The clinical, anatomical and repair integrity of the rotator cuff following open surgery in a South African sample

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Mashangu wa Mhlaba
Mhlaba wa Resenga
Resenga wa Riholo
Riholo wa Goshane
Goshane wa Mpyisi
Mpyisi wa Shimambane
Shimambane wa Dlamani
Dlamani wa Maxakadzi
Maxakadzi wa Malenga
I vaka Maluleke
I van'wanati
I vaka Xinyela babeni
I va Macimba ya tihuku ta ko lema rihlelo
I va Timamba ku lurha
Ti luma va makhombo, loko u nga ri na ma khombo a ti ku lumi

Chapter 1: Introduction

Rotator cuff (RC) repair has been, and is currently one of the most common surgical procedures performed on the shoulder (Iannotti, 1994; Smith *et al.*, 2000; Galatz *et al.*, 2001; Pai and Lawson, 2001; Romeo *et al.*, 2004; Sgroi and Cilenti, 2018). The RC refers to the muscles that function as the dynamic stabilizers of the glenohumeral joint. The muscles that comprise this unit/cuff include the supraspinatus, infraspinatus, subscapularis and teres minor. These muscles, in conjunction with the coracohumeral ligament and the joint capsule, converge and insert onto the humeral tuberosities.

Tears of the RC are often either due to injuries sustained when performing strenuous movements of the shoulder or these tears can result from degenerative changes in and around the joint associated with ageing. Although there are cases documented where the tears may occur spontaneously, these are rare (Novi *et al.*, 2018). This is consistent with two cases recorded by Codman (1911, 1990) and a study conducted by Depalma (1963). In his article titled "*Surgical anatomy of the rotator cuff and the natural history of degenerative periathritis,"* Depalma (1963) discusses 96 cadaveric shoulders in which partial or complete tears of various tendons around the shoulder were encountered. The cadaver specimens mentioned had no history of shoulder problems, yet 38% (n=20/96) presented with RC tears (Depalma, 1963). The tears encountered were commonly described using an assortment of factors such as the shape of the tear (crescent, triangular, etc.), size (small, medium, etc.), grades (grade 1, 2, 3 and 4), location (articular surface, bursal surface, complete tear), groups (group I, II, III and IV) and types of tears (type I, II, III and IV) (Habermeyer *et al.,* 2006). In Chapter 6 of this thesis, such instances were encountered in the included cadaver sample, although not as high a percentage as encountered by DePalma (1963). The tears identified were classified accordingly.

RC tears lead to a variety of clinical manifestations, including debilitating shoulder dysfunction and impairment. In attempting repairs of the RC unit, treatment options have evolved over the past two decades from the more traditional approach (open procedure) to an arthroscopic-assisted (mini-open) technique and now an all-arthroscopic technique (Bigliani *et al.*, 1992; Bennett, 2003; Bennett, 2003). All the available methods attempt to repair the damaged tendons to the point where post-operatively the patient can have pre-trauma functionality returned. Each of the methods have their merits and areas of concern in relation to the pain encountered and the range of motion (ROM) possible at the joint post-surgery. The main goal of RC repair is to eliminate pain and improve function with increased shoulder strength and ROM (Ghodadra *et al.*, 2009).

The open technique, a more 'traditional' method, is usually only selected when the RC tear is large, complex or requires additional reconstruction such as a tendon transfer. This method is invasive and entails the detachment of the deltoid muscle from its proximal attachment, for better access to the underlying torn RC tendon (Armstrong *et al.,* 2017*)*. The deltoid muscles' reattachment to the acromion is a critical component of open RC repair, as post-operative rehabilitation outcomes are affected by a poorly repaired deltoid muscle. A strong and meticulous repair of both the superficial and deep deltoid fascial layers is essential to avoid post-operative dehiscence during rehabilitation (DeOrio and Cofield, 1984). The anatomy of the deltoid muscle is such that it is made up of three parts (anterior, middle and posterior), with the fibres performing various movements separately or as a unit. This muscle is innervated by the axillary nerve and is known as a stabilizer of the glenohumeral joint and assists in maintaining the head of the humerus in the glenoid cavity during arm movements (Moore e*t al.*, 2014). Several complications exist with regard to RC repair, regardless of the use of either open- or arthroscopic procedures. The main issue experienced in both procedures is the poor healing of the reattached tendon to the bone and the subsequent increase in retear rate following surgery, with ranges documented between 15% and 90% (Klepps, 2004; Boileau *et al.*, 2005; Ratti *et al.*, 2005; Bishop *et al.*, 2006; Jost *et al.*, 2006; Liem *et al*., 2007). The main reason for this failure is the inability to restore the blood flow to the tendon and bone; ultimately resulting in unsuccessful healing and reattachment of the tendon-to-bone complex.

Therefore, one of the aims of this study was to investigate the macroscopic anatomy of the RC complex together with its blood supply by studying the branching pattern of the axillary artery and its related variations on a cadaver sample. The suprascapular artery was also investigated, as it is found supplying blood supply to the RC muscles. Several variations relating to the branching of the axillary artery are documented in

Chapter 4, with an additional case study of the superficial ulnar artery variation recorded in Chapter 5.

In this study, a cadaveric and clinical component were explored, in which the objectives of the cadaveric component included the following:

- An attempt to ascertain and reinforce the insertion of the RC muscles through reverse dissection of the RC complex.
- An investigation of the blood supply to the RC unit. This component of the study included dissection and descriptive analysis of the RC blood supply and extensive investigation of the axillary artery branching pattern and related variations. Measurements of the full length as well as the various parts of the axillary artery were taken and the results analysed and compared to published literature.
- Pathology encountered during the data collection was recorded and further analysed. The results were compared to documented data on the prevalence and common pathology related to the RC complex.
- The RC tears found on the cadavers were classified according to pre-defined definitions. Age, sex and BMI comparisons were made for cases where RC tears were documented, in order to note whether any correlations existed.

The clinical component of this study included observations made by the primary investigator, at the Life Groenkloof Hospital, on patient volunteers meant to undergo open RC surgery. The surgical interventions were carried out by the study advisors, Dr MA de Beer and by Dr C Kilian. The study also included a documentation of the common acromion types presented during shoulder examination. Several authors have previously documented a relationship between RC tears and acromial morphology, with the most common being the type III acromion (Bigliani *et al.*, 1991; Epstein *et al.*, 1993; Nicholson *et al.*, 1996; Worland *et al.*, 2003). The length of the tears was measured where possible, the results analysed and further discussed in Chapter 7. In some of the older patients who had a prolonged RC injury prior to surgical intervention, the torn layer was found stretched as though it was attempting to re-attach itself to the humerus. During the repair procedure, this layer was trimmed and biopsies were taken for further histological analysis in order to ascertain the accuracy of the hypothesis. The clinical component also sought to document the following:

- The range of motion (ROM) possible at the glenohumeral joint following injury. In addition, muscle strength tests were used to assess the ROM at the pre-operative stage, at eight- weeks post-surgery and six-months post-surgery. Muscle functionality tests were also carried out at the pre-operative stage.
- Shoulder functionality tests, which included the VAS pain score, the ASES score, the SST and the constant score were carried out pre-operatively and the results documented for further analysis. These results were further compared to available literature when the open- and arthroscopic repair was used.
- The rehabilitation protocol following open surgery was looked at, with various exercises performed by patients post-surgery in order to maximise the healing of the RC and return the shoulder to pre-injury ROM. The ROM was then documented at eight-weeks and six-months post-surgery and the results compared to the pre-operative outcomes.
- Hand dominance versus the affected arm was documented and the results compared to available literature.

Problem Statement

This study attempted to firstly evaluate the clinical, anatomical and repair integrity of the RC following open RC surgery. One of the challenges encountered with RC repair is the reduced blood supply to both the RC and the head of the humerus post-surgery, often resulting in poor healing of the tendon and in rare cases, osteonecrosis of the humeral head. Therefore, blood supply was investigated on the cadaver sample while documenting variations related to the axillary artery and related branches. Secondly, the clinical component critically looked at the acromial types and their relationship to the size of tears commonly encountered in a South African sample. The common pathology related to the RC was also documented in the cadaver sample, with tears classified according to the pre-existing classification. There exists a paucity in current literature when looking at the ROM documented at different post-operative stages, therefore, the study also sought to add to the knowledge base and show the ROM possible at different stages following open RC surgery. These results were compared to arthroscopic outcomes as the open technique is mostly administered in developing countries due to its cost-effective nature, and remains the preferred mode of repair for large to massive RC tears.

Chapter 2: Literature Review

The functional and anatomical composition of the shoulder joint has been a point of fascination for surgeons and anatomists alike, with ongoing debates on the actual cause of rotator cuff (RC) tears. A link and causality is still being sought between trauma, disease, degeneration and attrition in the production of RC tears. In the following sections, reviewed literature related to the anatomy of the axillary artery, blood supply to the shoulder joint and RC muscles will be discussed in more detail. The anatomy of the shoulder joint, pathology thereof and the clinical repair of the RC using open surgery will be explored, concluding with the post-operative follow-up and related full-functionality clinical tests.

2.1. Cadaver Component

2.1.1 Axillary artery – Blood supply

The axillary artery, an extension of the subclavian artery, starts at the lateral border of the first rib and continues through the axilla to its terminal point at the inferior border of the teres major muscle, where it continues as the brachial artery in the arm. At its point of origin, the axillary artery lies deep to muscles, fascia and skin and later courses more superficially towards its terminal point, covered only by fascia and skin. The axillary artery is typically found giving off six branches with the pectoralis minor muscle dividing it into three parts.

The variability in the branching pattern of the axillary artery is a common feature in anatomy dissection halls. Studies have shown that the classic "textbook" pattern of six branches originating distinctly from the axillary artery is only encountered in around 28% of documented cases (Gaur *et al*., 2012; Xhakaza and Satyapal, 2014; Dimovelis *et al.*, 2017). Twenty-three different arterial patterns of the axillary artery have been recognized and documented by De Garis and Swartley (1928), with the tendency of these occurrences found mainly in females (Trotter *et al.*, 1930; Pandey *et al.*, 2004). Variations in the course and branching pattern of the axillary artery have been documented by several other authors as well (Patel *et al.*, 2013; Gupta *et* al., 2014; Aastha *et al.*, 2015; Chotai *et al.*, 2016; Akhtar *et al.*, 2018; Keet and Louw, 2018; Nyemb *et al.*, 2018), with a South African case study by Keet and Louw (2018) detailing the course of the axillary artery, accompanied by the brachial plexus, running superficial to the pectoralis minor muscle. In cases of documented variations, the lateral thoracic artery, subscapular artery and the posterior circumflex humeral artery are found to be the most variable in their origin, while the area of distribution remains consistent (Loukas *et al.*, 2014).

The embryological basis for these variations is noted during embryogenesis. The axillary artery is derived from the lateral branch of the seventh cervical intersegment artery (Jurjus, 1999). This lateral branch becomes enlarged to form the axial artery of the upper limb, which further develops becoming the axillary artery, brachial artery, proximal part of the ulnar artery between the levels of the origin of the radial - and common interosseous arteries, the common interosseous artery and the anterior interosseous artery (Arey, 1957). Arey (1957) ascribes the unusual blood vessels to a variety of factors, including the choice of unusual paths in the primitive vascular plexus, the persistence of vessels normally obliterated in the course of development, the disappearance of vessels normally retained and the incomplete development, fusion and absorption of the parts usually distinct (Arey, 1957). The variations in the origins of the axillary artery are further explained by the embryological origin of the limb buds (Jurjus, 1986). A model was therefore proposed by Senior (1926) and Singer (1933) to summarise and demonstrate the five-stage development of the upper limb.
The model proposed the development of the upper limb as a five stage process, with the axial system seemingly developing first, followed by other branches later emerging from it. Subsequently, the axial system forms part of the adult axillary artery, brachial artery and anterior interosseous artery (Sawant *et al.,* 2012). In the second stage of development, the median artery develops, arising from the anterior interosseous artery, following the course of the median nerve. Regression of the anterior interosseous artery follows. A branch is noted arising from the brachial artery, the ulnar artery, which unites with the median artery to form the superficial palmar arch (Stage three). Stage four is marked by the development of the superficial brachial artery which continues as the radial artery. The now definitive radial artery there, is the marked regression of the median artery and an anastomosis between the brachial artery and superficial brachial artery, followed by the regression of the superficial brachial artery (Tan, 1994). Defects in the embryological development of the vascular plexus of the upper limb bud result in these arterial variations (Hamilton *et al.,* 1972).

Numerous publications have noted anomalous branching of the axillary artery (Bergman *et al.,* 1988; Safiye *et al.,* 2000; Vijaybhaskar *et al.,* 2006; Ramesh *et al.,* 2008; Satabdi *et al.,* 2014; Kanaka *et al.*, 2015; Patil *et al.*, 2016; Akhtar *et al.*, 2018). Sawant *et al.* (2012) noted five distinct variations of the axillary artery in 50 upper limbs that were dissected in an Indian sample. In one observation the axillary artery was found branching into superficial and deep brachial arteries. The superficial brachial branch bifurcated in the cubital fossa, dividing into the radial and ulnar arteries, without giving any branches in its course. The deep brachial artery was found giving off all the branches normally associated with the axillary artery: the superior thoracic, thoracoacromial, lateral thoracic as well as articular branches of the glenohumeral joint that divide into the anterior and posterior divisions (Sawant *et al.,* 2012). In another case, Sawant *et al.* (2012) observed that the anterior and posterior circumflex humeral and profunda brachii arteries are related to the anterior division of the brachial plexus on one side and by the posterior division on the other side.

Cases of the emergence of the superficial brachial artery from the axillary artery have also been documented, with the superficial brachial artery emerging mostly from the third part of the axillary artery. The course of this anomalous branch is quite variable with the termination also exhibiting variations from the norm. In some cases, the superficial brachial artery was found continuing as the radial artery in the forearm (Cavdar *et al.*, 2000). This occurrence is found in 0.1% to 3.2% of the documented sample (Cavdar *et al.*, 2000).

Sawant e*t al.* (2012) also documented a case where the axillary artery terminated by dividing into a superficial and a deep brachial artery. Upon observation, it was noted that the branches of the axillary artery emerged from the trunk that continued as the deep brachial artery. The superficial branch terminated in the cubital fossa by bifurcating into the radial and ulnar arteries (Sawant e*t al.*, 2012). These observations are similar to study findings by De Garis *et al.* (1928) who noted instances where the axillary artery exhibited a superficial and deep stem with the percentages of occurrences noted as variable in black and white populations. These percentages were documented as 13.4% and 4.6%, respectively.

2.1.1.1 First part of axillary artery

In the first part of its course, the axillary artery is accompanied by the axillary vein and brachial plexus, enclosed by the axillary sheath, a continuation of the deep cervical fascia. In this region, the anterior covering of the artery is attributed to the clavicular portion of the pectoralis major muscle and the clavipectoral fascia. Posteriorly, this part of the axillary artery is related to the first intercostal space, the corresponding external intercostal muscle, serratus anterior muscle and various neurovascular structures. At the lower border of the subclavius muscle, the axillary artery gives off the superior thoracic artery which gives blood supply to the first and second intercostal spaces (Gray, 1918; Moore e*t al.*, 2014). In variable instances, the superior thoracic artery may be found arising from the thoracoacromial artery.

2.1.1.2 Second part of axillary artery

The second part of the axillary artery courses posterior to the pectoralis minor muscle and gives off two branches, the lateral thoracic and thoracoacromial arteries. The thoracoacromial and the lateral thoracic arteries arise medial and lateral to the pectoralis minor muscle, respectively. The thoracoacromial artery pierces the clavipectoral fascia and further divides into four branches: the clavicular, acromial, deltoid and pectoral branches. The pectoral branch is the largest branch of this tetrafurcation (Gray, 1918; Moore e*t al.*, 2014). The lateral thoracic artery has a larger diameter in females, giving off lateral mammary branches for blood supply of the breast (Sawant *et al.*, 2012; Moore e*t al.*, 2014). Loukas *et al.* (2014) theorised that the lateral thoracic artery may even play a role in the blood supply to the areola and nipple, where improper ligation or damage to this vessel may possibly cause necrosis to this area.

Other variations noted in the second part include a documented case report by Srimathi (2011), which noted a common trunk in the second part of the axillary artery that gave rise to the thoracoacromial, lateral thoracic, subscapular and posterior circumflex humeral arteries. Additional variations are that of a third branch that may sometimes arise, the alar thoracic artery. The alar thoracic artery is usually found in this region giving blood supply to the axillary fat, lymph nodes, fascia and skin of the axilla (Bergman *et al.*, 1999; Williams *et al.*, 1999). A study by Pantaik *et al.* (2000) however, found the emergence of the alar thoracic artery from the third part of the axillary artery. The second part may also exhibit only one branch, the thoracoacromial artery, with an absent lateral thoracic artery (Sawant *et al.*, 2012). Kogan and Lweinson (1998) documented a rare case of a 'thoraco-epigastric' artery, which, upon closer scrutiny was decided to be a longer alar thoracic artery, with some muscular branches (Rusu, 2005). Rusu (2005) noted characteristics of the alar thoracic artery, which include that the artery may exhibit bilateral characteristics in the axilla, it may exhibit bilateral asymmetry, a higher origin in the axilla which usually presents a deeply descending segment followed by a subcutaneous branch and an alar artery of lower origin that usually presents with an ascending branch, followed by a subcutaneous branch (Rusu, 2005). Knowledge of this variant arterial branch is important during surgical interventions of the axilla.

2.1.1.3 Third part of axillary artery

The last part of the axillary artery is wedged between the pectoralis major muscle anteriorly, and the subscapularis muscle posteriorly. Three branches are given off by this part of the axillary artery: the subscapular artery and the anterior- and the posterior circumflex humeral arteries (Gray, 1918; Moore e*t al.*, 2014). The subscapular artery terminates by bifurcating into the circumflex scapular artery and the thoracodorsal artery, contributing towards the anastomosis around the scapula. The anterior circumflex humeral artery is usually the smallest branch of the third part of the axillary artery and courses around the surgical neck of the humerus, most often forming an anastomoses with the posterior circumflex humeral artery. The anterior circumflex humeral artery then further gives off an ascending branch which is variable in its course and terminates by supplying the head of the humerus and glenohumeral joint. The posterior circumflex humeral artery courses posteriorly as the larger of the circumflex arteries, normally arising from the same area as the anterior circumflex humeral artery. The posterior circumflex humeral artery accompanies the axillary nerve through the quadrangular space in its course to supply the lateral and posterior aspects of the proximal humerus and glenohumeral joint. A descending branch, (which forms an anastomoses with the deep artery of the arm) is often found emerging from the posterior circumflex humeral artery (Standring, 2008).

One of the more common variations with regard to the way in which the third part of the axillary artery may branch is, two circumflex arteries arising from a common trunk along with the profunda brachii artery, without the subscapular artery. The third part of the axillary artery may also give off a common trunk from which the subscapular artery, anterior- and posterior circumflex humeral arteries and the profunda brachii- and ulnar collateral arteries may arise (Ravikumar and Siri, 2016). Ramesh and co-workers (2008) noted that the third part of the axillary artery gave rise to a common trunk that branched into the subscapular artery, anterior and posterior circumflex humeral arteries, profunda brachii artery and ulnar collateral artery. Other cases of the third part dividing into superficial and deep brachial arteries have also been documented (Ramesh *et al.,* 2008). Vijaybhaskar *et al.* (2006) reported a case where the third part of the axillary artery divided into superficial and deep brachial arteries. The superficial branch continued in the brachium and divided in the cubital fossa, terminating as the radial and ulnar arteries. The deep brachial artery gave rise to the subscapular artery, profunda brachii artery, articular branches to the glenohumeral joint and anterior and posterior circumflex humeral arteries. Safiye *et al.* (2000) and Vijaybhaskar *et al.* (2006) made similar findings, with the division in the third part of the axillary artery into superficial and deep brachial arteries in a Turkish population.

Another variation, found by Satabdi *et al.* (2014), described an anterior circumflex humeral artery and a common trunk, where the common trunk further divided into four branches supplying the arm. Data collected over a period of five years, led to observations by Ravikumar and Siri (2016) in a 60-year old male cadaver where a unilateral variation was found in the left arm. Only two branches were found, namely: the subscapular artery and a common trunk which gave rise to five branches. The five branches observed were the anterior circumflex humeral artery, the nutrient artery of the humerus, the profunda brachii artery, superior ulnar collateral artery and the inferior ulnar collateral artery. The last four branches are normally associated with the brachial artery, therefore, the brachial artery was located and followed to the cubital fossa, where it terminated as the ulnar and radial arteries (Ravikumar and Siri, 2016). Gaur *et al.* (2012) noted variations related specifically to the subscapular artery. The authors found this artery to emerge from the second part of the axillary artery in 4% of cases, with 30% of cases sharing a common trunk with the posterior circumflex humeral artery. The subscapular artery was also found emerging from the first part in 0.6% of the studies cases, with 15.7% and 79.2% from the second and third parts, respectively (Huelke, 1959). Rao *et al.* (2008) reported a case where a common trunk was noted in the third part of the axillary artery, giving rise to the subscapular, the anterior and posterior circumflex humeral, profunda brachii and ulnar collateral arteries. Another common trunk was reported by Samuel *et al.* (2006) that gave rise to the anterior and posterior circumflex humeral arteries, the subscapular artery and, then continuing in the arm by giving off the radial, middle and superior ulnar collateral arteries. A large, uncommon trunk was reported by George *et al.* (2007), which gave rise to a common circumflex humeral-subscapular trunk and the profunda brachii artery.

Collateral circulation around the scapula is an occurrence that is noted between the branches of the subclavian and axillary arteries. Thorough knowledge of these variations is paramount to surgical removal of axillary lymph nodes by surgeons operating in this region, or for anaesthesiologist and orthopaedic surgeons conducting procedures in this region. As indicated, the branches of the axillary artery may arise separately from a known location or separately through a common trunk (Hollinshed, 1958). Vascular radiologists also note these variations which play a crucial role in proper radio-diagnostic techniques during traumatic injuries. These variations are also important to anatomists and interventional cardiologists and the awareness of these variations may assist in more accurate diagnostic interpretations and surgical interventions.

2.1.2. Shoulder joint, rotator cuff (RC) unit and related pathology

The pectoral girdle involves a variety of joints working in unison in order to achieve the movements of the proximal part of the upper limb. The pectoral girdle consists of the scapula, clavicle and proximal humerus, which articulate to form the acromioclavicular and the glenohumeral joints. The movement of the pectoral girdle is achieved by the sternoclavicular-, acromioclavicular-, scapulothoracic- and glenohumeral joints (Moore *et al.*, 2014). The glenohumeral joint is classified as a multi-axial synovial ball-and-socket joint that permits a variety of movements, and as such, is more susceptible to injury and instability. The positioning of the head of the humerus in the glenoid cavity is assisted by the musculotendinous cuff that is formed by the RC muscles. Movement at the glenohumeral joint involves these joints working in unison or alone in order to allow for the correct and accurate positioning and precise motor movement of the upper limb (Donnelly *et al.*, 2013).

The fibrous layer of the joint capsule surrounds the glenohumeral joint, attaching medially to the margin of the glenoid cavity and laterally to the anatomical neck of the humerus. Two openings are associated with the joint capsule, namely the opening between the tuberosity of the humerus which allows the passage of the tendon of the long head of the biceps brachii muscle and the opening situated anteriorly, inferior to the coracoid process, which allows communication between the subtendinous bursa of subscapularis and the synovial cavity of the joint (Moore *et al.*, 2014). The inferior portion of the joint capsule is not reinforced by the RC muscles, however, the weakest point of the shoulder capsule is situated anterior to the attachment of the long head of the triceps brachii muscle, resulting in most dislocations in this inferior, anterior region (Moore *et al.*, 2014). Primary movements of the shoulder are abduction, adduction, flexion, extension, internal/medial rotation and external/lateral rotation. The ability to achieve these movements is dependent on a variety of factors including age, sex, hand dominance and pathology (Barnes *et al.*, 2001).

Pathology of the shoulder joint and related musculoskeletal disorders presents in many forms, with the resultant outcome leading to disruption in the normal functioning of the glenohumeral joint. Shoulder complaints are one of the most common musculoskeletal problems in the general population with the leading condition being RC tears (Picavet and Schouten, 2003). RC tears are classified into two main types: partial tears and full-thickness tears with each type often causing shoulder pain, stiffness to the joint, weakness and ultimately affecting the joint range of motion (ROM) (Matthewson *et al.*, 2015). There are cases of asymptomatic RC tears described by numerous publications, with Minagawa (2013) documenting the prevalence as high as 50% in individuals around 50 years of age (Milgrom *et al.*, 1995; Sheer *et al.*, 1995; Templehof *et al.*, 1999; Minagawa *et al.*, 2013). RC tears where partial or full-thickness tears are noted, are usually a result of physical activity in individuals younger than 40 years, or due to degenerative changes in the older population. Degenerative changes to the RC are found to manifest in different sizes, parts and forms, with the severity of the tear found to be variable. It is worth noting that the size of the tear does not account for the severity of the symptoms, with some minor tears found to cause severe pain and symptoms when compared to much larger tears (Fukuda, 2003). Larger tears, however, present with other problems such as secondary atrophy and gradual loss of muscle function due to fat accumulation (Lamplot *et al.*, 2014).

In the clinical setting, RC related pathology accounts for about 65% of all shoulder related complaints, with the remaining percentages being linked to pericapsular soft-tissue pain (11%), acromioclavicular joint pain (10%) and referred pain from cervical spine pathology (5%) (Vecchio e*t al.*, 1995). Acute onset of pain is often a consequence of some traumatic event resulting in an injury; these are usually associated with a younger population (Green, 2003). Chronic injuries, on the other hand, seem to be afflictions in the older population usually linked to overhead activities. In the older population a common complaint is the gradual loss of strength, with the onset of these symptoms usually triggered by something small and worsening with time, known as acute-on-chronic injury (Green, 2003; Bishay and Gallo, 2013). Pathology linked to RC injury is usually felt in the anterolateral aspect of the shoulder, with the severity of the pain increasing towards the end of the day or when the arm is abducted more than 90º.

Some patients with full thickness- or partial tears, however, may be asymptomatic with the diagnosis only made following an MRI, as is usually the case in patients older than 60 years. Musculoskeletal evaluation of the affected limb should involve observation, palpation, ROM, motor strength, sensation and pulses, with the physician encouraged to compare such findings with the contralateral limb (Bishay and Gallo, 2013).

2.2. Clinical Component

2.2.1. Surgical intervention - History

The main goal of any surgical procedure is to alleviate pain and improve functionality of the repaired tissue. RC surgery is no exception, with the surgical intervention taking the form of open surgery, mini-open- or arthroscopic surgery (Depres-Tremblay *et al.*, 2016). Studies have been performed that advocate for the various repair procedures and several studies have shown the efficiency of both open- and mini-open procedures (Guity and Eraghi, 2015; Parada *et al.*, 2015). Arthroscopic repair has also been shown to pose certain advantages, with this form of treatment being favoured in developed countries due to its less invasive nature and the ability for application to all types of tears (Burkhart and Lo, 2006; Zuke *et al.*, 2017). However, concerns related to the arthroscopic repair have been raised, including the inability to fully repair RC tears and the resultant loss of performance due to the difficulty in performing this procedure (Bishop *et al.*, 2006). The open repair is advantageous in developing countries due to its cost-effective nature (Nafisi *et al.*, 2018).

The first recorded case of shoulder manipulation dates back 3000 years, when a depiction of a leverage method of shoulder reduction was captured by Egyptian hieroglyphs. The hieroglyphs recorded forty-eight types of medical problems, along with the anatomical observations, examination, diagnosis, treatment and prognosis thereof. The method of treatment using a leverage was re-introduced in 1870 by Theodor Kocher, but due to the possible complications that may arise from the use of this technique, the method was discontinued (Broca and Hartmann, 1890; Smith, 1930; Burkhead, 2011). In 400 BC, Hippocrates introduced the traction method to reduce the shoulder. This method required the patient to lie in a supine position with the physician standing on the side of the affected arm, traction was then applied. The physician would use his foot (covered in a stocking) as a counter-traction by placing it in the patient's axilla. This form of shoulder manipulation remained for centuries (Broca and Hartmann, 1890).

Prior to recordings made by Hippocrates, evidence of anatomical dissection was found, as carried out by Susruta and Atreya, 150 years before Hippocrates (Hoernle, 1907; Persaud, 1984; Jobe, 1990). Susruta and Atreya are recorded as having placed a body in a river for seven nights, allowing the skin to macerate and revealing the underlying muscles, tendons and bones (Burkhead, 2011). Hippocrates also discussed the shifting of tendons following dislocations, and/or inflammation of tendons around the shoulder with the recommendation of gentle early motion around the joint (Burkhead, 2011). It must be noted, however, that the observations made by Hippocrates, just like those of Aristotle, were purely speculative, as theirs were experiments carried out on animal specimens and otherwise limited to wound care (Burkhead, 2011). The recorded cases of some of the first human dissections are credited to the man often called "the father of anatomy" Herophilus, who is said to have carried out these dissections on bodies often belonging to criminals of Alexandria during the period subsequent to Hippocrates (Hippocrates, 1972). In the Middle Ages, advancements in human anatomical knowledge slowed down due to prevailing religious beliefs until the 13th century, when the capsular rupture of a necropsy specimen with a dislocated shoulder was described by Ruggerio (Reeves, 1928). After anatomical teachings were allowed, Andreas Vesalius (a Belgian anatomist) authored a series of publications "*De Corpora Humanis Fabrica Libri Septem*" (English: "On the composition of the human body in seven books") in which the anatomy of the RC was depicted (Codman, 1908; Saunders e*t al.*, 1950). The first recorded description and depiction of a torn RC is found in the book authored by Alexander Munro in 1788, *"A Description of All the Bursal Mucosae of the Human Body"*, which documents a tear of the supraspinatus and infraspinatus muscles (Munro, 1788). This was followed by Smith's publications on a series of RC ruptures in 1834, which described most tear types as currently known today (Burkhead, 2011).

In the 1800s, Eduard Albert was the first to perform shoulder arthrodesis (Broca and Hartmann, 1890). The credit for the first description of ruptures of the shoulder, however, is often given to JG Smith, who in 1834 described the occurrence of a rupture relating to the tendon of the shoulder during injury (Smith, 1834). Smith then went on to publish a series of cadaver RC tears that included dislocation of the long head of biceps brachii muscle and RC arthropathy (Smith, 1834). Many of the tear types described are consistent with current documented cases. The role of dislocations in the causation of RC avulsions as identified in cadavers was hypothesised by Jean-François Malgaigne in 1855 (Malgaigne, 1855). Malgaigne (1855) detailed the pathology related to the RC and how impingement plays a role in RC tears following a dislocation (Jössel, 1871; Jössel, 1880; Kronlein, 1882; Jössel, 1884; Malgaigne, 1840). Subsequent to this study, two authors, Flower (1861) and Adams (1873) described RC tears where a link was made between arthritic-, rather than traumatic events as the cause of the pathology. RC tears are at times noted following a dislocation as was documented by Franz Freiherr von Pitha and Joessel and von Waldeyer-Hartz (1884) in the same period. The resultant fat infiltration to the degenerating muscle was noted following the dislocation (Billroth *et al.*, 1865; Joessel and von Waldeyer-Hartz, 1884). Other dislocation related documentations included the re-attachment of the torn tendons to the humerus as noted by Krönlein (1882) and Bardenheuer (1888), respectively. Further investigations into the dislocation of the glenohumeral joint necessitated the understanding of the detailed anatomy of the glenohumeral ligament complex and its association with chronic instability of the shoulder, these studies were carried out by Broca and Hartman (Broca and Hartmann, 1890). Between 1860 and 1980, further descriptions and investigations of shoulder pain were documented, which included impingement of the bursa under the acromion, entrapment and/or dislocations of the long head of the biceps brachii muscle and subacromial stiffness and adhesion (Jaravay, 1867; Duplay, 1872).

Karl Hüter (1870) is credited with the first attempts at surgical repair of a torn cuff tendon by attaching it to the humeral diaphysis following a humeral head resection. Success was achieved by Wilhelm Müllller (1898) who repaired RC tears to the humeral head during a shoulder stabilization surgery (Perthes, 1906). However, the first shoulder arthroplasty was performed by Jules Péan, who in 1893, carried out this procedure in a case of shoulder joint destruction due to tuberculosis (Lugli, 1978; Wirth and Rockwood, 1996). The prosthesis used for this procedure was designed by a dentist, with the prosthesis humeral stem made of leather and platinum and the articulating component, the glenoid cavity, made of paraffin coated ebonite. This devise was removed after two years, due to chronic infection that developed (Iqbal *et al.*, 2013). The development of prosthetic placements came to a halt, until Neer performed the first hemi-arthroplasty for a comminuted proximal humerus fracture fifty years later (Neer *et al.*, 1953). Further shoulder related repairs were attempted by Perthes (1906), and later Bankart (1923), ascertaining that the detachment of the glenoid labrum caused instability of the shoulder and emphasized reattachment of the glenoid labrum to stabilize the joint. The operative method developed by Perthes entailed using bone clips and transglenoidal stitches. This technique, with some modifications, is still used to date (Perthes, 1906; Iqbal *et al.*, 2013). In this period, Perthes (1906) reported a series of three RC repairs where he documented the first-time use of suture anchors.

The repair of RC tears is a common surgical procedure with notable publication on the attrition theory of cuff ruptures being documentedd by Meyer in 1924 (Meyer, 1924). A further description was provided by Codman, who in 1934, summarized his 25 years of observations on the supraspinatus tendon (Codman, 1934). This publication was followed by McLaughlin’s detailed work on RC repairs and their management (McLaughlin, 1944; McLaughlin and Asherman, 1951). Codman (1911), in a milestone article on RC surgery, described the surgical technique for supraspinatus tendon repair. McLaughlin (1944) is also credited with the first classification of tears where they were subdivided into categories of transversal, vertical and retracted tears. This classification system was expanded upon by De Orio and Cofield (1984), Harryman *et al.* (1991), Ellman and Gartsman (1993) and Snyder (2003).

Shoulder repair methods started with the use of open techniques with the first RC repair performed by Codman in 1911 (Codman, 1911; Yamaguchi *et al.*, 2003). Codman is credited with the initial reports of successful RC repair in 1908 and 1910 (Mallon, 2000). Knowledge of RC tendon tears and their repair was expanded upon by Codman in his work, "*The Shoulder: rupture of the supraspinatus tendon and other lesions in or about the subacromial bursa"* (Codman, 1934). In the same period, Goldthwait wrote on the role of the wear of the acromion, coracoid process and arthritic acromioclavicular joint, and their significant contribution to RC tears (Goldthwait, 1909). Stevens (1909) also described the biomechanics of the RC and the contribution of alternating coupling forces to the subacromial symptoms. Codman's methods were later modified by Neer in 1972, which included a description of five fundamentals to open RC repair techniques (Neer, 1972; Yamaguchi *et al.*, 2003). The methods as proposed by Neer, included meticulous repair of the deltoid muscle origin, subacromial decompression, surgical releases as necessary to obtain freely mobile muscle-tendon units, securing transosseous fixation of the tendon to the greater tuberosity and closely supervised rehabilitation with early passive motion (Yamaguchi *et al.*, 2003). Neer is also credited with popularizing the concept of impingement syndrome and its classification of three phases: acute, chronic and chronic with associated RC tear (Neer, 1972; Matsen, 1994).

The development of RC repair was further accelerated by advancements in imaging techniques, with new possibilities of visualising the internal structures of the joint. This arthrography method was used in 1949 in the diagnosis of RC tears (Withers, 1949). Kessel (1950) strengthened this form of diagnosis by applying it to traumatic bursitis, frozen shoulder diagnoses, RC tears and osteochondromatosis. Arthrography was further used as an established diagnostic tool in the treatment of the "frozen shoulder", twenty-five years following its introduction (De Seze *et al.*, 1961; Andren and Lundberg, 1965; Nelson and Burton, 1975). The "frozen shoulder" is a clinical term used to describe adhesive capsulitis, a condition resulting in stiffness and pain of the shoulder joint. The introduction of magnetic resonance imaging (MRI) brought about

a new era in shoulder imaging, allowing better classification of RC tears. This allowed surgeons to visualise the tears prior to surgically repairing them, therefore creating an advantage of planning the repair procedure thoroughly (Randelli *et al.*, 2014).
In order to repair RC tears, various methods are used one of which is the open technique, which uses the transosseous suture repair method with the use of the locking-stitch known as the modified Mason-Allen stitch (Gerber *et al.*, 1994; Caldwell *et al.*, 1997), and was considered the gold standard until the onset of the new century (Hawkins *et al.*, 1985; Ellman *et al.*, 1986; Iannotti *et al.*, 1996; Gupta *et al.*, 1997; Rokito *et al.*, 1999; Aleem and Brophy, 2012). Various cadaveric studies investigating transosseous repairs showed good biomechanical characteristics after repairs (Ahmad *et al.*, 2005; Chhabra *et al*., 2005; Bicknell *et al.*, 2005; Tuoheti *et al.*, 2005; Yu *et al.*, 2005; Behrens *et al.*, 2012). The open technique continues to be used by many surgeons in repairing large or massive tears (Ghodadra *et al.*, 2009).

The methods implored in open surgery entail performing the repair with the patient in the beach-chair position. The beach-chair position describes the position assumed by patients in theatre, where patients sit at an angle in the ranges of 30º-90º above the horizontal plane. The patient is appropriately padded with the head secured in the head rest. Following the identification, and at times, marking of the appropriate landmarks, an incision is made over the anterior superior aspect of the shoulder in line with Langer's lines. Detachment of the deltoid muscle from the acromion follows with the muscle then being split laterally. Subacromial decompression, bursal resection and debridement are performed prior to bone preparation. The greater tuberosity is then prepared with a burr osteotome. Drill holes are made in the cortical bone which will allow for the suturing of the torn tendon. A modified Mason-Allen stitching technique is used to repair the torn tendon. The deltoid muscle is reattached to the acromion and the longitudinal deltoid split is closed (Randelli *et al.*, 2014).

The advantage of the open technique is its ability to repair tissue even though the remaining tissue may be poor and significant tendon retraction and adhesion is likely, therefore making the use of the arthroscopic method undesirable (Ghodadra *et al.*, 2009). Multiple studies have shown that 80 – 94% of the patients who have undergone open RC repair have excellent results post-surgery (Hawkins *et al.*, 1985; Ellman *et* *al.*, 1986; Neer *et al.*, 1988; Cofield *et al.*, 2001). There are, however, some disadvantages associated with the use of the transdeltoid open repair approach, such as deltoid dysfunction and postoperative pain (Rokito *et al.*, 1996; Rokito *et al.*, 1999; Yamaguchi *et al.*, 2003) although, these claims have been refuted by some authors (Vastamaki and Vastamaki, 2014; Williams *et al.*, 2014). Other repair methods used include the single row, double row, suture bridge double row transosseous equivalent technique as well as the subacromial bursectomy, with or without acromioplasty (Pandey and Willems, 2014). With all the techniques that have evolved over the years, there is still disagreement amongst various surgeons as to the optimal repair method. Park *et al.* (2005) promoted the transosseous techniques due to its having a better contact area and interface pressure over the RC footprint, as compared to the anchor techniques. In their study, Park *et al.* (2005) also demonstrated that even the double row technique only restores 50% of the contact area and 80% of the contact pressure, as compared to the transosseous technique. The clinical results of open transosseous, suture anchor and transosseous equivalent technique are comparable (Behrens *et al.*, 2012; Maier *et al.*, 2012). Single row techniques, however, although cheaper, quicker and simpler, show higher reoccurrence of ruptures after two years (Galatz *et al.*, 2004; Tuoheti *et al.*, 2005; Ide *et al.*, 2005; Suyaga *et al.*, 2005; Charousset *et al.*, 2010).

