation and tracking for the saw blade was made available to the surgeon on a computer monitor. The tracking provided version, neck shaft angle and head cut height. Each of these parameters were displayed as real time tracking position and as the targeted numbers. These target numbers were based on the preoperatively planned osteotomy plane in Mimics.

When the cut height was within 2mm of error, and the angles of the neck shaft angle and version were within 2 degrees of error, green indicators lit up beside the numbers (Figure 3-5).

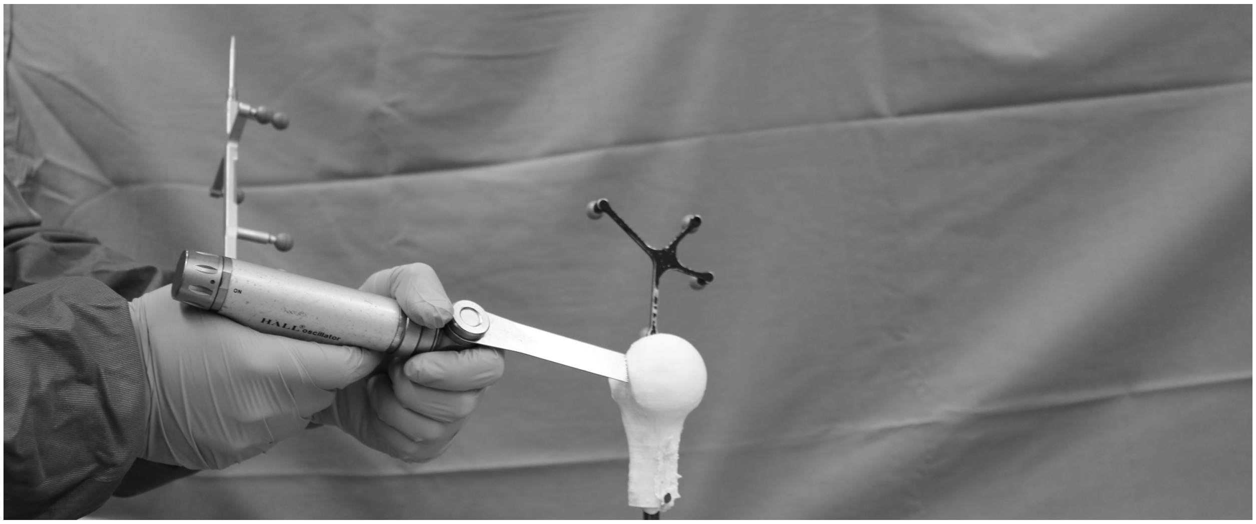
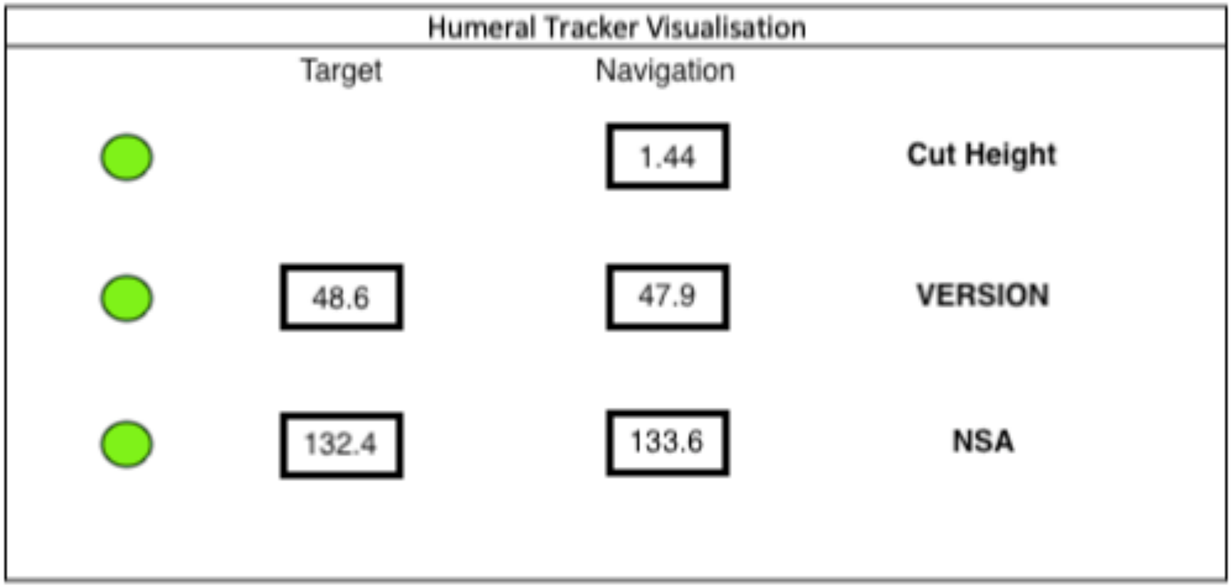


Figure 3-4: Navigated Osteotomy

Image depicts navigated saw osteotomy cut of the proximal humerus. The saw is mounted with an optical tracker. A similar optical tracker is also attached to the proximal humerus.