In repairing RC tears, initial fixation strength is vital, a concept that has been highlighted by various biomechanical studies that have focused on highlighting the strongest devices, knots, and repair configurations for RC repair (Craft *et al.*, 1996; Reed *et al.*, 1996; Caldwell *et al.*, 1997; Goradia *et al.*, 2001; Koh *et al.*, 2002; Schneeberger *et al.*, 2002; Demirhan *et al.*, 2003; Waltrip *et al.*, 2003; Ma *et al.*, 2004; Lee *et al.*, 2005). Numerous factors have been shown to contribute to the optimal repair of the RC, these include: repaired RC tendon-footprint motion (Ahmad *et al.*, 2005), increased tendon-footprint contact area (Apreleva *et al.*, 2002; Park *et al.,* 2007(a); Park *et al.*, 2007(b)) and tissue quality of tendon and bone (Lee, 2013).

2.2.2. Pre-operative examination, post-operative care and follow-up

Several factors contribute to the ultimate repair of the RC. These include high fixation strength, minimal gap formation, maintenance of mechanical stability under cyclic loading and proper healing of tendon-to-bone fixation. In addition to all these factors involving adequate surgical repair, proper rehabilitation is important for optimal repair of the RC (Ghodadra *et al.*, 2009).

Numerous shoulder functionality tests are conducted pre- and post-surgery to determine the full extent of RC damage. Following surgical repair of the RC, various post-operative mechanisms are implored in the attempt to return the patient to full pre-injury functionality. A variety of muscle strength tests are conducted and exercises carried out, usually by a physiotherapist or biokineticist, in an attempt to return to the full ROM as prior to the injury. During this period, two types of integrity tests are conducted: tests that determine whether a movement can be undertaken actively and tests that investigate the maintenance of a passive position or lag signs. Studies conducted by Gerber and Krushell (1991), Gerber *et al.* (1996) and Hertel *et al.* (1996) have documented a number of these signs.

The lift-off test was first described by Gerber and Krushell (1991) for examination of an isolated rupture of the subscapularis tendon (Figure 2.1). In their study, the authors reported on a test, based on their observation that weakness of internal rotation is most easily demonstrated at the limit of amplitude of contraction of the muscle when the arm is fully extended and internally rotated. Gerber and Krushell (1991) noted how a patient with a subscapularis rupture was unable to lift the dorsum of his hand off his back, a finding which is referred to as a 'pathologic lift-off test.' These findings were further validated in a study by Greis *et al.* (1996) who confirmed, in the analysis of the lift-off test, that the subscapularis muscle was most active with the hand in midlumbar position when resistance was applied. A study by Stekfo *et al.* (1997) looked at the lift-off test in which further analysis for alternative hand positions was conducted for patients with a normal subscapularis muscle and patients with muscle-deficient subscapularis muscles following anaesthetic blockade to the muscle. The findings indicated an inability to perform the lift-off test when in maximum internal rotation when the hand was held up against the inferior aspect of the scapula (Stekfo *et al.*, 1997). Gerber *et al.* (1996) described another shoulder functionality test for subscapularis muscle rupture, the lift-off test (Lag Sign). In their study, this test was performed by bringing the arm passively behind the body into maximum internal rotation. Normal results are documented if the patient maintains maximum internal rotation after the clinician releases his/her hand (Gerber *et al.*, 1996). The belly press test, as described by Gerber *et al.* (1996), is conducted in patients displaying a decrease in internal rotation of the arm. In the performance of the test, the patient is required to press the abdomen with the palm of the hand and attempt to keep the arm in maximum internal rotation while performing this action (Figure 2.2). Injury to the subscapularis is detected by the inability to maintain maximum internal rotation; the patient feels weakness and the elbow is noted as dropping behind the trunk.

Other tests were described by Hertel *et al.* (1996), which included the external rotation lag sign, drop sign and the internal rotation lag sign. The external rotation lag sign test is performed with the patient seated and his/her back turned to the clinician. The elbow is flexed passively at 90° and the shoulder is held at a 20° elevation, in the scapular plane, and near maximum external rotation by the clinician. The patient is requested to maintain the position of external rotation as the clinician releases the wrist, while maintaining support of the limb at the elbow. A positive sign is documented when a lag or angular drop occurs (Gerber *et al.*, 1996; Hertel *et al.*, 1996). In the drop sign test, the patient sits with his/her back turned to the clinician. The clinician holds the arm at 90° of elevation, in the scapular plane, at almost full external rotation with the elbow flexed at 90° (Figure 2.3). The infraspinatus muscle is mainly functioning in this position, maintaining external rotation of the shoulder. As the clinician releases the wrist while supporting the elbow, the patient is asked to actively maintain this position during this release. A positive test is documented if the arm drops due to pain and weakness which may indicate injury to the infraspinatus muscle. The internal rotation lag sign is performed with the patient’s back to the clinician and affected arm held at maximum internal rotation by the clinician (Figure 2.4). The affected arm is flexed to 90°, and the shoulder held at a 20° elevation and at 20° of extension. The dorsum of the hand is passively lifted away from the lumbar region until almost full internal rotation is reached. The patient is required to actively maintain this position as the clinician releases the wrist while still supporting the elbow. The sign is positive when a lag occurs. An obvious drop of the hand is indicative of large tears. A slight lag is indicative of a partial tear to the upper part of the subscapularis tendon.

Shoulder functionality tests also include impingement tests, which are intended either to reproduce symptoms or produce pain that is indicative of focal abnormalities. Neer’s impingement sign and impingement test was first mentioned in 1972 when Neer described one of the diagnostic features as being “pain at the anterior edge of the acromion on forced elevation” (Neer, 1972). Neer offered a more comprehensive description 1983 in his article entitled *Impingement lesions*. In this article, the following description is offered: “The impingement sign is elicited with the patient seated and the examiner standing. Scapular rotation is prevented by one hand as the other raises the arm in forced forward elevation (somewhere between flexion and abduction), causing the greater tuberosity to impinge against the acromion” (Neer, 1972). This manoeuvre, however, is found to cause pain in patients with impingement lesions of all stages and to patients with numerous other shoulder conditions. These conditions include stiffness/partial frozen shoulder, instability, arthritis, calcium deposits and bone lesions. Findings documented in an anatomical study revealed soft tissue contact with the medial aspect of the acromion in all specimens when the shoulder was in the “Neer position” (Valadie *et al.*, 2000).

A study by Hawkins and Kennedy (1980) presented an alternative test (Hawkins’ test) to the one described by Neer, despite the test being regarded as less reliable than Neer’s test. This test included the forward flexion the humerus to 90° and forcibly internally rotating the shoulder in an attempt to diagnose impingement. This manoeuvre reproduces the pain associated with impingement by moving the greater tuberosity further under the coracoacromial ligament. An anatomical study demonstrating the Hawkins’ test found that all specimens used were found making contact between the coracoacromial ligament and either the RC or the biceps brachii tendon. Contact was also made between the articular surface of the cuff and the anterosuperior glenoid rim (Valadie *et al.*, 2000).

Yocum’s test was described in 1983 by Yocum in the attempt to selectively test the function of the supraspinatus muscle. His method includes the abduction of the patients’ arm at 90º with the arm flexed forward at 30º and the arm maximally internally rotated with the thumb down (Figure 2.5). This description appears very similar to that offered in Jobe’s test (Yocum, 1983). The Jobe’s test is conducted with the patient’s arm at 30° of abduction in the scapular plane, with the elbows flexed at 90° and the hands pointing inferiorly with the thumbs directed medially. A positive test is indicated when pain or weakness on resisting downward pressure on the arms, or an inability to perform the tests is noted (Parentis *et al.*, 2004). This test was initially described by Jobe and Jobe (1983) who reported it as a 'supraspinatus test'. In this description, the test is performed by first assessing the deltoid muscle with the arm at 90° of abduction and neutral rotation. Internal rotation of the shoulder angled forward at 30° then follows, with the thumb pointing towards the ground. Weakness or insufficiency of the supraspinatus muscle against resistance, and pain experienced, will indicate the presence of a tear associated with RC impingement (Jobe and Jobe, 1983). A study by Jobe and Moynes (1982) also cites this testing mechanism, however, in this article the muscle strength test was described as a rehabilitation procedure and not a proactive test.

The internal rotation resistance stress test (IRRST) as described by Zaslav (2001), relates to the attempt to differentiate between intra-articular syndrome and outlet impingement syndrome. The inclusion criteria for this study, involving 110 patients, included a positive Neer impingement sign. The test is performed with the patient in the standing position and the clinician positioned behind the patient. The patients arm is positioned in 90° of abduction in the coronal plane and approximately 80° of external rotation. A manual isometric muscle test is performed for external rotation and then compared with findings for internal rotation in the same position. If a patient with a positive impingement sign has good strength in external rotation in this position and apparent weakness in internal rotation, the IRRST result is considered positive (Zaslav, 2001).

Gerber's subcoracoid impingement test was described by Gerber *et al.* (1985). Two tests to reproduce entrapment of the RC between the humeral head and the coracoid process were described, with the most sensitive of the tests described as "Abduction to 90°". This test includes abduction at 90º combined with medial rotation which is restricted and consistently painful, at times producing radiation to the upper arm and forearm (Figure 2.6). This position was found decreasing and resulting in the smallest coracohumeral distance. The second test, which assessed forward flexion combined with medial rotation, was the most sensitive at detecting impingement produced as a result of iatrogenic or traumatic change in the anatomy of the RC (Gerber *et al.*, 1985).

Hamner *et al.* (2000) described the modified relocation test, a variation of Jobe's relocation test, which assesses "internal impingement." The modified relocation test was performed with the shoulder abducted at 90°, 110° and 120° in maximum external rotation. The modification included additional testing positions at 110° and 120°. The test was done with the patient supine and with the affected arm in maximal external rotation and abducted in the coronal plane. Pain was evaluated by the clinician when an anterior- and then a posterior directed force was applied to the proximal humerus. A positive test was obtained if the patient experienced pain with an anterior force and the pain was relieved with a posterior directed force (Hamner *et al.*, 2000).

Other shoulder evaluation tests include, but are not limited to, the following: The ROM test is used as an assessment tool during the patient history evaluation, prior to any surgical intervention. This test is also used post-surgically to test the level of movement at the repaired site. The patient's ability to perform a variety of movements around the glenohumeral joint is tested. Due to the complexities of the glenohumeral joint, the patients' affected arm is tested and compared with the unaffected limb, this way, the patients' normal or base ROM can be determined. The movement tests included forward flexion, abduction, external rotation and internal rotation at the shoulder joint of the affected limb (Figure 2.7). Shoulder abduction for instance, involves the movement of the glenohumeral joint and scapulothoracic articulation. It is possible to isolate the movement of these joints. The glenohumeral joint for instance is tested separately by holding the patients' scapula with one hand while the patient abducts their arm. External rotation is assessed with the arms on the side and the elbow flexed at 90º. Internal rotation is tested by asking the patient to reach behind the back and touch the inferior portion of the scapula on the opposite side (Woodward and Best, 2000).

The strength test evaluates the patient's ability to perform predetermined movements. This test assesses the strength of certain muscles such as supraspinatus and subscapularis. The supraspinatus strength is tested with the arm held at 90° of scapular elevation. The patient is required to resist a downward force applied by the doctor on his/her arm. The strength of the subscapularis muscle is tested by placing the hand of the affected shoulder behind the back. The patient pushes outwards, countering an inward push on the palm applied by the doctor. The doctor measures the current strength of the patient's subscapularis muscle by determining how much force was needed to resist the patient's attempt to lift his/her hand from the back (van Kampen *et al.*, 2014).

Shoulder scores refer to clinical methods used in assessing the functionality of the shoulder joint. These tests are computer based assessments and are used to assess the functionality and limitations of the shoulder. The ASES (The American Shoulder and Elbow Surgeons) shoulder score is a patient self-evaluation that assesses the patient's daily activities. This evaluation can be applied to a wide spectrum of shoulder pathology patients regardless of the specific diagnosis (Booker *et al.*, 2015). The Constant-Murley score is a 100-point scale, first presented in 1987, and is used to assess the overall function of the shoulder. Four different aspects of shoulder related pathology are assessed by the Constant-Murley score, these include: pain, activity of daily living, ROM and strength (Constant and Murley, 1987). The VAS (Visual Analog Scale) score is used to measure the intensity of pain by using a scoring system ranging from 0 – 10, with 0 indicating no pain and 10 being the highest intensity of pain.

The Simple Shoulder Test (SST) is a shoulder functionality test important for systematic documentation of shoulder function. This test was developed by Rick Matsen and has been reported as a reliable self-assessment tool proven to be valid and highly reliable. The test normally consists of a series of 12 'yes' and 'no' questions that the patient answers related to shoulder function (Roy e*t al.*, 2010). The Rowe score is a scoring system for the postoperative assessment of Bankart's repair. Bankart repair refers to the surgical intervention for the repair and reattachment of a torn labrum. The Rowe score is used to address the categories of shoulder stability, motion and function. Scores range from 0 – 100 with a score of 90 – 100 points indicating an excellent evaluation, 75 – 89 points indicating a good evaluation, 51 – 74 points indicating a fair evaluation, and 0 – 50 points indicating a poor evaluation (Terra *et al.*, 2019).

The speeds test includes evaluation with the patient seated, elbow extended and forearm in full supination (Figure 2.8). The doctor resists active forward flexion from 0°to 60°. A positive test is achieved when pain increases in the shoulder and the patient localises the pain to the bicipital groove (Cook *et al.*, 2012). The test was initially described by Crenshaw and Kilgore (1966) and entails examination with the patient's shoulder elevated anteriorly against resistance, with the elbow extended and forearm supinated. A positive result is indicated if the pain is localised to the bicipital groove (Crenshaw and Kilgore, 1966).

The O'Brian's test (Compression rotation test/ Crank test) is carried out with the patient in a standing position. The affected shoulder is at 90° of flexion, 10° of horizontal adduction and maximum internal rotation with the elbow in full extension. The clinician then applies a downward force at the wrist of the involved arm which the patient must resist (Figure 2.9). Any pain experienced "on top of the shoulder" (acromioclavicular joint) or "inside the shoulder" (SLAP lesion) is reported accordingly. The patient's shoulder is then moved to a position of maximum external rotation and the downward force is repeated. A positive test is indicated by pain or painful clicking in shoulder internal rotation and less or no pain in external rotation (Cook *et al.*, 2012).

Yergason's test is used to diagnose labral tears or bicipital tendinopathy. The patient is asked to flex their elbow with the forearm in a prone position. This test was initially described by Yergason (1931) and assesses the 'supination sign'. In the described method, the elbow is flexed at 90º with the forearm pronated, while the clinician holds the patient's wrist with the purpose of resisting supination (Figure 2.10). Active supination is then attempted against this opposing force and any pain linked to the bicipital groove indicates damage to the tendon of the long head of biceps brachii, or synovitis in the tendon sheath thereof. This is regarded as a positive sign (Yergason, 1931).

In the biceps load test, a positive test is indicated as a reproduction of concordant pain during resisted elbow flexion. At the beginning of the test, the patient lies in a supine position with the clinician sitting at the side of the patient's involved limb. The clinician places the patient's shoulder in 120° of abduction, the elbow in 90° of flexion and the forearm in supination (Figure 2.11). The clinician moves the patient's shoulder to end-range external rotation (apprehension position) and then asks the patient to flex his/her elbow while the clinician resists this movement (Cook *et al.*, 2012).

It must be noted that, since a large number of tests are used for shoulder examination, it is up to the clinician to selectively and carefully choose appropriate tests for diagnostic purposes. The concern for many physicians following RC repair is the possibility of shoulder stiffness, therefore, necessitating initiation of motion of the affected shoulder as soon as possible. In the rehabilitation process, it is important to exercise caution and for the specialist to take it slow initially, a balance between applied force and tissue-healing constraints is important, as an aggressive approach could compromise the repair process. Numerous rehabilitation techniques are currently in use with effectiveness measuring higher in some than in others. Seven shoulder exercises were performed by Dockery *et al.* (1998) where electromyographic surface electrodes were introduced in order to measure various activity levels. The best approach for passive joint mobility was documented with the patient in a supine position, with the muscles being more active when the rope-and-pulley ROM exercises were implored. The rope-and-pulley ROM entails passive movement of the shoulder using a pulley mechanism, which allows you to pull one end of the pulley with the unaffected arm, allowing the affected arm to relax while performing the necessary passive ROM (Figure 2.12). Ghodadra *et al.* (2009) documented the need to apply passive ROM in the initial stages and progressively accelerate ROM in line with tissue healing. In their study, the passive shoulder external rotation was restricted to 45º with the arm at 30º - 45º of abduction in the scapular plane. Forward elevation was limited to 120º in an attempt to restrict damage to the healing tissue (Ghodadra *et al.*, 2009). Ghodadra *et al.* (2009) also recommended the use of isometric exercises in the prevention of muscle atrophy and minimisation of RC inhibition.

A study by Hawkins *et al.* (1985), in which 100 patients were followed-up for a period of 4.2 years post-surgery, documented findings that indicated that 86% of patients experienced slight or no pain following repair using the open-surgery technique. Noted also in the study was the improvement in the ROM during this period, with the improvement from 81º preoperatively to 125º post-operatively (Hawkins *et al.*, 1985). Neer *et al.* (1988) documented a 91% patient satisfaction rate in 245 patients who had undergone open RC repair. Cofield e*t al.* (2001) reviewed 105 patients who had open RC repair surgery and found tear size to be the most important determinant of outcome, when looking at the active motion, strength, satisfaction following surgery and the need for reoperation. In their study, Rokito *et al.* (1999) reported a 76% patient satisfactory outcome in 30 patients on whom large and massive tears had been repaired; the follow-up period was for up to five years. Their post-operative tests included passive ROM exercises and the use of an arm sling for six weeks. Active ROM was introduced following the six-week recovery period, with the addition of isometric and isotonic RC muscle strengthening exercises (Rokito *et al.*, 1999). A 68% tendon healing satisfaction outcome was also reported by Harryman e*t al.* (1991) in a sample of 105 patients after a five-year follow-up period. Several other authors have also documented positive post-operative results following surgical repair using the open technique (Neer *et al.*, 1988; Harryman e*t al.*, 1991; Rokito *et al.*, 1999).

Figure 2.1: Subscapularis lift off test is demonstrated. The positive lift-off test shows the starting point (a) and termination (b) of the test. It can be seen in image (b) that the patient is unable to move her forearm from her lower back. *Image Source: Clark et al., 2002.*

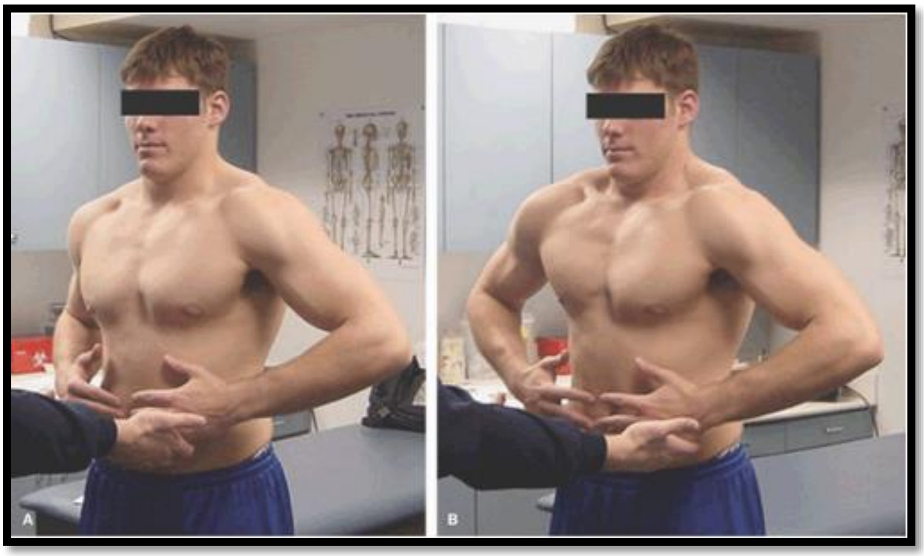

Figure 2.2: The belly press test is demonstrated in this figure with (A) showing a positive belly press test. It can be seen from this image that the elbow moves posterior to the trunk with the patient demonstrating the inability to maintain internal rotation. Image (B) shows maintained internal rotation with the elbow situated anterior to the trunk. *Image Source: https://musculoskeletalkey.com/subscapularis-repair-open-surgical-technique/*

Figure 2.3: Demonstration of the drop sign test. The clinician holds and elevates the patients arm at 90º in the scapular plane, the elbow is flexed at 90º with the arm at almost full external rotation. *Image Source: https://musculoskeletalkey.com/physical-examination-4/*

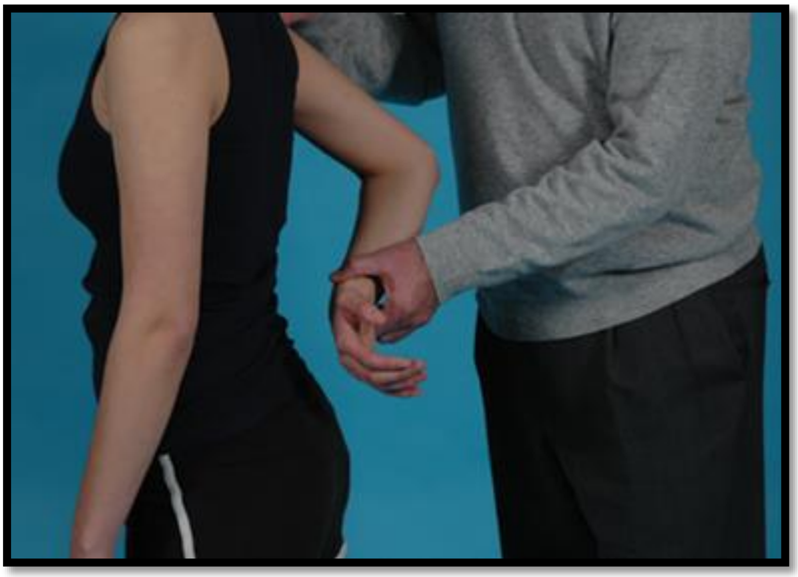

Figure 2.4: Demonstration of the internal rotation lag sign test. The patients' arm is held at maximal internal rotation by the clinician. The affected arm is flexed at 90º and the shoulder held at 20º elevation and 20º extension. The dorsum of the hand is passively lifted away from the lumbar region until full internal rotation is achieved. *Image Source: www.accessphysiotherapy.com*

Figure 2.5: Demonstration of the Yocum sign test, which tests functionality of the supraspinatus muscle. The patients' arm is abducted at 90º by the clinician, while flexed at 30º and maximally internally rotated with the thumb down. *Image Source: https://musculoskeletalkey.com/physical-examination-4/*

Figure 2.6: The Gerber subcoracoid impingement test includes the medial rotation and abduction of the patients' arm at 90º by the clinician. *Image Source: https://www.slideshare.net/PraveenKumarReddyGorantla/shoulder-impingement-syndrome-86040342*

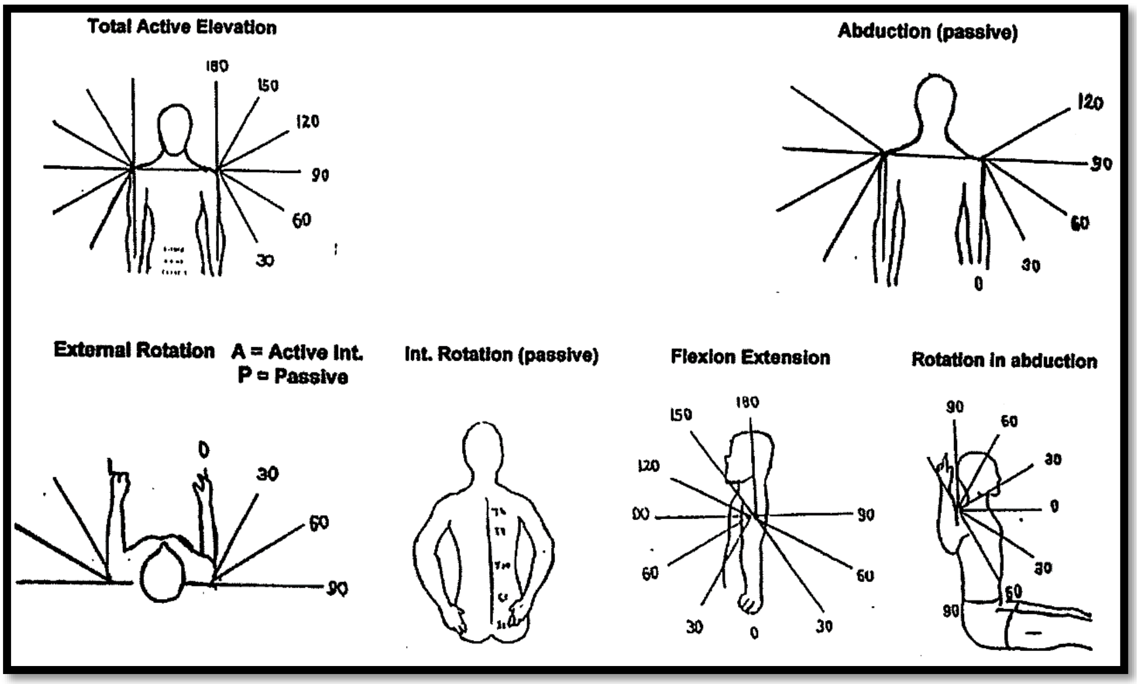

Figure 2.7: Range of motion (ROM) test. *Image Source: Dr MA de Beer, 2018.*

Figure 2.8: With the speed test, the patient sits and the elbow is extended with the forearm in full supination. The clinician resists active forward flexion from 0º - 60º. *Image Source: https://musculoskeletalkey.com/physical-examination-4/*

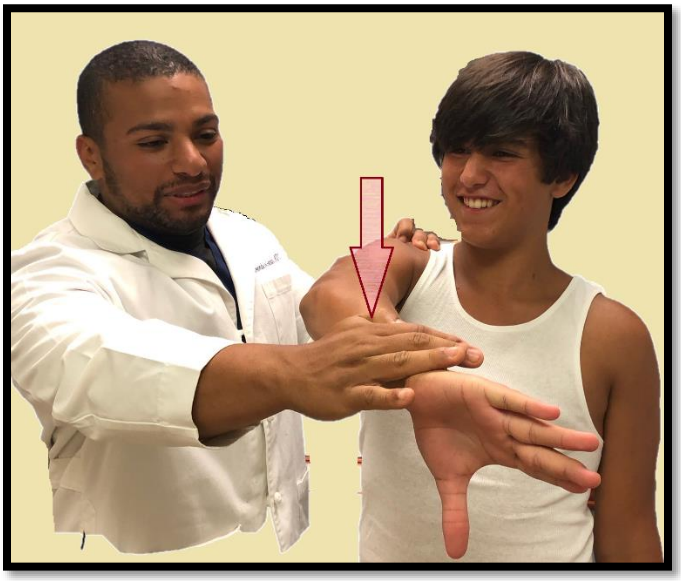

Figure 2.9: The clinician demonstrating the O'Brien's test. The patient is required to elevate his arm at 90º and adduct the arm at 15º across his body. This will cause internal rotation of the arm. The patient is then asked to pronate with the thumb pointing down. The arm is pushed downwards by the clinician with a positive sign is achieved if the force applied causes the same pain during supination. *Image Source: https://www.orthopaedicsone.com/display/Main/FPT+Disorders+of+the+labrum+and+biceps*

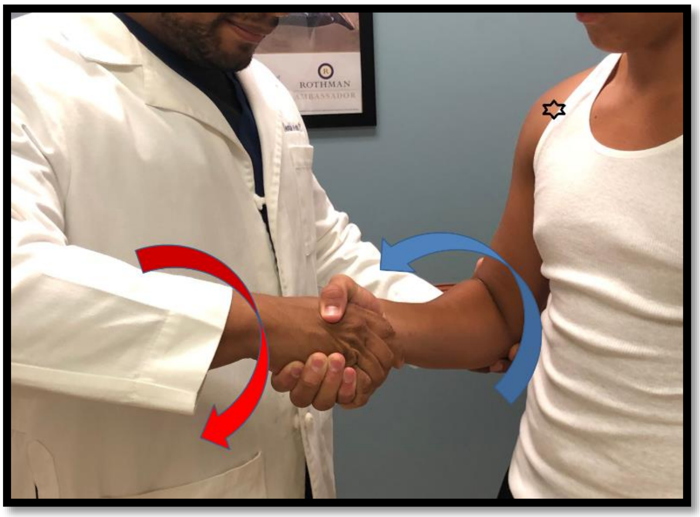

Figure 2.10: Yergason's test is performed by asking the patient to actively supinate against the clinician's resistance. A positive response is recorded if the pain is experienced in the bicipital groove of the patient (black star). *Image Source: https://www.orthopaedicsone.com/display/Main/FPT+Disorders+of+the+labrum+and+biceps*

Figure 2.11: Demonstration of the biceps load test. The patient lies in the supine position and the arm is elevated to 120º and maximallly externally rotated with the elbow at 90º of flexion, the forearm is in a supine position. The clinician asks the patient to flex the elbow while its resting in the clinician's hands. *Image Source: Kim et al., 2001*.

Figure 2.12: Demonstration of the rope-and-pulley ROM for healing the 'frozen shoulder' following RC surgery. *Image Source: https://www.lifelinefitness.com/econo-shoulder-pulley.html*

PART I – CADAVER COMPONENT

Chapter 3: Materials and Methods

The sample used in this part of the study comprised of a hundred (n=100) adult (>18 years) left and right formalin fixed cadaveric shoulders (50 no pathology and 50 with pathology). Thirty (n=30) male and twenty-two (n=22) female cadavers of which 9 were black (n=9) and 43 white (n=43) were included in the study. The age of the cadaver sample ranged from 28 to 98 years (mean=70 years). The arterial supply of the shoulder was investigated through bilateral dissections of the root of the neck, the axilla and the area around the proximal humerus. The cadavers used were obtained from the Department of Anatomy, University of Pretoria (Ethical clearance: 419/2017). The methods used followed the guidelines as set out by a study conducted by Vosloo *et al.* (2016) with some modifications to suit the current study. The blood supply to the rotator cuff (RC) complex was also investigated in this cadaveric sample.

3.1. Inclusion criteria

The study sample included cadavers of varying body mass index (BMI) (range of ± 18 – 30 kg/m^2). BMI was calculated as per the definition, wherein weight (in kilograms) of each cadaver was divided by the height (in meters) squared (BMI = weight (kg)/height (m)^2). Cadavers with any RC – related pathology were included in the study, as this was part of the scope set out for this study. Evidence of previous surgery was included and recorded under pathology found, in cadavers where the axillary artery and its branches were uninterrupted. Cadavers whose records had some data missing, such as age, were also included in the study, as observations could still be made on the anatomy of the RC blood supply.

3.2. Exclusion criteria

Cadavers below 18 years of age were excluded. In cadavers where the subclavian– or axillary artery had been incised by previous dissections, only unilateral measurements were taken on the limb with intact vessels. The presence of the pectoralis minor– and teres major muscles was also deemed crucial for the accurate measurements of the three parts of the axillary artery, therefore, the sides of the cadavers on which the abovementioned muscles been incised by previous dissectors, were also excluded.

3.3. Methods

The methods described followed the dissection procedure with the cadaver in the supine position with all landmarks easily palpable. The jugular notch, xiphoid process, costal line/margin, greater tuberosity of the humerus and the clavicle were firstly palpated and incisions made along these lines (Figure 3.1). The first incision was made from the jugular notch to the acromion process of the scapula along the superior border of the clavicle. The second incision was made from the jugular notch to the xiphoid process of the sternum. This incision was extended to the midaxillary line along the costal margins. The last incision was made from the acromion process of the scapula, descending along the lateral aspect of the upper limb to the middle part of the brachium. From this point, a circular incision was then made around the circumference of the brachium (Figure 3.1).

The skin, together with the breast (in female cadavers) and areola (in male cadavers) was reflected laterally to expose the superficial fascia. The skin surrounding the proximal half of the brachium was removed in its entirety, exposing the anterior and posterior compartments of the brachium. The deltoid muscle was identified and the fascia surrounding the muscle dissected to the point of insertion of the muscle on the deltoid tuberosity.

The superficial fascia was dissected in order to visualise the borders of the pectoralis major muscle. This muscle was subsequently detached along its clavicular, sternal and costal attachments and reflected laterally, leaving the muscle attached to its insertion on the lateral lip of the bicipital groove. The pectoralis minor muscle was then identified and exposed, as well as the pectoral branch of the thoracoacromial artery as it courses anterior to the muscle. The insertion point of the pectoralis minor on the coracoid process of the scapula was identified. Prior to reflecting pectoralis minor superiorly, the subclavian artery was followed to its terminal point at the lateral border of the first rib, in order to trace and measure the axillary artery. The three parts of the axillary artery were marked with coloured pins. The pectoralis minor muscle was detached from its origin (anterior surface of ribs 3-5) and reflected superiorly towards the coracoid process attachment, further exposing the axillary artery along its entire length. In cases where dissecting the axillary artery proved difficult, the clavicle was disarticulated from the acromioclavicular joint and the sternoclavicular joint. The deltoid muscle was reflected from the deltoid tuberosity, leaving the muscle attached to the lateral third of the clavicle, acromion and spine of the scapula. This allowed for the preservation of the arterial branches coursing deep to the muscle (Figure 3.2).

Once the axillary artery was exposed, pins were placed at the start and termination of each of its three parts: the first pin was placed at the start of the first part and was aligned with the lateral border of the first rib; the second pin was placed at the end of the first part and start of the second part and aligned with the medial border of the pectoralis minor; the third pin was placed at the end of the second part and start of the third part and aligned with the lateral border of the pectoralis minor muscle; the fourth pin was placed at the end of the third part and aligned with the inferior border of the teres major muscle (Figure 3.2). The first set of measurements relating to the length of the three parts of the axillary artery included the following:

- *First part of axillary artery*: Measured from the pin positioned at the start of the axillary artery (aligned with the lateral border of the first rib) to the pin positioned at the end of the first part and start of second part (aligned with the medial border of the pectoralis minor).
- *Second part of axillary artery*: Measured from the pin at the end of the first part and start of the second part (aligned with the medial border of pectoralis minor) to the pin at the end of the second part and start of the third part (aligned with the lateral border of pectoralis minor).
- *Third part of axillary artery*: Measured from the pin at the end of the second part and start of the third part (aligned with the lateral border of pectoralis minor) to the pin at the end of the third part of the axillary artery (aligned with the inferior border of the teres major).

Following the above measurements and observations, the axilla along with the axillary fascia and fat, was further cleaned to clearly identify and follow the branches of the axillary artery. The subclavian, axillary, cephalic and brachial veins were carefully removed to further expose and follow the branches of the axillary artery. All the branches arising from the three parts of the axillary artery were observed and any variations noted (Figure 3.3). Variations of the branching pattern of the axillary artery were documented and are further discussed in Chapter 4. Variations in the origin of the suprascapular artery as it emerges from the thyrocervical trunk (a branch of the first part of the subclavian artery) were also noted and documented. The arterial blood supply to the proximal humerus and RC was exposed, which included:

- The ascending branch of the anterior circumflex humeral artery
- The posterior circumflex humeral artery
- The acromial branch of the thoracoacromial artery
- The suprascapular artery, a branch of the thyrocervical trunk.

Following the above mentioned observations, all cadavers were then further dissected using the reverse dissection method, to better visualise the structures of the RC unit. The reverse dissection method entailed dissecting each RC muscle away from its origin on the scapula towards its tendinous insertion on the proximal humerus. The complete RC unit (tendon and internal capsule) was separated from the scapula attachment by firstly removing the muscles from their origins and then cutting as close as possible to the connection with the glenoid labrum. Supraspinatus was firstly identified and then detached from the supraspinous fossa. Infraspinatus was detached from the infraspinous fossa. The teres minor was also identified and detached from the dorsal surface of the lateral border of the scapula. Lastly, subscapularis was identified and detached from the subscapular fossa. The RC unit was then reflected towards its insertion on the humerus and detached from the glenoid rim. Once detached from the glenoid rim of the scapula, the RC unit was separated from its humeral attachment by cutting through the insertion points on the greater and lesser tuberosity from medial to lateral. The removal of the RC unit in this manner allowed for analysis of the insertion and interdigitation fusion analysis of the unit (Vosloo *et al*., 2016).

Any tears found on the RC muscles, tendons and joint capsule were documented and classified according to the existing classification of RC tears. Any pathologies encountered during this stage of the study were also noted and documented on a data capturing sheet.

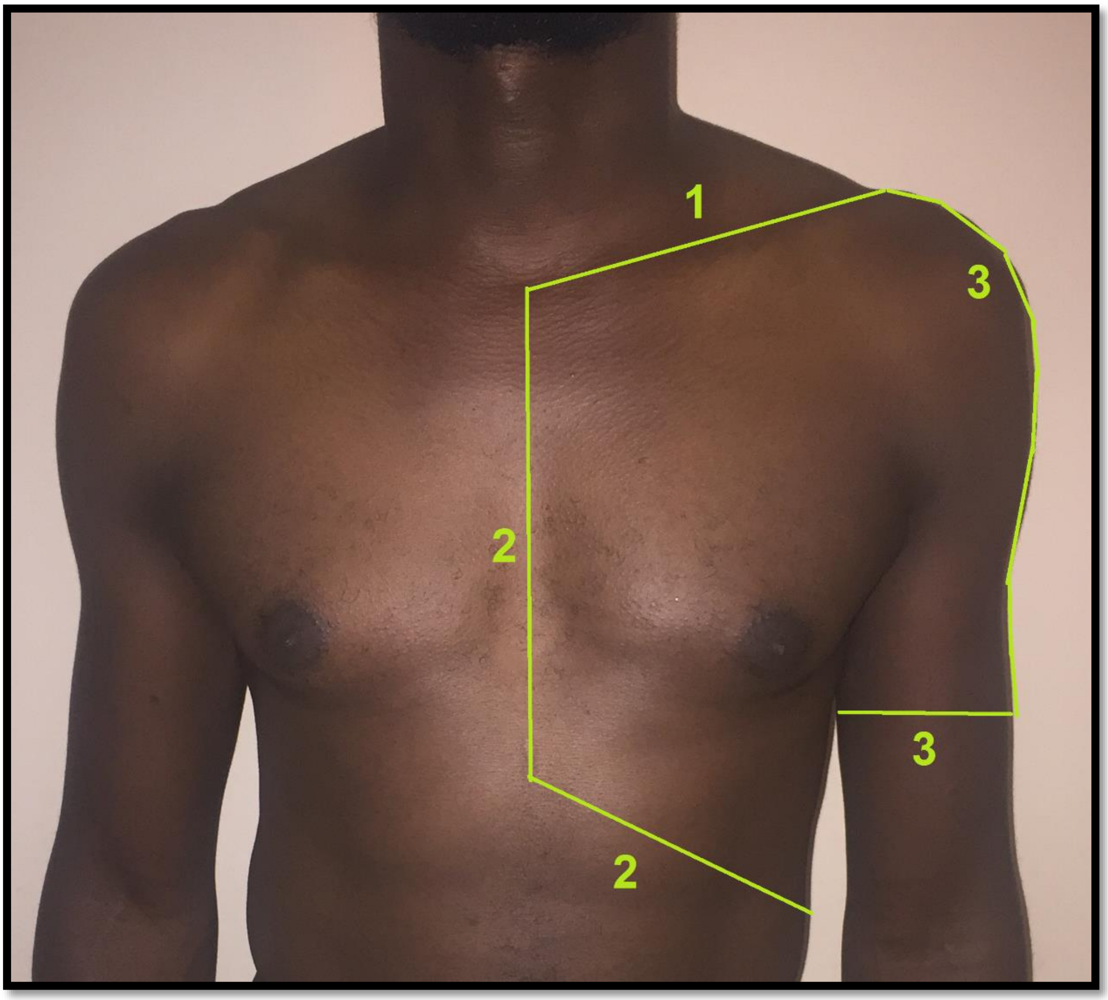

Figure 3.1: Indicating incisions made on the cadaver from the jugular notch to the acromion process of the scapula along the superior surface of the clavicle (1). The second incision was made from the jugular notch to the xiphoid process, and extended to the midaxillary line, along the subcostal line. The last incision (3) was made from the acromion process of the scapula, descending along the lateral aspect of the upper limb to the middle part of the brachium.

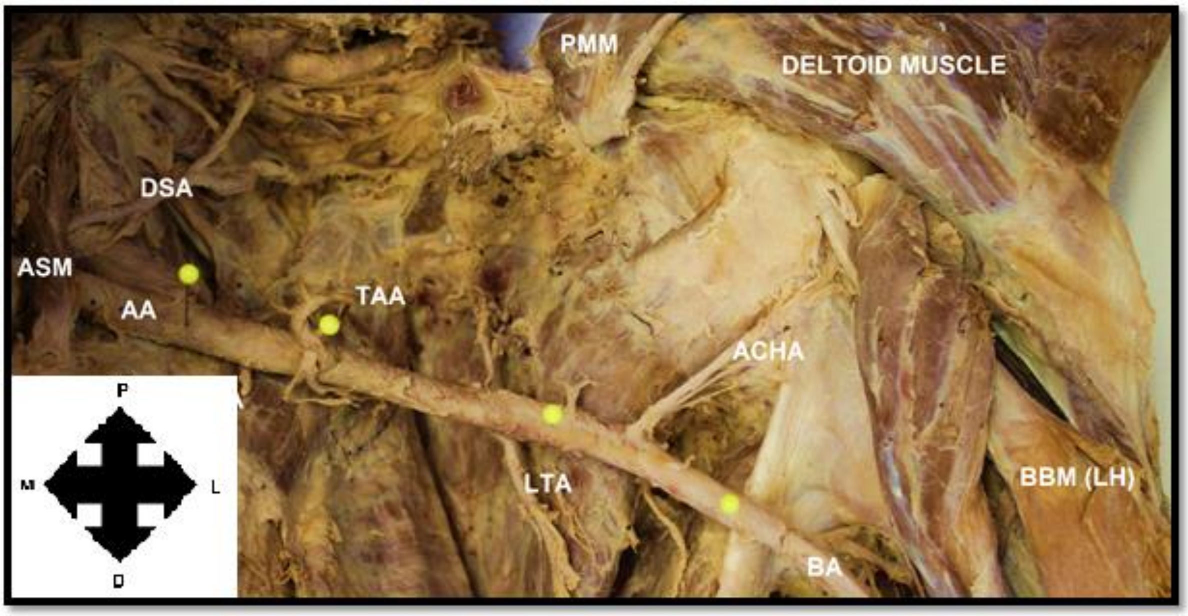

Figure 3.2: Dissection of the root of the neck and axilla showing the reflected pectoralis minor muscle (PMM) and deltoid muscle. The course of the axillary artery (AA) and some of the branches given are indicated. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, ASM – Anterior Scalene Muscle, AA – Axillary artery, DSA – Dorsal scapular artery, STA – Superior thoracic artery, TAA – Thoracoacromial artery, LTA – Lateral thoracic artery, ACHA – Anterior circumflex humeral artery, BA – Brachial artery, PMM – Pectoralis minor muscle*, *BBM (LH) – Biceps brachii muscle (Long head)*

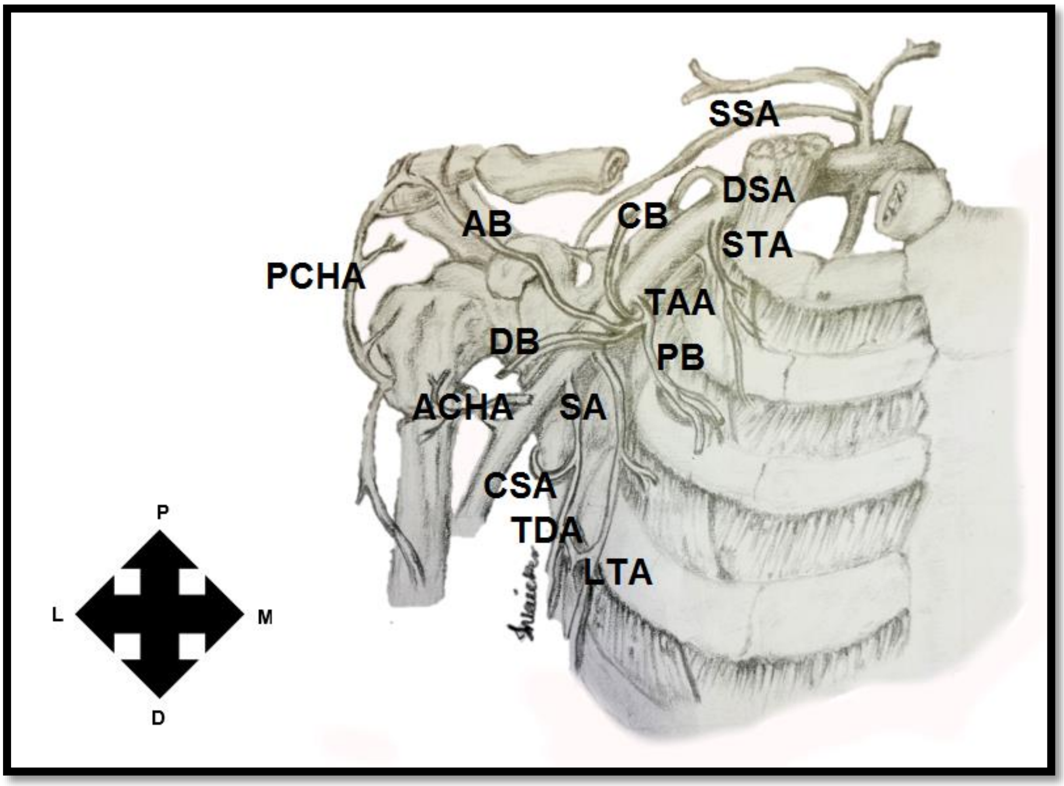

Figure 3.3: Annotated diagram showing the axillary artery and related branches. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, SSA – Suprascapular artery, DSA – Dorsal scapular artery, STA – Superior thoracic artery, TAA – Thoracoacromial artery, PB – Pectoal branch, DB – Deltoid branch, AB – Acromial branch, CB – Clavicular branch, LTA – Lateral thoracic artery, ACHA – Anterior circumflex humeral artery, PCHA – Posterior circumflex humeral artery, SA –Subscapular artery, CSA – Circumflex scapular artery, TDA – Thoracodorsal artery*

3.4. Interobserver and Intraobserver analyses

Inter- and intra-observer analyses were carried out to test the reliability of the measurements documented for distances of the axillary artery between the relevant anatomical landmarks. An independent sample *t*-test was used to measure if there were differences in measurements obtained by a different observer when 10% (n=10) of the sample was re-measured. Observations on the variations in the branching pattern of the axillary artery were noted and documented. The results of the reliability testing as pertaining to Chapter 4 are captured in Table 4.1.

3.5. Ethical clearance

Ethical approval to conduct this study was obtained from the Faculty of Health Sciences Research Ethics Committee, University of Pretoria (Protocol Number: 419/2017) prior to the commencement of the data collection phase of the study. All cadavers used in this study were obtained and dissected in accordance with the rules and regulations defined within Chapter 8 of the South African National Health Act No. 61 of 2003. All data was collected from full body cadavers. The cadavers were handled with respect (and properly safeguarded) at all times. No information which could possibly reveal the identities of the cadavers was obtained. Access to personal information regarding the cadaver's age, height and weight was noted, and restricted to the primary investigator. No other personal information was obtained.

3.6. Data processing

The following standard statistical analyses and comparisons were made using SAS® version 9.4 analytical software:

- The mean/average of each measurement was calculated using a paired sample *t*-test for measurements of the first, second and third part of the axillary artery. The mean was calculated to indicate the central tendency of the entire distribution.
- The standard deviation was calculated to establish the range or how spread out the distribution of the sample is. The standard deviation is therefore a way to measure variability from the mean of a sample or population. A paired sample *t*-test was used to calculate this deviation from the mean.
- 95% confidence interval was used to establish the true sample value for the statistic value, including upper and lower ranges. A paired sample *t*-test was used to achieve this outcome.
- A paired *t*-test was performed to assess the existence of any significant difference (p-value of <0.05 was regarded as statistically significant). Measurements for the left and right sides of the axillary artery were analysed. A p-value of <0.05 would allow the sample to be combined and therefore create a larger pool of 100 dissected shoulders.

  Nonparametric tests were conducted using the Mann-Whitney U-test and Wilcoxon W-test for the left and right side measurements of the different parts of the axillary artery. These tests were applied to age, sex, height and BMI analysis of the cadaver measurements. The Mann-Whitney U-test is used to compare two sample means that come from the same population, and used to test whether two sample means are equal or not. The Mann-Whitney U-test is used when data is ordinal or assumptions of the *t*-test are not met. The Wilcoxon signed-rank test is a nonparametric statistical hypothesis test which is used to compare two related samples, matched samples or repeated measurements on a single sample in order to assess whether their population mean ranks differ. This test is regarded as a paired difference test.

- Further analysis for BMI was conducted using the Kruskal-Wallis test. In cases where asymptotic significances were displayed (significance level <0.05), pairwise comparisons of BMI were conducted with significant values adjusted by the Bonferroni correction for multiples test. The Kruskal-Wallis nonparametric test is used when the assumptions of one-way ANOVA are not met. When using the Kruskal-Wallis test, no assumptions are made that the dependent variable is normally distributed and there is equal variance on the scores across groups. This test can therefore be used for both continuous and ordinal-level dependent variables.

The data analysis included the use of frequency tables, descriptive statistics and inferential statistics. Descriptive statistics were used to describe the basic features of our sample distribution. The selection of the tests depended on the sample size and the distribution of the data. The frequency tables assisted in displaying the number of occurrences of a particular value or characteristic in the measured sample.

Inferential statistics were used to describe and make inferences or interpretations about the study sample. These inferential statistics are used to make judgements of the probability that an observed difference between groups is a dependable one, or one that might have happened by chance in the study. Scatterplots are used in Chapter 4, section 4.4. to firstly note the overall trend among the variables used in this study, secondly, to note any outliers in our study sample which may influence the overall results, and lastly, to note the shape and strength of the trends created by the measurements taken for the different variables. Results from the current study were compared to results from other studies. Details of these comparisons are documented in Chapter 4, section 4.4.

Chapter 4

Manuscript 1

Title: Variations of the branching pattern of the axillary artery and its related branches: A cadaveric study

Abstract

The rotator cuff (RC) muscles, which contribute to the movement of the shoulder joint, receive their main blood supply from the subscapular and suprascapular arteries. Knowledge of the normal and variable anatomy of the RC blood supply is important for diagnostic interpretation and surgical intervention. As such, the subscapular, suprascapular and axillary arteries were studied as relating to RC vasculature. The axillary artery was investigated along with its anomalous branching pattern and variations documented. A hundred (n=100) cadaveric shoulders (left and right) of age range 28 – 98 years were dissected. The three parts of the axillary artery were pinned, measured and branches emerging from these parts observed. Differences were documented in the length of the second ($p<0.000$) and third parts ($p<0.014$) of the artery. Statistically significant differences were noted for the height ($p<0.025$) of individuals ≤1.6m and >1.6m and BMI ($p<0.023$) differences between individuals <18kg/m^2 and ≥25.1kg/m^2. Variations that were noted in this study included the collateral brachial artery in 3% of cases. These included the emergence of the clavipectoral trunk (1%), suprascapular artery (4%), thoracoacromial artery (34%) from the first part of the axillary artery. Common trunks were documented between the thoracoacromial and lateral thoracic artery (8%); as well as the lateral thoracic, subscapular and posterior circumflex humeral artery (3%). The subscapular artery emerged from the second part in 18% of cases. Knowledge of axillary artery variations is important for accurate diagnostic interpretations of ultrasounds and MRI images as well as in the prevention of intra-operative bleeding.

Keywords: Axillary artery, variations, axilla, subscapular artery common trunk, collateral brachial artery

4.1. Introduction

The main source of blood supply to the rotator cuff (RC) muscles has been found to be via the subscapular and suprascapular arteries in conjunction with their branches (Moore *et al.,* 2014; Maruvada and Varacallo, 2018). The branching pattern of these vessels have been well documented by various authors who not only studied the blood supply of the RC vasculature, but also the variations relating to the axillary artery (Maral *et al.*, 1993; Determe *et al.*, 1996; Abrassart *et al.*, 2006; Standring *et al.*, 2008; Naidoo *et al.*, 2014). Knowledge of the normal vascular anatomy along with the possible variations is essential for accurate diagnostic interpretation and surgical intervention (Maral *et al.*, 1993). In relation to the current study, knowledge of variations pertaining to the blood supply of the RC unit and related osteology is important in the prevention of possible post-operative complications such as osteonecrosis, when clamps or surgical devices are used or implanted during surgical procedures. Better understanding of the vascular supply of the RC could also assist in understanding pathological factors of RC disease (Determe *et al.*, 1996).

Goto *et al.* (2013) attributed the possibility that osteonecrosis could occur to the use of multiple anchors during arthroscopic RC surgical repair. These anchors were suggested to obstruct blood flow, leading to post-operative humeral head collapse. Although a direct link between humeral head osteonecrosis following the use of metal anchors has not yet been established, cases of humeral head deformity were reported by Beauthier *et al.* (2010) and Manabe *et al.* (2011). In the study by Beauthier *et al.* (2010), three anchors placed close to one another were used between the greater tuberosity and the humeral head, while Manabe *et al.* (2011) used five anchors. These stated cases are consistent with possible obstruction of the anterolateral branch of the anterior circumflex humeral artery that, if interrupted, may result in osteonecrosis of the humeral head (Pateder *et al.*, 2004; Beauthier *et al.*, 2010). Radiologists therefore employ Doppler- and contrast imaging when studying the vessels located in this region to make sure that blood flow is not reduced post-operatively (Akhtar *et al.*, 2018).

One of the challenges encountered with RC repair is the reduced blood supply to both the RC complex and the head of the humerus post-surgery, often resulting in poor healing of the tendon-bone construct and, in rare cases, osteonecrosis of the humeral head. It is known that the blood supply to the RC complex and the humeral head is highly variable (De Garis and Swartley, 1928; Venieratos and Loris, 2001; Samuel *et al.*, 2006). These variations are clinically relevant to vascular surgeons who frequently perform procedures in this region with some studies also noting differences in the branching pattern amongst different populations (Saralaya *et al.*, 2008; Majumdar *et al.*, 2013). Accidental severing of these vessels may cause reduced blood supply to areas such as the humeral head, resulting in the development of osteonecrosis to this region or in extreme cases intra-operative bleeding may result. Therefore, the blood supply to the RC complex was investigated in the cadaveric anatomy and any variations related to the normal anatomy of the axillary artery documented. To achieve this objective, male and female cadavers of different population groups, age groups, body mass index (BMI) and sex were dissected in the root of the neck, pectoral regions, axilla region and proximal brachium; the axillary artery was followed from its origins to the terminal point. The course of the axillary artery, together with its branches that provide blood supply to major components of the RC unit, was studied on a cadaveric sample to establish the frequency and type of variations present.

The detailed knowledge of the anatomy of the axillary artery and its variations are imperative to clinicians operating in and around the pectoral- and axillary regions, using various invasive procedures in fields such as vascular surgery. The arterial supply is essential in preventing injuries that may result from inadequate blood supply of the rotator cuff tendons in the watershed regions.

4.2. Materials and methods

The study sample comprised of one hundred (n = 100) left and right shoulders dissected from a cadaveric sample with an age range of 28 - 98 years (mean = 70 years). The arterial supply was investigated through bilateral dissections of the root of the neck and proximal humerus. The cadavers used were obtained from the Department of Anatomy, School of Medicine, Faculty of Health Sciences, University of Pretoria and dissected in accordance with the National Health Act No. 61 of 2003. Male (n = 30) and female (n = 22) adult cadavers (black = 9 and white = 43) with varying BMI (range of ± 18 – 30 kg/m^2) were included in the study. Ethical clearance was obtained from the Faculty of Health Sciences Research Ethics Committee (No: 419/2017) prior to data collection. Cadavers with any RC related pathology were not excluded in the study, as these were part of the scope set out for the study.

With the cadaver in the supine position, the skin was incised from the jugular notch to the xiphisternum, along the costal margins and along the superior border of the clavicle, then reflected laterally to the midaxillary line. The superficial fascia was dissected until the pectoralis major and deltoid muscles could be identified; these were reflected to their insertional sites. The pectoralis minor muscle was then identified along with the axillary artery and any visible arterial branches. The three parts of the axillary artery were marked with coloured pins (see below), and measurements taken prior to the superior reflection of the pectoralis minor muscle to its point of insertion (Figure 4.1).

Following the exposure of the axillary artery, pins were placed at selected points from its origin to its termination; the first pin was placed in the artery at its origin which is positioned at the lateral border of the first rib; the second pin was placed at the medial border of the pectoralis minor muscle; the third pin was placed at the lateral border of the pectoralis minor; the fourth pin was placed at the termination of the third part, which is aligned with the inferior border of teres major muscle (Figure 4.2). Once the pins were secured, the pectoralis minor muscle was detached from its costal attachments and reflected superiorly towards the coracoid process. The brachial plexus cords, terminal branches and related venous vessels were dissected out to expose all the branches of the axillary artery.

Measurements relating to the length of the three parts of the axillary artery included the following:

- *First part of axillary artery*: Measured from the pin positioned at the commencement of the axillary artery (lateral border of the first rib) to the pin positioned at the termination of the first part and commencement of second part (medial border of the pectoralis minor).
- *Second part of axillary artery*: Measured from the pin at the termination of the first part, commencement of the second part (medial border of pectoralis minor) to the pin at the termination of the second part, commencement of the third part (lateral border of pectoralis minor).
- *Third part of axillary artery*: Measured from the pin at the termination of the second part, commencement of the third part (lateral border of pectoralis minor)

to the pin at the termination of the third part of the axillary artery (inferior border of the teres major).

The axillary artery was observed and the branching pattern of the different parts documented for further analysis. These observations included variations in the branching pattern and origin from anomalous locations. The second part included the documentation of the thoracoacromial- and lateral thoracic arteries and the frequency of origin from this part. Variations in the branching pattern of the third part were also noted.

Statistical comparisons were made using SAS® version 9.4 analytical software. A p-value ≤ 0.05 was considered statistically significant. Paired sample *t*-test and paired samples correlations were carried out in order to document the mean, standard deviation, standard error mean and 95% confidence intervals with upper and lower limits, for the right and left sides of the first, second and third parts of the axillary artery (Table 4.1 and 4.2). Nonparametric tests such as the Mann-Whitney U-test and Wilcoxon W-test were used to further analyse the sample. To compare age, sex, height and BMI for 50 left- and right shoulders. The Independent-Samples Mann-Whitney U-test revealed results of the test statistics, standard error, standardized test statistics, asymptotic significance (2-sided test) and exact significance (2-sided test). A pairwise comparison was therefore carried out where significant values were adjusted by the Bonferroni correction for multiple tests (Table 4.5.1).

Figure 4.1: Dissection of the left upper limb showing the pectoralis minor muscle as it divides the axillary artery into three parts. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal*

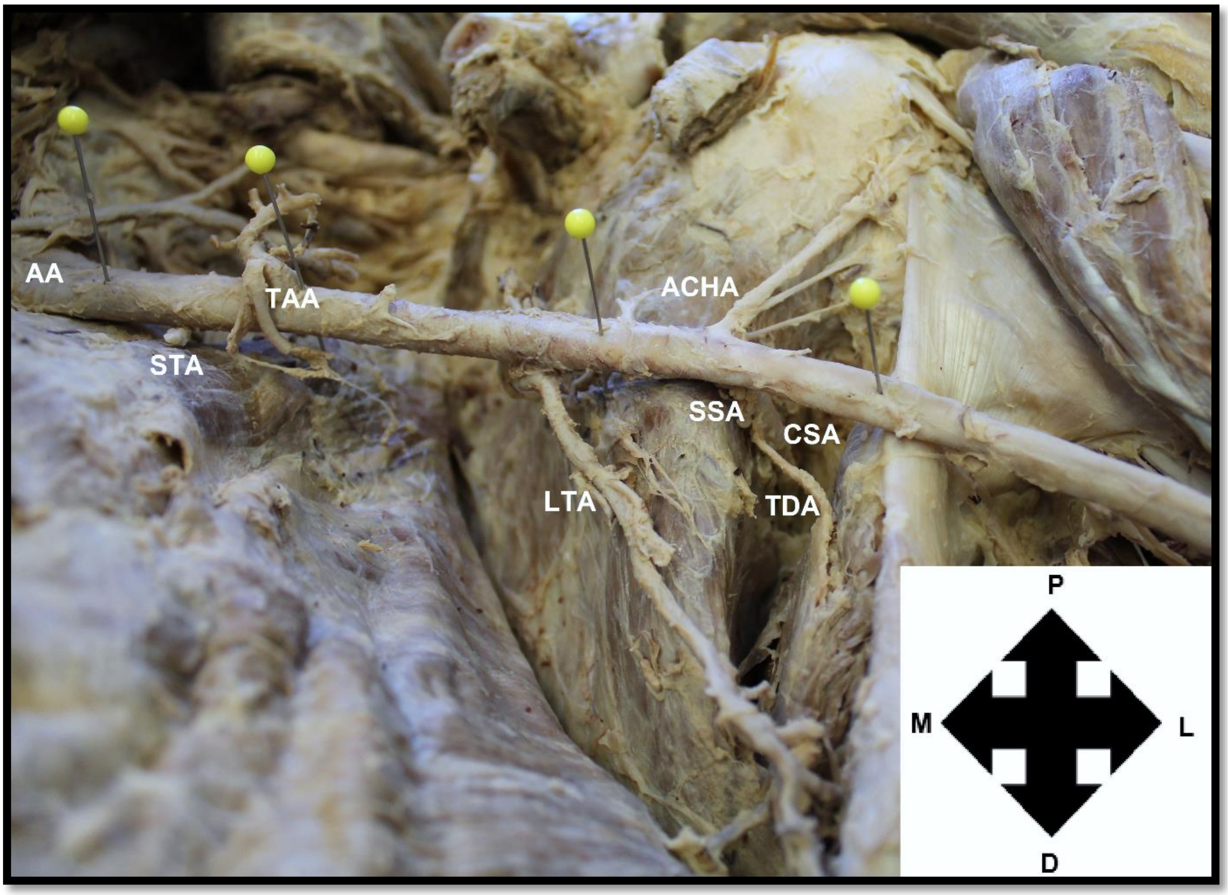

Figure 4.2: Dissection of the left axilla showing the three parts of the axillary artery (AA) and some of the branches given off in its course. The superior thoracic artery (STA) is found emerging slightly posterior to the first part of the axillary artery. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, TAA – Thoracodorsal artery, LTA – Lateral thoracic artery, ACHA – Anterior circumflex humeral artery, SSA – Subscapular artery, CSA – Circumflex scapular artery, TDA – Thoracodorsal artery*

4.3. Results

Dimensions of the axillary artery

No significant differences were noted in the length of the first part of the axillary artery between the left and right sides (p=0.155). However, differences were noted in the second (p=0.000) and third (p=0.014) parts. A paired sample statistic for the bilateral dissections of 48 right- and left limb measurements of the three parts of the axillary artery are presented in Table 4.1. On average the length of the first part was 32.66 ± 8.75mm, for the second part, 35.79 ± 8.71mm on the right side and 33.76 ± 7.76mm the left side. The average length for the third part was 44.19 ± 9.62mm on the right side and 44.68 ± 11.16mm on the left side. The average length for the entire axillary artery was documented at 109 ± 24.82mm for the left side, and 113 ± 25.67mm for the right side.

A paired sample correlation test revealed significant differences for some parameters between the second and third parts of the left and right measurements with a p-value of $p<0.000$ and $p<0.014$ for the second and third part, respectively (Table 4.1.). This indicates variable distances for the second and third parts of the axillary artery, which could be attributed to the pectoralis minor muscle having changed in form or shape due to previous dissections prior to the commencement of the data collection for this study and/or the difference in function.

The right- and left sided measurements comparison for different age groups, using independent samples Mann-Whitney and Wilcoxon W-tests are summarised in Table 4.2. Asymptotic significances revealed no significant difference in the sample composition of individuals of ages ≤50 years and >50 years. In all instances, the null hypothesis can be retained, indicating that the right- and left parts distribution is the same across the different parts of the axillary artery, across all age categories. In the sample comparison between the sexes (females and males) using independent samples Mann-Whitney and Wilcoxon W-tests, (Table 4.3) no significant differences were found. The null hypothesis is retained for this sample composition, indicating that the distribution on the left- and right side is the same across the categories of sex (females and males). Samples comparison for height for individuals ≤1.6m and >1.6m using independent samples Mann-Whitney and Wilcoxon W-tests indicated significant differences for the right side measurement of the first part of the axillary artery ($p<0.025$). The null hypothesis is therefore rejected, indicating differences in the distribution of the right first part of the axillary artery for categories of height (Table 4.4.).

Measurements in different BMI groups for individuals <18kg/m^2, 18-25kg/m^2 and ≥25.1kg/m^2 is compared using the independent samples Kruskal-Wallis-test (Table 4.5.). Significant differences are detected in the first part of the axillary artery on the left side ($p<0.023$). The null hypothesis is rejected for comparisons in individuals of BMI <18kg/m^2 and BMI ≥25.1kg/m^2 (Table 4.5.1). Pairwise comparisons for BMI are further carried out using Bonferroni correction for multiple tests, in order to eliminate a Type I Error.

Branching patterns of the axillary artery

Observations relating to the branching pattern of the axillary artery revealed various findings. Cases were noted where a common trunk was shared with other branches, duplication of branches and sometimes absence of origin found in main branches or sub-branches. The superior thoracic was found emerging from the first part of the axillary artery in 97% of cases (n=97/100), from the second part in 2% of cases (n=2/100) and completely absent in 1% of cases (n=1/100).

The clavicopectoral trunk was noted in 1% of the sample (n=1/100) emerging from the first part of the axillary artery. In 2% of cases (n=2/100) the thoracoacromial artery emerged from the first part of the axillary artery, accompanied by the superior thoracic and the suprascapular arteries. The lateral thoracic artery was found emerging from the first part in 18% (n=18/100) of the sample, with a common trunk shared with the thoracoacromial artery in 8% (n=8/100) of these cases. In the third part of the artery, a common trunk of the lateral thoracic, subscapular and posterior circumflex humeral artery was found in 3% (n=3/100) of the sample. The suprascapular artery was only emerging from the first part of the axillary artery in 4% (n=4/100) of the study sample. The thoracoacromial trunk was present in 100% (n=100/100) of the study cases and was found emerging from the first part in 34% (n=34/100) of cases and from the second part in 66% (n=66/100) of the sample. In two cases, both on the right sides, the pectoral and acromial branches of the thoracoacromial artery were found emerging directly from the second part of the axillary artery. The current study noted a common trunk between the suprascapular- and thoracoacromial artery in the first part of the axillary artery. In 6% (n=6/100) of cases, the lateral thoracic artery shared a common trunk with the subscapular and posterior circumflex humeral artery.

In 2% (n=2/100) of the sample, an anomalous bilateral collateral brachial artery was found in a 69-year-old white male cadaver (Figure 4.3). The collateral brachial artery was found terminating in brachium, giving blood supply to the axillary lymph nodes and muscles of the anterior brachium. A similar anomaly was documented in a 92-year-old white female cadaver on the right side (Figure 4.4). In the brachium, the artery was found coursing between the biceps brachii and brachialis muscle and providing blood supply to the muscles in the anterior compartment.

In 18% of the study sample (n=18/100) the subscapular artery was found emerging from the second part of the axillary artery. In the sample, 17% (n=17/100) displayed a trifurcation of the anterior circumflex humeral-, posterior circumflex humeral- and subscapular arteries from the third part of the axillary artery. A common trunk shared between the anterior and posterior circumflex humeral artery was found in 3% (n=3/100) of the sample size (Figure 4.5). The posterior circumflex humeral artery was found sharing a common trunk with the subscapular artery in 48% cases (n=48/100). In 11% (n=11/100) of the cases, the common trunks emerged in the second part of the axillary artery. Therefore, the current study documented 59% of cases (n=59/100) where a common trunk was shared between the posterior circumflex humeral artery and the subscapular artery.

Table 4.5 displayed noted differences (p=0.023) for the first part of the left side measurement of the axillary artery when comparing BMI, resulting in the rejection of the null hypothesis. Frequencies are summarised in Table 4.6, where the number of occurrences of a particular value or characteristic in the measured sample is indicated. Descriptive statistics indicating the basic features of the sample distribution are captured in Annexure C. Further observations regarding the variations in the branching pattern of the axillary artery were documented and are discussed in section 4.4.

Table 4.1: Paired sample statistics for right and left side measurements of the three parts of the axillary artery (N – 100; Std. D – 9.13). *(Key: Mm – millimetres; Com. Mean – Combined Mean; Std. D – Standard Deviation; Std. Error Mean – Standard Error Mean; Std. CI – Confidence Interval; Cor. Sig. – Correlation Significance)*

Sample										
Side Length (mm)	**Axillary Artery Parts**	**N**	**Com. Mean**	**Std. D**	**Mean**	**Std. D**	**Std. Error Mean**	**95% CI (Right – Left side)**		**Cor. Sig.**
								Upper	**Lower**	
Right		48			33.81	7.84	1.13			
Left	1^{st}	48	32.66	8.75	31.52	9.66	1.39	5.51	-0.94	0.1550
Right		48			35.79	8.71	1.26			
Left	2^{nd}	48	-	-	33.76	7.76	1.12	4.47	-0.40	0.0000

Right	3rd	48	-	-	44.19	9.62	1.39	2.97	-3.94	0.0140
Left		48			44.68	11.17	1.61			

Table 4.2: Right and left side measurements in a sample of ages ≤50 years and >50 years using independent samples Mann-Whitney and Wilcoxon W-tests *(Key: Mm – millimetres; Test Stat. – Test Statistic; Std. Error – Standard Error; Std. Test Stat. – Standard Test Statistic; Asymptotic Sig. – Asymptotic Significance; Exact Sig. – Exact Significance)*

Sample									
Side Length (mm)	**Axillary Artery Parts**	**N**	**Mann-Whitney U**	**Wilcoxon W**	**Test Stat.**	**Std. Error**	**Std. Test Stat.**	**Asymptotic Sig. (2-sided test)**	**Exact Sig. (2-sided test)**
Right	1st	50	169.00	1159.00	169.00	33.50	1.105	0.269	0.284
Left		50	155.00	1145.00	155.00	33.50	0.687	0.492	0.511
Right	2nd	50	136.00	1126.00	136.00	33.50	0.119	0.905	0.919
Left		50	128.50	1118.50	128.50	33.50	-0.104	0.917	0.919
Right	3rd	50	190.00	1180.00	190.00	33.50	1.732	0.083	0.086
Left		50	190.00	1180.00	190.00	33.50	1.732	0.083	0.086

Table 4.3: Right and left side measurements in a samples comparing sexes (males and females) using independent samples Mann-Whitney and Wilcoxon W-tests. *(Key: Mm – millimetres; Test Stat. – Test Statistic; Std. Error – Standard Error; Std. Test Stat. – Standard Test Statistic; Asymptotic Sig. – Asymptotic Significance)*

Sample								
Side Length (mm)	**Axillary Artery Parts**	**N**	**Mann-Whitney U**	**Wilcoxon W**	**Test Stat.**	**Std. Error**	**Std. Test Stat.**	**Asymptotic Sig. (2-sided test)**
Right	1st	50	357.50	792.50	357.50	50.87	1.042	0.297
Left		50	304.00	739.00	304.00	50.87	-0.010	0.992
Right	2nd	50	317.00	752.00	317.00	50.87	0.246	0.806
Left		50	400.50	835.50	400.50	50.87	1.887	0.059
Right	3rd	50	389.50	824.50	389.50	50.87	1.671	0.095
Left		50	366.50	801.50	366.50	50.87	1.219	0.223

Table 4.4: Right and left side measurements in a samples comparing height for individual ≤1.6m and >1.6m using independent samples Mann-Whitney and Wilcoxon W-tests. *(Key: Mm – millimetres; Test Stat. – Test Statistic; Std. Error – Standard Error; Std. Test Stat. – Standard Test Statistic; Asymptotic Sig. – Asymptotic Significance)*

Sample								
Side Length (mm)	**Axillary Artery Parts**	**N**	**Mann-Whitney U**	**Wilcoxon W**	**Test Stat.**	**Std. Error**	**Std. Test Stat.**	**Asymptotic Sig. (2-sided test)**
Right	1st	50	327.00	1068.00	327.00	44.02	2.249	0.025
Left		50	184.00	964.00	184.00	42.70	-0.714	0.475
Right	2nd	50	293.00	1034.00	293.00	44.02	1.477	0.140
Left		50	261.50	1041.50	261.50	42.70	1.101	0.271
Right	3rd	50	188.00	929.00	188.00	44.02	-0.909	0.364
Left		50	244.50	1024.50	244.50	42.70	0.703	0.482

Table 4.5: Right and left side measurements in a samples comparing BMI for individuals <18kg/m^2, 18-25kg/m^2 and ≥25.1kg/m^2 using independent samples Kruskal-Wallis test. *(Key: Mm – millimetres; Asymptotic Sig. – Asymptotic Significance)*

Sample					
Side length (mm)	**Axillary Artery Parts**	**N**	**Test Statistic**	**Degree of freedom**	**Asymptotic Sig. (2-sided test)**
Right	1st	50	3.215	2	0.200
Left		50	7.563	2	0.023
Right	2nd	50	0.702	2	0.704
Left		50	0.658	2	0.720
Right	3rd	50	1.095	2	0.579
Left		50	5.336	2	0.069

Table 4.5.1: Pairwise comparison of BMI for left side measurements for individuals <18kg/m^2, 18-25kg/m^2 and ≥25.1kg/m^2. *(Key: Std. Error – Standard Error; Std. Test Statistic – Standard Test Statistic; Sig – Significance; Adj. Sig. – Adjusted Significance)*

Sample 1-Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig**	**Adj. Sig. [a]**
1.00 <18-2.00≥18-25	-6.258	4.45	-1.407	0.159	0.478
1.00 <18-3.00≥25.1	-17.238	6.36	-2.710	0.007	0.020
2.00≥18-25-3.00≥25.1	-10.981	6.33	-1.736	0.083	0.248

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 4.6: Frequency table for height, BMI, age and sex measurements

	Variables	Frequency	Percentage
Height (≤1.6m and >1.6m)	1.00≤1.6m	12	23.1
	2.00>1.6m	40	76.9
	Total	52	100.0
BMI (<18kg/m^2, 18-25kg/m^2 and ≥25.1kg/m^2)	1.00<18	22	42.3
	2.00≥18-25	22	42.3
	3.00≥25.1	8	15.4
	Total	52	100.0
Ages (≤50 years and >50 years)	1.00≤50	6	11.5
	2.00>50	46	88.5
	Total	52	100.0
Sex (Male and Female)	Female	22	42.3
	Male	30	57.7
	Total	52	100.0

4.3.1. Inter- and intra-observer analysis

The independent sample t-test was used to measure whether there were differences between the measurements obtained by the observers and, as such, testing reliability. The results are captured in Table 4.7.

Table 4.7: *T*-test results for the inter- and intra-observer error analysis for 10% of the sample size

				Sample			Inter-observer Error			Intra-observer Error			Sample vs Inter		Sample vs Intra		Inter-observer Error vs Intra-observer Error	
				N	Average	Std	N	Average	Std	N	Average	Std	t	p-value	t	p-value	t	p-value
SIDE	R	LENGTH (MM)	1ST PART	50	33.6	7.8	5	35.3	3.4	5	31.4	9.5	0.476	0.636	0.588	0.559	0.854	0.418
			2ND PART	50	36.0	8.6	5	33.0	5.3	5	30.7	10.0	0.745	0.459	1.296	0.200	0.466	0.654
			3RD PART	50	44.8	10.2	5	44.0	4.2	5	47.3	6.8	0.160	0.874	0.541	0.591	0.913	0.388
	L	LENGTH (MM)	1ST PART	50	31.2	9.6	5	34.2	1.8	5	27.4	3.7	0.691	0.493	0.880	0.383	3.732	0.006
			2ND PART	50	33.6	7.6	5	33.5	7.1	5	28.6	3.2	0.036	0.971	1.440	0.156	1.401	0.199
			3RD PART	50	44.8	11.0	5	43.2	9.8	5	47.1	8.5	0.315	0.754	0.459	0.648	0.680	0.516
COMMON	R	LENGTH		18	23.0	13.1	5	23.6	13.0				0.088	0.930				
TRUNK	L	LENGTH		25	18.1	7.8	5	15.7	7.1				0.631	0.531				

4.4. Discussion

Variations in the anatomy of the axillary artery may be attributed to the defects noted in the embryological development of the vascular plexus of the upper limb bud. During the development stage, the lateral branch of the seventh intersegmental artery gives rise to the axial artery of which the proximal part transforms into the axillary- and brachial artery. These variations, in what is deemed as the normal anatomy, may occur due to arrest at any developmental stage of the vessels of the upper limb such as regression, retention, or reappearance of new blood vessels (Hamilton and Mossman, 1972; Yang *et al.*, 2008). The axillary artery continues developing, resulting in the three parts, divided by the pectoralis minor muscle.

The axillary artery is enclosed within the axillary sheath. The first part of the axillary artery is positioned between the lateral border of the first rib and the medial border of the pectoralis minor muscle. One branch, the superior thoracic artery emerges from this part of the axillary artery. The second part of the axillary artery lies posterior to the pectoralis minor muscle, with two branches arising from this part, the thoracoacromial artery and the lateral thoracic artery. The third part of the axillary artery extends from the lateral border of the pectoralis minor muscle to the inferior border of the teres major muscle. Three branches emerge from the third part of the axillary artery: the subscapular-, the anterior circumflex humeral- and posterior circumflex humeral arteries (Moore *et al.,* 2014). In the current study, the average length of the axillary artery was documented at 109mm (SD = 24.82) and 113mm (SD = 25.67) on the left and right sides, respectively. These measurements are comparable with findings made by Patnaik *et al.* (2000) and Majumdar *et al.* (2013) who documented these measurements at 102mm (10.17cm) and 102mm (10.15cm), respectively.

4.4.1. First part of axillary artery

The first part of the axillary artery was found to be 32.66 ± 8.75mm in length. Previous literature documenting the lengths of the various parts of the axillary artery could not be found. The superior thoracic artery is known, and taught, to be the first and only branch of the first part of the axillary artery. However, this artery is often very small and highly variable with regard to origin and course. If clearly present, this artery arises just inferior to the subclavius muscle. In its path it courses inferomedially, posterior to the axillary vein and supplies the subclavius muscle, the muscles in the first and second intercostal spaces, the superior slips of the serratus anterior muscle, as well as the overlying pectoral muscles. It often forms an anastomosis with the intercostal- and/or internal thoracic arteries *(*Moore *et al*., 2014*).*

In the current study, variations where noted when observing the first part of the axillary artery, with cases of more than one branch emerging. These included the thoracoacromial artery, lateral thoracic artery, clavicopectoral artery and the suprascapular artery. Patel *et al.* (2013) noted the emergence of the lateral thoracic artery in two limbs. In the current sample, the superior thoracic artery was present in 99% of the study cases with 97% originating from the first part and 2% originating from the second part of the axillary artery. An absent superior thoracic artery was noted in 1% of the sample. These findings are similar to the documented case by Arquez (2015) who noted this absence in two limbs. In a 64-year-old black male cadaver, the superior thoracic artery was found emerging from the thoracoacromial artery, accompanied by the lateral thoracic artery in the first part of the axillary artery. Kanaka *et al.* (2015) found the superior thoracic artery to be variable in 5% of their study sample, while Aastha e*t al.* (2015) mentioned an unusual variation in the course of the superior thoracic artery in relation to the brachial plexus.