Humeral Tracker Visualisation

	Target	Navigation	
🟩		1.44	Cut Height
🟩	48.6	47.9	VERSION
🟩	132.4	133.6	NSA

Figure 3-5: Humeral Tracking Visualization

Rendition of the humeral tracking screen visible to the surgeon while navigated cuts are being executed. The markers on the left turn green when parameter is within accepted error. Accepted error defined as 2 millimeters for cut height, and 2 degrees for version and neck shaft angle (NSA) compared to preoperatively planned osteotomy.

3.2.3 Outcome Variables

The primary outcome variable was the resultant cut plane error from the pre-operative planned cut in terms of version angle, neck shaft angle, and cut height. Each of these outcomes were calculated as the difference between our actual cut value and our desired value, as defined by the pre-planned osteotomy which was performed for each specimen in Mimics, and reported in absolute value for all four cut groups investigated.

We also collected data for the neck shaft angle, version angle and cut height prescribed by both the fixed angle and patient specific humeral cutting guides prior to making the cut. This allowed evaluation of the positioning of the guides compared to the desired templated osteotomies to assess how well we positioned our guides. It also allowed comparison of the values prescribed by the guide versus the actual cut produced with the guides, to permit the quantification of any error associated with the actual cutting process during a cut with a guide.

A secondary outcome variable was the resulting target registration error for each specimen using our landmark index of three points and the 2 traces, reported in mm for our humeral reference point.

3.3 Statistical Analysis

A series of paired, two-tailed T-tests were used for statistical analysis of the comparisons of the error of each cut method (SPSS Version 26.0; SPSS Inc, Chicago, IL, USA). For the analysis of the healthy vs. OA groups, a series of unpaired (unequal variance), two-tailed T-tests were performed. Statistical significance was defined as $p < 0.05$.

3.4 Results

3.4.1 Target Registration Error

Our average target registration error overall was 2.5±1.2 mm. This indicated that with our 3 landmarks and 2 traces we could estimate the superior reference point within a 2.5 mm range. This was an improvement from what was exhibited in initial development of the navigation technique as described in chapter 2. The target registration error of the non-osteoarthritic models was 2.46 mm, and the osteoarthritic models 2.54 mm. There was no statistical significance between the groups (p=0.84).

3.4.2 Version

Version angle was measured across all the 10 models in each 4 groups for a total of 40 specimens. Comparison across the groups was evaluated, as well as subgroups for healthy and osteoarthritic models humeri. Our performed osteotomies had an average retroversion of 33.6º compared to the epicondylar axis. The range was from 3º to 65º.

The average version error of the free hand cut was 2.89±2.17º (range: 0.26 – 8.0), fixed angle guide 3.09±2.0º (range: 0.64 – 7.07), patient specific instrumentation 2.55±2.94º (range: 0.05 – 9.23), and the navigation 0.67±0.58º degrees (range: 0.04 – 1.75).

The version angle error of the navigated cut was significantly less than the error of both the free hand (p=0.014) and fixed angle guide (p=0.003) cuts (Figure 3-6). The patient specific guide wasn't significantly better than the free hand or the fixed angle guide (p=0.77, p=0.32), and no significant difference was detected between the patient specific guide and navigation (p=0.059).

Further evaluation of the patient groups revealed that there was no statistically significant difference in the version cuts in any of the four cut groups between the control and osteoarthritic groups (p>0.11).

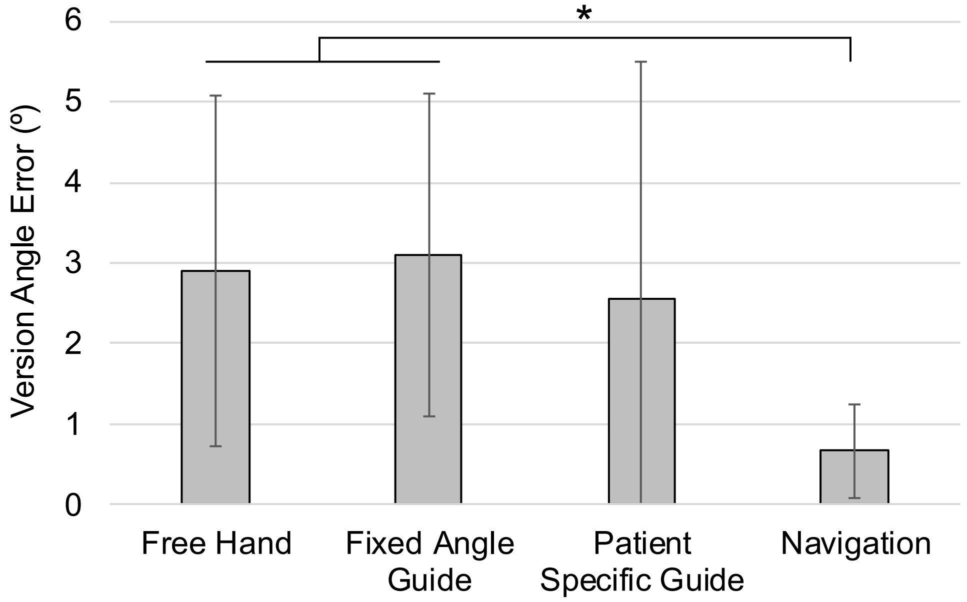


Figure 3-6: Version Angle Error

Mean (+/- 1 SD) error in degrees of each of the four cut groups. Error is measured from pre templated osteotomy.

3.4.3 Neck Shaft Angle

Neck shaft angle was measured across all the 10 models in each 4 groups for a total of 40 specimens. Comparison across the groups was evaluated, as well as subgroups for osteoarthritic models and non-osteoarthritic models. Our performed osteotomies had an average of 132.6º (range: 124.7-136.5)

The free hand cut group had an average neck shaft angle error of 5.78±5.19º (range: 0.69 – 16.8), the fixed angle guide 7.75±5.52º (range: 0.67 – 15.63), the patient specific instrumentation had an error of 4.30±3.63º (range: 0.43 – 11.41), and the navigation group 1.42±1.40º (range: 0.19 – 4.51),

Navigation performed had significantly less error than the free hand (p=0.025), fixed angle guide (p=0.003), and the patient specific guide (p=0.023). The patient specific guide was also significantly better than the fixed angle guide (p=0.007). There was no statistical difference between the free hand and fixed angle groups. (Figure 3-7).

Further evaluation in the individuals cuts groups revealed that there was no statistically significant difference in the neck shaft angle cuts in any of the four cut groups between the control and osteoarthritic groups (p>0.19).

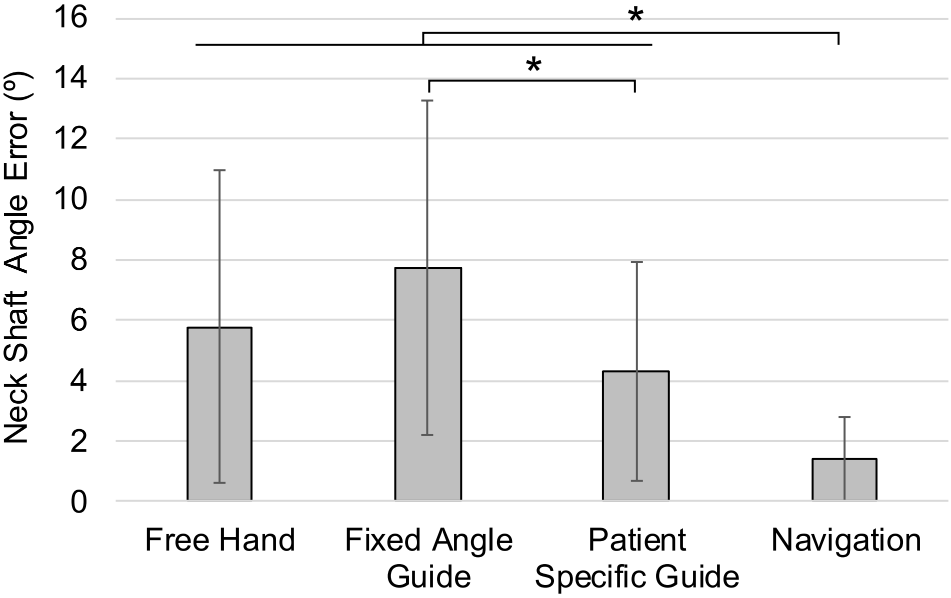


Figure 3-7: Neck Shaft Angle Error

Mean (+/- 1 SD) error in degrees of each of the four cut groups. Error is measured from pre templated osteotomy.

3.4.4 Cut Height

The free hand group had an average cut height error of 2.47±1.76 mm (range: 0.15 – 5.37), fixed angle guide 2.26±1.32 mm (range: 0.01 – 4.13), patient specific instrumentation 2.35±1.54 mm (range: 0.14 – 4.86), and the navigation 2.90±1.73 mm (range: 0.30 – 5.90). None of these cuts were statistically different from any of the other cut groups (p>0.39).

Further evaluation in the individuals cuts groups revealed that there was no statistically significant difference in the cut height in any of the four cut groups between the control and osteoarthritic groups (p>0.14).