In 34% of the sample, the thoracoacromial artery emerged from the first part of the axillary artery. This high incidence of origin from the first part could not be found in previous literature. Reported cases only showed the following: the absence of the common trunk but emergence of the deltoacromial and clavipectoral sub trunks, one branch emerging from the second part of the axillary artery while the other branches arose from the thoracoacromial artery, all branches emerging directly from the second part of the axillary artery amid the presence of a common trunk (Sreenivasulu *et al.*, 2015). In another individual (right shoulder), the clavicopectoral trunk (a common trunk formed by the clavicular and pectoral branches of the thoracoacromial artery) was found coming off the first part of the axillary artery, while the acromial and deltoid branches emerged directly and separately from the second part of the axillary artery. Astik and Dave (2012) reported a 5% frequency of the thoracoacromial trunk dividing into the deltopectoral and clavicopectoral trunks.

In two individuals (right shoulders) from the current study, the thoracoacromial artery emerged from the first part of the axillary artery, accompanied by the superior thoracic- and the suprascapular artery also branching directly from the first part. A common trunk for the thoracoacromial artery and the lateral thoracic artery was noted in 8% of the cadavers in the current study and is the same percentage reported in a study by Patel *et al.* (2013).

Patel *et al.* (2013) documented the emergence of the lateral thoracic artery from the first part in 2% of the cases. Patnaik *et al.* (2000) reported incidences of the lateral thoracic arising from second part of the axillary artery in 92% of the upper limbs, and in 6% cases this origin was found arising from the first part. In the current study, the frequency of the origin of the lateral thoracic artery from the first part of the axillary artery was documented at 18%. In this sample, a common trunk was shared with the thoracoacromial artery in 8% of the study cases. The occurrence of this common trunk could not be found in previous literature.

The suprascapular artery has been documented as emerging from the first part of the axillary artery in various studies ranging from 1.6-3.6% across several populations (Mishra and Ajmani, 2003; Cummins *et al*., 2008; Singh, 2018). The results of this study present similarities in the emergence of this artery with 4% of sample displaying the same origin. Tountas and Bergman (1993) went on to document the variable origin of the suprascapular artery as arising from various parts of the subclavian as well as the axillary artery in 10% of cases. The artery has, however, been found originating from other vessels such as the subclavian artery in 21.3% of cases (Read and Trotter, 1941), the internal thoracic artery in 1-1.5% (Read and Trotter, 1941), the costocervical trunk in 1% (Lippert and Pabst, 1985) and even a dorsal scapular artery origin noted by Saadeh (1979). In the current study, the suprascapular artery was found giving blood supply to the RC muscles as previously documented in literature (Maral *et al.*, 1993; Determe *et al.*, 1996; Abrassart *et al.*, 2006; Standring *et al.*, 2008; Naidoo *et al.*, 2014).

4.4.2. Second part of axillary artery

The current study documented the mean length of the second part at 35.79 ± 8.71mm on the right side and 33.76 ± 7.76mm the left side, with this part marked by the emergence of the thoracoacromial- and lateral thoracic arteries. In the current study, variations were noted to the superior thoracic artery which was found emerging from the second part in 2% of the cases. Similar findings were previously documented by Verma *et al.* (2014) and Satapathy *et al.* (2015), who observed the unilateral emergence of the superior thoracic artery.

Astik and Dave (2012) noted the emergence of branches of the thoracoacromial artery directly from the axillary artery in 8.8% of cases. In the current study, the thoracoacromial was found emerging from the second part of the axillary artery in 66% of the sample, with two cases noting the pectoral- and acromial branches emerging directly from the second part of the axillary artery instead of from the thoracoacromial artery. A case presented by Chitra and Anandhi (2013) noted a complete absence of the thoracoacromial trunk, with all four branches rather arising directly from the second part of the axillary artery. Previous literature also noted additional branches arising from the thoracoacromial artery or the emergence of an additional common trunk giving rise to the thoracoacromial artery and other established branches of the axillary artery. In the current study, a common trunk was noted between the suprascapular- and thoracoacromial artery (1%) in the first part of the axillary artery. Similar findings were recorded by Kanaka *et al.* (2015) in 15% of the study sample, however, this variation was in the second part of the axillary artery.

A study by Huelke (1959) documented the emergence of the lateral thoracic artery from the first part of the axillary artery in 10.7% of the cases, from the second part in 52.2% of the cases and from the third part in 1.7% of the study cases. In the current study, the lateral thoracic was found arising from the first part in 18% of cases, slightly higher than reported by Heulke (1969). In 6% of the study sample, the lateral thoracic artery shared a common trunk with the subscapular- and posterior circumflex humeral artery, the same occurrence was documented by Patel *et al.* (2013) in 2% of cases, while Ojha *et al.* (2015) found this bilateral common trunk in 13% of the study cases. In 5% of cases, the lateral thoracic was found emerging from a common trunk shared with the subscapular artery. This occurrence was noted by Lippert and Pabst (1985) in 10% of their study sample, Astik *et al.* (2012) in 22.5% of their sample, while Satapathy *et al.* (2015) noted this bilateral occurrence in only one cadaver.

The high bifurcation of the brachial artery has previously been documented. Lufukuja (2018), noted this incidence in 8.3%, Sharma *et al.* (2009) and Sawant *et al.* (2012) also reported the bilateral superficial/collateral brachial artery while Yang *et al.* (2008) found this incidence in 12.2% of cases in the Korean sample. The current study noted an anomalous bilateral branching of the collateral brachial artery in the second part of the axillary artery in 2% of cases. A collateral brachial artery was found in a 69-year-old white male cadaver (Figure 4.3). The collateral brachial artery was found terminating in the brachium, giving blood supply to the axillary lymph nodes and muscles of the anterior brachium. A similar branching pattern was found in a 92-year-old white female cadaver, where this variation was documented on the right side (Figure 4.4). In the brachium, the artery was found coursing between the biceps brachii- and brachialis muscle, providing blood supply to the muscles in the anterior compartment of the arm. Although the brachial artery may not be clinically significant in diagnostic procedures, the superficial course of the collateral brachial artery may, however, increase the vulnerability of the vessel during cannulation or traumatic injury (Lufukuja, 2018).

Findings by Huelke (1959), Patnaik *et al.*, (2000), Huelke (2005) and Bergman *et al.*, (2006) documented the emergence of the subscapular artery from the second part in 15.7%, 16%, 15.7% and 15% of the study cases, respectively. The current study noted this variation in 18% of the study sample, which is slightly higher than the previous studies. Documented cases of the subscapular artery emerging from the second part of the axillary artery have been indicated to vary from 4% to 15% by Gaur *et al.* (2012) and Huelke (1959), respectively.

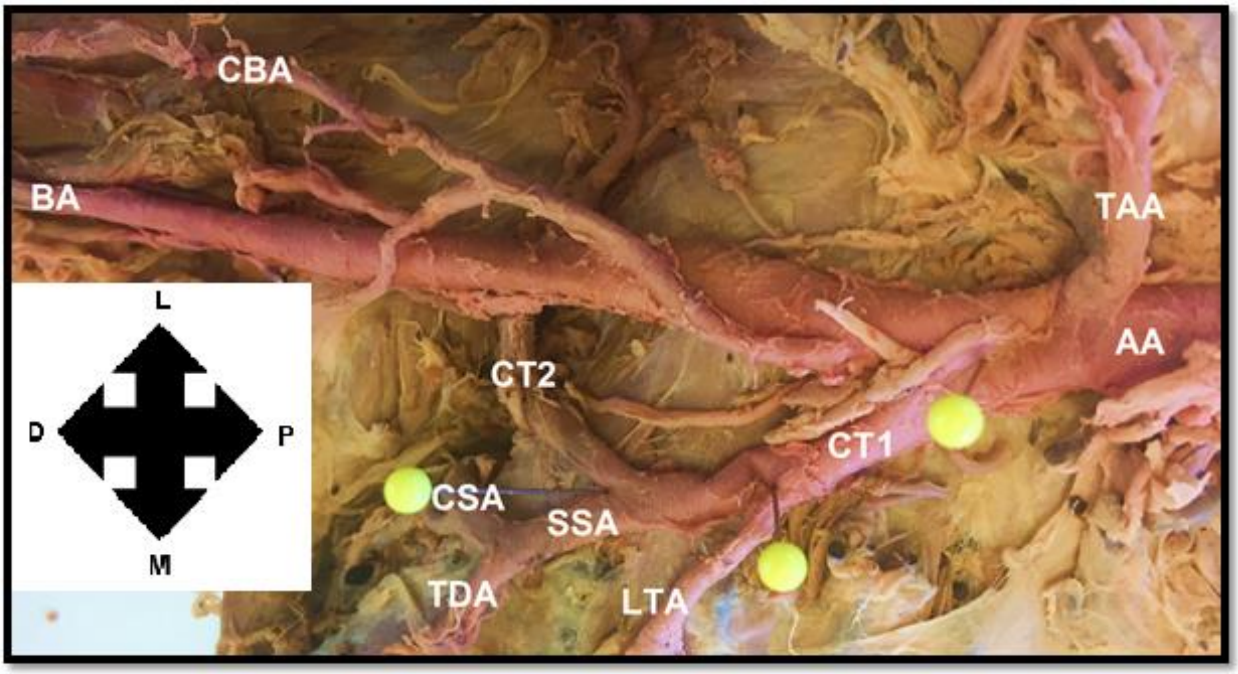

Figure 4.3: Dissection of the right axilla showing the second part of the AA and some of the branches given off in its course. A common trunk (CT1) is shared by the SSA and the LTA. A common trunk further shared by the SSA and second common trunk (CT2). CT2 terminates in the ACHA and the PCHA. A variation is noted in the second part of the axillary artery from which the collateral brachial artery (CBA) arises. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, AA – Axillary artery; TAA – Thoracodorsal artery, LTA – Lateral thoracic artery, ACHA – Anterior circumflex humeral artery, SSA – Subscapular artery, CSA – Circumflex scapular artery, TDA – Thoracodorsal artery, CBA – Collateral brachial artery; BA – Brachial artery*

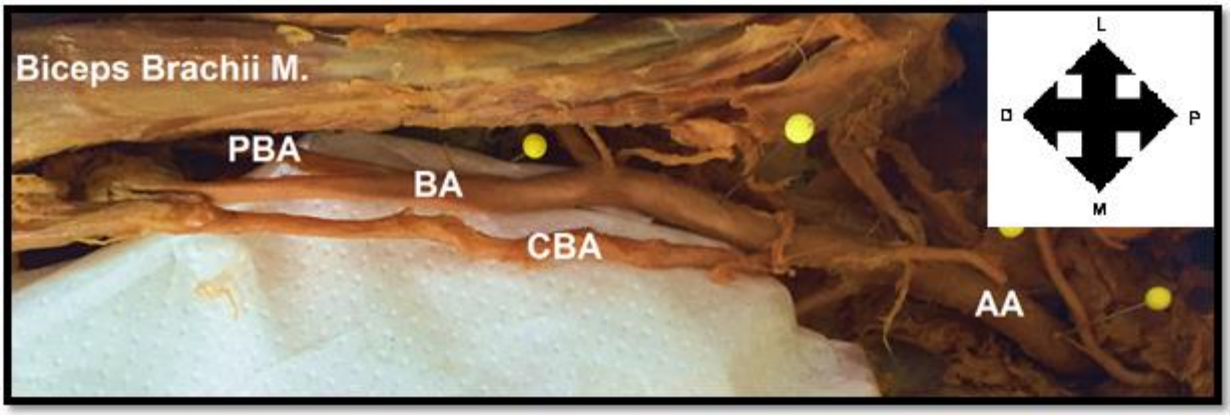

Figure 4.4: Dissection of the right axilla showing the arm fully abducted exposing the AA in its course. The CBA is given off from the second part of the AA. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, AA – Axillary artery; CBA – Collateral brachial artery; BA – Brachial artery; PBA – Profunda brachii artery*

4.4.3. Third part of axillary artery

The current study noted the mean length of the third part of the axillary artery as 44.19 ± 9.62mm on the right side and 44.68 ± 11.16mm on the left side. Part of the variations noted in this part included a common trunk for the lateral thoracic-, subscapular- and posterior circumflex humeral artery which was documented in 3% of the sample. Similar findings were previously documented by Ojha *et al.* (2015), who found this variation in 2% of the sample; however, this was in the second part of the axillary artery.

Patel *et al.* (2013) and Saeed *et al.* (2012) documented a common trunk trifurcation of the anterior circumflex humeral-, posterior circumflex humeral- and subscapular arteries from the third part of the axillary artery in 8% and 3.8% cases, respectively. In the current study, the trifurcation was documented in 17% of the study sample, which is significantly higher than the two prior studies. The same trifurcation was also noted in the second part of the axillary artery in 2% of the sample. Similar findings were made by Ojha *et al.* (2015), who noted these occurrences in 13% of the cases, while Chitra *et al.* (2013) documented a common trunk for all the branches of the second and third parts of the axillary artery. The study also noted a common trunk shared by the posterior- and anterior circumflex humeral artery in 3% of the sample size (Figure 4.5). Patel *et al.* (2013) documented similar findings in the third part of the axillary artery in 5% of cases, while Rao *et al.* (2008) noted a common trunk shared by the anterior- and posterior circumflex humeral arteries, following the initial bifurcation from a shared trunk with the subscapular artery.

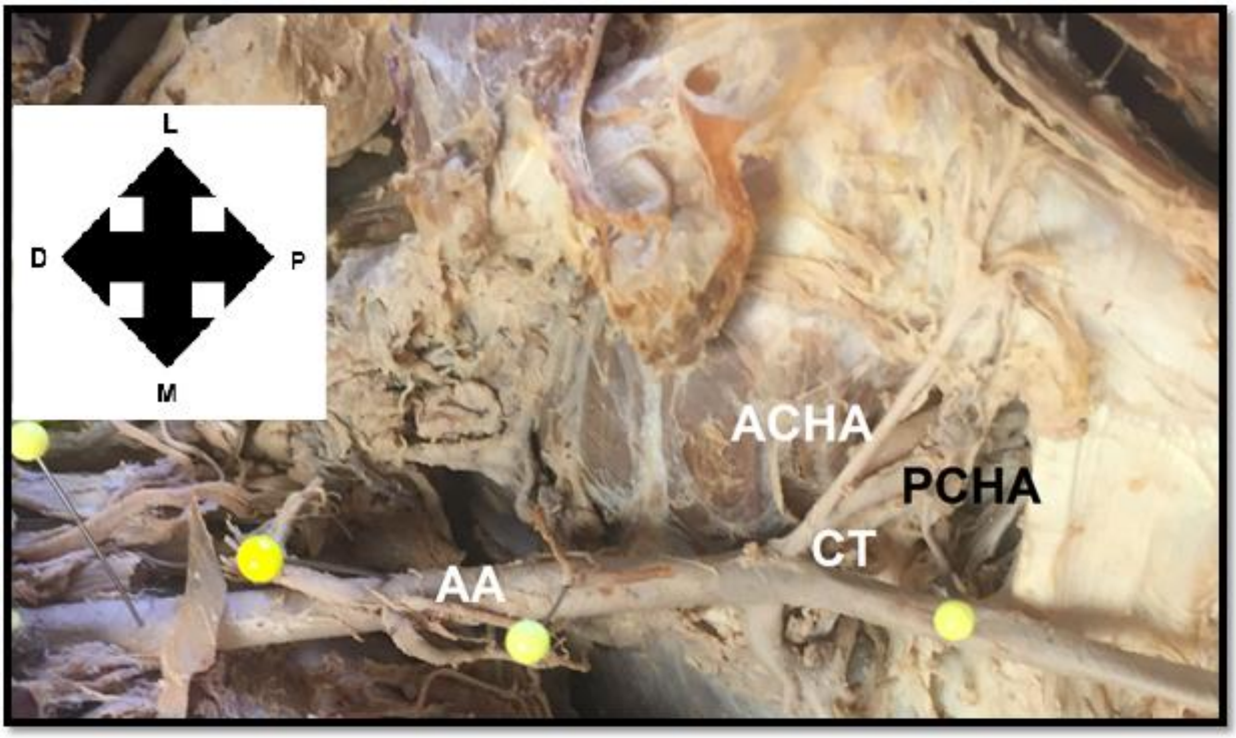

Figure 4.5: Dissection of the left axilla showing a common trunk shared by the ACHA and the PCHA in the third part of the AA. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, AA – Axillary artery; ACHA – Anterior circumflex humeral artery; CT – Common trunk; PCHA – Posterior circumflex humeral artery*

Patel *et al.* (2013) noted the emergence of a common trunk shared between the posterior circumflex humeral artery and the subscapular artery in 2% of cases. In the current study, this variation was noted in 48% of cases, with 11% of cases indicating the emergence of the common trunk in the second part of the axillary. The current study therefore noted the existence of a common trunk in 59% of cases. Gaur *et al.* (2012) and Sreenivasulu *et al.* (2015) found this common trunk in 30% of cases, while Huelke (1959) documented the emergence in 67.5% of cases.

In the 100 dissected axillae, the subscapular artery was found emerging in five variable ways. Comparative study findings are summarised in Table 4.8.

Table 4.8: A comparison in the variable origins of the subscapular artery.

Author	Variation of Origin	Sample Size	Incidence
DeGaris and Swartley (1928)	Second part of axillary artery	512	5.1%
	Third part of axillary artery		94.1%
Huelke (1959)	First part of axillary artery	89	0.6%
	Second part of axillary artery		15.7%
Lippert and Pabst (1985)	Common trunk with posterior circumflex humeral artery from axillary artery	Not recorded	20%
	Common trunk with lateral thoracic artery from axillary artery		10%
Patnaik *et al.*, (2000)	Second part of axillary artery	50	16%
	Third part of axillary artery		80%
Saeed *et al.*, (2003)	Common trunk with posterior circumflex humeral artery	106	3.8%
Huelke (2005)	Second part of axillary artery	178	15.7%
Bergman *et al.*, (2006)	Second part of axillary artery	Not recorded	15%
	Common trunk with transverse cervical artery from thyrocervical trunk of subclavian artery		6%
Karambelkar *et al.*, (2011)	Second part of axillary artery	60	1.66%
	Common trunk with posterior circumflex humeral artery		8.33%
Gaur *et al.*, (2012)	Second part of axillary artery; did not give rise to circumflex scapular artery	50	4%
Xhakaza and Satyapal (2014)	Second part of axillary artery	89	52.8%
	Third part of axillary artery		47.2%
Current study (2019)	**Second part of axillary artery**	**100**	**18%**
	Third part of axillary artery		**82%**
	Common trunk with posterior circumflex humeral artery		**59%***
	Common trunk with lateral thoracic artery and posterior circumflex humeral artery		**6%***
	Common trunk with lateral thoracic artery		**4%***
	Common trunk with anterior and posterior circumflex humeral arteries		**19%***

**59%, 6%, 4% and 19% are subdivisions of the classified origin from the second and third parts*

Surgical implications relating to the anatomical variations encountered in the origin of the subscapular artery are important to take cognisance of. The subscapular arterial system is appreciated during arterial graft in the attempt to restore upper limb circulation, where this network serves as a donor (Valnicek, 2004; Masden *et al.,* 2012). Flaps are also created using this network; these include the subscapular flap from the circumflex scapular artery, the serratus anterior flap from the thoracodorsal artery and the latissimus dorsi flap, also from the thoracodorsal artery. The use of these flaps is in combination with cutaneous-, subcutaneous-, muscular- and bony elements (Mayou *et al.,* 1982; Uglesić *et al.,* 2000). The use of the subscapular arterial system even extends to the coverage of defects in the lateral thoracic wall, mastectomy restoration and oromandibular defects (Tukiainen, 2013; Loukas *et al.,* 2014; Shaw *et al.,* 2015). Previous research studies have shown that branches from the subscapular artery have a significantly larger diameter, making them suitable for flap transfer. The subscapular arterial diameter has been recorded as 4 - 6mm and the thoracodorsal artery diameter as 3 - 5mm across a variety of studies (Valnicek *et al.,* 2004; Kawamura *et al.,* 2005; Jesus *et al.,* 2008).

4.5. Conclusion

The unusual branching pattern of the axillary artery appears to be the norm rather than the exception. Numerous variations with regard to origin of branches were documented in this study and follow close similarities with previously published literature on the matter. In our study, variations in the branching pattern of the first part of the axillary artery included the origin of the superior thoracic artery from the thoracoacromial trunk accompanied by the lateral thoracic artery in 1% of cases, the branching of the suprascapular artery in 4% of cases, the origin of the lateral thoracic artery in 18% of cases and branching of the superior thoracic artery from the second part, in 2% of cases. Additionally, the origin of the thoracoacromial artery was seen from the first part in 34% of the sample. This high incidence was not found in previous literature and provides a novel addition to the possible variation for this specific trunk. The variations in the second part included a common trunk for the thoracoacromial artery and the lateral thoracic artery in 8% of cases and in 3% of the sample a collateral brachial artery was found, giving blood supply to the anterior compartment of the brachium. The third part showed a common trunk trifurcating into the anterior circumflex humeral, posterior circumflex humeral and subscapular arteries in 17% of cases. A common trunk shared by the anterior- and posterior circumflex humeral arteries was found in 3% of cases. The posterior circumflex humeral artery was found sharing a common trunk with the subscapular artery in 59% of cases and in 18% of the study sample, the subscapular artery was found branching from the second part of the axillary artery. It is imperative that vascular surgeons and/or specialist operating in the regions related to the branching of these vessels familiarise themselves with existing deviations. Thorough knowledge of this region will assist in better patient outcomes and evasion of intra-operative bleeding and related post-surgical complications.

4.6. Limitations

The disparities in the number of the sample size (n = 48, n = 47, n = 52) are due to some limitations encountered during the data collection phase of the study. Bilateral dissections were only possible in 48 of the cadavers dissected, unilateral dissections were carried out on four cadavers in order to bring the sample size to 50 right and 50 left dissected shoulders. The cadavers used for this study were taken from the second year medical- and dentistry dissection groups, where the axillary and/or subclavian artery was sometimes transected, resulting in unilateral dissection of the intact artery. The pectoralis minor muscle was at times partly or totally incised, resulting in the exclusion of the affected limb from the study sample. In many instances, the suprascapular artery was cut in its course, only leaving the origin, thereby limiting the ability to follow the blood supply to its termination point. Some branches of the axillary artery had also been cut during undergraduate dissection, leaving only the origin of these branches from the axillary artery.

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Chapter 5

Manuscript 2

Title: The unusual unilateral high bifurcation of the ulnar artery from the second part of the axillary artery: A case report

Abstract

Variations with regard to the axillary artery's branching pattern are fairly common. However, there is one particular variation, a high emergence of the superficial ulnar artery (SUA), which has only been reported sporadically throughout literature. During a routine dissection by second year dentistry students, this unilateral variation in the branching of the superficial ulnar artery was found in a 74-year-old white male cadaver on the right side. The SUA was seen emerging from the second part of the axillary artery, coursing between the medial root of the median nerve and the ulnar nerve. The SUA was found giving off muscular branches to the anterior compartment muscles of the arm before entering the cubital fossa and coursing superficial and medial to the bicipital aponeurosis. More muscular branches were noted to the muscles of the medial aspect of the forearm. The superficial ulnar artery terminated by forming the superficial palmar arch and contributing to the formation of the deep palmar arch. This variation is of substantial interest to orthopaedic surgeons, plastic surgeons, radiologists and anatomists due to its superficial course, making it susceptible to damage. Damage to this vessel may result in haemorrhage, which may lead to the development of an air embolism and ischemia. The SUA may also be mistaken for a vein which could result in intra-arterial injections.

Key words: Axillary artery, ulnar artery, superficial ulnar artery, variations, superficial palmar arch, upper limb

5.1. Introduction

The course of the axillary artery is typically described as originating at the lateral border of the first rib as the continuation of the subclavian artery, and terminating at the inferior border of the teres major muscle to continue as the brachial artery. The axillary artery is divided into three parts by the pectoralis minor muscle with six branches emerging along its course.

Variations in the branching pattern of the axillary artery have been mentioned in several publications with numerous anomalous case reports (Maral *et al.*, 1993; Determe *et al.*, 1996; Abrassart *et al.*, 2006; Standring *et al.*, 2008; Swamy *et al.*, 2013; Naidoo *et al.*, 2014; Akhtar *et al.*, 2018). The high origin of the ulnar artery from either the axillary, brachial or superficial brachial artery has previously been reported in the literature and all variations are considered clinically significant with reported frequency rates of between 0.17% - 2% (Nakatani *et al.*, 1996; Jacquemin *et al.*, 2001; Natsis *et al*., 2006; Dartnell *et al.*, 2007; Bhat *et al*., 2008; Vollala *et al.*, 2011; Swamy *et al.*, 2016). The aptly named superficial branch is positioned superficial in the arm and forearm, coursing superficial to the bicipital aponeurosis while coexisting with a brachial or superficial brachial artery. This brachial artery usually terminates in the cubital fossa by branching into both the radial artery and a common interosseous artery or, less frequently, into the radial and an additional ulnar artery (Rodríguez-Niedenführ *et al.*, 2001; Mannan *et al.*, 2005). The variant superficial ulnar artery (SUA), when present, most often terminates in the hand by forming the superficial palmar arch.

5.2. Case Report

An unusual unilateral branching pattern was found on the second part of the axillary artery on the right side in a 74-year-old white male cadaver during routine anatomical dissection in the Department of Anatomy (Figure 5.1). The first part of the axillary appeared normal with the origin of the superior thoracic artery clearly identified. Although the thoracoacromial and lateral thoracic arteries had been transected by previous dissectors, the roots of these arteries could still be seen emerging from the second part of the axillary artery (Figure 5.2). The axillary artery was subsequently found giving off an additional branch in the second part, the superficial ulnar artery (SUA), which coursed between the medial root of the median nerve and the ulnar nerve (Figure 5.3). The third part gave rise to the anterior and posterior circumflex humeral arteries along with the subscapular artery, the latter which could be found branching into the circumflex scapular and thoracodorsal arteries as normal text describes.

After the termination of the third part of the axillary artery at the inferior border of the teres major muscle, the brachial artery gave rise to the profunda brachii artery and followed its usual course and arterial distribution (Figure 5.2). The variant SUA was dissected out and found to pass deep to the deep fascia of the arm, accompanying the ulnar nerve along its course until entering the cubital fossa. Muscular branches to both the biceps brachii and brachialis muscles were noted. In the cubital fossa, the SUA was positioned superficial and medial to the bicipital aponeurosis, accompanied by its venae comitantes. Only smaller, muscular branches to the muscles in the medial aspect of the forearm were observed and no other branches usually associated with the ulnar artery in this region, were noted. The normal origin of the ulnar artery was absent at the apex of the cubital fossa with the brachial artery bifurcating into the radial and common interosseous arteries. The common interosseous artery further divided into the anterior and posterior interosseous branches continuing into, and supplying the anterior and posterior forearm compartments (Figure 5.4). Muscular branches were also noted emerging from the anterior interosseous branch with the common interosseous artery giving off the recurrent interosseous artery. The radial artery was followed to its terminal point, which ended at the radial palmar carpal and deep palmar arch contributions. The SUA terminated by forming the superficial palmar arch in the hand and contributing a deeper branch to the formation of the deep palmar arch, as most commonly observed with the presence of a normal ulnar artery (Figure 5.5).

5.3. Discussion

Previous studies on the branching pattern variation of the axillary artery indicated that 28% of cases displayed some variability, with 16% of these variations occurring along the second part of the axillary artery (Gaur *et al.*, 2012). In an interesting case report by Ramesh *et al.* (2008), a common trunk was observed in the third part of the axillary artery which gave rise to the subscapular, anterior and posterior circumflex humeral, profunda brachii and ulnar collateral arteries, a variation not commonly mentioned in the literature. The exact cause of the high variation rates in the anatomy of the axillary artery has not yet been established however, some embryological hypotheses have been proposed, with Natsis *et al.* (2006) suggesting the result to be from modifications to the normal pattern of capillary vessel maintenance and regression.

Despite various hypotheses being suggested, a unanimous decision with regard to the embryological development of the arterial system has not yet been reached either. Rodríguez-Niedenführ *et al.* (2001), who conducted a large embryological study, proposed that the normal arterial system develops by selective enlargement or regression of a capillary plexus and not by budding from a main axial trunk. Therefore, several authors have stated that the SUA may be the result of a persistent capillary bud coming from the axillary artery (Rodríguez-Niedenführ *et al.*, 2001; Bhat *et al.*, 2008). The high bifurcation of the ulnar artery is not unique to the current study, but remains a rare occurrence, with a prevalence of only 0.7% - 9.4% in reported populations (Hazlett, 1949; McCormack *et al.*, 1953; Weathersby, 1956; Rodriguez-Baeza *et al.*, 1995; Devansh, M.S., 1996; Fadel and Amonno-Kuofi, 1996; Nakatani *et al.*, 1998; Rodriguez-Niedenfuhr *et al.*, 2000; Jacquemin *et al.*, 2001; Rodriguez-Niedenfuhr *et al.*, 2001; Latha *et al.*, 2002; D'costa *et al.*, 2004; Chin and Sing, 2005; Sieg *et al.*, 2006; Vollala *et al.*, 2011; Shetty *et al.*, 2013).

The variant origin of the ulnar artery, when present, is more commonly found arising from the third part of the axillary artery with the origin being either from the axillary artery and in some cases, the more proximal aspect of the brachial artery, displaying various modes of arterial distribution (Jacquemin *et al.*, 2001; Natsis *et al.*, 2006; Panagouli *et al.*, 2009). The course of the SUA in the current study, is similar to previous studies with the blood vessel passing superficial to the bicipital aponeurosis and muscles of the forearm (Jacquemin *et al.*, 2001; Natsis *et al.*, 2006; Panagouli *et al.*, 2009). In a study by Bhat *et al.* (2008), the SUA was found coursing deep to the bicipital aponeurosis and was similarly reported by Swamy *et al.* (2013), who documented the course of a superficial/variant ulnar artery as emerging from between the two roots of the median nerve and then passing deep to the deep fascia of the arm and forearm, the median cubital vein, bicipital aponeurosis and the palmaris longus muscle. The diameter of the SUA has also been found to be variable (Swamy *et al.*, 2013). In the current study, the radial and ulnar arteries displayed similar calibres resulting in the formation of the superficial palmar arch being by the SUA. The deep palmar arch was largely formed by the radial artery, as in normal arterial distributions, with a contribution from the SUA.

The superficial course followed by the variant SUA is such that it crosses over subcutaneous veins, which may pose possible complications relating to intravenous drug administration, venipuncture or percutaneous brachial catherization (Yazar *et al.*, 1999; Chin and Singh, 2005; Bhat *et al.*, 2008). This vessel, due to its superficial position at the cubital fossa, is more prone to injury which may lead to haemorrhaging, air embolism and possibly permanent damage resulting in ischaemia. It may also be mistaken for a vein during its course or even a persistent median artery in the distal end of the forearm (Yazar *et al.*, 1999; Chin and Singh, 2005). Instances where the SUA may be mistaken for a vein could possibly result in intra-arterial injection and difficulties in angiographic procedures (Chin and Singh, 2005).

The variable diameter and high origin of the ulnar artery should also be made known to surgeons performing procedures such as free radial forearm flaps, as post-surgical blood supply of the forearm would depend entirely on this superficial/variant ulnar artery (Senanayake *et al.*, 2007). Surgeons may also harvest these vessels during coronary bypass surgeries to be used as conduits (Swamy *et al.*, 2013). Knowledge of the occurrence and variable course of these vessels would prevent possible surgical complications for orthopaedic surgeons operating through an anterior incision in the repair of a ruptured distal bicipital tendon (Boyd and Anderson, 1961). In instances where the SUA may be located in close proximity to the veins in the roof of the cubital fossa, advertent penetration of the artery may occur during venepuncture of the median cubital vein. Other cases of caution include intervention during a thrombosed forearm presentation accompanied by poor collateral circulation and in vascular puncture of the basilic vein (Dartnell *et al.*, 2007). Therefore, thorough knowledge of this variation may prevent traumatic profuse bleeding of this vessel following accidental damage, where the SUA may have been a major source of blood supply to the area of trauma.

Figure 5.1: Dissection of the right upper limb showing the axillary artery (AA) with the superficial ulnar artery (SUA) emerging from the second part of the AA. The SUA terminates by forming the superficial palmar arch (SPA) and contributing to the formation of the deep palmar arch (DPA). *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, BBM (SH) – Biceps brachii muscle (Short Head), BA – Brachial artery, RA – Radial artery, RPCA – radial palmar carpal artery*

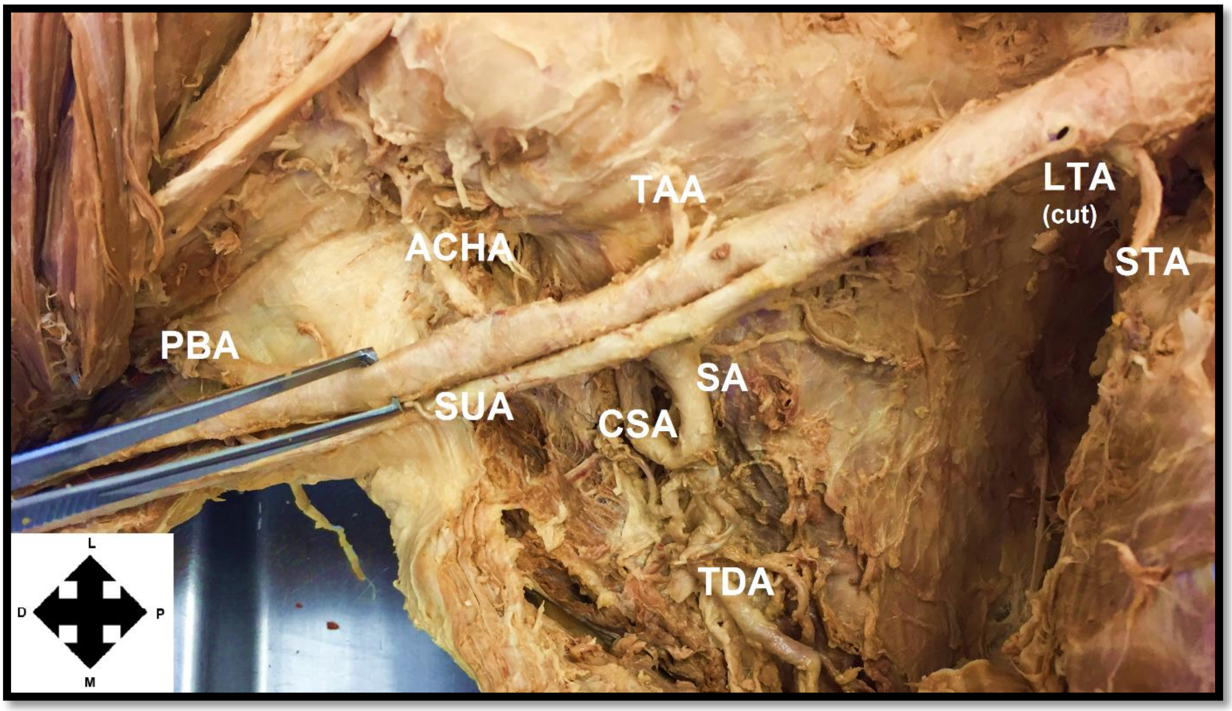

Figure 5.2: Dissection of the right axilla showing the three parts of the axillary artery, with the second part giving off the superficial ulnar artery (SUA). The anterior circumflex humeral (ACHA), posterior circumflex humeral (not visible) and the subscapular artery (SA) were also seen emerging from the third part of the axillary artery. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal*

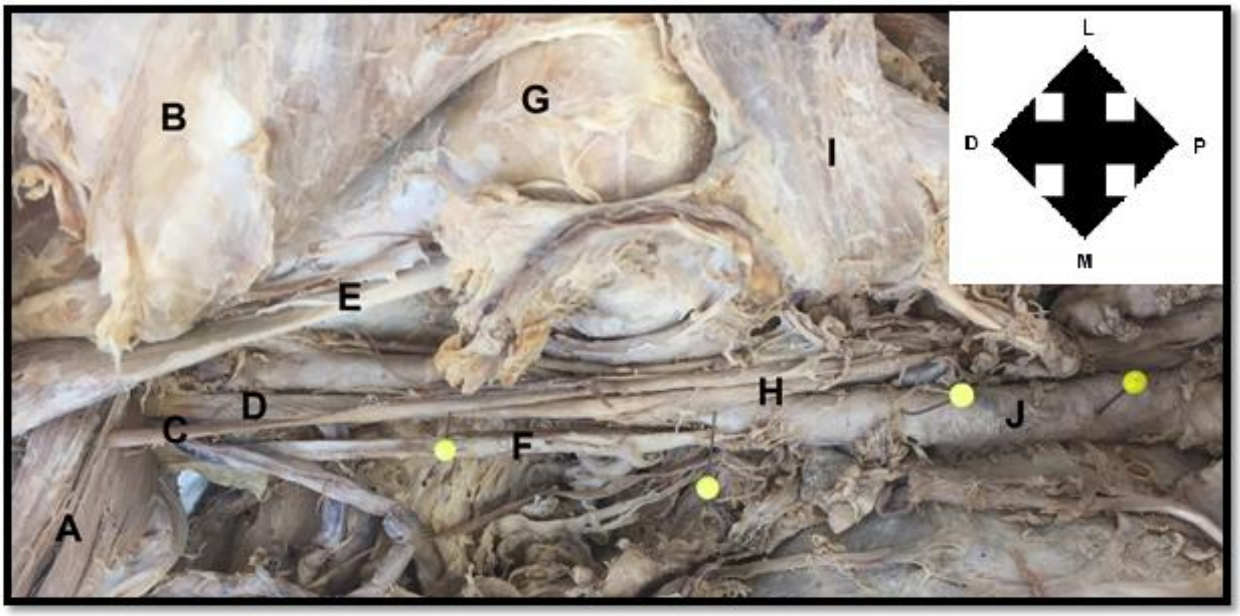

Figure 5.3: Dissection of the right axilla showing the relation of the superficial ulnar artery (SUA) to the medial root of the median nerve. The three parts of the axillary artery are marked with yellow pins. The ulnar nerve was transected to better visualise the SUA. The following structures can be seen in the image above: A – Coracobrachialis muscle (reflected), B – Deltoid muscle (reflected, C – Musculocutaneous nerve; D – Median nerve; E – Long head of biceps brachii muscle; F – Superficial ulnar artery (SUA), G - Lateral aspect of the proximal humerus, H – Medial root of the median nerve, I – Pectoralis minor muscle (reflected), J – Axillary artery. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal*

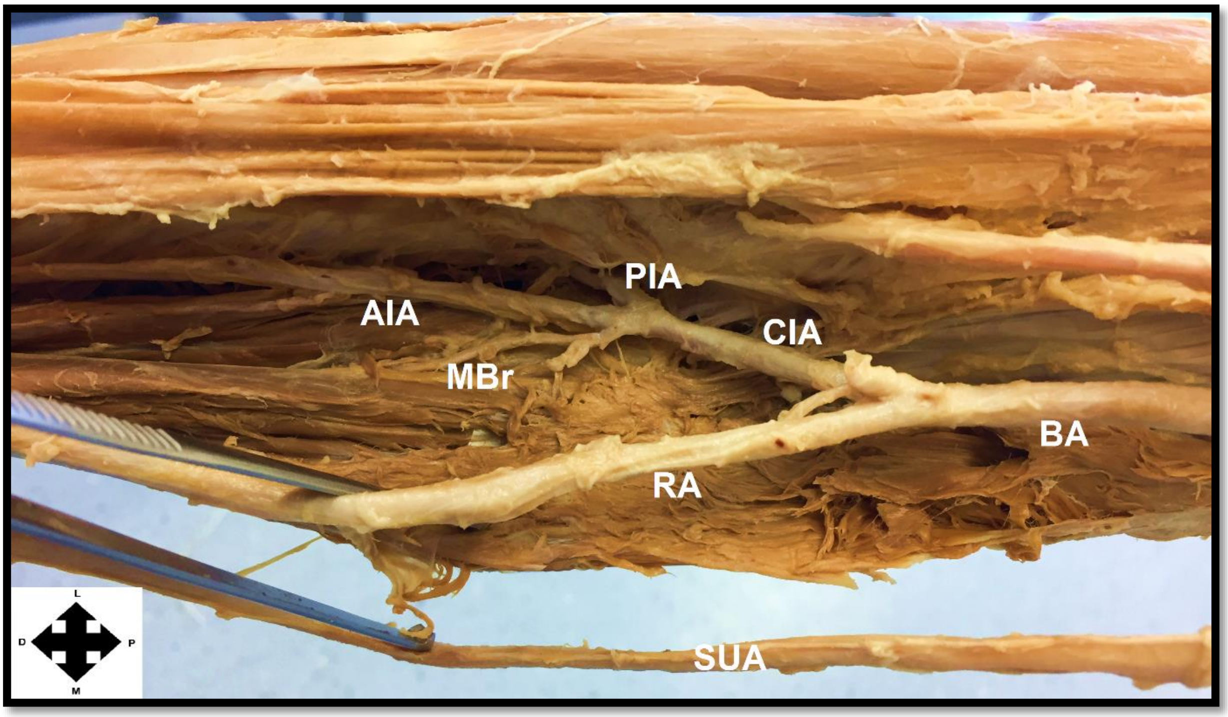

Figure 5.4: Dissection of the right upper limb showing the brachial artery (BA) giving off a radial (RA) and common interosseous artery (CIA). The RA was moved medially to allow for better visualisation of the BA bifurcation and the CIA branches. The CIA further divides into the anterior interosseous (AIA) and the posterior interosseous (PIA) branches. The AIA can be seen giving off muscular branches (MBr). *Key: M – Medial, L – Lateral, D – Distal, P - Proximal*

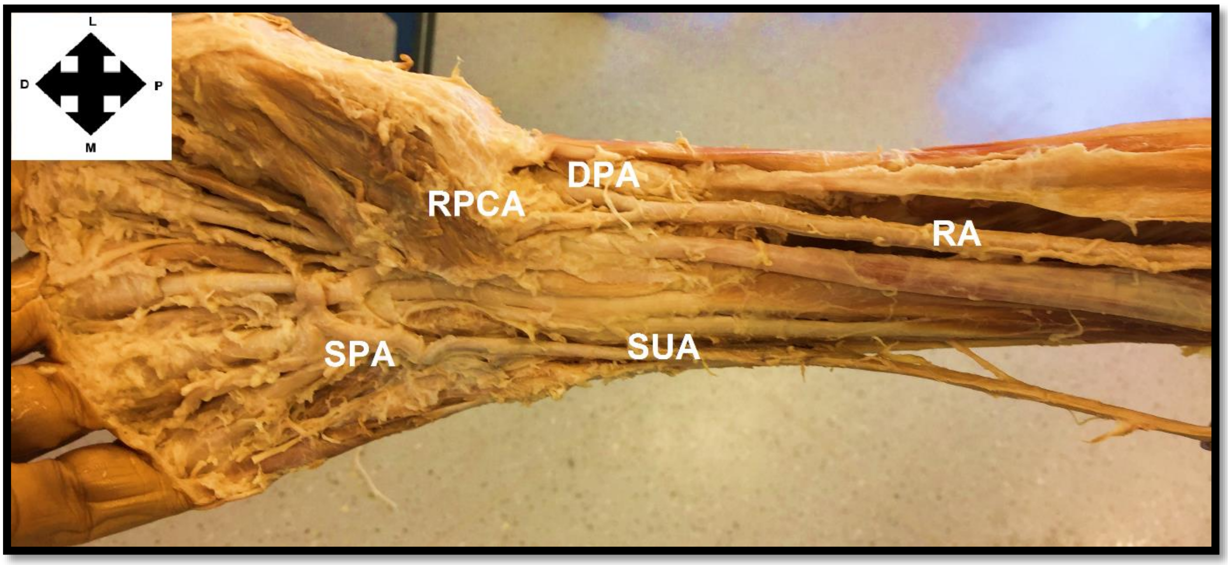

Figure 5.5: Dissection of the right upper limb showing the superficial ulnar artery (SUA) terminating by contributing to the formation of the superficial palmar arch (SPA). The radial artery (RA) can be seen bifurcating into the radial palmar carpal artery (RPCA) and the branch which contributes to the formation of the deep palmar arch (DPA). *Key: M – Medial, L – Lateral, D – Distal, P - Proximal*

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Chapter 6

Manuscript 3

Title: The morphology and prevalence of shoulder pathology in a South African cadaveric sample

Abstract

Pathology of the shoulder is a common phenomenon with shoulder related surgeries noted as the second highest following lumbar surgeries. The biomechanical function of the glenohumeral joint is affected by shoulder pathology, usually leading to a decrease in the ROM. The aim of this study was to document the prevalence of various RC and glenohumeral joint pathologies noted on the cadaver sample. The sample consisted of 104 left and right cadaveric shoulders from male and female cadavers between the ages of 28 to 98 years. The shoulder muscles (deltoid, trapezius) were reflected until the RC unit could be identified. Further dissection of the RC muscles included the reverse dissection in order to view all aspects of the RC unit as well as the glenohumeral joint for any possible signs of pathology. Glenohumeral joint and/or RC pathology, where identified, was documented and any RC tears classified according to the pre-existing classification categories. RC and glenohumeral joint related pathologies were recorded in 33% of the sample. Pathologies found ranged from small to massive tears, osteophytes and the possible onset of osteonecrosis. Bilateral marbleisation of the humeral head was also documented in one cadaver, where the movement of this limb had resulted in an absent cuff. Soft tissue pathology was found as well, with one cadaver displaying a degenerative long head of biceps brachii muscle but no clear sign of Popeye's deformity. The blood supply to all the areas with pathology had not been affected, the anterior- and posterior circumflex humeral arteries were clearly seen encircling the surgical neck of the humerus. In 3% of the study sample, signs of the onset of osteonecrosis of the proximal humerus were documented.