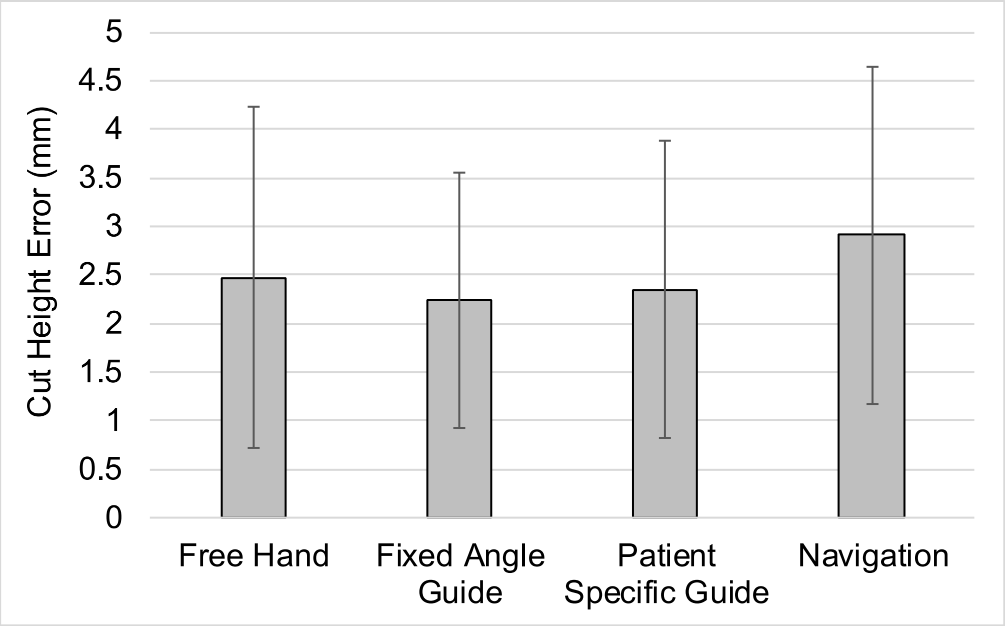


Figure 3-8: Cut Height Error

Mean (+/- 1 SD) error in millimeters of each of the four cut groups. Absolute value of error was calculated. Error is measured from pre templated osteotomy.

3.4.5 Guide Placement vs Osteotomy

3.4.5.1 Fixed Angle Guides

Each specific model underwent an osteotomy with a fixed angle cutting guide. This was placed onto each specimen after visualization of the preoperatively planned osteotomy plane on the monitor. This was done to ensure best placement. The osteotomy plane was measured for all three of our outcome variables parameters, as well as the angles and position of the guides prior to cutting.

There was no statistically significant difference in the version, neck shaft angle or height of templated osteotomy, guide placement or the executed osteotomy.

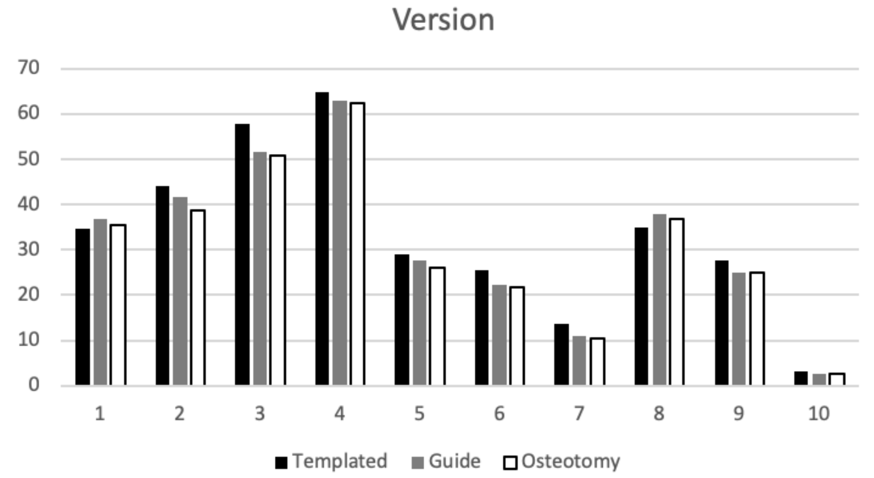


Figure 3-9: Version

Chart above shows the templated, placed guide and osteotomy version angles. Specimen 1-5 are non-osteoarthrtic and 6-10 are the osteoarthritic

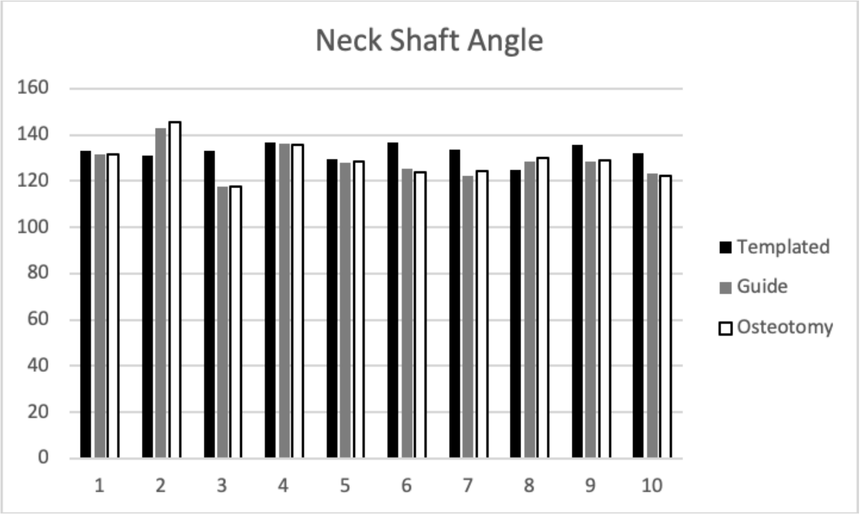


Figure 3-10: Neck Shaft Angle

Chart above shows the templated, placed guide and osteotomy neck shaft angles. Specimen 1-5 are non-osteoarthritic and 6-10 are the osteoarthritic

Figure 3-11: Cut Height

Cut height error for placement of guide as well as executed osteotomy cut. Specimen 1-5 are non-osteoarthritic, and 6-10 osteoarthritic models

3.4.5.2 Patient Specific Guides

Each specific model underwent an osteotomy with a patient specific guide. This was placed after visualization of the osteotomy plane, to ensure best placement. The osteotomy plane was measured for our 3 parameters, and the cut guide surface was as well. There was no statistically significant difference in the version, neck shaft angle or height of templated osteotomy, guide placement or the executed osteotomy.