Key words: Shoulder pathology, glenohumeral joint, rotator cuff pathology, cadaver osteophytes, rotator cuff tears

6.1. Introduction

Rotator cuff (RC) injuries are one of the most common causes of shoulder pain and discomfort, and are most commonly observed in individuals over 40 years of age (Bartowszewski and Parnes, 2018). The glenohumeral joint is formed by the articulation between the head of the humerus and the glenoid cavity of the scapula, and is stabilized by the formation of several additional joints, such as the acromioclavicular joint. Other structures such as; bones, ligaments, muscles, tendons and bursae also contribute to the stabilization and function of the glenohumeral joint (Carmichael and Hart, 1985; Chang and Varacallo, 2019). The RC muscles form a musculotendinous cuff and together with the deltoid muscle, play a crucial role in the structural integrity of the glenohumeral joint. The development of RC injury is often thought to be secondary to a number of other pathologies such as, impingement, degenerative changes, subacromial bone spurs, poor blood supply, or overload. In instances of RC injuries, the supraspinatus muscle is most often involved due to its close association with the under surface of the acromion process (Carmichael and Hart, 1985; Bartowszewski and Parnes, 2018).

Biomechanical function of the glenohumeral joint and the related soft tissue is affected by the onset of pathology. Van der Windt *et al.* (1995) and Michener *et al.* (2003) documented shoulder impingement as a common condition attributed to the progression and initial development of RC related pathologies. The various impingement types seem to be responsible for the development and progression of tendinopathy to the long head of the biceps brachii muscle and RC pathology (Soslowsky *et al.* 2002). The numerous mechanisms by which impingement may result include abnormality in the pattern observed during certain aspects of the range of motion (ROM), a reduction in the motion at the joint or excessive increase in the motion found at the joint (Michener *et al.* 2003). Changes in the normal anatomy of the humerus and/or acromion have also been linked with impingement. It must be noted, however, that RC pathology may still develop without noted impingement. This development may instead be due to tissue degeneration or through tensile overload to the area thereby affecting the biomechanical function of the shoulder and limiting the ROM or the degree of motion possible at the glenohumeral joint (Soslowsky *et al.*, 2002).

Studies relating to RC pathology have been conducted with Smith (1834) reporting the first case of RC tears. These studies include cases of symptomatic and asymptomatic patients, imaging and cadaveric studies. Cadaveric studies using an elderly sample have estimated the prevalence of full thickness tears to range from 5 – 30% (Lehman *et al*., 1995; Sher *et al.*, 1995; Via *et al.*, 2013). Full thickness tears have also been reported in 28% of cases in patients older than 60 years (Sher *et al.*, 1995). A cadaveric study conducted by Reilly (2006), with a sample size of 4629, reported the prevalence of RC tears at 23%. Milgrom (1995) noted the increase in RC tears in patients older than 70 years, with the prevalence as high as 65%. Milgrom (1995) also documented the linear increase in the prevalence of RC tears from the third decade, with the 40s to 50s showing an increase from 33% to 55%, respectively. Several other pathologies relating to the glenohumeral joint have also previously been documented. A study by Konno *et al.* (2002) noted the contribution of glenoid osteophytes to RC tears in 30 of the 86 (35%) cadaveric shoulders used in their study. Other factors found to increase the occurrence of RC tears include, history of trauma, limb dominance, contralateral shoulder, smoking, hypercholesterolemia, posture and occupational dispositions (Gumina *et al.*, 2013; Abate *et al.*, 2014; Sambandam *et al.*, 2015).

Therefore, RC and glenohumeral joint pathology was investigated in a South African cadaver sample to further understand the prevalence of most common pathologies associated with the RC and glenohumeral joint, and to classify the most notable RC tear types according to pre-existing definitions. The common pathologies were documented and the results compared to available literature.

6.2. Materials and methods

The study sample comprised of one hundred and four (n=104) left and right cadaveric shoulders of ages 28-98 years (mean=70 years). Shoulder pathology was investigated through bilateral dissections of the shoulder joint. The cadavers used were obtained from the Department of Anatomy, School of Medicine, Faculty of Health Sciences and handled in accordance with the National Health Act No. 61 of 2003. Male (n=30) and female (n=22) adult cadavers (black=9 and white=43) with varying BMI (range of ± 18 – 30 kg/m^2) were included in the study. Ethical clearance was obtained from the Faculty of Health Sciences Research Ethics Committee (No: 419/2017) prior to the commencement of the data collection phase of the study.

With the cadaver in prone position, the skin was incised and reflected from the median plane to the midaxillary line, along the costal margins and superior border of the scapula. The superficial fascia was dissected until the supraspinatus, infraspinatus, teres major, teres minor and the deltoid muscle could be identified. All cadavers were dissected using the reverse dissection method, to better visualise the structures of the RC unit. The reverse dissection method entailed dissecting the deltoid and each RC muscle away from its origin on the scapula towards its tendinous insertion on the proximal humerus. This allowed for better visualisation of RC complex and any related pathology (Figure 6.1).

The complete RC unit (tendon and internal capsule) was separated from the scapula attachment by firstly removing the muscles from their origins and then cutting as close as possible to the connection with the glenoid labrum. The supraspinatus was firstly identified and then detached from the supraspinous fossa, specifically along the medial aspect of the scapula. The infraspinatus muscle was then identified and also detached from the medial aspect of the infraspinous fossa. The teres minor was identified and detached from the lateral border on the posterior surface of the scapula. Lastly, the subscapularis muscle was identified and detached from the subscapular fossa as it lies within most of the costal surface of the scapula (Moore *et al*., 2014). The collective RC unit was then reflected along with the glenoid labrum***.*** Once detached from the scapula the RC unit was separated from its humeral attachment by cutting through the insertion points on the greater and lesser tuberosities. The removal of the RC unit in this manner allowed for analysis of the insertion and interdigitation fusion analysis of the unit (Vosloo *et al*., 2016).

Any tears found and identified on the cadavers were documented, and the tears classified according to the existing classification of RC tears. Any other pathologies in and around the glenohumeral joint encountered during this stage of the study were also noted and documented on a data capturing sheet for further analysis.

Figure 6.1: Posterior view of the shoulder joint showing the reflected deltoid muscle and rotator cuff unit. Some pathology is noted, a crescent shaped tear in the supraspinatus muscle is seen**.** The infraspinatus muscle is outlined in red and the teres minor is outlined in green. The following structures can be seen in the image above: A – Deltoid muscle (reflected proximally), B – Acromion, C – Crescent shaped tear in the supraspinatus muscle, D – Proximal humerus, E – Deltoid muscle (reflected distally), F – Posterior circumflex humeral artery, G – Triceps brachii muscle (reflected). *Key: M – Medial, L – Lateral, P – Proximal*

6.3. Results

In the one hundred and four (n=104) cadaveric shoulders, pathology was identified in a third (n=31/104; 33%) of the sample (Table 6.1). Pathology was noted at a slightly higher percentage in the male sample, 37% (n=22/60) than in the female group, which was at 32% (n=14/44). Documented pathology ranged from an abscess in the subscapularis (Figure 6.1), RC tears (Figure 6.1, 6.2, 6.3 and 6.4), osteophytes and calcification (Figure 6.4), absence of the RC and at times the labrum as well, the RC muscles were still intact (Figure 6.5), evidence of shoulder surgery (Figure 6.6), a growth on the biceps brachii tendon (Figure 6.7) and possible onset of osteonecrosis (Figure 6.8). Bilateral pathology was noted in twelve cadavers (23% of shoulders) mostly related to osteophyte development and/or calcification in the head of the humerus; all other pathology was unilateral (Figure 6.2). Cadaver specific pathology is documented in Table 6.2.

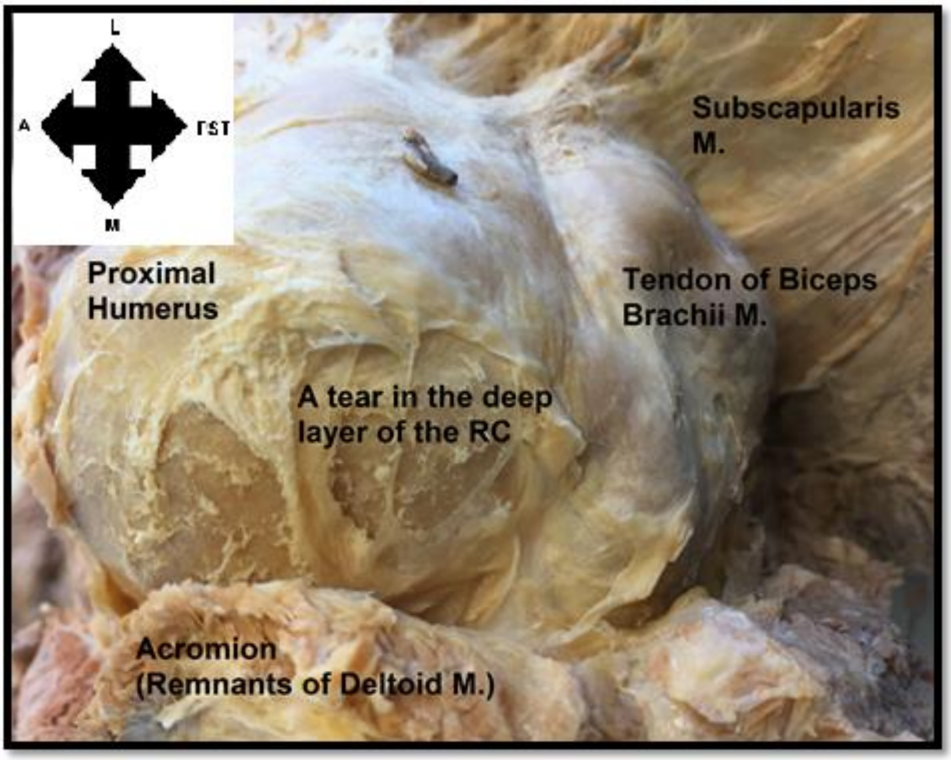
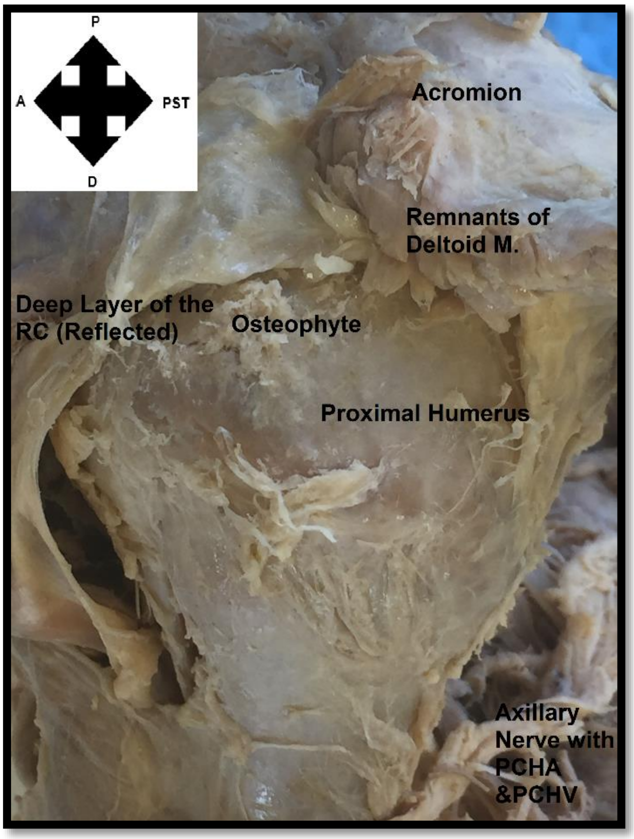


Figure 6.2: Superior view of the shoulder joint displaying visible tears to the rotator cuff hood. Osteophytes are noted on the head of the humerus, possibly contributing to the massive tear of the RC. *Key: M – Medial, L – Lateral, A - Anterior, PST – Posterior, M – Muscle, RC – Rotator Cuff*



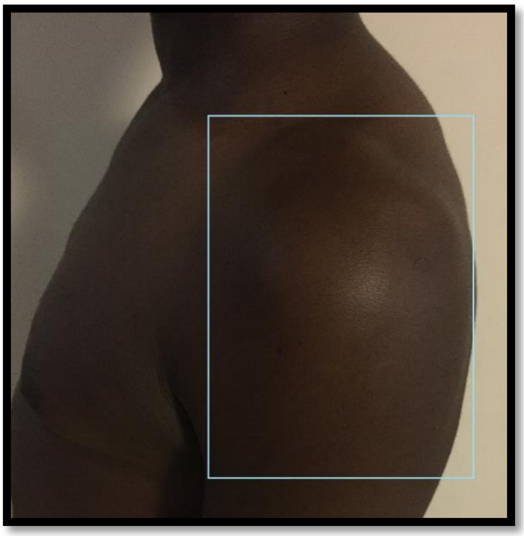


Figure 6.3: Lateral view of the shoulder, the deltoid muscle was reflected along with the RC. An osteophyte can clearly be seen on the head of the humerus. *Key: A – Anterior, PST – Posterior, D – Distal, P – Proximal, N – Nerve, PCHA – Posterior Circumflex Humeral Artery, PCHV – Posterior Circumflex Humeral Vein*

Table 6.1: Summary of the documented pathology in a sample of 104 cadaveric shoulders

		Total No.:	Sex			
			Male		Female	
			Right	Left	Right	Left
Pathology Types	**Osteophytes/ Calcification**	22	6	8	3	5
	Tears	4	1	1	1	1
	Absent Cuff/ Labrum	3	2	1	-	-
	Abscess and tear	1	-	1	-	-
	Evidence of previous surgery	1	1	-	-	-
	Biceps brachii pathology	1	-	-	1	-
	Other (undefined)	1	-	-	1	-
	Osteonecrosis	3	-	1	1	1
	TOTAL	36*	10	12	7	7

Pathology was documented in 31 cadavers. The total of 36 indicates overlapping pathologies, where some cadavers presented with more than one pathology

Table 6.2: Cadaver pathology overview

	Age	Race	Sex	Tear(s) Present (Yes/No)	Figure Number	Pathology Description
1	69	White	Male	Yes	6.1.	An abscess was found on the left side nested in the subscapular fossa, covered by the subscapularis muscle
2	84	White	Female	Yes	6.2.	A massive tear was documented, osteophytes were also noted in this cadaveric shoulder, possibly accounting for this pathology
3	28	Black	Male	Yes	6.3.	An osteophyte has developed on the head of the humerus
4	76	White	Female	Yes	6.4.	a U-shaped tear which was noted on a shoulder displaying other forms of pathology not clearly definitive
5	74	White	Male	No cuff	6.5.	Bilateral marbleisation was documented where the cuff and labrum were completely eroded. It was clearly notable that the under surface of the acromion had direct contact with the head of the humerus, thereby giving it its shiny appearance. The blood supply to the head of the humerus was still intact and therefore no osteonecrosis was noted.
6	82	White	Male	No cuff	6.6.	A fixation plate was found on the shaft and anatomical neck of an 82 year old white male cadaver on the right side
7	91	White	Female	No	-	A growth was found on the long head of the biceps brachii muscle
8	92	White	Female	Yes	6.7.	A massive tear on the left and onset of osteonecrosis on the right side
9	66	White	Male	No	6.8.	Calcification was documented on the left side, with possible onset of osteonecrosis on the proximal humerus

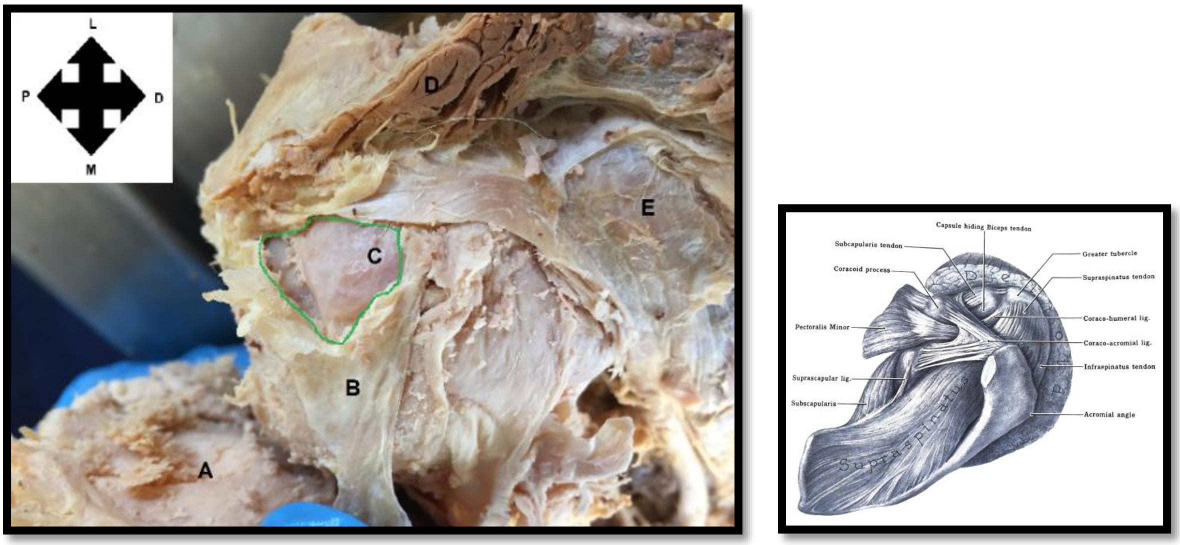


Image Source (Right): Grant's Atlas (7th Edition)

Figure 6.4: Superior view of the shoulder joint, a U-shaped tear was noted (highlighted in green). Blood supply to this region was found to be intact. The following structures can be seen in the image above: A – Acromion, B – Deep layer of the RC, C – Tendon of supraspinatus muscle, D – Deltoid muscle (reflected), E – Tendon of infraspinatus muscle. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, M – Muscle, RC – Rotator Cuff*

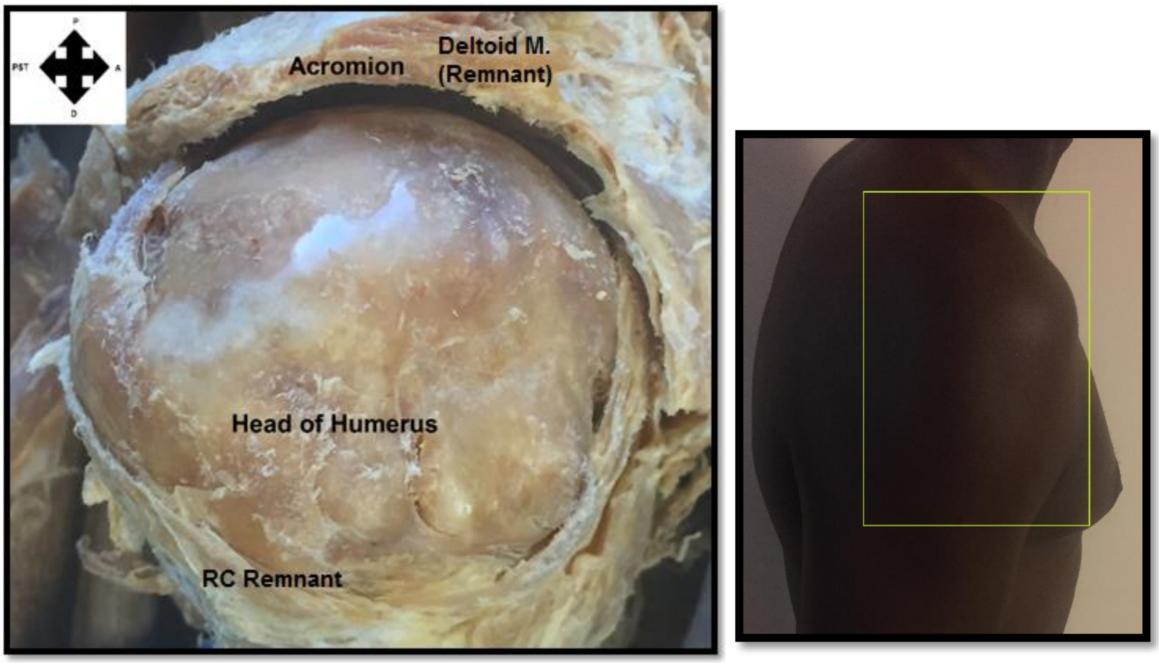
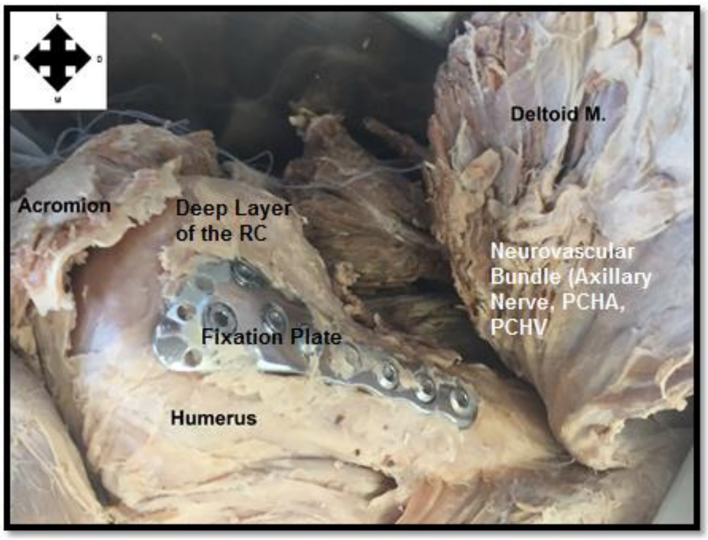


Figure 6.5: Lateral view of the shoulder joint where marbleisation was found in this region. The RC cuff was absent in the bilateral dissection of this cadaver. *Key: A – Anterior, PST – Posterior; D – Distal, P – Proximal, M – Muscle, RC – Rotator Cuff*



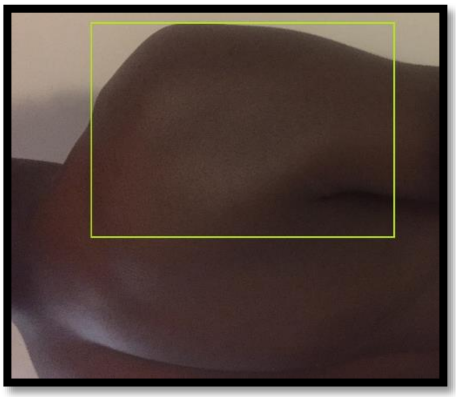
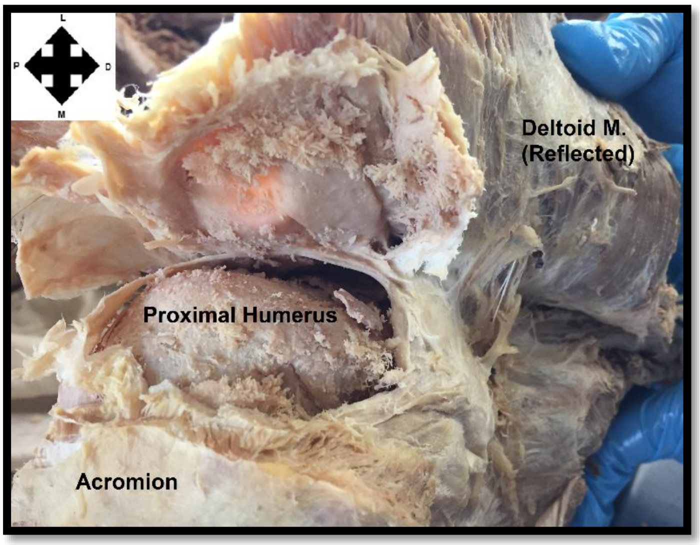


Figure 6.6: Dissection of the shoulder joint showing a fixation plate to the surgical neck and head of the humerus. Blood supply to the head of the humerus was completely restored and no other pathology was noted. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal*



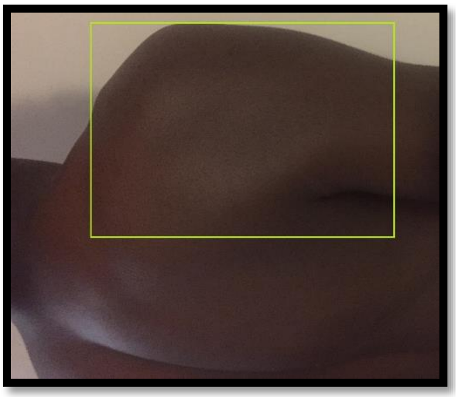


Figure 6.7: Shrunken and distorted greater tuberosity, a possible indication of the onset of osteonecrosis. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, M – Muscle, RC – Rotator Cuff*

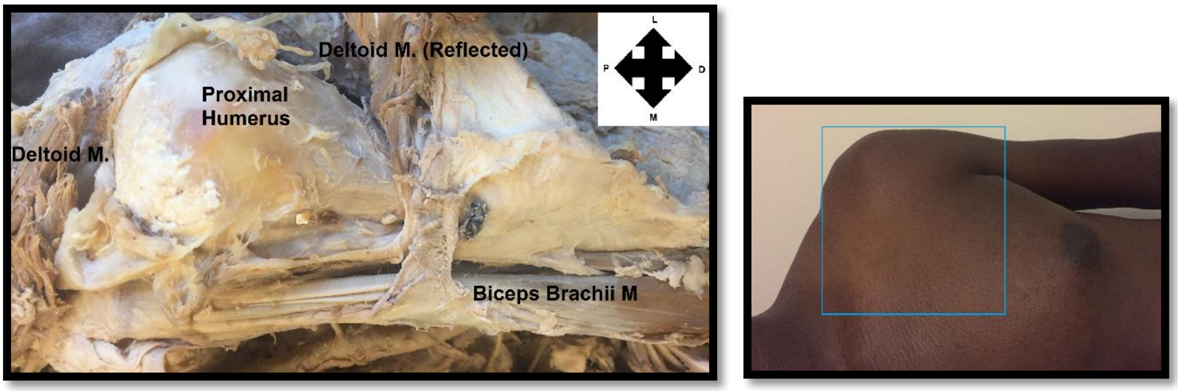


Figure 6.8: Anterior view of left arm showing the inferiorly reflected deltoid muscle with signs of calcification on the greater tuberosity of the humerus. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal, M – Muscle*

6.4. Discussion

The results of this study indicate that a third of the sample population (33%) presented with some form of shoulder pathology, with the most common pathology being the presence of osteophytic changes in and around the glenohumeral joint. These results are similar to findings by Konno *et al.* (2002) who noted pathology in 35% of their cadaveric sample, with glenoid osteophytes being the main contributors to the pathology.

In the current study, no full thickness tears were documented, however partial tears were observed in 5% of the sample, findings similarly documented by Neer (1983), Schibany *et al.* (2004) and Moosmayer *et al.* (2009). However, observations made by Schibany *et al.* (2004) and Moosmayer *et al.* (2009) were in relation to full thickness tears, with percentages documented at 6% and 7.6%, respectively. Previous cadaveric studies have revealed varying results relating to RC tears and their prevalence. Several authors have shown the prevalence of RC tears ranging from less than 5% to 38.9% (Neer, 1983, Lehman *et al.*, 1995; Schibany *et al.*, 2004; Reily *et al.*, 2006, Moosmayer *et al.*, 2009). In the current study, all the cadavers with observed tears (4%) were noted to fall within the age range of between 69 and 92 years. Lehman *et al.* (1995) documented the prevalence of RC tears at 6% in cadavers younger than 60 years and 30% in cadavers above the age of 60 years, clearly showing an increase in full thickness tears incidence relating to age. However, in the current study this high prevalence of RC tears in individuals over 60 years of age was not noted. Higher incidences of RC tears were documented by Reily *et al.* (2006), where comparisons were made between cadaveric and radiological studies. Final results as published by Reily *et al.* (2006) was 30.3% for the cadaveric studies and 38.9% in the ultrasound studies. This occurrence was noted at 38.9% in asymptomatic individuals and 41.4% in symptomatic patients.

In the current study, bilateral pathology was noted in 23% of the study sample, with osteophytes accounting for most of the pathology. Previous studies documented a higher percentage of bilateral pathology in instances where RC tears were found. The incidence of bilateral tears was also noted as increasing with age; Yamaguchi *et al.* (2006) noted the likelihood to increase to about 50%. Other studies have documented the prevalence of RC tears in patients 60 years and older to range from 20% to 30%, the percentage increased significantly in patients of 80 years and older, going up to about 62% (Neer, 1983; Lehman *et al.*, 1995; Tempelhof *et al.*, 1999; Yamaguchi *et al.*, 2006; Fehrigher *et al.*, 2008; Kim *et al.*, 2009; Moosmayer *et al.*, 2009; Teunis *et al.*, 2014). Other pathologies found were easier to identify, including an abscess in the subscapularis muscle which was identified in a 69-year-old white male cadaver, a small tear was also found on the contralateral side. The abscess of the subscapularis muscle is rare with only a few recorded cases and only one recording a fatality (Joaquin and Kimball, 1980; Handorf, 1983; Nowinski and Duchene, 2004; Saxena *et al.*, 2008; Babayiğit *et al.*, 2009; Koratala *et al.*, 2017; Patel *et al.,* 2018). A cadaveric study with similar outcomes could not be found. The cause of death to this cadaver was recorded as septic shock.

Several other pathologies including the presence of osteophytes (21%) were noted. The presence of osteophytes or bone spurs is linked with the diagnosis of osteoarthritis. The development for these fibrocartilage-capped bony outgrowths seems heightened in older individuals, especially in those with a higher BMI and individuals exposed to more vigorous physical activity (Kellgren and Lawrence, 1957; Wong *et al.*, 2016). In the current study, the mean BMI in individuals displaying osteophyte presence was documented at 20.14 kg/m^2. O'Neill *et al.* (1999) documented a correlation between an increased BMI with the presence of osteophytes at the lumbar spine. In the current sample, the presence of osteophytes was the most prevalent pathology, and was always associated with those individuals who presented with RC tears, suggesting a clear link between the two conditions. Arthroscopic subacromial decompression surgery is usually implored in the attempt to remove the bony spurs, which has been suggested as a leading factor to the development of RC tears. Osteophyte investigation in a study by Nove-Josserand *et al.* (2005) found humeral and/or glenoid osteophytes in 23% of the 200 patient shoulders studied while the current study showed a prevalence of 21% (n=22/104) in a sample of mean age 77 years.

While the presence of osteophytes may increase the development of RC tears, a bilateral absence of the RC and labrum may possibly be the most debilitating to the movement of the glenohumeral joint. This pathology was noted in a 74-year-old white male cadaver (Figure 6.5). The absent RC attachment and labrum resulted in marbleisation of the proximal humerus and the under surface of the acromion. Marbleisation refers to the polished appearance of the proximal humerus due to an absent RC and glenoid labrum, resulting in bone-to-bone contact during movement of the glenohumeral joint. Functionally, the glenoid labrum plays an important role in the expansion of the articular surface with the head of the humerus, thereby increasing the contact surface area and further stabilising the glenohumeral joint. The glenoid labrum also anchors capsuloligamentous structures and injury to this structure was deemed by Bankart (1923) as the reason for high incidences of recurrent anterior dislocations (Moseley and Overgaard, 1962). Konno *et al.* (2002) noted degenerative changes in the cuff and labrum, where these were observed in the inferior portion of the glenoid. In their study, these findings correlated with cadavers on whom full thickness tears were found. A link was also found between the degenerative changes to the glenoid labrum and the presence of osteophytes in this cadaver sample. In the same study, it was also noted that most of the shoulders displaying degenerative changes to the glenoid cartilage or labrum had RC tears, therefore suggesting a link between these two pathologies (Konno *et al.*, 2002). These findings were previously documented by Petersson (1983) whose study noted a relationship between cartilage degeneration and rupture or cartilage degeneration in 76% of the 34 cadaveric shoulders studied. In the current study, the RC was completely eroded, resulting in the bilateral marbleisation of the proximal humerus. This degenerative change to the shoulder limits the movement of the joint, and may cause substantial pain to the patient.

Other traumatic changes noted in the study sample, included a fixation plate on the shaft and anatomical neck of an 82-year-old white male cadaver on the right side (Figure 6.6). Onset of osteoporosis in older individuals seems to account for an increase in proximal humeral fractures in this group. Hall and Rosser (1963) and Rose *et al.* (1982) noted an increase in the incidences of proximal humerus fractures in individuals of ages 40 years and older. The metaphyseal flaring surgical neck of the humerus just below the tuberosities, is found to be the common site of humeral fractures in the elderly population (Hall and Rosser, 1963). However, no clear signs of osteoporosis could be detected on this cadaver.

Other pathological changes in the area around the shoulder were noted. An atrophying long head of biceps brachii was found in a 91-year-old white female cadaver which presented like a growth on this tendon. In instances where injury to the long head of biceps brachii muscle occurs, a common resulting consequence is the manifestation of Popeye deformity, thereby decreasing the function of this muscle. Ruptures linked to the long head of the biceps brachii account for 96% of all biceps brachii injuries, a common condition in individuals over the age of 50 (Elser *et al.*, 2011) and are commonly associated with RC pathology. Injury to the long head of the biceps has been associated with shoulder pain due to its origin on the supraglenoid tubercle of the scapula and the resulting nerve fibre interruption at this point (Mazzocca *et al.*, 2005). Previous studies testing the biomechanical properties of the long head of biceps brachii have indicated its significant role in stabilizing the glenohumeral joint when the shoulder is moved in all directions (Elser *et al.*, 2011; Longo *et al.*, 2011). Previous studies have noted the varied roles of the long head of the biceps with Rodosky *et al.* (1994) noting its role during throwing and Pagnani *et al.* (1996) associating the role of the biceps with joint stability during internal and external rotation. However, due to this being a cadaver study, the resulting outcome on the functional ability of this left shoulder was unknown, however, Chillag and Chillag (2014) highlighted a case study where injury to the long head of the biceps brachii had occurred resulting in Popeye’s deformity but shoulder functionality was undeterred. Biceps tenotomy and biceps tenodesis are the two most common techniques used in repairing a ruptured long head of the biceps brachii muscle (Elser *et al.*, 2011). Studies by Szabo *et al.* (2008) and Kim *et al.* (2012) have documented findings indicating the effectiveness of biceps tenotomy in pain resolution in 3% - 70% of cases but with the possible outcome of Popeye deformity. A tenodesis on the other hand, may allow for the maintenance of normal anatomy by maintaining the tendon length and often resulting in less cosmetic complaints and muscle ache, it has however been associated with bicipital groove pain (Romeo *et al.*, 2004; Elser *et al.*, 2011; Longo *et al.*, 2011; Scheibel *et al.*, 2011).

Possibly the most interesting degenerative change was noted in a 92-year-old white female cadaver where the proximal humerus on the right side was clearly distorted and malformed (Figure 6.8). It is unclear as to what the possible cause of this pathology was. Evidence of signs related to the onset of osteonecrosis were found in 3% of the 104 dissected shoulders. Harreld *et al.* (2009) states that the second most commonly affected site for the development of osteonecrosis, second the head of the femur, is the head of the humerus. Although this condition is relatively rare, it is found commonly in the male population between ages 20 – 50 years (Harreld *et al.*, 2009), making our study findings variable from the norm. As osteonecrosis is a disease caused by both traumatic and atraumatic signs, corticosteroid therapy is found to be the most common cause of the atraumatic osteonecrosis to the humeral head (Cruess, 1976; Mankin, 1992; Poignard *et al.*, 2012; Byun, 2014). Blood supply interruption is commonly accepted as part of the cause to the onset on osteonecrosis, however, in our cadaver sample blood supply to the proximal humerus was found intact in all the cases.

6.5. Conclusion

Pathologies of the shoulder account for a large part of shoulder pain and are found in various forms ranging from RC tears to osteonecrosis of the proximal humerus. RC tears were found in a small percentage of the total sample, making the study findings different from previous studies. The largest form of documented pathology was found to be the presence of osteophytes or bone spurs. Interestingly, blood supply to the proximal humerus was found to be intact in all cadavers, including cases where the onset of osteonecrosis was documented.

6.6. Limitations and future direction

Due to the primary investigator not being a pathologist, judging the pathology of the joint and muscle was subjective. We do note that pathology occurs on a histological level and this was not investigated. The study will in the future attempt to include a pathologist or a specialist in order to fully investigate the cadaver pathology. The study will in the future investigate if a relationship exists between signs of osteonecrosis of the shoulder and the hip in the same cadaver. The possibility of this occurrence was suggested by Byun *et al.* (2014).

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PART II – CLINICAL COMPONENT

Chapter 7

Manuscript 4

Title: Clinical outcomes before and after rotator cuff repair using the traditional open technique: a 6-month prospective study

Abstract

Rotator cuff (RC) tears are a common occurrence with some publications documenting them as the most frequent presentation in clinical practice after lumbar injuries. This phenomenon seems to increase with the aging process. The aim of this study was to assess RC repair success after an open arthroscopic approach by evaluating a set of predefined pre- and postoperative variables pertaining to the surgery. Eighty patients (n=80) of age 40 years and older were recruited from the Life Groenkloof Hospital. Full medical history was taken and ultrasound performed on the affected shoulder to assess and confirm the RC tear and the size. Pre-surgery shoulder examination included identifying acromial type, measuring pain scores using the visual analogue scale (VAS) system and assessing the range of motion (ROM). Various shoulder performance scores were taken using the Simple Shoulder Test (SST), Constant score and American Shoulder and Elbow Surgeon (ASES) score. The shoulder was operated on, where the tear was re-measured and biopsies taken in patients on whom the torn RC was found reattaching to the humerus, histological analysis of the sample was carried out. The range of motion (ROM) was then re-documented at eight weeks and at six months' follow-up; this was compared to the initial assessment. A type II acromion was the most common, present in 84% of the patients. The VAS pain score was documented at 6 points, with the SST at 3 points and the ASES and constant score at 47.319 and 59.36, respectively. Significant differences were noted in the ROM between initial assessment and the eight-week follow-up (p = 0.000) and between eight-weeks and six-months follow-up (p = 0.008), with clear signs of healing and positive rehabilitation. No retears and/or complications were noted at the sixth month post-surgery.

Key words: Shoulder, rotator cuff tear, shoulder repair, arthroscopy, range of motion (ROM)

7.1. Introduction

A variety of factors contribute to the development of rotator cuff (RC) tears and subsequent pathology (Neer, 1972; Bigliani *et al.*, 1991; Tingart *et al.*, 2003; Tingart *et al.*, 2004; Cadet *et al.*, 2008; DeFranco and Cole, 2009; Pandey and Willems, 2015). RC tears are known to be a common cause of shoulder dysfunction and pain, with the symptoms noted as traumatic and at times non-traumatic (Braune *et al.*, 2003; Yamaguchi *et al.*, 2006; Kukkonen *et al.*, 2013). The prevalence of RC tears has been documented at around 20% - 30% in individuals between the ages of 60 and 80 years (Sher *et al.*, 1995; Tempelhof *et al.*, 1999; Fehringer *et al.*, 2008) with some authors further detailing these percentages at 15 - 20% in 60 year olds, 26 - 30% around the age of 70 years and 36 - 50% at the age of 80 years (Templehof *et al.*, 1999; Minagawa *et al.*, 2013)

The foundation of any RC surgical repair seems to be rooted in the understanding of the basic functions of the shoulder joint and related soft tissue, in the attempt to repair the pathology and return the shoulder joint to full, pre-injury function. Neer (1983) attributed the development of RC tears to the acromial impingement of the supraspinatus tendon (Kim *et al.*, 2010; Moosmayer *et al.*, 2010; Kukkonen *et al.*, 2013). However, more recent reports attribute the development of RC tears to intrinsic tendon degeneration as the main cause (Ozaki *et al.*, 1988; Hallgren *et al.*, 2012; Gumina *et al.*, 2013). With the expansion of research into RC tears and related pathology, other factors have been highlighted as relating to the prevalence of tears, such as the influence of the anatomy of the acromion, coracoacromial ligament and coracoid process (DeFranco and Cole, 2009). Previous studies have cited the presence of an os acromiale (a developmental aberration in which the distal acromion fails to fuse) as a possible reason for RC tears, though further research has proven how in most cases the os acromiale is asymptomatic and can be ignored as a possible cause of the RC tears. Nonetheless, in instances where MRI shows the os acromiale as a source of pain, the treatment of this iatrogenic instability would involve resection or rigid fixation.

Another possible cause is cited as the involvement of subacromial impingement in RC tears, a concept that was developed by Neer (1972) and has influenced the ideology for the need for acromioplasty during RC repairs. Bigliani *et al.* (1991) further used a classification system to define subacromial impingement. Acromial morphology was classified into three primary types; flat (type I), curved (type II) and hooked (type III), a classification system used by numerous physicians (Bigliani *et al.*, 1991). A study by Bigliani *et al.* (1989) found the hooked (type III) acromion to be closely associated with RC tears and subsequent impingement. This finding was noted by several other authors who also documented a relationship between the hooked (type III) acromion and resulting cuff tears (Bigliani *et al.*, 1991; Epstein *et al.*, 1993; Nicholson *et al.*, 1996; Worland *et al.*, 2003).

In the repair of the diseased RC, certain factors such as the stability of the humerus have to be taken into account in the attempt to reduce post-surgical complications, and allow for proper fixation of the repaired tendon. The decrease in the bone mineral density of the greater tuberosity (osteopenia) has been linked to complications related to the surgical repair and subsequent healing of the RC tendon. Following a RC tear, the forces normally exerted onto the greater tuberosity are no longer present, resulting in the gradual loss of bone density (Tingart *et al.*, 2003; Tingart *et al.*, 2004; Cadet *et al.*, 2008). Neer *et al.* (1983) described atrophy of the RC muscles following a tear, resulting in weakness in the external rotation and abduction, leading to a decrease in the range of motion (ROM) and instability of the humeral head, thereby affecting the biomechanical function of the joint. A study by Cadet *et al.* (2008) showed osteopenic increase in patients with retracted RC tears. This factor is further corroborated by Wolff's law, which hypothesizes that bone remodelling follows the response to mechanical stress which helps determine bone density (Wolff, 1892). Full thickness tears would cause more bone loss than partial-thickness tears (Jiang *et al.* 2002; Meyer *et al.*, 2004). Therefore, the knowledge of the RC footprint assists in the ability to correctly repair RC tears. A study by Dugas *et al.* (2002) reiterated this fact and suggested that recreating the normal anatomy prior to injury increased the likelihood of healing and return to normal function.

RC tears are commonly repaired using the open-, mini-open or arthroscopic technique. The open technique is referred to as a more 'traditional' method which involves making incisions that are several centimetres long. This method is usually the chosen form of repair when the tear is large, complex or requires additional reconstruction such as tendon transfer (Armstrong *et al.,* 2017). Several complications exist with regard to RC repair, whether it be open- or arthroscopic procedures. The main concern in both repairs is the poor healing of the reattached tendon to the bone and the subsequent increase in retear rate following surgery. The main reason for this failure is the inability to restore the blood flow to the tendon and bone; this results ultimately in unsuccessful healing and reattachment of the tendon to bone. Although the open technique may be move invasive, its advantage of being cost-effective, makes it's the preferred repair method in developing countries (Nafisi *et al.*, 2018). The arthroscopic repair also possesses a challenge with its inability to fully repair RC tears and the resultant loss of performance linked to the difficulty in performing the procedure (Bishop *et al.*, 2006). Retear rates remains one of the concerns associated with both procedures with the open technique showing superior healing rates for large and massive tears (60% and 40%, respectively) and the arthroscopic repair yielding lower numbers (24% and 12%, respectively) (Bishop *et al.*, 2006; Liem *et al*., 2007).

Therefore, this study sought to investigate the link between RC tears and the types of acromion presented during shoulder examination, the association between RC tears and age, and to evaluate improvement rates associated with the RC repair following the open technique in a South African sample.

7.2. Materials and methods

A prospective, clinical research study was conducted on patients with small to full-thickness tears, scheduled to undergo RC repair surgery using the open approach technique. Data were collected for a period of 18 months (2018 – 2019) and a total of 80 patients (n = 80), over the age of 40 years, with confirmed RC tears were included in the study. The patient sample included male (n = 47) and female (n = 33) individuals from different population groups. The clinical component of the research study sought to document the range of motion (ROM) of the shoulder that could be performed by the patient prior to and following open RC repair surgery. Patients under the age of 40 years were excluded, as the golden standard for diagnosis of a RC tear in these individuals will require an MRI, whereas the golden standard for diagnosis in patients over 40 years is via ultrasound. All the patients who participated in the study were recruited from Life Groenkloof Hospital following ethical clearance from the University of Pretoria (Ethical clearance: 419/2017). Informed consent forms were given to patients who volunteered to be part of the study and data were collected accordingly.

The study was divided into three phases; 1) the pre-operative, 2) the operative and 3) the post-operative stage, with follow-up into the sixth month post-surgery. Two experienced orthopaedic surgeons were responsible for the surgical procedure. The demographic data of patients which included sex, age, duration of preoperative clinical symptoms, and underlying conditions such as diabetes and the severity of preoperative tear were recorded.

Phase One

The pre-operative stage

During this phase of the study, patients who agreed to be included in the study, completed a consent form. A full medical history was taken by the operating surgeon which comprised of demographic information, history of the present illness, surgical history. The severity of patients' pain prior to surgery was measured using the visual analogue scale (VAS) pain system. A diagnostic ultrasound of the injured shoulder was taken by the surgeon. During ultrasound the tear was measured and classified according to its size and position. Any uncertainty that arose regarding the tear properties, resulted in the patient being sent for an MRI. Following the ultrasound, the patients were required to undergo a number of shoulder functionality tests to determine the parameters of injury. These tests included muscle strength test, the SST (simple shoulder test), the constant score, the VAS (pain) score, the range of motion (ROM) as well as the ASES (American Shoulder and Elbow Score) score of the affected arm. These results were all recorded for further analysis by the primary investigator. Diagnostic images (radiographic evaluation) were also assessed by the surgeon.

Phase Two

The operative phase

This stage of the project took place in theatre. Following general anaesthesia, the patients were placed in a beach-chair position (Figure 7.1). The affected limb was suspended with a traction, sterilised and draped. Shoulder arthroscopy was performed from the posterior aspect of the shoulder, for thorough examination of the injury prior to incision (Figure 7.2). The RC and intra-articular structures were assessed for any tears using the arthroscope. The arthroscope was further navigated around to see if any tears were present in the bursal layer of the RC and/or on the articular side. The inferior surface of the acromion was also checked for any damage. Following this inspection, the arthroscope was removed, the traction released and the arm sterilised and draped further. The bony landmarks (lateral border of acromion and clavicle) were identified and marked, and a ±50mm incision was made, in line with the anterior axillary skin crease and the deltopectoral interval. The biceps brachii muscle was assessed for any signs of rupture or fraying and where present, dislocated anteriorly. A deltoid split was created, granting access to the point of the acromion and the acromioclavicular (AC) joint. The distal 1 – 2mm of the clavicle was inferiorly loosened from the AC joint. An acromioplasty was then performed along the long curved tip of the acromion with a high-speed burr. The RC and associated tear was exposed in order to begin the repair procedure (Figure 7.3). In certain instances, the repair necessitated that the existing tear be extended slightly posteriorly (this was done after initial measurement of tear was recorded) and a keyhole leg plug biceps tenodesis be performed. Following the biceps tenodesis, where necessary, the deep and superficial layers of the RC were then pulled together in preparation for the repair process. The area of the greater tuberosities over the area of the tear was roughened and prepared with a high-speed burr.

During surgery, the tear was once again measured (AP/longitudinal diameter). Tears involving both the superficial and deep layers of the RC were noted and measurements taken of the tears in both layers. High quality photographic images of the tears were taken (Figure 7.3). The torn RC tendon was trimmed in order to create a smooth surface and straight edge to allow for re-attachment to the proximal humerus. In patients who had a prolonged RC tear, the torn layer was found at times stretched, therefore necessitating the trimming of this layer prior to reattachment. In some patients, the stretched layer was found partially reattached to the bone. In these patients, the stretched layer was trimmed and the tissue removed during this stage and stored in a phosphate-buffered saline (PBS) solution for further histological and microscopic analysis. This tissue was then embedded in wax and sectioned. Microscopic analysis entailed observing if any fibroblast activity could be noted and photographic images taken.

The RC was then attached to the roughened greater tuberosity with number 2-orthocord stitches through bone tunnels according to the Mason-Allen technique

(Figure 7.4). The superficial layer that runs through the biceps tunnel was attached using a number 1-vicryl and the rotator hood was also repaired with number 1-vicryl stitches. The very proximal part of the biceps was incorporated into these stiches. Following this step, final debridement was done and haemostasis ensured, and the wound rinsed well. The deep layer of the deltoid muscle was repaired first to maximise function, followed by the repair of the superficial layer (Figure 7.5). A suction drainage system was installed, the wound was attached in layers, bandaged and the shoulder immobilized into a shoulder immobilizer. This was concluded by the recording of concomitant procedures, releases performed, tear size and type and method of fixation. Various pain medications were prescribed for the management of postoperative pain.

Phase Three

The post-operative stage

This stage involved rehabilitation, where a prescribed rehabilitation program was recommended to the patient by the consulting physician. The rehabilitation process entailed pendulum exercises that were performed by the patients under the supervision of a physiotherapist or biokineticist. During this phase, the patient was required to come for a two-week follow-up session to evaluate the healing of the surgery (check the stitches, record any complaints), an eight weeks follow-up session and a six month follow up session. During the eight week and six-month follow-up sessions, an ultrasound was taken of the repair to evaluate the healing. The ultrasound evaluation was conducted by the operating Doctor who provided a detailed report of the findings. During the same period, a repeat of all the functionality tests was conducted and recorded for further analysis.

Data was analysed using the IBM SPSS Statistics version. The analysis consisted of frequency tables (percentages and counts) for categorical variables and descriptive stats (means and standard deviations) for continuous variables.

Figure 7.1: The patient in a beach-chair position following posterior examination using an arthroscope. The patients arm is sterilised and draped in preparation for surgical intervention using the open technique.

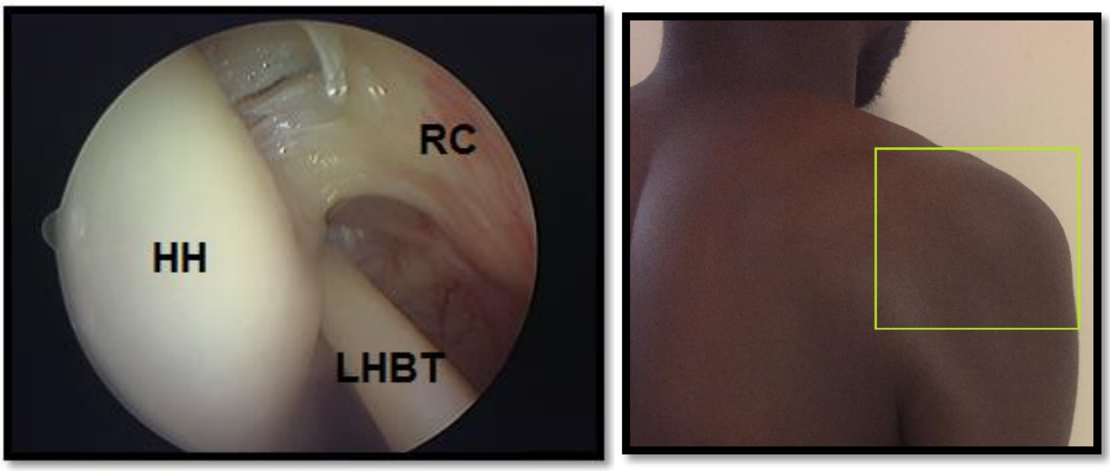

Figure 7.2: Arthroscopic view of the shoulder showing the joint from a posterior view as seen with an arthroscope. *Key: HH – Head of the Humerus; LHBT – Long Head of Biceps Tendon, RC – Rotator Cuff*

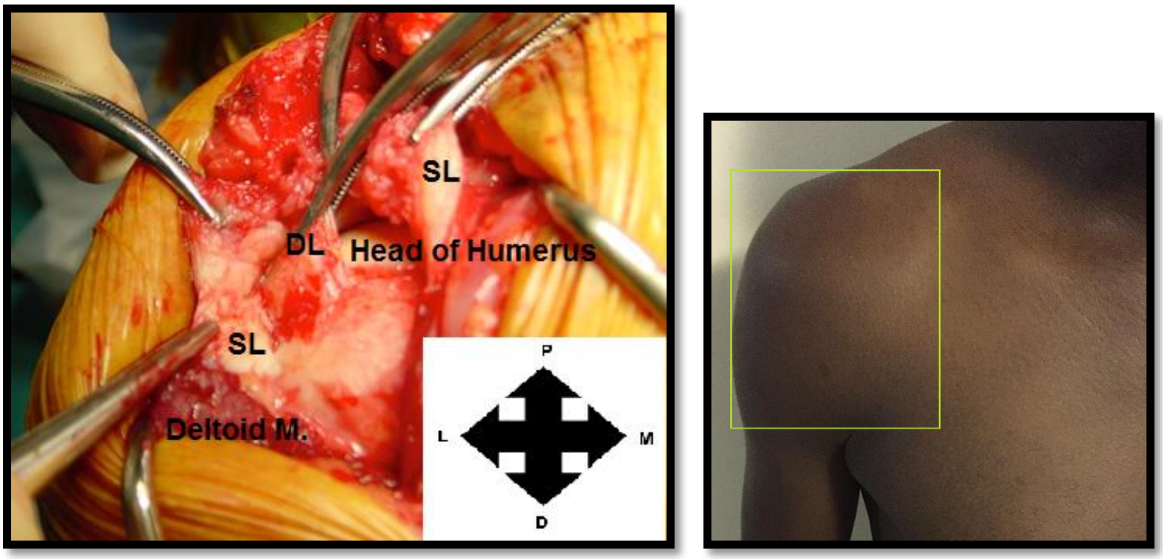

Figure 7.3: Anterior view of the right shoulder showing a tear in the deep layer (DL) of the rotator cuff hood. The superficial layer (SL) was incised to access the DL for the repair procedure.

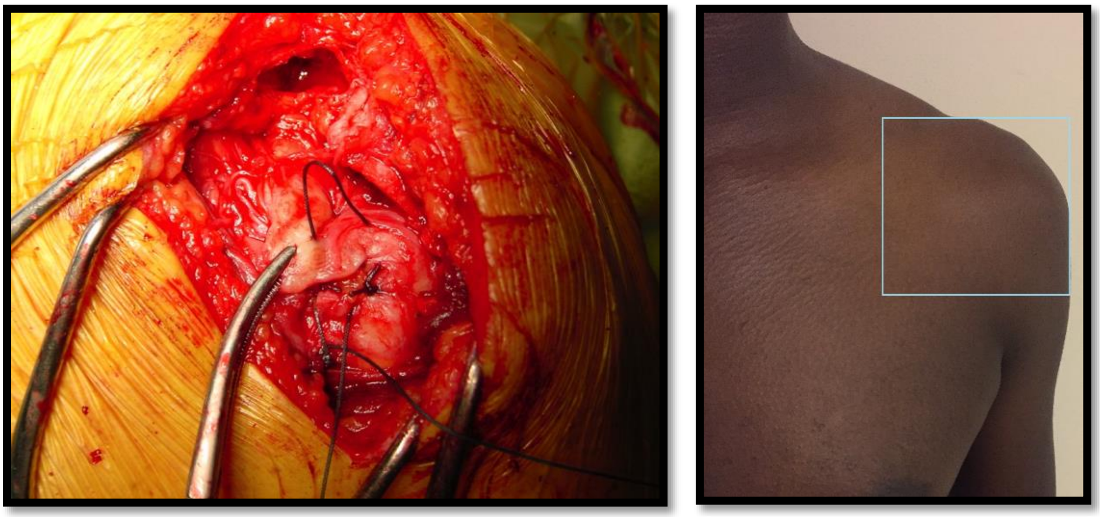

Figure 7.4: Anterior view of the left shoulder showing repair of the superficial layer using the Mason-Allen suture technique.

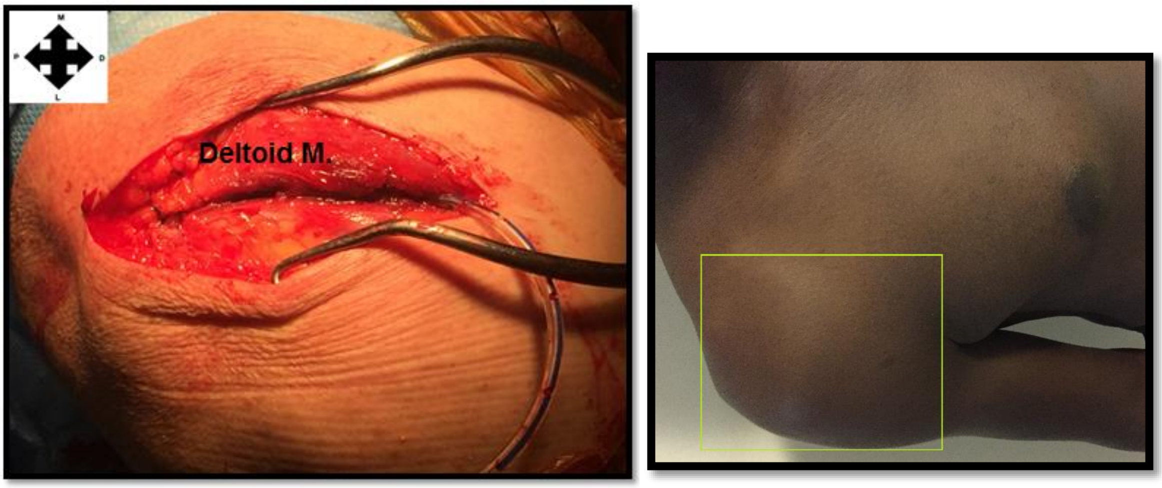

Figure 7.5: Anterolateral view of the shoulder showing the final stages of the open repair technique, the final stages of the deltoid repair is shown with the drain already in place. *Key: M – Medial, L – Lateral, D – Distal, P – Proximal*

7.3. Results

A total of 80 shoulders were available for analysis for the data collected over the 18-month period. At the end of this period, the dropout rate of patients was documented as 20% (n = 16). All the shoulders analysed in this study presented with a RC tear with the mean sagittal size of the tear documented as 2cm (SD = 1.06). The largest tear recorded in this group measured 5cm with the smallest tear repaired measuring 1cm. The acromion analysis was recorded in 91% (n = 73) of the 80 patients. In the current study 1% (n = 1) of patients were found displaying a type I or flat acromion and 84% (n = 61) type II or curved and type III or hooked was found in 15% (n = 11) of the sample. Patient history was recorded; the results are displayed in Table 7.1. Of the 80 patients included in the study, 26% (n = 21) were recorded as being on chronic medication. Hypertension and medical allergies were also documented as present conditions in 15% (n = 12) of the study sample. In Table 7.2, a mean of 6 points (SD = 1.77) was recorded for the VAS pain score (Figure 7.6). The ASES score displayed a mean of 47.319 (SD = 10.47) (Figure 7.7), while the Constant Score was documented at a mean of 59.36 (SD = 9.42) (Figure 7.8). The SST score displayed a mean of 3 points (SD = 2.10) (Figure 7.9).

Significant differences were documented when total active elevation was compared between week eight and six-month follow-up post-surgery (p = 0.008). Total active elevation was also found to be significant ($p = 0.000$) when the initial assessment was compared with the results documented at eight-week (Table 7.3). In Table 7.4 the total active elevation mean was documented as 156.01º (SD = 31.80) for the initial assessment, 128.55º (SD = 23.85) for the eight-week follow-up and 156.18º (SD = 18.59) for the six-month muscle strength test. The mean for passive abduction was documented at its peak in the sixth month post-surgery, this was recorded as 94.06º (SD = 12.00). The external rotation was found documenting the highest mean during the initial shoulder examination, 62.78º (SD = 8.04) while the six-month follow-up displayed results similar to the initial assessment, 62.35^0 (SD = 9.37).

Table 7.1: Patient characteristics

Medical Condition	No. of Patients Presenting with Condition
Thrombosis	4
Varicose veins	10
Medical allergies	12
Hormone replacement therapy	6
Herbal medicine	3
Chronic medication	21
Diabetes	2
Peptic ulcers	5
Smoker	5
High cholesterol	8
Hypertension	12
Previous anaesthetic problems	4
Previous shoulder/neck operation	11
Other medical issues	12

Table 7.2: Pain severity, ASES, Constant and SST score before surgery

Variables	Mean	Standard Deviation
VAS Score	6	1.7647
ASES Score	47.319	10.4694
Constant Score	59.36	9.420
SST	3	2.1038

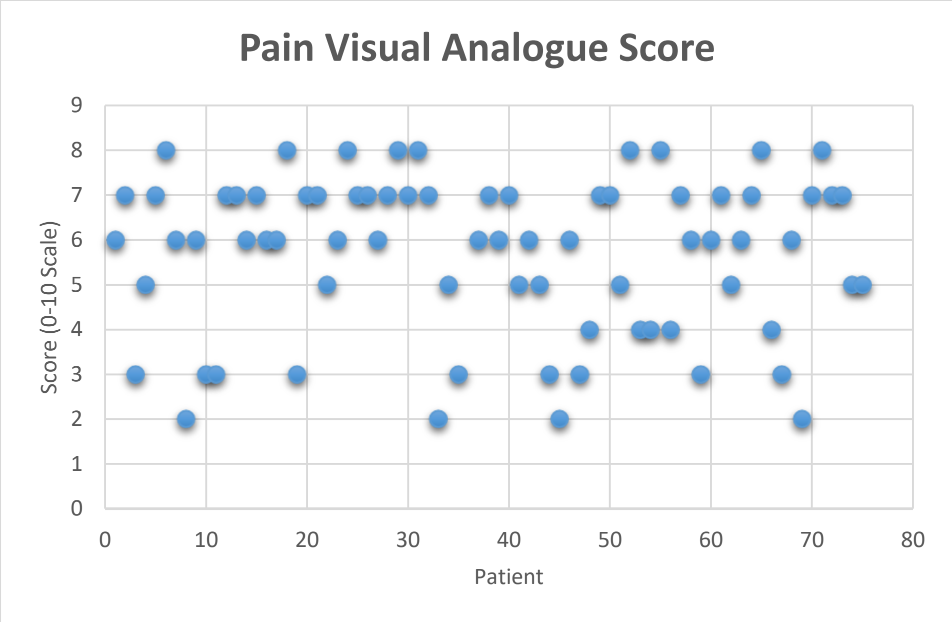

Figure 7.6: Vas Score distribution of patients before surgery (0 = No pain; 10 = Severe pain)

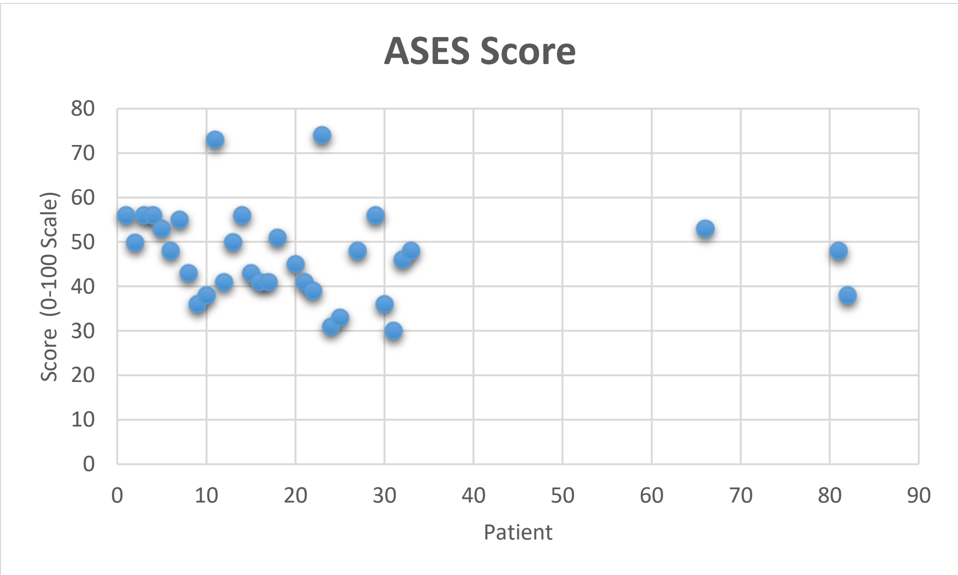

Figure 7.7: ASES Score distribution of patients before surgery

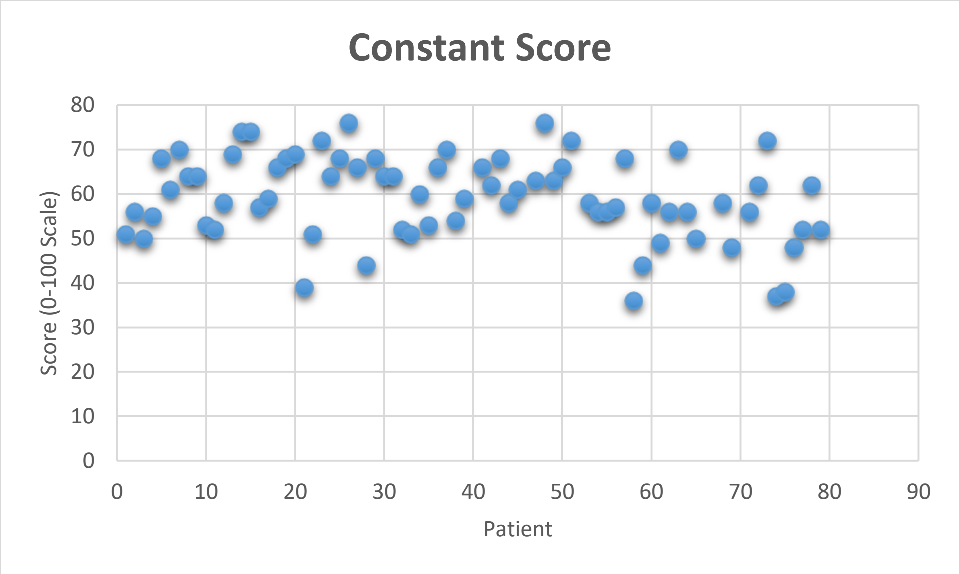

Figure 7.8: Constant Score distribution of patients before surgery

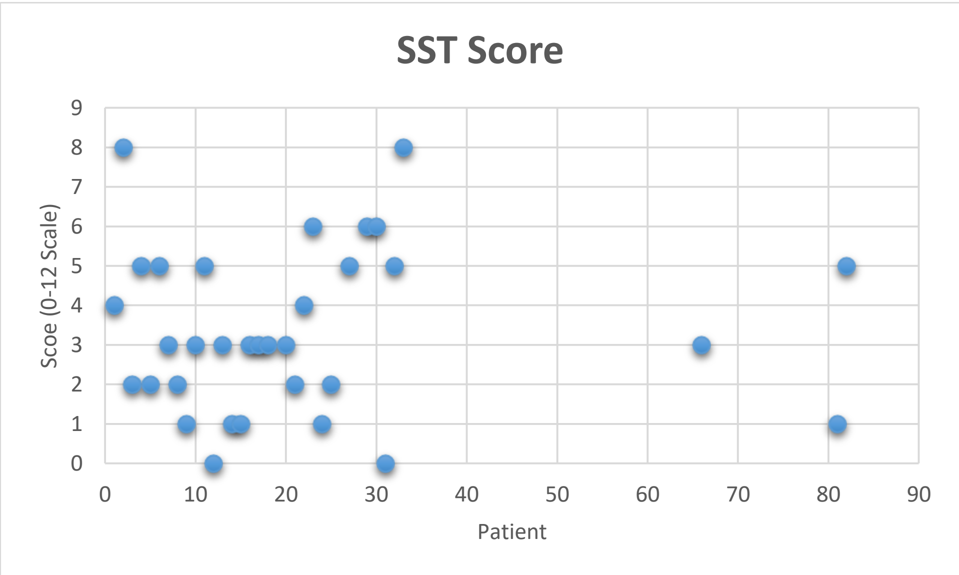

Figure 7.9: SST Score distribution of patients before surgery

Table 7.3: The comparison for total active elevation at the initial assessment versus eight-weeks and six-months post-surgery

Pairwise Comparisons					
Sample 1 – Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
Total Active Elevation 8weeks-Total Active Elevation 6mnths	-1.136	0.426	-2.665	0.008	0.023
Total Active Elevation 8weeks-Total Active Elevation Initial	1.727	0.426	4.051	0.000	0.000
Total Active Elevation 6mnths-Total Active Elevation Initial	0.591	0.426	1.386	0.166	0.497

Table 7.4: Comparison between the left and right side for total active elevation at the initial assessment versus eight-weeks and six-months post-surgery

	Dominant Side (L/R)											
				L			R					
	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Total Active Elevation (Initial)	2	165.00	21.213	5	162.00	34.928	67	155.30	32.121	74	156.01	31.795
Total Active Elevation (8 weeks)	2	120.00	0.000	4	125.00	23.805	25	129.80	25.103	31	128.55	23.847
Total Active Elevation (6 months)				3	145.00	27.839	14	158.57	16.458	17	156.18	18.585
Passive Abduction (Initial)	2	95.00	21.213	5	98.00	13.038	67	92.76	16.150	74	93.18	15.910
Passive Abduction (8 weeks)	2	70.00	0.000	4	76.25	7.500	26	75.58	17.224	32	75.31	15.706
Passive Abduction (6 months)				2	107.50	17.678	14	92.14	10.509	16	94.06	12.003
External Rotation (Initial)	2	65.00	7.017	4	60.00	0.000	66	62.88	8.323	72	62.78	8.044
External Rotation (8 weeks)	2	37.50	3.536	4	48.75	8.539	26	49.62	12.403	32	48.75	11.846
External Rotation (6 months)				3	66.67	5.774	14	61.43	9.889	17	62.35	9.374

Histology component

During the operating procedure, biopsies were taken from four patients (n=4) on whom evidence of RC reattachment following a tear was noted. The hypothesis by one of the clinicians was that the torn RC tendon attempts reattachment to the humerus following injury, a phenomenon he had noted in older patients. Four patients (n=4) were found displaying these characteristics, therefore, biopsies were taken, processed and further analysed. This tissue is what would have been sectioned, removed and discarded as biohazardous waste. The biopsies were first embedded in wax, sectioned and then stained with an H&E stain. Some fibroblast activity was noted in all four samples but not definitive in three of the four samples. In the sample removed from a 69-year old female, fibroblast activity could clearly be seen (indicated by arrows) (Figure 7.10 and 7.11). The injury was documented on the left side with the patient noted to possess a Type II acromion.

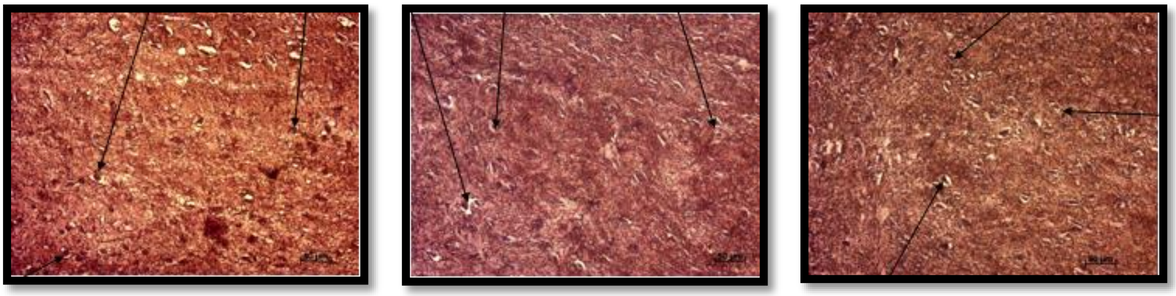

Figure 7.10: Biopsy at 20x magnification, showing fibroblast activity (indicated with arrows) at area of RC reattachment to the humerus

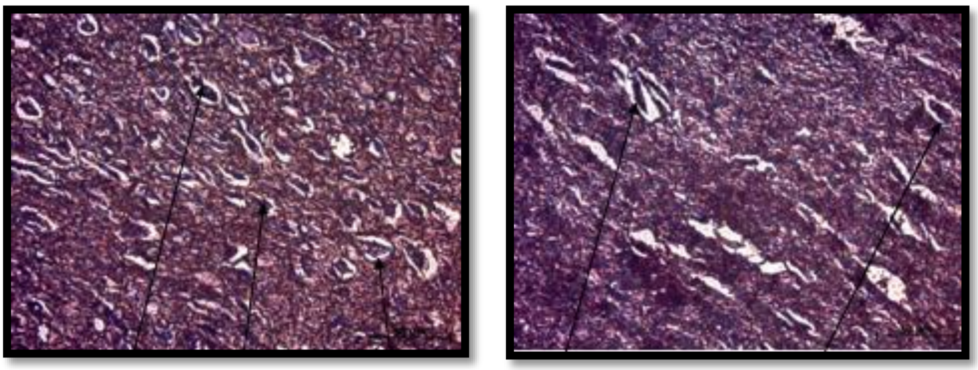

Figure 7.11: Biopsy at 40x magnification, showing fibroblast activity (indicated with arrows) at area of RC reattachment to the humerus

7.4. Discussion

Table 7.1 highlights the characteristics found in the patients who presented with small to massive tears in the study. Age has been highlighted by several authors as one of the predisposing factors to the development of RC tears. The mean age was documented as 61 years in the current study. Similar findings were made by Gumina *et al.* (2013) who documented the mean age at 59 years. Gumina *et al.* (2013) also noted the increase in the size of tear presented when the patient was older than 60 years, these were usually large to massive tears. In the current study, the mean age for patients presenting with large to massive tears was 62.4 years. Hand dominance seems to play a role in the prevalence of tears, in the current study 65% (n = 52) of patients presented with a tear in their dominant arm. These findings were also documented by Milgrom *et al.* (1995), Brasseur *et al.* (2004) and Yamamoto *et al.* (2010). Contralateral tears were documented in 30% (n = 24) of the patients, Ro *et al.* (2015) noted a higher prevalence of RC tears in contralateral shoulders, findings different from the current study. The rest of the patients had incomplete data for hand dominance (n = 4).