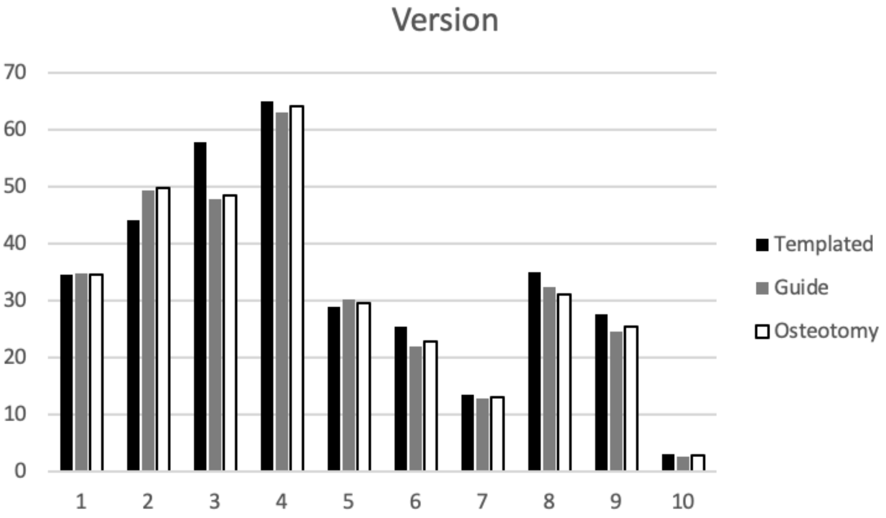


Figure 3-12: Version

Chart above shows the templated, placed guide and osteotomy version angles. Specimen 1-5 are non-osteoarthrtic and 6-10 are the osteoarthritic

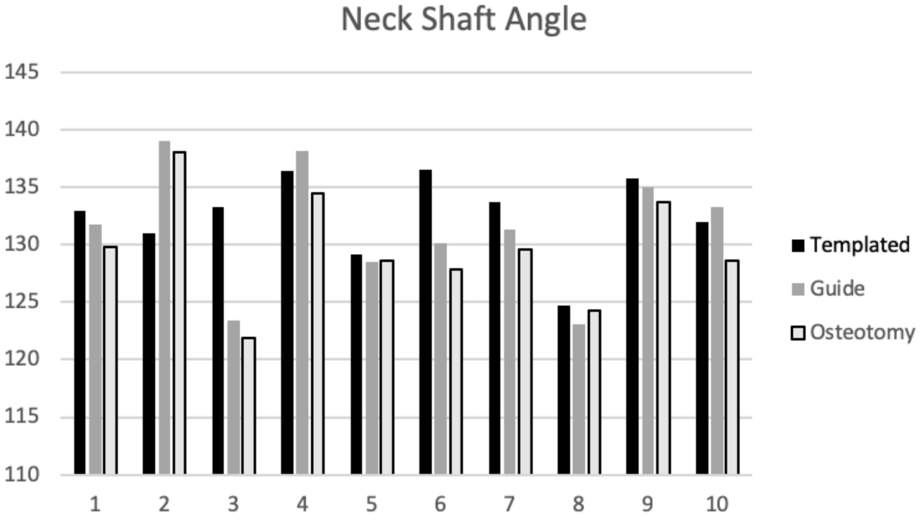


Figure 3-13: Neck Shaft Angle

Chart above shows the templated, placed guide and osteotomy neck shaft angles. Specimen 1-5 are non-osteoarthritic and 6-10 are the osteoarthritic