The RC tears were then assessed for severity by using the VAS pain score, the ASES and Constants score of the affected side. The mean VAS pain score for this study sample was documented at 6 points with the SST recorded at 3 points. The ASES and Constant score were recorded at 47.319 and 59.36, respectively. Millar *et al.* (2009) documented the pre-operative results for ASES at 46, making the current study findings similar. Tonotsuka *et al.* (2019) documented the pre-operative ASES scores as 14.3, 27.4 and 30.3 in the different arthroscopic groups included in their study; scores significantly lower than those noted in the current study. Several studies have sighted the asymptomatic nature displayed by most RC tears, which would account for the tear size not being an indicator for the pain experienced as well as pain thresholds are different across different individuals. In the majority of the tears documented in the current study, there was no correlation between the tear size and VAS pain score obtained. A study by Dunn *et al.* (2014) documented the median for VAS pain score as 4.4. Dunn *et al.* (2014) concluded that a lower VAS score would account for patients not presenting immediately following an injury. A lower ASES score seems to be associated with larger tears (Sambandam *et al.*, 2015).

Acromion morphology has been noted by previous studies to be linked to the RC tear prevalence (Nyffeler and Meyer, 2017). In the current study, 84% of patients were found with a type II acromion. The classification of the acromion was initially documented by Bigliani *et al.* (1986) who divided these into three different types. Nyffeler and Meyer (2017) documented the most prevalent type of acromion associated with RC tears to be type III, these findings varied greatly with the current study. Type III acromial types were only found in 15% of the documented cases, while most of the RC tears were linked to type II acromial morphology. A study by Mohamed and Abo-Sheisha (2014) using MRI documented a prevalent type II acromion in 44.6% of their study sample who presented had presented with partial or full thickness tears, these percentages were however lower than those documented in the current study. Paraskevas *et al.* (2008) describes the prevalence of type I acromion as a commonality in females, however, in the current study the only type I acromion recorded was found in a 62-year-old male patient. Male patients were found displaying a higher occurrence of type II acromion, these were recorded in 57% (n = 35/61) of the sample; these findings are similar to Paraskevas *et al.* (2008) who in their study found the occurrence in 56% of the male patients.

The presenting RC tears were measured in this study with a mean sagittal size of 2cm, findings similarly documented by Millar *et al.* (2009) who also noted medium size tears in the majority of the study cohort which presented with RC tears. Following RC tear measurement, other shoulder functionality scores were assessed and the ROM documented. Muscle strength tests documented total active elevation results similar results to the initial assessment, indicating that healing had taken place, these results would most likely improve in another six months, which would then indicate an improvement in the ROM to the repaired area. Findings documented by Miller *et al.* (2009) noted total active elevation at 163º for six-months post-surgery, when the open and knotted arthroscopic repair were compared, making their findings slightly higher than our study findings. The current study findings documented a mean of 156º. The anterior fibres of the deltoid muscle play an important role in total active elevation at the shoulder joint. In the current study, the mean for total active elevation was documented similar at the initial assessment and at six-month post-surgery. It is reasonable that total active elevation would document low scores at the eighth-week follow-up as the anterior fibres of the deltoid muscle, which are split during the open technique surgery, would still be in the recovery phase. At the six-month follow-up, the now repaired anterior fibres of the deltoid muscle would have mended, allowing for near maximum active elevation which is reached at 180º.

External rotation, however, displayed the highest mean during the initial shoulder examination (pre-surgery) at 62.8º. Millar *et al.* 2009 noted these findings at 39º and 32º at the initial assessment for the open- and arthroscopic repair, respectively. The current study displayed similar results to the initial assessment at the six-month follow-up, which was recorded at 62.4º. Millar *et al.* (2009) noted these findings at 62º and 60º for the open- and knotted arthroscopic repair, respectively, showing a clear improvement in the external rotation in their sample. It is unclear as to the possible reason external rotation in the current study did not show improvement or that it was maybe not affected in the first place as evidenced by the pre- and post-assessment. External rotation of the humerus is an action attributed to infraspinatus and teres minor and therefore, unless both muscles are injured, external rotation of the humerus would not necessarily be affected during both the initial assessment and at the six-month follow-up. In the majority of cases of RC tears, the supraspinatus muscle is mostly affected, with such tears affecting abduction of the arm and potentially not the external rotation.

Multiple studies have shown 80-94% of patients who have undergone open RC repair to have good to excellent results (Hawkins *et al.*, 1985; Ellman *et al.*, 1986; Neer *et al.*, 1988; Cofield e*t al.*, 2001). In the current study, results documented in the six-month post-surgery follow-up were similar to the results obtained during the initial assessment. Due to the follow-up period for this study only ending at six-months, improvements in the active elevation, passive abduction and external rotation would most likely be documented at one-year follow-up post-surgery when full repaired to the injured tissue would most likely have occurred. At one-year follow-up, the shoulder functionality tests and muscle strength tests would possibly indicate improved ROM. Fawzy *et al.* (2016) documented an improvement in the ROM at one year post-surgery, results which were higher than their six-month follow-up. Similarly, Seker *et al.* (2018) also noted improved ROM in the periods between one to two years post-surgery. No re-tears were documented in the current study, however, there were 16 patients who failed to complete the follow-up to the sixth month with no reasons provided. A study by Rashid *et al.* (2017) highlights a relationship between tear size and subsequent failure rate of the repaired RC. In their study, a 43% failure rate was documented at 12 months post-surgery, although it is worth noting that the current study follow-up period ended at six months post-surgery with no failure rates recorded. RC retear rates are documented as ranging from 15% to 90% by several authors using the open- or arthroscopic technique (Klepps, 2004; Boileau *et al.*, 2005; Ratti *et al.*, 2005; Jost *et al.*, 2006). Rashid *et al.* (2017) documented a relationship between tear size and healing rate. In the current study, the patient with the largest tear size documented (5cm) had ROM below the mean at six-month follow-up.

In four of the patients included in the study, a stretched torn RC layer was found seemingly attempting to re-attach itself onto the humerus. The stretched layer was removed during the surgical procedure and processed histologically for further analysis, and to see if any fibroblast activity was present at this site. Fibroblast activity was observed in all four removed biopsies with one definitive sample showing numerous fibroblasts. The presence of fibroblasts is clearly indicative of the healing process (Massoud, 2013) and their presence strengthens the hypothesis that in older patients, the torn tendon attempts to heal itself by reattaching to the humerus. This group of patients would mostly likely have a prolonged RC tear and only seek medical support sometime after tearing the RC. To the author's knowledge, this is the first study to document this hypothesis and subsequent evidence by noting fibroblast activity at the injury site and is an avenue worth further and more thorough investigation.

7.5. Conclusion

RC surgical repair using the open technique was found yielding acceptable results at the sixth month follow-up with study findings comparing well with the arthroscopic repair at this stage. The advantage of the open technique still remains the ease of performing this surgery and the cost-effective nature of the repair, making it ideal repair procedure in developing countries. The majority of patients displayed similar results in the ROM as those recorded during the initial assessment. During this period no retears were documented, unlike other studies were high retear rates were noted.

The type II acromion was found in the majority of the study sample, making these findings different from previous literature. In patients on whom the torn RC was found attached during the surgical repair, biopsy results documented fibroblast activity at this site, possibly indicating the attempt of the torn RC to repair itself, this was documented in older patients.

7.6. Limitations and future direction

Incomplete data due to patient drop-out was the main limitation, these factors affected the data captured for the ROM and shoulder scores. The study will attempt to contact all the volunteers who partook in the study and finished the rehabilitation to date, clinical assessment and shoulder scores will be undertaken in this patient cohort at one-year follow-up post-surgery and the results compared to available literature. A limitation was also documented in this study, where no baseline scores were recorded for the unaffected shoulder during the initial assessment and subsequent follow-up periods. A baseline score of the unaffected shoulder will in future be recorded during the one-year follow-up consultation.

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Chapter 8

Manuscript 5

Title: Post-operative care and follow-up in patients, 40 years and older, following rotator cuff repair surgery using the open technique

Abstract

Successful healing and return of normal function of the rotator cuff (RC) following RC repair surgery is dependent on the rehabilitation protocol followed and the post-surgical management of the torn cuff. Previous literature has documented great post-surgical outcomes following the repair of the torn RC using the open technique. Rehabilitation protocols are variable, often depending on the rehabilitation specialist, size of the tear and the clinical experience of the said expert. The aim of this part of the study was therefore, to describe the rehabilitation protocol followed which strives to protect the repaired RC following open surgery by minimising stiffness to the joint and muscle atrophy. The study also aimed to compare results obtained during the various stages of follow-up in patients, and to note the level of improvement (if any) in the range of motion (ROM) following RC open surgery. Demographic information and pre-existing medical conditions of 80 male and female patients (n=80) recruited from the Life Groenkloof hospital were recorded. Ultrasound examination was performed during the initial shoulder examination for RC tear diagnosis and confirmation and repeated at the six-month follow-up. Not all patients successfully completed the post-operative rehabilitation programme, with 16 drop-out cases recorded. Statistical significance was documented for total active elevation when the ROM was compared at the initial assessment to the eight-weeks post-surgery and with the eight-weeks versus six-months comparison. The rehabilitation protocol followed post-surgery should be sufficient to prevent stiffness, yet gentle enough to allow for tendon healing. In the patient sample examined, no re-tears were documented.

Key words: Rotator cuff tear, shoulder, open surgery, shoulder rehabilitation, rotator cuff injury

8.1. Introduction

Shoulder related complaints remain one of the biggest reasons for consultations to date (Boykin *et al.*, 2010). In a population of 1366 individuals, Yamamoto *et al.* (2017) recorded a 20.7% of full-thickness rotator cuff (RC) tears. In their study, it was noted that the biggest risk factors associated with these tears were age, dominant arm and history of trauma (Yamamoto *et al.*, 2017). Disturbance in the RC function, despite its initial cause, results in the abnormal function of the shoulder and usually limited ROM. RC surgery has been shown to improve ROM and decrease pain to the affected area (Matsen and Arntz, 1990; McKee and Yoo, 2000). However, the ultimate success and complete healing of the repaired RC depends on the integrity of the repair, a factor which is strengthened by a good post-surgical rehabilitation programme.

Rehabilitation programmes following any RC repair are structured with the aim and primary goal of protecting the repaired tear, promoting healing of the injured area and, restoring passive motion and muscular strength in order to achieve maximum restoration of function. In the attempt to return the now surgically repaired RC to full function, a variety of factors must be taken into consideration, these include; the type of surgical approach used, tear size, quality of tissue and fixation methods used (Ghodadra *et al.*, 2009). Rodeo *et al.* (1993) sights the need for patient education regarding the repair site as a necessity for healing, with special caution and patience to be paid to any soft tissue-to-bone healing. Levine e*t al.* (2008) recommends 12 weeks of healing in order to allow strength recovery to the repair site. A certain amount of pressure and tendon immobilization is deemed necessary for the initial tendon-to-bone healing process (Weiler *et al.*, 2002; Weiler *et al.*, 2002).

Ghodadra *et al.* (2009) highlights twelve factors which, significantly affect post-operative rehabilitation and should therefore be a consideration for any physiotherapist, following shoulder arthroplasty. In cases where the deltoid muscle was detached from the acromion and/or clavicle, such as is commonly performed during open surgery, Ghodadra *et al.* (2009) recommends that active deltoid muscle contraction only be performed 6-8 weeks post-surgery to allow the muscle to heal. Tear size prior to the surgical intervention should also be taken into consideration as larger tears more often retract and involve a greater area of the muscle (Debeyre *et al.*, 1965; Post *et al.*, 1983; Gore *et al.,* 1986; Watson *et al.*, 1985; Romeo *et al.*, 1999).

Tissue quality also plays a vital role and it has been noted that with more fatty deposits detected during an MRI it often results in slower healing of the affected area. The method of fixation implored in surgery will affect the rate and progress of the postoperative healing process. Other factors include; location and type of tear, mechanisms of failure of the RC tear and timing of the repair process; surrounding tissue quality; patients characteristics; access to care and the philosophical approach of the doctor (Wolfgang, 1974; Kessel and Bayley, 1982; Neer, 1983; Ellman *et al.*, 1986; Cofield *et al.*, 1990; Wilk *et al.*, 2000; Ghodadra *et al.*,2009).

In the current study, rehabilitation of the repaired site was only initiated two-weeks following immobilisation of the joint. The rehabilitation protocol was carried out by various physiotherapists as recommended by the clinician or at times preferred by the patient. In the two-week follow-up, no muscle strength tests were performed allowing the clinician to only look at the progress of healing and document any pain and/or complaints from the patient. At eight-week follow-up, muscle strength tests were performed and recorded in order to document the stages of healing to the repaired site. The last follow-up period was documented at six-month where all the functionality tests, performed during the initial examination were repeated and results documented and compared with the initial findings. No re-tears were recorded in this patient sample group.

Full repair of the RC depends on the understanding by the physician and physiotherapist/biokineticist of the anatomy, biomechanics and evidence based exercise progression (Sgroi and Cilenti, 2018).

8.1.1. Biomechanics

The RC complex is anatomically comprised of tendons of the subscapularis-, supraspinatus-, infraspinatus- and teres minor muscles, which interdigitate and form a dynamic stabiliser of the glenohumeral joint. The biomechanical properties of the glenohumeral joint are such that the RC complex prevents the superior displacement of the head of the humerus, provides internal and external rotation of the glenohumeral joint and allows for initiation of abduction of the shoulder (Bateman, 1971; Dugas *et al.*, 2002). Proper understanding of this mechanism in healthy and injured tissue is an essential component for successful rehabilitation of the RC complex post-surgery.

8.2. Materials and methods

In this prospective clinical study, a total of 80 patients, over the age of 40 years (40 – 75 years), following RC open repair surgery were included in the study (n = 80). The patient sample included male (n = 47) and female (n = 33) individuals of varying ancestry. All the patients included in the study presented with a repairable RC tear ranging from minor to massive tears. All the patients who participated in the study were recruited from Life Groenkloof Hospital following ethical clearance from the University of Pretoria (Ethical clearance: 419/2017). Consent forms were given to patients who volunteered to be part of the study and data was collected accordingly. Patients were excluded if they were younger than 40 years of age as diagnosis would entail the use of MRI instead of just ultrasound. Data was collected for a period of 18 months (2018 – 2019).

Following surgical intervention by two equally skilled surgeons, patients were referred to a physiotherapist or biokineticist for shoulder rehabilitation. In instances where proximity might pose challenges, patients could choose their own rehabilitation specialist. Guidance was provided to the patients for exercises to be conducted at home, with exercises structured with the aim of improving glenohumeral motion. The physiotherapist provided the patients with information and guidance exercises for shoulder rehabilitation. Patients were required to consult with the surgeon at two-weeks, eight-weeks and six-months post-surgery. The consultation at two-weeks included inspection of the wound and progress of healing. The eight-week follow-up entailed assessing the progress of healing and noting any complaints experienced by the patient. The clinician also studied the notes from the physiotherapist regarding the ROM achieved by the patient to date. These movements included flexion, extension, abduction and external rotation. Barring any other complications, the patient consulted again at six months post-surgery where shoulder functionality tests and muscle strength tests were conducted by the clinician. These tests were the same as at the initial shoulder examination, the results were captured and data further analysed for signs of improvement.

Data was analysed using the IBM SPSS Statistics version. The analysis consisted of frequency tables (percentages and counts) for categorical variables and descriptive stats (means and standard deviations) for continuous variables.

8.2.1. Rehabilitation protocol

The rehabilitation procedures followed in this study were directed to the patient by the physiotherapist. The patient was required to immobilise the shoulder with a sling for the first six weeks post-surgery. The patients were issued with notes containing strict exercises pertaining to the rehabilitation procedure to be followed. The elbow was required to rest in front of the body, with the elbow bent at a right angle and the hand located slightly higher. Patients could only remove the sling for exercises as prescribed by the physiotherapist, icing, dressing and showering. Within the six-week period, some exercises were initiated once or twice a week, additional home exercises were also introduced for ROM and postural exercises. Strengthening exercises were prescribed at the physiotherapist’s discretion. The frequency of treatment was tailored according to the needs of the patient, as strengthening exercises typically begin only after six weeks post-surgery.

Patients were requested to support the arm by placing a towel under the elbow when lying on their back, however, they were not to reach the behind their back with the affected arm. The arm was not to be actively moved away from the body for the six-week post-surgery and no objects were to be lifted using the affected limb in that period. Caution was exercised when the forearm was rotated away from the body in order to protect tendons and muscle. A recliner could be used in this period for the patients comfort. Other daily activities that were affected post-surgery include dressing, bathing and driving. The patients were cautioned against using the affected limb for such activities. The patients could eat, shave and dress themselves with the affected limb on condition that they did not abduct the limb and did not cause an increase in pain. The arm was not to be actively moved away from the body even when using a keyboard and mouse. When showering, the patient could wash under the affected arm pit by bending forward to let the affected arm hang freely and reaching under the arm with the opposite limb. The arm was not to be used to push up/off the bed and/or chair during this period. The patients were advised to seek permission from the physiotherapist or surgeon prior to commencement of any sports and recreational activities, as return to such activities is generally no sooner that four- to six-weeks post-surgery.

Rehabilitation was initiated the first day after surgery, while the patient was still hospitalised, and once a day until the patient was discharged. The patients were then required to consult with the physiotherapist twice a week for the first two weeks, in a few cases patients were requested to consult thrice a week. In most instances, these consultations were for three months post-surgery. The rehabilitation procedure included some restrictions and limitations in order to allow for proper tendon healing. In the first six-weeks, no external rotation was permitted beyond neutral, no active flexion, elevation or abduction was allowed. The movement of the patients repaired RC complex was limited to passive to auto assisted to free movement and short lever and then long lever exercises.

Patients were then given exercises which were to be performed twice a day with 10 repetitions each, these included the following:

- Opening and closing of the hand in big movements, in order to improve circulation to the affected limb (Figure 8.1).
- Flexion and extension at the wrist joint, in big movements (Figure 8.2).
- Flexion and extension at the elbow joint. The patient was required to attempt completely straightening the arm during flexion. If difficulty was encountered, the other hand could be used in the initiation of the movement (Figure 8.3).
- With the arm hanging loosely forward, the patient was required to make small circles with the arm, using the body weight as momentum (Figure 8.4).
- The patient was required to stand up straight, pinch the shoulder blades together for three seconds and then relax (Figure 8.5).
- With the patient sitting on a chair, their arms were to hang loosely on the side of their body. The body was to be moved away from the arm, the arm kept relaxed and then move back to an upright sitting position (Figure 8.6).

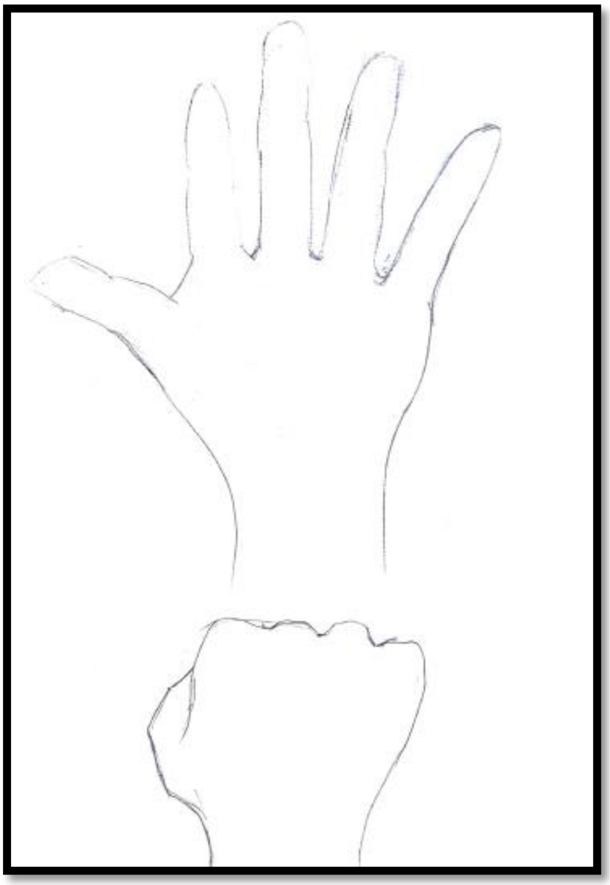

Figure 8.1: Opening and closing of hand exercise.

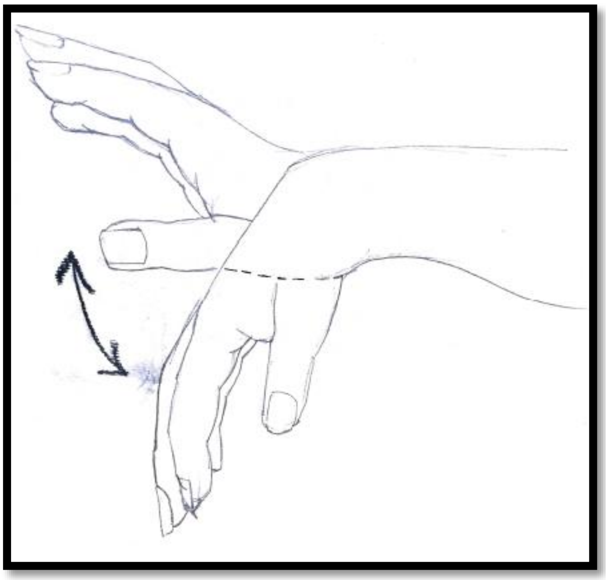

Figure 8.2: Flexion and extension at the wrist joint exercise.

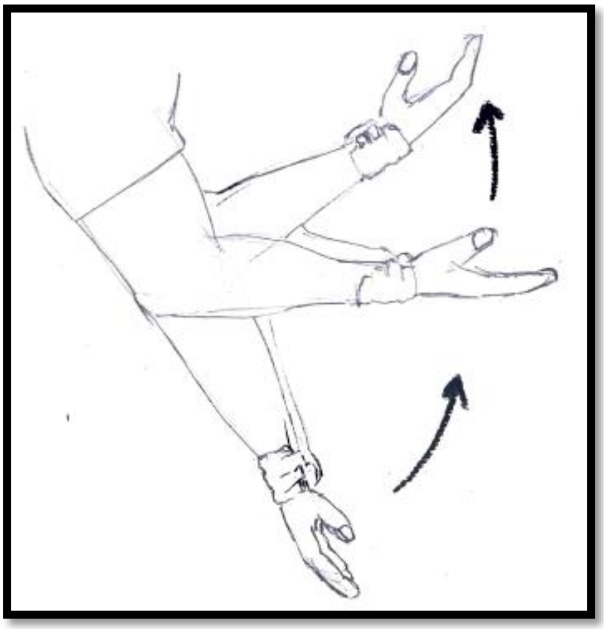

Figure 8.3: Flexion and extension at the elbow joint exercise.

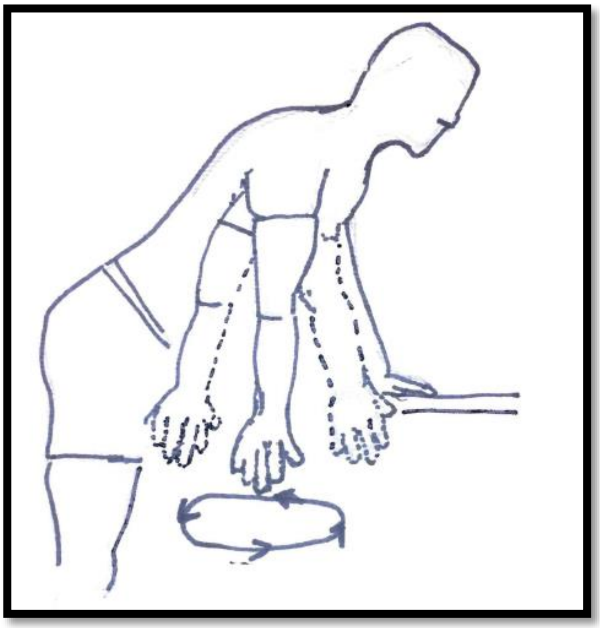

Figure 8.4: Circumduction exercise.

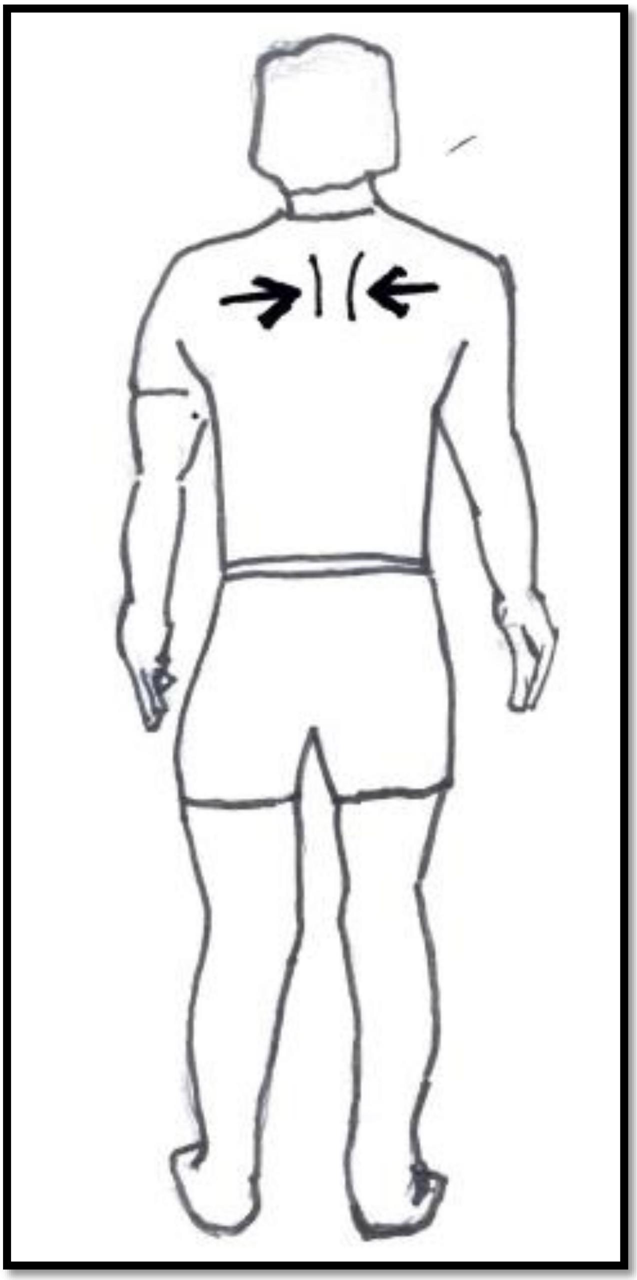

Figure 8.5: Adduction of shoulder blades exercise.

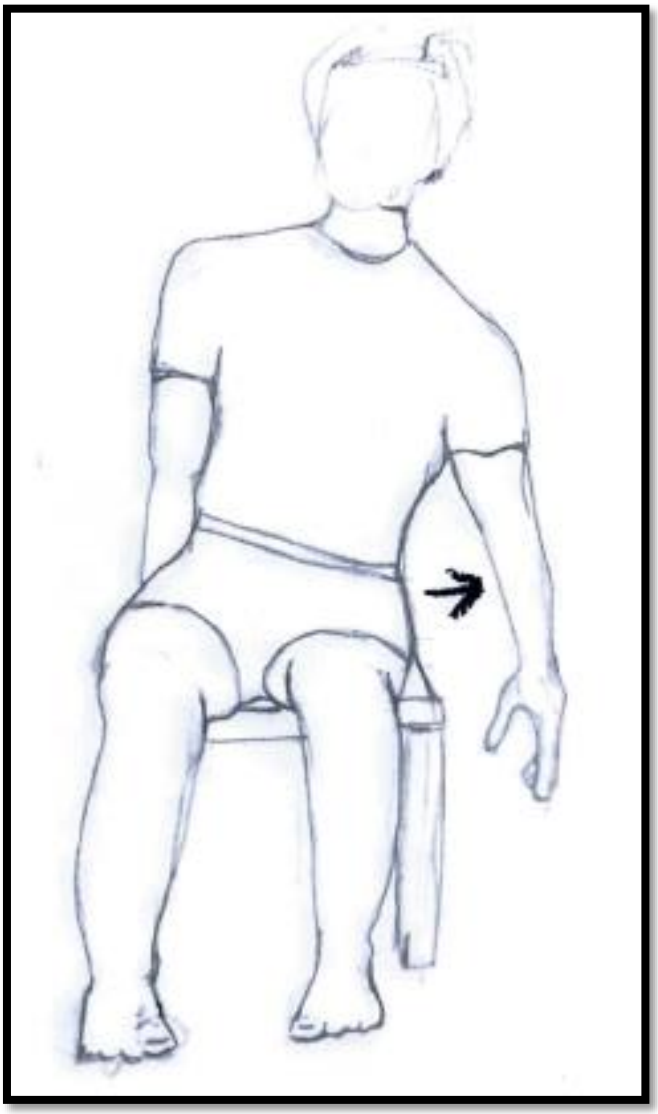

Figure 8.6: Chair exercise entailing moving the body away from the affected limb and then back to sitting position.

8.3. Results

A total of 80 patient shoulders were available after 18 months for analysis. The data on the drop-outs in the study is presented in Table 8.1. A total of 16 patients were recorded in Table 8.1 with two patients not returning for follow-up at two-week post-surgery, one falling out at eight-weeks and 13 not presenting for the six-month follow-up.

Friedman's two-way analysis of variance by ranks was used in the comparison of the three related samples. When the data for active elevation collected at the initial examination was compared to outcomes recorded at eight-weeks, the mean rank was recorded as 1.83 and 1.17, respectively (Figure 8.7). The comparisons made between the initial examination and six-month follow-up resulted in the mean rank of 1.66 and 1.34, respectively (Figure 8.8). In the comparison of active elevation of eight-weeks and six-months, the mean rank was recorded at 1.00 and 2.00, respectively (Figure 8.9). The last comparison was made between the initial examination, eight-weeks and six-months follow-up, the mean rank was recorded as 2.77, 1.05 and 2.18, respectively (Figure 8.10). The reasons for dropping out were not documented.

In Table 8.2 each row tested the null hypothesis that the sample 1 and sample 2 distributions were the same. Asymptotic significances (2-sided tests) were displayed with the significance level as 0.05. Significant differences were noted in the comparison of total active elevation at eight-weeks versus six-months post-surgery ($p = 0.008$). The same was documented for total active elevation at the initial assessment versus at eight-weeks ($p = 0.000$). The total elevation of the patients showed improvement from the eighth-week to six months post-surgery period. The values in the last row of Table 8.2 were adjusted by the Bonferroni correction for multiple tests. Total active elevation was compared between the left and the right side at different consultation stages (Table 8.3). At the initial shoulder examination, the mean for total active elevation is documented as 162º (SD = 34.93) on the left and 155.3º (SD = 32.12) on the right side. Active elevation at eight-weeks was noted as 125º (SD = 23.81) and 129.8º (SD = 25.13) for the left and right side, respectively. Total active elevation at six-months was documented as 145º (SD = 27.84) for the left side and 158.6º (SD = 16.46) for the right side.

Passive abduction was documented as variable at different stages of healing. At the initial shoulder examination, passive abduction was documented as 98º (SD = 13.04) on the left side and 92.8º (SD = 16.15) on the right side. At eight-weeks post-surgery, the measurements are documented as 76.3º (SD = 7.50) and 75.6º (SD =17.22) for the left and right sides, respectively. At six-months follow-up, these measurements are captured as 107.5º (SD = 17.68) and 92.1º (SD = 10.51) for the left and right sides, respectively (Table 8.3).

External rotation at the initial consultation was documented as 60º (SD =0.00) on the left side and 62.9º (SD = 8.32) on the right side. At eight-weeks, such outcomes are documented as 48.8º (SD =8.54) on the left side and 49.6º (SD = 12.40) on the right side. Six months post-surgery, external rotation was captured as 66.7º (SD = 5.77) and 61.4º (SD = 9.89) for the left and right sides, respectively (Table 8.3).

Table 8.1: Patients lost to follow-up

Age	Sex	Time of drop-out (months)	Cause of RC tear
63	Male	6.0	Spontaneous
49	Male	6.0	Injury
63	Male	6.0	Injury
51	Male	6.0	Injury
72	Male	6.0	Injury
40	Female	6.0	Injury
64	Female	6.0	Injury
60	Male	6.0	Spontaneous
65	Male	6.0	Injury
74	Female	6.0	Spontaneous
67	Male	6.0	Not specified
59	Male	6.0	Injury
64	Female	2 weeks	Spontaneous
61	Male	6.0	Injury
49	Male	8 weeks	Not Specified
69	Female	8 weeks	Spontaneous

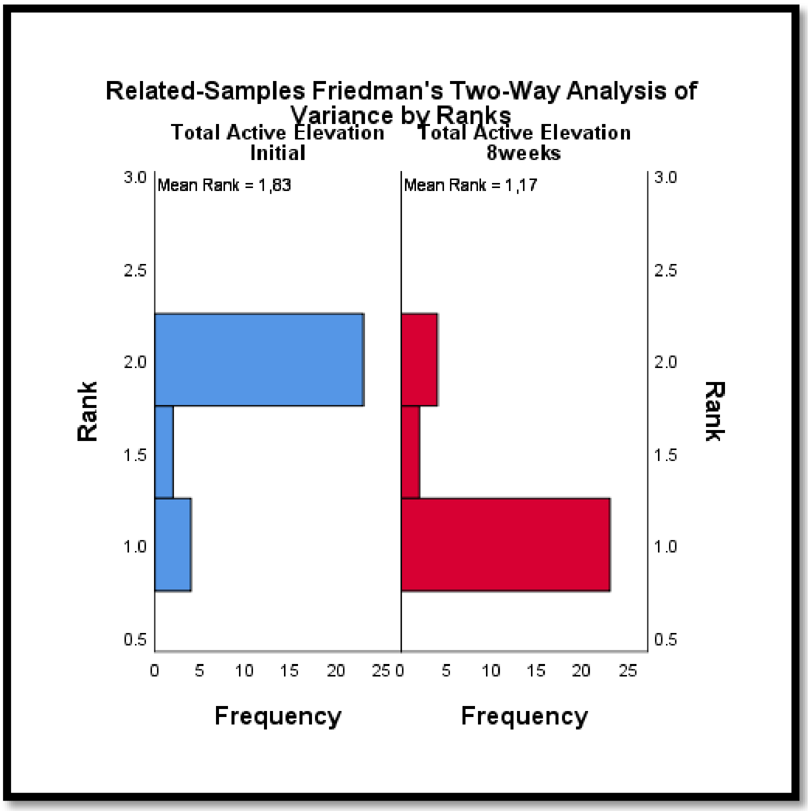

Figure 8.7: Friedman's two-way analysis of variance by ranks for related samples at the initial examination of the injured area versus eight-weeks post-surgery. The mean ranks are recorded as 1.83 and 1.17 for the initial period and eight weeks post-surgery, respectively.

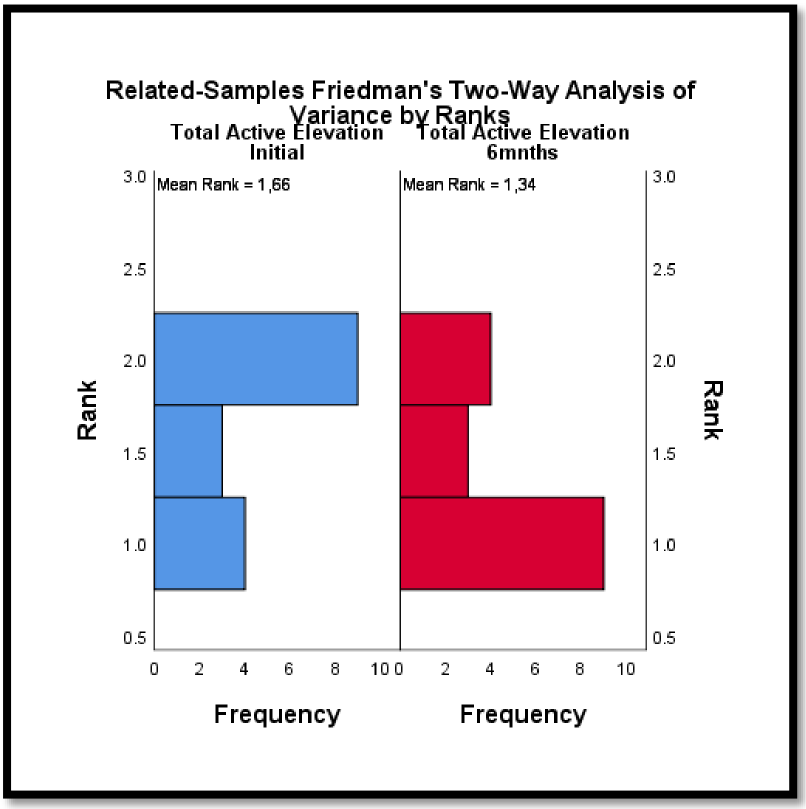

Figure 8.8: Friedman's two-way analysis of variance by ranks for related samples at the initial examination of the injured area versus six-months post-surgery. The mean ranks are recorded as 1.66 and 1.34 for the initial period and eight-weeks post-surgery, respectively.

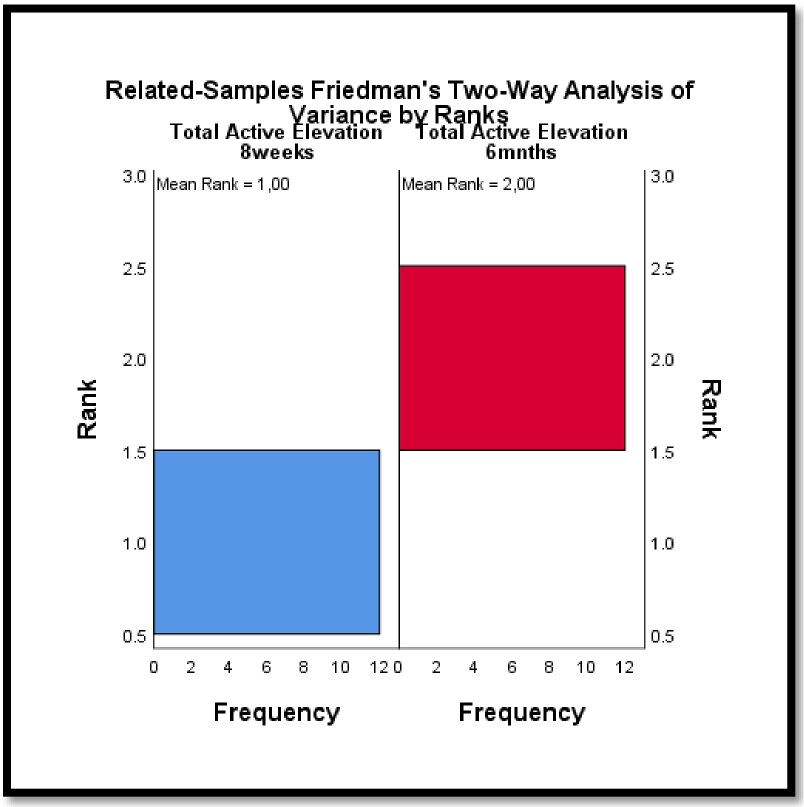

Figure 8.9: Friedman's two-way analysis of variance by ranks for related samples at eight weeks post-surgery versus six-months post-surgery. The mean ranks are recorded as 1.00 and 2.00 for the initial period and eight-weeks post-surgery, respectively.