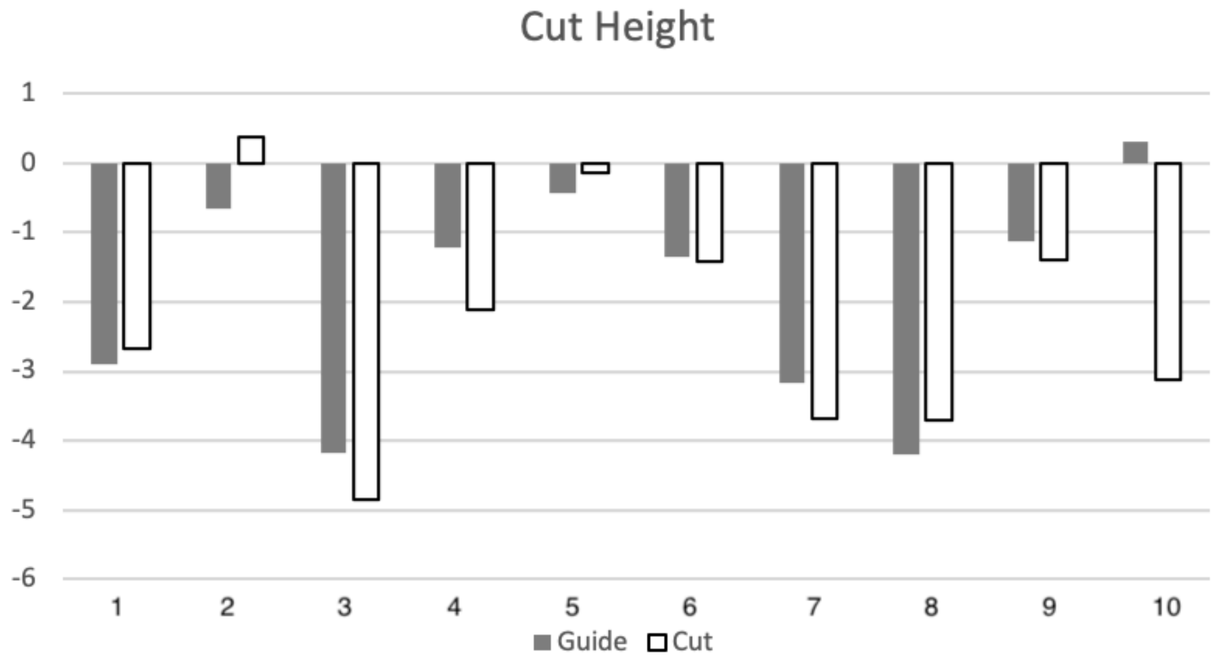


Figure 3-14: Cut Height

Cut height error for placement of guide as well as executed osteotomy cut. Specimen 1-5 are non-osteoarthritic, and 6-10 osteoarthritic models

3.5 Discussion

The aim of this study was to evaluate four methods for executing humeral head osteotomies including free hand, commercially available fixed angle guides, patient specific instrumentation, and navigated cuts. The outcomes measured for each osteotomy were version of the cut, neck shaft angle, and the humeral head cut height. These were all compared to a baseline pre-operatively planned osteotomy, as previously described in the literature (Raniga et al., 2019; E. A. West et al., 2018).

The navigated humeral head osteotomies were statistically significantly closer to the version of the pre-operatively planned osteotomy than both the free hand and fixed angle guides. The neck shaft angles of the navigated cuts were statistically significantly closer to the preoperatively planned osteotomy neck shaft angles compared to the free hand, fixed angle guide and patient specific guide cuts. Also, the patient specific guide had less neck shaft angle error than the fixed angle guide.

Even when in instances where not statistically significant, the navigated version and neck shaft angle performed the best in all groups with average errors of 0.67º and 1.42º, respectively. The next best performing method was the patient specific guide, with version and neck shaft angle errors of 2.55º and 4.30º, respectively. Both the version and neck shaft angles are of importance in the outcome, wear, and range of motion of both anatomic and reverse total shoulder arthroplasty (Gobezie et al., 2019; Gutiérrez et al., 2008; Keener et al., 2017; Kontaxis et al., 2017; Langohr et al., 2016; Oh et al., 2020; Stephenson et al., 2011).

The humeral head height cut error across the four methods was very similar. The error similarity across the guides is likely a representation of the placement error associated with guides, as there was no significant difference in placement of the guide and the metrics of the final osteotomy. The similarities in free hand cut and the navigated cuts may be a representation of similar start points, in addition to the surgeon having the availability of the preoperative plan. Version and neck shaft angle may be more adjustable through the course of the cut, while start point has more implication on the height of the cut.

Our secondary outcome of target registration error also improved to 2.5 mm. This improvement was most likely secondary to our conditions of testing. The original development of the navigation and collection of target registration error was done outside the lab secondary to COVID19 and the lab being shut down. The lighting was more controllable in the lab, more mimicking the environment of an operating room.

Our other findings exhibited that there were no significant differences in the pre templated osteotomies, placement of the guides or executed osteotomies for any of the three parameters; version, neck shaft angle or cut height. Error occurs across these steps, and consistency is important to minimize error across these steps.

3.6 Strengths and Limitations

This is the first, to our knowledge, comparison of humeral head osteotomies across the arms of our study – free hand, fixed angle guide, patient specific guide, and real time navigated. Although intraoperative navigation has been utilized to template an osteotomy plane, it has not been used for real time guidance and feedback of the osteotomy.

We were able to exhibit navigation was significantly better than fixed angle guides in both version and neck shaft angle, and patient specific guides were also better than fixed angle guides in neck shaft angle.

We also studied guide placement and subsequent guide cut. This allowed us to evaluate each sequential step in using an osteotomy guide and assess for error in this process. Although there was no difference exhibited, it was the first, of our knowledge, comparison of the error of guide placement and cut.

There were numerous limitations associated with this study. We were unable to truly blind the surgeon to what specimen was being cut. Although they were not privy to information regarding what subgroup – osteoarthritic or non-osteoarthritic – the models displayed evidence of osteoarthritic changes to their surface anatomy that made them evident to even the untrained eye. We best limited this with our randomization among specimens as well as cut group order.

These cuts also have some variation from a true intraoperative osteotomy as we did no resection of osteophytes. This is commonly done in the surgical cases before osteotomies are performed. This may have influenced the positioning of our cutting guides, and our osteotomies, due to the irregular osteophyte anatomy.

We were reliant on the models that we had produced. Although we took great effort to best replicate the anatomy, density and thickness of the models, they did differ slightly from that of true bone. The slightly thicker and tougher cortical replicate may have influenced our osteotomies.

Another limitation was that we did not complete the implantation of the humeral head. Although the cut surface is the large determinant of the final positioning of the humeral component we cannot exactly report any small changes from cut surface to final component position. The final component position being of most importance.

3.7 Conclusion

Future direction includes validation of our study in cadaveric models. This would attempt to control for multiple limitations in our study. First any potential limitations derived from using 3D printed models instead of true bone would be minimized. This includes error in the osteotomy cut secondarily to the surrogate material we used that was previously mentioned. Cadaveric models would also contain the osteophytes as well as soft tissue that would be encountered in the true operative field, and therefore be a better representation of the operative conditions.

We have also demonstrated a reliable method for navigating the proximal humerus. Any future navigation of the proximal humerus will be able to use this as a framework moving forward. One example may be its utilization for implantation of the humeral component. Given the final step of implantation was not studied here, this may be of further value, as error may exist in implantation of the component. Navigation may be able to assist in definitive component placement.

Although no significance was found there were general trends in improved version and neck shaft angle with the navigated cuts were exhibited. How these trends would carry out over a greater number of tested specimens would be of value, in any future study. Further work, with increased numbers, may lead to a better understanding of the value and potential utilization of navigation and patient specific instrumentation in shoulder arthroplasty.

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Chapter 4

4 Thesis Conclusions

The humeral head osteotomy is a critical step in shoulder arthroplasty. It influences the version, neck shaft angle and height of the humeral component. This is true for both anatomic and reverse total shoulder arthroplasties. Little, however, has been done to evaluate or assess the accuracy of the various techniques to perform the cut. The purpose of this thesis was to develop and evaluate a humeral navigation technique, along with other methods of executing the humeral head osteotomy.

The primary objectives of this thesis are:

1. To review the anatomy of the proximal humerus and develop a registration technique applicable for intraoperative use (Chapter 2)
2. To evaluate the accuracy and repeatability of proximal humerus registration techniques and validate these techniques (Chapter 2)
3. To evaluate the accuracy of different methods of humeral head osteotomies (Chapter 3)
4. To evaluate the accuracy of guide placement, and accuracy of guide based humeral head osteotomies (Chapter 3)

4.1 *Summary of Chapter 2*: Registration of the Proximal Humerus

This chapter focused on the development and verification of navigation of the proximal humerus. We first evaluated the repeatability error in the selection of anatomic points on the humerus. Our next outcome was to determine the groups of anatomic points that would best accommodate the registration process and estimate a defined proximal humeral landmark. Our last outcome was which method of collection: points, tracings or a combination of the two would produce the lowest registration error to estimate the proximal landmark.

Our first hypothesis was that we would be able to measure anatomic landmarks within 2 millimeters of error over multiple iterations. We had selected these anatomic points based on previous literature on proximal humeral anatomy, intraoperative availability and potential repeatability. Our results were two of our nine points were collected within two millimeters of error over multiple iterations. These were the medial and lateral epicondyles. Five other points were just over two millimeters of error over the multiple collections. Two were greater than three millimeters of error. Of these points, the greater tuberosity had statistically significantly greater mean error across iterations compared to all other points.

Our second hypothesis was that we would be able to register the humerus to a pre-operative plan to within two millimeters of error. Our hypothesis was refuted, as we were only able to achieve a registration error of just over three millimeters. The development of our registration technique involved determining which anatomic landmarks to use, and how to collect them. We evaluated the error for all combinations of any three of our nine anatomic landmarks. We exhibited multiple combinations to be statistically worse at estimating the superior point of the humerus, but no single three-point combination was significantly better than all the others. We also evaluated the registration error using point selection, point tracings, and a combination of the two. We found no significant difference for registration error in terms of collection technique. We selected a combination of three points, and tracings of the biceps groove and humeral head as our method of registration. The three points being the superolateral ridge of the greater tuberosity, the lesser tuberosity and the humeral head center. These points in addition to the tracings, was one of the lowest target registration error methods tested.

In the 10 landmark indexes that were statistically significantly poor, the medial and lateral epicondyle were often present as one, or two, of the three anatomic points. This indicates they may be contributing to the poor registration of those indexes. Their distance from the superior humerus likely plays a role in this.

This is one of the first studies to focus on development on navigation for the proximal humerus. It provides a working method for estimation of proximal humeral anatomy. The findings allow for further work and improvement in registration proximal humeral anatomy. It provides us with a means of developing navigated osteotomies for the proximal humerus.

4.2 *Summary of Chapter 3*: Navigation and Patient Specific Guides for Humeral Head Osteotomies

The purpose of this study was to evaluate different methods of humeral head osteotomies for shoulder arthroplasty. The different groups were free hand cut, fixed angle guide, patient specific guide, and our navigation method developed in house. We compared each method in relation to a preoperatively planned osteotomy plane for each specimen.

Our first outcome was the osteotomy parameters; version, neck shaft angle and cut height. It was hypothesized that navigation and patient specific guides would provide statistically significant reduction in error in version and neck shaft angle compared to fixed angle guides and free hand cuts. This hypothesis was refuted for version. There was no significant version error between the navigated and patient specific osteotomies as we had hypothesized. The version of the navigated osteotomies was statistically significantly closer to the preoperative plan compared to fixed angle guides and free hand cut as was hypothesized. However, there was no difference in version error between the fixed angle and free hand osteotomies compared to the patient specific guide osteotomies. The hypothesis was also refuted for neck shaft angle. The navigated cut was statistically significantly closer to our preoperatively planned osteotomy for fixed angle guides and free hand cuts. But, the navigated cut was also significantly closer to preoperatively planned than the patient specific guides. The patient specific guide osteotomies were significantly closer to replicating the neck shaft angle compared to the fixed angle guides, but not the free hand cut. There was no difference across cut heights in the four groups, which confirmed our hypothesis.

Our second outcome was target registration error. When registering the humeri before osteotomies were performed, we had an average error of 2.5 millimeters. This was an improvement of original testing in Chapter 2, likely secondary to improved conditions and equipment.

Our third outcome was guide placement. We hypothesized there would be no difference in any of the parameters, which was true. We did not show significant changes in version, neck shaft angle or cut height from our pre operatively planned osteotomies, to guide placement, to the executed osteotomies. This is an important finding, in that it shows that error in cuts with guides are influenced by each step, and not one in particular.

This study was the first to evaluate these methods of osteotomies, osteotomy outcomes, and the placement of guides. It shows there are trends towards, and in some instances, significant improvement in osteotomies when utilizing navigation and patient specific guides. Our work can serve as a framework for further study, and improvement in the humeral component of shoulder arthroplasty.

4.3 Future Direction

This study examined registration of the proximal humerus, and various cutting methods for executing the humeral head osteotomy. This was done with the use of 3D printed cadaveric models. The next step in this research would be the implementation of this study in cadaveric models, due to the potential limitations of using isolated bone models as noted in the previous section. Introducing soft tissue, and the true consistency of bone for the osteotomies, would provide further important data. Given the findings of trends towards improvement in both version and neck shaft angle in navigated osteotomies, it would be of further value to study this trend in greater numbers, and better understand the impact of humeral navigation.

4.4 Significance

Shoulder arthroplasty, both anatomic and reverse, has increased in numbers over the last decade. These numbers are projected to continue to grow. The scope of patients also continues to grow. As these numbers continue to rise, a continued focus on implant longevity and outcome should be taken. For both these, implant positioning in an important determinant. Studies have predominantly been focused on the glenoid, with both navigation and patient specific instrumentation utilized in improving the glenoid component positioning.

Our study first validated a navigation technique for the proximal humerus. Utilizing anatomic landmarks and tracings, we were able to register this unique anatomical structure. Any further work in this area can be built upon our results. Our ability to accurately register the proximal humerus allowed us to develop a navigation technique for the humeral head osteotomy. We showed the ability for improvement in both version and neck shaft angle with navigation and patient specific guides. Our work is a novel focus on navigation and patient specific guides. With further study and improvement, a better control of version, neck shaft angle and cut height may be achieved. This in turn, may increase longevity, outcomes and patient satisfaction in total shoulder arthroplasty.

Curriculum Vitae

Joseph Cavanagh
Department of Surgery, Division of Orthopaedic Surgery
Western University
London, ON

Education

Orthopaedic Surgery Residency (In Progress)
2017-2022
Western University, London, Ontario

Bachelor of Medicine, Bachelor of Surgery
2013-2016
University of Queensland, Brisbane, Australia

Bachelor of Science (Honours) Kinesiology
2008-2012
Queens University, Kingston, Ontario, Canada

Academic Highlights and Achievements

Western Graduate Research Scholarship- University of Western Ontario 2019-2020

Licentiate of the Medical Council of Canada- 2019

W Harvey Bailey Award Runner Up – 2019. Awarded to top two basic science presentations at Annual Western Resident Research Day

Professional Memberships

Canadian Orthopaedic Association – 2017 - present

Ontario Medical Association – 2017 – present

Arthroscopy Association of Canada – 2020 - present

.

Research Projects

1) **Cavanagh J**, Lockhart J, Langohr D, Johnson J, Athwal G. Navigation and Patient Specific Instrumentation in Shoulder Arthroplasty
Master of Science in Surgery Thesis (in progress).

2) **Cavanagh J**, Zomar B, Marsh J, Lanting B. Retrospective Cost Analysis of Non-Infected Revision Total Knee Arthroplasty. Presented at Research Day 2018

3) **Cavanagh J**, Raniga S, Knowles N, Ferreria L, Athwal G. Humeral Torsion in the Walch Type A Shoulder. Manuscript in progress

4) Sidhu SP, Atwan Y, **Cavanagh J**, Lawendy AR. High Energy Transsyndesmotic Ankle Fracture Dislocation- Injury Characteristics, Radiographic Outcomes, and Factors Affecting the Rate of Post-traumatic Arthritis in Logsplitter Injuries.
Manuscript being edited for journal submission.

Publications

1) Atwan Y, Charron BP, Sidhu SP, **Cavanagh J**, Degen R. Publication Productivity Among Academic Orthopaedic Surgeons in Canada. Cureus. 2020 Jun;12(6): e8441. doi:10.7759/cureus.8441