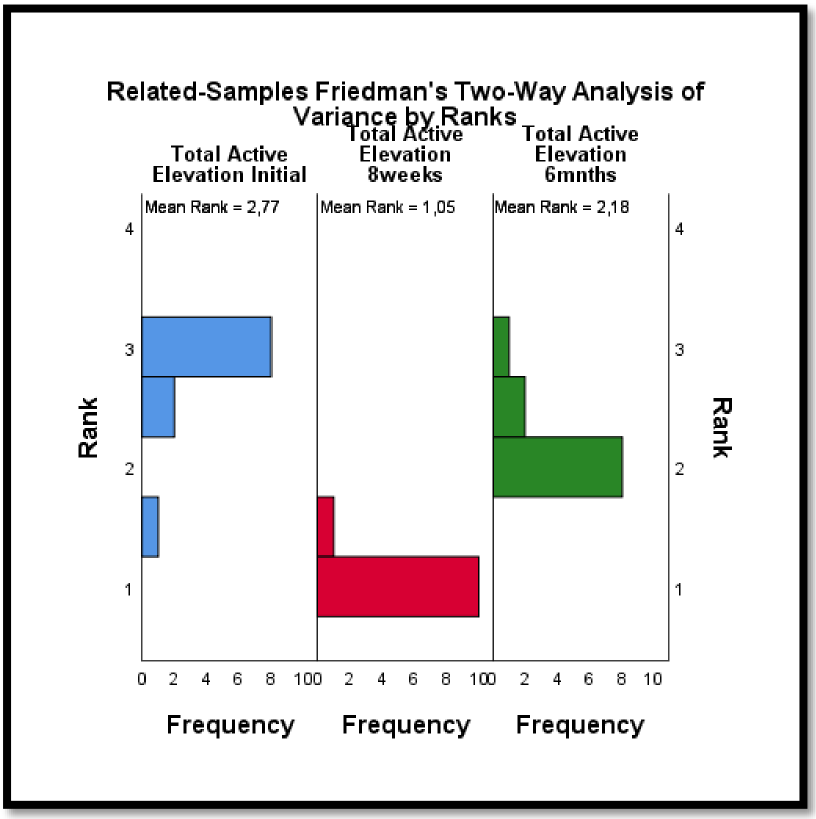

Figure 8.10: Friedman's two-way analysis of variance by ranks for related samples at the first examination, eight-weeks post-surgery and six-months post-surgery. The mean ranks are recorded as 2.77, 1.05 and 2.18, respectively.

Table 8.2: Indicating the comparison for total active elevation at the initial assessment versus eight-weeks and six-months post-surgery

Pairwise Comparisons					
Sample 1 – Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
Total Active Elevation 8weeks-Total Active Elevation 6mnths	-1.136	0.426	-2.665	0.008	0.023
Total Active Elevation 8weeks-Total Active Elevation Initial	1.727	0.426	4.051	0.000	0.000
Total Active Elevation 6mnths-Total Active Elevation Initial	0.591	0.426	1.386	0.166	0.497

Table 8.3: Comparison between the left and right side for total active elevation at the initial assessment versus eight-weeks and six-months post-surgery

	Dominant Side (L/R)											
				L			R					
	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Total Active Elevation (Initial)	2	165.00	21.213	5	162.00	34.928	67	155.30	32.121	74	156.01	31.795
Total Active Elevation (8 weeks)	2	120.00	0.000	4	125.00	23.805	25	129.80	25.103	31	128.55	23.847
Total Active Elevation (6 months)				3	145.00	27.839	14	158.57	16.458	17	156.18	18.585
Passive Abduction (Initial)	2	95.00	21.213	5	98.00	13.038	67	92.76	16.150	74	93.18	15.910
Passive Abduction (8 weeks)	2	70.00	0.000	4	76.25	7.500	26	75.58	17.224	32	75.31	15.706
Passive Abduction (6 months)				2	107.50	17.678	14	92.14	10.509	16	94.06	12.003
External Rotation (Initial)	2	65.00	7.017	4	60.00	0.000	66	62.88	8.323	72	62.78	8.044
External Rotation (8 weeks)	2	37.50	3.536	4	48.75	8.539	26	49.62	12.403	32	48.75	11.846
External Rotation (6 months)				3	66.67	5.774	14	61.43	9.889	17	62.35	9.374

8.4. Discussion

After successful repair of the torn RC tendon, follow-up was scheduled for each patient at two-weeks, eight-weeks and six-months post-surgery. A rehabilitation schedule was agreed upon by the patient and their consulting physiotherapist, in the attempt to return the shoulder to pre-injury conditions. Friedman's two-way analysis of variance by ranks was used in the comparison of the three related samples. The rehabilitation schedule takes into consideration the duration needed for tendon-to-bone fusion, which is six- to eight-weeks post-surgery (Cohen *et al.*, 2002). In the current study, a majority of the patients were right handed (n=75) and presented more with RC injuries on the right hand side (n=49).

Two-weeks follow-up

Following surgical repair, the affected shoulder was immobilised. At the two-week follow-up, consultation entailed assessing the progress of healing and documenting any other complaints and degree of pain. No clinical tests were conducted at this stage, to allow healing to occur. In the current study, one patient, a 64-year-old female did not present for the two-week follow-up resulting in the first drop-out case (Table 8.2).

Immobilisation of the shoulder joint in the two-weeks post-surgery promotes tendon-to-bone healing. When immediate motion is initiated at the repair site, instead of reducing post-operative stiffness as previously documented, more recent research has shown that this may be detrimental, leading to poorer outcomes following the repair (Zhang *et al.*, 2013). A study by Uezono *et al.* (2014), using animal models, noted how delaying passive motion had no effect on strength and maturity of the repaired or remodelled tendon. Peltz *et al.* (2009) noted how increased scar formation may result as a consequence of early passive motion. Histologically, immobilization in the first two-weeks post-surgery assists the extracellular matrix in displaying characteristics of pre-injury tissue. In this period of immobilization, an increase is noted in type I collagen fibres and subsequent reduction in scar tissue formation. A decrease in the load also allows for proper tendon-to-bone fusion (Thomopoulos *et al.*, 2003). In the current study, rehabilitation exercises in the first two-weeks post-surgery entailed passive motion at the repair site as the focus in this period is to maintain the integrity of the repair site by excluding any active motion in this region. Nikolaidou *et* *al.* (2017) notes that some stiffness may result as a consequence of prolonged immobilisation of the repaired shoulder, a theory supported by the current study as limited passive motion was initiated at the repair site a day after the operation. Numerous authors also document variable opinions on the period of mobilisation following RC surgery, however, it seems that most authors agree that this period should be limited to the first four to six weeks post-surgery (Millett *et al.*, 2006; Nikolaidou *et al.*, 2017). In the current study, immobilisation of the repaired tendon was limited to six-weeks post-surgery, active motion was only introduced following this period, similar to the rehabilitation protocols reviewed by Nikolaidou *et al.* (2017). The position of the arm during the immobilisation period is another important factor as previous studies have suggested an improvement in vascularisation and a decrease to the tension experienced at the repair site (Rathbun and Macnab, 1970; Hatakeyama *et al.*, 2001). In the current study, the elbow was kept resting in front of the body, bent at a right angle and the hand positioned slightly higher.

Eight-weeks follow-up

During this period, active motion was introduced, which included external rotation, flexion, extension, and abduction exercises. At the eight-weeks follow-up, the consulting clinician assessed the wound for healing and noted any complaints relating to the repaired area. In the current study, two patients fell out at eight-weeks follow-up. Muscle strength exercises were also performed during this period and the results compared to outcomes documented at the initial shoulder examination.

Significant differences were noted in the comparison of total active elevation at eight-weeks versus six-months post-surgery. The lowest motion outcomes were documented for total active elevation, passive abduction and external rotation during this period. During this period, it is noted that the inflammation that followed the surgical repair is normally reduced and the repair process has moved to the collagen remodelling stage (Long *et al.*, 2010). The eighth week follow-up recorded lower percentages in the ROM due to the healing of the affected shoulder. These weak results may possibly be due to the post-operative inflammatory and repair phases, which at six- to eight-weeks post-surgery have progressed to the collagen remodelling stage and insufficient healing has occurred to the repair site (Long *et al.*, 2010). In the fourth to the eighth week post-surgery, the tendon to bone healing is progressively increasing and the delayed introduction of any active motion allows for orientation of fibres within the collagen matrix which results in enhancing the tensile strength of the repaired tendon (Long *et al.*, 2010). In the current study, external rotation was only introduced after six weeks post-surgery. The goal of this phase of the rehabilitation process is to continue passive ROM and ultimately introduce active-assisted ROM exercises. The degree of healing at this stage is variable in patients, with various factors affecting the desired outcomes. The healing of the repaired RC is depended on the quality and size of the repair, the age of the patients and various other factors. During this phase, the clinicians' attempts to introduce active-assisted ROM while minimizing the pain and inflammation of the joint and improving neuromuscular control and strength (Nikolaidou *et al.*, 2017). Kelly *et al.* (2000) advises against introducing any resistance or strength activities and rather focusing on attaining a full active ROM.

Six-months follow-up

At this stage, ROM had improved from the results recorded at the eigh-week follow-up, the histological remodelling phases and tendon-to-bone healing had progressed to a stage of strength exercises. At this point of the rehabilitation process, the patient should have full passive ROM without experiencing any pain. During this consultation, the clinician performed a variety of muscle strength tests and shoulder functionality tests. The shoulder functionality tests included total active elevation, passive abduction, active and passive external rotation, passive internal rotation, flexion extension and rotation in abduction. An ultrasound was performed on the affected shoulder to assess the progress of the healing RC (Figure 8.11). Exercises performed at this stage assist in strengthening the RC and related muscles.

Total active elevation for the patients improved during this period, with post-operative outcomes indicating higher percentages at six-months than at eight-weeks. The higher percentages noted during this rehabilitation stage are due to muscle strengthening exercise introduced between the eight-weeks and six-months follow-up, targeting the RC muscles and surrounding muscles. In the current study, 13 patients fell out at six-months and no reasons were provided for missing the follow-up. At six-months post-surgery, the results documented were mostly similar to the findings made during the initial examination, indicating the continued healing of the RC before reaching a full ROM. A study by Cohen *et al.* (2002) indicated that patients continue to show signs of improvement for at least a year post-surgery. In their study, maximum improvements for small tears were recorded at four- to six months, medium tears at six- to eight months, large and massive tears at eight- to twelve months (Cohen *et al.*, 2002). It is worth noting that the current study only documented results to the sixth month post-surgery when the full ROM had not yet been reached by the patient. However, a study by Lee *et al.* (2012) showed no significant difference in abduction for six to twelve months post-surgery following arthroscopic repair. Similar results were documented by De Roo *et al.* (2015) who studied the six weeks and four months post-surgery period. In the current study, no significant differences were documented in the ROM for passive abduction at eight-weeks but improvements in shoulder function were recorded. It is probable that at one-year post-surgery, the results recorded by the current study would indicate a significant improvement in the ROM.

Figure 8.11: Ultrasound image showing a healed rotator cuff (RC) hood/complex (indicated by arrows).

8.5. Conclusion

Post-operative follow-up and rehabilitation following RC surgery is a demanding process, with some patients choosing not to follow through when symptoms experienced prior to surgery are alleviated or when they feel satisfied with the movements now possible at the affected arm. It is, however, imperative that the rehabilitation process is followed through in order to achieve maximum functional outcomes. The results of this study also indicate an improvement in the ROM in patients who underwent physiotherapy following RC open surgery. In the current study, improved ROM was documented in most patients, when comparing the outcomes of eight-weeks follow-up to six-months follow-up.

8.6. Limitations

Patient drop-out following RC repair was the main limitation, resulting in incomplete data for the ROM and shoulder scores. Not all patients followed the rehabilitation programme as set out by the physiotherapist, the data was therefore incomplete for the ROM at eight-weeks and six-months post-surgery. Numerous publications indicate significant improvements to the ROM only a year post-surgery. The follow-up period of the current study ended at six-months post-surgery, thereby limiting the documented outcomes.

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Chapter 9: Synopsis

Part of the aims of this study were to investigate the macroscopic anatomy of the RC complex along with the blood supply to the RC muscles. The study achieved this through reverse dissection of the RC muscles in a 100 cadaveric shoulders. This dissection technique also allowed for the documentation of pathology to the RC complex, glenohumeral joint and surrounding soft tissue. The axillary artery was studied extensively, with the branching pattern and any related variations documented and analysed (Chapter 4). The lengths of the three parts of the axillary artery were measured and variations occurring at the different parts, analysed. A case study, which noted the superficial ulnar artery as a branch of the second part of the axillary artery, was also documented in Chapter 5. The superficial ulnar artery was dissected further and followed to its terminal point. Blood supply to the RC muscles was looked at and the findings corroborated with current literature, which states that the blood supply mainly originates from the suprascapular- and subscapular arteries. Chapter 6 further noted pathologies of the RC in a cadaver sample. Pathology was documented in a third of the cadaveric sample, with the most noted pathology being the presence of osteophytes on the humeral head. RC tears contributed to a small percentage of the pathology, findings that were different from most of the current literature. In all the documented pathologies of the RC, blood supply to the head of the humerus was found intact, including the documented case of clear signs of osteonecrosis of the head humerus (Chapter 6).

The clinical component of the study entailed documenting RC-related pathology by studying the range of motion (ROM) achieved pre- and post-surgically at the glenohumeral joint. In order to achieve this goal, 80 male and female patients of age of 40 years and above, were recruited from the Life Groenkloof Hospital. Patients who agreed to be part of the study were required to complete consent forms. The study documented results obtained from shoulder functionality tests, and compared these to available literature. Shoulder functionality tests included the VAS pain score, the ASES score, the SST and the constant score. The ROM was noted at the different rehabilitation stages; these included the pre-operative stage, at eight-weeks post-surgery and six-months post-surgery (Chapter 7 and 8). At six-months post-surgery, results documented were similar to findings made at the initial assessment. Previous literature documented significant improvements to the ROM at one-year post-surgery. Therefore, the current study would record these improvements only a year following surgical intervention. The RC tear sizes were also measured in this study and findings compared to current literature. During the operative procedure, the RC layer was found attempting to reattach itself to the humerus in some older patients. Biopsies were therefore performed and histologically analysed. The study also attempted to document the relationship between acromial morphology and the RC tear noted. These were examined in X-ray images where the most prevalent acromial type was noted as the type II acromion. RC tears were also investigated in terms of the hand dominance to determine a possible link between the side of the RC tear and the dominant hand. Most of the patients in this study were right handed, with most tears also documented on the right hand side. In the patient sample that completed the follow-up, muscle strengthening was documented, where the ROM results indicated results similar to pre-operative outcomes. In this study cohort, no retears were documented.

Chapter 10: Conclusion

In the current study, several findings in both the cadaver and the clinical component of the study, were documented. The findings observed in the cadaver component are documented as follows:

- In the documented length of the three parts of the axillary artery, statistically significant differences were noted in the second ($p<0.000$) and third parts ($p<0.014$) of the artery. Statistically significant differences were also noted in the right side length of the first part of the axillary artery ($p<0.025$) in individuals of different height. Comparisons for individuals of BMI <18kg/m^2 and ≥25.1kg/m^2 yielded statistically significant differences on the right side ($p<0.023$).
- No studies could be found documenting the lengths of the different parts of the axillary artery. In the current study, the lengths of the different parts of the axillary artery was documented as well as the total length, were documented. The average length of the first part of the axillary artery was documented as 32.66 ± 8.75mm. Numerous arterial variations were noted in the first part of the axillary artery.
    - The superior thoracic artery was documented in 99% of cases, with 97% emergence from the first part of the axillary artery:
    - In 34% of the sample, the thoracoacromial artery emerged from the first part of the axillary artery. No reference to this high incidence of origin from the first part could be found in previously documented literature.
    - A clavicopectoral trunk was found arising from the first part of the axillary artery, while the acromial- and deltoid branches emerged directly from the second part of the axillary artery.
    - A common trunk for the thoracoacromial artery and the lateral thoracic artery was noted in 8% of cases.
    - The lateral thoracic artery was found emerging from the first part in 18% of cases.
    - The suprascapular artery emerged from the first part of the axillary artery in 4% of cases.

- The average length of the second part of the axillary artery was documented as 35.79 ± 8.71mm on the right side and 33.76 ± 7.76mm the left side. The following variations were noted in the second part:
    - In 2% of the sample, the emergence of the superior thoracic artery was observed from the second part of the axillary artery.
    - In 6% of cases, the lateral thoracic artery shared a common trunk with the subscapular- and posterior circumflex humeral artery.
    - Collateral brachial arteries were documented in 3% of cases, with 2% being bilateral.
    - In 18% of the study sample, the subscapular artery emerged from the second part of the axillary artery.
- The average length of the third part of the axillary artery was recorded as 44.19 ± 9.62mm on the right side and 44.68 ± 11.16mm on the left side, with the following variations noted:
    - A common trunk shared by the lateral thoracic-, subscapular- and posterior circumflex humeral artery was found in 3% of cases.
    - In our sample, 17% of cases presented with a common trunk for the anterior circumflex humeral-, posterior circumflex humeral- and subscapular artery.
    - The posterior- and anterior circumflex humeral artery shared a common trunk in 3% of cases.
    - The posterior circumflex humeral artery shared a common trunk with the subscapular artery in 48% of cases.
- One unilateral superficial ulnar artery (SUA) was documented on the right side. The SUA emerged from the second part of the axillary artery, coursing between the medial root of the median nerve and the ulnar nerve. In its course, muscular branches were given off to the anterior compartment muscles of the forearm before entering the cubital fossa and coursing superficial and medial to the bicipital aponeurosis. More muscular branches were noted supplying the muscles on the medial aspect of the forearm before terminating. The SUA then terminated by forming the superficial palmar arch and contributing to the formation of the deep palmar arch.

- Rotator cuff (RC) related pathologies were recorded in 33% of the sample size. The pathologies found ranged from small- to massive tears, osteophytes and the possible onset of osteonecrosis. The following pathologies were documented:
  - Bilateral marbleisation of the humeral head was observed in one cadaver.
  - A degenerative long head of biceps brachii muscle was noted, but no clear sign of Popeye's deformity was found.
  - Signs of the onset of osteonecrosis were noted in 3% of the sample.
  - RC tears were noted in 5% of the cadaver sample.
  - Bilateral pathology was noted in twelve cadavers (23%), mostly related to osteophyte development and/or calcification in the head of the humerus.
  - Osteophytes presence was noted in 21% of the study sample. The mean BMI of individuals in whom osteophytes were documented, was 20.14 kg/m^2.

The findings revealed by the clinical component of the study were documented as follows:

- Shoulder functionality tests conducted at the pre-operative stage of the study noted the following results:
  - The VAS pain score was documented at 6 points, with the SST at 3 points and the ASES and constant score at 47.319 and 59.36, respectively.
- Statistically significant differences were noted in the ROM when the initial assessment was compared to the eight-week follow-up (p = 0.000) assessment. When the eight-week follow-up assessment was compared to the six-month follow-up (p = 0.008), a further improvement in the ROM was noted.
  - The mean value for the total active elevation mean was documented as 156.01º (SD = 31.795) for the initial assessment, 128.55º (SD = 23.847) for the eight-week follow-up and 156.18º (SD = 18.585) for the six-month muscle strength test.

- Passive abduction measured at eight weeks post-surgery, was documented as 76.3º and 75.6º for the left and right sides, respectively. At the six-month follow-up assessment, these measurements were captured as 107.5º and 92.1º for the left and right sides, respectively. The mean for passive abduction was documented at its peak in the sixth month post-surgery, as 94.06º.
- External rotation was recorded as 48.8º on the left side and 49.6º on the right side at eight weeks post-surgery. At six months post-surgery, external rotation was captured as 66.7º and 61.4º (SD = 9.889) for the left and right sides, respectively. The external rotation, however, revealed the highest mean during the initial shoulder examination, at 62.78º. The lower numbers recorded during the eight weeks post-surgery could possibly be due to limited muscle use during the rehabilitation process.

- Of the patients who presented with a RC tear, 65% was noted in the dominant arm. Contralateral tears were documented in 30% of patients.
- No retears and/or complications were noted at the sixth month post-surgery.
- A type II acromion was found in 84% of patients who had presented with an RC tear. These results were different from previous studies that reported an association between RC tears and type III acromia.
- The mean sagittal size of the RC tears documented was 2cm, with the largest tear noted at 5cm.
- During the operative stage of the study, the torn RC was found re-attaching to the humerus. The hypothesis is that the torn RC attempted to heal itself. Biopsies were removed from this stretched tissue. Histological analysis revealed fibroblast activity at this attachment site, possibly validating the hypothesis.

Future recommendations

- The current study revealed a paucity in the literature documenting the exact ROM at the various post-operative stages when the open technique was used. Further studies documenting these results would assist in validating the use of the open technique, especially in third world countries where the cost-effective nature of the open technique is still the main drive for its use.

- Further studies documenting the long-term follow-up of results obtained using the open- and arthroscopic technique, are necessary. Although some current literature comparing the two techniques is available, it is not enough. As each technique has its merits, it would be beneficial for the patient to know which technique is less likely to cause long-term post-operative complications.
- This study found that, in older patients who may have had an asymptomatic RC tear for a prolonged period, the layers of the RC were stretched. The hypothesis, as stated by the current study, is that the torn RC attempted to repair itself by reattaching to the humerus. As fibroblast activity was noted in the histological analysis of the biopsies, it stands to reason that further studies investigating this phenomenon are needed. This could assist in answering the question of why not all RC tears are detected.
- The study findings relating to the most noted type of acromion found in the diagnosed RC tears, vary greatly from current literature. A cadaver study analysing the different types of acromia associated with RC tears may be necessary to add to the pool of current literature.

Chapter 11: Limitations and future direction

11.1. Limitations

Cadaver Component

The disparities in the number of the sample size (n = 48, n = 47, n = 52) are due to some limitations encountered during the data collection phase of the study. The cadavers used for the study were obtained from the second year medical and dentistry dissection groups resulting in the limitations encountered.

- Bilateral dissections were only possible in 48 of the cadavers dissected, unilateral dissections were carried out on 4 cadavers in order to bring the sample size to 50 right- and 50 left dissected shoulders.
- The axillary- and/or subclavian artery were sometimes transected, resulting in unilateral dissection of the axillary artery.
- The pectoralis minor muscle was at times partly or totally incised, resulting in the exclusion of the affected limb from the study sample.
- In many instances, the suprascapular artery was cut, leaving only the origin, thus making it impossible to follow the blood vessel to its termination.
- Some branches of the axillary artery had also been cut during undergraduate dissection, leaving only the origin of the vessel.
- Due to the primary investigator not being a pathologist, judging the pathology of the joint and muscle was subjective. We do note that pathology occurs on a histological level and this was not investigated.

Clinical Component

- The study documented incomplete data due to patient drop-out, a factor that affected the data captured for the ROM and shoulder scores.
- Only two patients reported for their final X-rays at six-months, making it difficult to analyse results. These X-ray findings were, therefore, omitted from the study.
- Included in the aims of this study was to investigate the blood supply to the head of the humerus following open surgery. This was to be done using the Doppler system which was going to be performed by an independent clinician, familiar with this procedure. During the early stages of the data collection phase of the study, the said clinician withdrew from the study, leaving this important aspect impossible to complete and analyse.

- Not all patients successfully completed the Constant- and ASES score evaluations. Only the data obtained from patients who submitted the required forms, was analysed for these scores.
- No Constant-, ASES or VAS pain scores were recorded at the six-month follow-up, making it difficult to note if any improvement to these scores had occurred at six months post-surgery.

11.2. Future direction

- Future studies will investigate whether a relationship exists between signs of osteonecrosis of the shoulder and the hip of the same cadaver. The possibility of this occurrence was suggested by Byun *et al.* (2014).
- The study will in the future attempt to include a pathologist or a doctor in order to fully investigate the cadaver pathology.
- The study will attempt to contact all the volunteers who partook in the study and finished the rehabilitation to date. Clinical assessment and shoulder scores will be undertaken in this patient cohort. The results will be compared to available literature. The follow-up will be attempted for as long as possible and the data analysed and published accordingly.
- During all future follow-up consultations, baseline scores of the unaffected shoulder will be taken and the results compared to the affected shoulder.

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Annexures

Annexure A

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 03/14/2020.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences Research Ethics Committee

12/10/2017

Approval Certificate
New Application

Ethics Reference No: 419//2017

Title: The clinical, anatomical and repair integrity of the rotator cuff following open surgery in a South African sample

Dear Ms Nkhensani Mogale

The **New Application** as supported by documents specified in your cover letter dated 28/09/2017 for your research received on the 6/10/2017, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 11/10/2017.

Please note the following about your ethics approval:
- Ethics Approval is valid for 3 years
- Please remember to use your protocol number (**419/2017**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the receipt of **6 monthly written Progress Reports**, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers; MBChB; MMed (Int); MPharMed,PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health).

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Annexure B

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 03/14/2020.

15 May 2019

Approval Certificate
Annual Renewal

Ethics Reference No.: 419/2017
Title: The clinical, anatomical and repair integrity of the rotator cuff following open surgery in a South Africa sample

Dear Mrs N Mogale

The **Annual Renewal** as supported by documents received between 2019-05-06 and 2019-05-15 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 2019-05-15.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2020-05-15.
- Please remember to use your protocol number (419/2017) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers
MBChB MMed (Int) MPharmMed PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
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Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure C

Frequency table showing descriptive statistics for height, weight, BMI, age and the different part of the axillary artery on the right and left sides

Variables	N	Minimum	Maximum	Mean	Std. Deviation
Height (m)	52	1.25	1.90	1.6888	0.11018
Weight (kg)	51	30.6	93.3	56.584	14.9519
BMI (kg/m^2)	52	0.00	44.93	19.6478	6.47405
Age (years)	52	21	94	70.35	16.879
Right 1st Part	50	13.71	52.80	33.6232	7.75398
Right 2nd Part	50	20.64	58.80	35.9676	8.57391
Right 3rd Part	50	17.92	71.40	44.7640	10.17556
Left 1st Part	50	11.20	60.86	31.2108	9.59098
Left 2nd Part	50	20.60	52.00	33.6042	7.64195
Left 3rd Part	50	25.00	70.30	44.7930	10.97357
R.C. Trunk*	18	8.43	45.76	22.9922	13.08246
L.C. Trunk*	25	5.94	39.08	18.0552	7.80205
Valid N	17				

**Key: R.C. – right common; L.C. – left common*

Annexure D

DATE: .... **SHOULDER EXAMINATION FORM** **FILE NO:** ____________

(Dr THYS DE BEER)

NAME : .... OCCUPATION :..

AGE : .... SEX: **M / F** HEIGHT :............ WEIGHT :.......... INV SHOULDER : **R / L** DOMINANT SIDE: **R / L**

SPORT/PHYSICAL ACTIVITIES :...

HISTORY

PAIN: Present since:........................... Severe since:..

Cause: Spontaneous / Injury:...

....

		Area:		**Painful Movements:**	
Grade: I II III		G.r Tuberosity	Post Shoulder	Elevation	Throwing
Pain lying on shoulder	+ -	Deltoid Area	Central	Across Body	Flexion (+ Pronation)
Night Pain	+ -	Lat side of arm	LHBT	Reaching back	Jerk
Neck Pain	+ -	Trapezius	ACJ	Painful Arc	
Headaches	+ -	Ant Shoulder	Neck	AER	

INSTABILITY: NO / YES First incident: .... Dead Arm Syndrome: No / Yes

Position of arm: .... Direction: Anterior / Posterior: How Reduced: 1st Bystander / Dr Analg. / GA Spont

Subsequent: ....

....

FUNCTION (ACTIVITIES OF DAILY LIVING): Normal: S/Impaired: Mod/Impaired: Sev/Impaired:

Injury:	Shoulder: No / Yes	Prev/Treatment: N/Y	Physio	Biokinet
	Neck: No / Yes		NSAID	Chiropractor
	Prev/Surgery: No / Yes		Steriod	Sling

MEDICAL HISTORY: Allergies: .... Smoke : Y / N

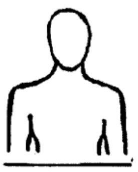
Other Disorders: .... DVT : Y / N

....

EXAMINATION Crepitus + - Ligament laxity (Thumb to forearm): N / Parallel / Touch **Posture:**

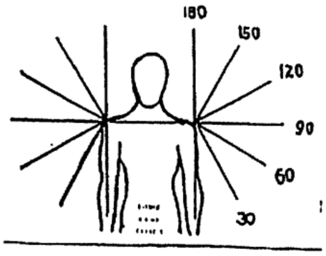
Atrophy: Nil Deltoid S/Spinatus I/Spinatus **Tenderness:** Nil Acromion R/Cuff ACJ SCJ Bic.tendon Other:

Scars

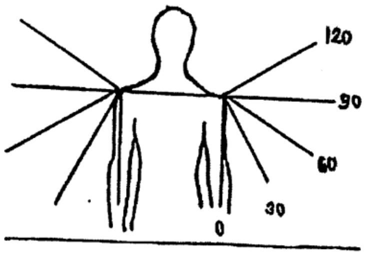


Sc Thor Rhythm
GH Rhythm

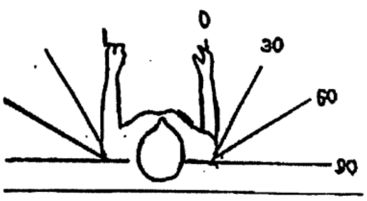
Total Active Elevation



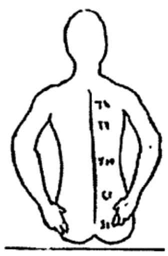
Abduction (passive)



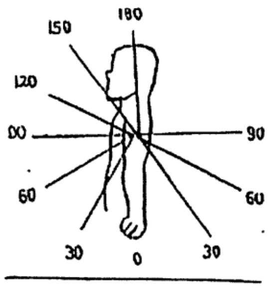
External Rotation **A = Active Int.** **P = Passive**



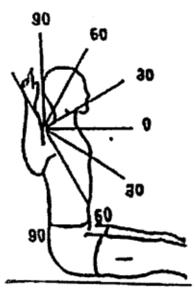
Int. Rotation (passive)



Flexion Extension



Rotation in abduction



Muscle Testing: (Strenght Test /5)

	Pain	**Power**
Ant Deltoid		
Mld Deltoid		
S/Spinatus: Jobe		
Serratus Ant (Winging		

	Pain	**Power**
Ext. Rotation		
Int. Rotation		
Lift Off		
Triceps		

		Pain	**Power**
Briceps	Elbow Flexion		
	Speed Test		
	Yergason		

Impingement sign + -
Mod. Imp. Sign (II) + -
Mod. Imp. Sign (III) + -
After local anesthetic + -

O'Brians Test : F - P + -
Palm Up + -
Mental attitude:

AC-JOINT Local tenderness + - Distraction test + - Passive mobility – Gr I II III IV
SC-JOINT Compression test + - Cross body Adduction + - Relief after injection + -

---

STABILITY: Apprehension test + - Ant. Subluxation + - Grind test + -
Jobe relocation test + - Post. Subluxation + - Sulcus sign + -
Pain with AER + - Ant. Trans. (Arm neutral) + - Jerk test + -

---

NECK: Tenderness + - C: ROM: N/ Spurling Ext + - Neck Trap L R
Crepitus scapula + - P.V. Spasm L R L LFE + - Neck Trap L R
Neuro Vascular: Thoracic outlet R LFE + - Neck Trap L R

ULTRASOUND: L R
1. R.C ....
2. LHBT ....
3. Sub-scap ....
4. AC-J ....
5. Labrum ....
6. Humeralhead ....

X-RAYS: L R

Acromion: type I II III

Gl-humeral joint

AC-J

MRI:

Calcification
Cervical spine:

Hill Sachs:
Os acromiale
CT:

DIAGNOSES: L R

RC IMPINGEMENT (M75.4)
RC TEAR (M75.1)
SUB-SCAP. TEAR (M75.1)
AC-DEGENERATION (S43.5)
AC-DISLOCATION (S43.5)
LHBT DISLOCATION (M75.2)
LHBT TENDONITIS (M75.2)

GLENO-HUM. ARTHRITIS (M19.01)
RC ARTHROPATHY (M19.01)
CALCIFIC TENDONITIS (M75.3)
FROZEN SHOULDER (M75.0)
ANT / POST G-H INST (S43.0)
LABRAL TEAR (S43.4)
SLAP LESION (S43.0)

CERVICAL SPINE (M50.9)
NERVE LESION (G56.2)
THORACIC.OUTLET SYND. (M54.0)
FRACTURE MAL-UNION (M84.21)
FRACTURE NON-UNION (M84.21)
TENNIS ELBOW (M77.12)
OTHER OSTEONECROSIS (M87.81)
PECTORALIS MAJOR (S46.7)

PROPOSED MX
Date: .... L R Age:.........

Position	Time	No. Ass	Hosp	Side
Beach			L G H	L
Lat				R

Conservative
Sub-acromial injection
Follow-up consultation

AC-J Injection
NSAI
Refer Physio / Rehab

SURGICAL PROCEDURES:

Acrom and excision lat. clavicle: Arthrosc (0667) Acromio (0617) Exci Lat Clav (0615) Debride (0614) RC Debride (0748)
R.C Repair : Arthros (0667) RC Rep (0747) Exci Lat. Clav (0615) Acromio (0617) Debride (0614)
LHBT tenodesis (0745) Bone trans (0507) Sub-scap (0578) RC Debride (0748)
AC-Joint Repair: Arthros (0667) AC-J Repair (0579) Debride (0614) Exci lat. Clav(0615) RC Debride (0748)
Stabil + Frac repair + Tenodesis: Arthrosc(0667) Recurrent dislocation (0578) Debride (0614) Repair fracture (0465) Tenodesis (0745) RC Debride (0748)
Remove calcification: Arthrosc (0667) Rem calcific (0746) Debride (0614) RC Debride (0748)
TSR / RTSR: Shoulder replace (0620) Debride (0614) Acromio (0617) Exci lat. Clav (0615) Bone Trans (0507) Sub-scap (0578) RC Repair (0747) Resec of Bone (0497) LHBT Tenodesis (0745) RC Debride (0748)
Revision TSR / RTSR ++ Revision (0058)
Shoulder Manipulation Arthroscopy (0667) Shoulder manipulation(0669) Debride (0614) RC Debridement (0748)

Other:

Neck manipulation	0929	Repair pect. Major	0794	LHBT Tenotomy	0781
Synovectomy	0592	Biopsy	0583	Removal Internal fixation	0884
Exostosis Removal	0537	Rotator Cuff Debridement	0748	Bone Resection	0497
Small Bursa / Ganglion	0853	Neurolise	2829	Pectoralis Major	0794

FOLLOW-UP:

Annexure E

PATIENT INFORMATION & INFORMED CONSENT DOCUMENT

STUDY TITLE: The clinical, anatomical and repair integrity of the rotator cuff following open surgery in a South African sample

SPONSOR: None

Principal Investigators: Ms Nkhensani Mogale

Institution: University of Pretoria, Department of Anatomy, School of Medicine, Faculty of Health Sciences

DAYTIME AND AFTER HOURS TELEPHONE NUMBER(S):

Daytime numbers: +27 (0) 12 319 2934

Afterhours: +27 (0) 725431458

DATE AND TIME OF FIRST INFORMED CONSENT DISCUSSION:

Dd	**mmm**	**Ivy**

:
Time

Dear Patient

Dear Mr. / Mrs. .... date of consent procedure ….…./….…../….......

1) INTRODUCTION

You are invited to volunteer for a research study. This information leaflet is to help you to decide if you would like to participate. Before you agree to take part in this study you should fully understand what is involved. If you have any questions, which are not fully explained in this leaflet, do not hesitate to ask the investigator. You should not agree to take part unless you are completely happy about all the procedures involved. In the best interests of your health, it is strongly recommended that you discuss with or inform your personal doctor of your possible participation in this study, wherever possible.

The rotator cuff refers to the muscles that function as dynamic stabilizers of the shoulder joint. Tears of the rotator cuff are often due to injuries sustained when performing strenuous movements of the shoulder or these tears can result from degenerative changes in and around the joint.

2) THE NATURE AND PURPOSE OF THIS STUDY

You are invited to take part in a research study. The aim of this study is to evaluate the anatomy of the rotator cuff and the postoperative rotator cuff integrity following traditional open surgery. By doing so we wish to learn more about the following:

- The study looks to ascertain and reinforce the insertion of the rotator cuff unit
- Blood supply to the rotator cuff unit will be investigated, and any variations to the recorded literature documented
- The study will also look to classify the common tears encountered in the South African population by individuals of different population groups, age groups, BMI and sex
- The healing of the repaired rotator cuff tendon will be evaluated using ultrasound at a 8 week and 6 month follow up

3) EXPLANATION OF PROCEDURES TO BE FOLLOWED

This study will involve all the procedure already associated with open rotator cuff surgery. These will include an ultrasound of the affected shoulder prior to operating on the shoulder. Your full medical history will be taken as well with various shoulder score test performed by the clinician, the scores will be recorded. Your medical history will include documenting height and weight. During the surgical procedure, measurements of the tear will be taken with the tear classified according to the various classes. Pictures of the tear will be taken at this stage as well, for further analysis. The tissue removed from your shoulder during the surgical procedure will be stored and further analysed for evidence of healing through a light microscope. This stored tissue will be discarded at the end of the study. Ultrasound will be performed on your shoulder at eight weeks and six months after the surgery. This will determine the healing of the rotator cuff tendon. Further shoulder tests will be performed and scores recorded for further analysis.

4) RISK AND DISCOMFORT INVOLVED.

There will be no additional risk to the operating procedure, all the risks related are those associated with undergoing open rotator cuff surgery. The University of Pretoria has limited insurance for research related injuries.

5) POSSIBLE BENEFITS OF THIS STUDY.

This study will enable the investigators to classify the common shoulder tears encountered in a South African sample by different population groups, age groups, BMI and sex. Any variations to the blood supply of the rotator cuff will be documented, which will assist clinicians for future operating procedures in different individuals. The study will give a guideline of the expectation of healing of the rotator cuff at different stages, and the motions you should be able to perform at 2 weeks, 8 weeks and 6 months post-surgery.

6) I understand that if I do not want to participate in this study, I will still receive standard treatment for my illness.

7) I may at any time withdraw from this study.

8) HAS THE STUDY RECEIVED ETHICAL APPROVAL?

This Protocol was submitted to the Faculty of Health Sciences Research Ethics Committee, University of Pretoria, telephone numbers 012 356 3084 / 012 356 3085 and written approval has been granted by that committee. The study has been structured in accordance with the Declaration of Helsinki (last update: October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

9) INFORMATION If I have any questions concerning this study, I should contact:

Dr MA de Beer tel : +27 (0) 12 460 0751 or cell: +27 (0) 834422846

10) CONFIDENTIALITY

All records obtained whilst in this study will be regarded as confidential. Results will be published or presented in such a fashion that patients remain unidentifiable.

11) CONSENT TO PARTICIPATE IN THIS STUDY.

I have read or had read to me in a language that I understand the above information before signing this consent form. The content and meaning of this information have been explained to me. I have been given opportunity to ask questions and am satisfied that they have been answered satisfactorily. I understand that if I do not participate it will not alter my management in any way. I hereby volunteer to take part in this study and fully understand that no financial compensation is included in participating in this study.

I have received a signed copy of this informed consent agreement.

....	....
Patient name	Date
....	....
Patient signature	Date
....	....
Investigator's name	Date
....	....
Investigator's signature	Date
....	....
Witness name and signature	Date

VERBAL PATIENT INFORMED CONSENT (applicable when patients cannot read or write)

I, the undersigned, Dr ……………………………………..…, have read and have explained fully to the patient, named ……………….. and/or his/her relative, the patient information leaflet, which has indicated the nature and purpose of the study in which I have asked the patient to participate. The explanation I have given has mentioned both the possible risks and benefits of the study and the alternative treatments available for his/her illness. The patient indicated that he/she understands that he/she will be free to withdraw from the study at any time for any reason and without jeopardizing his/her treatment.

I hereby certify that the patient has agreed to participate in this study.

Patient's Name ______________________

(Please print)

Patient's Signature ____________________ Date ______________

Investigator's Name ____________________

(Please print)

Investigator's Signature ____________________ Date ____________

Witness's Name ______________ Witness's Signature __________ Date ____________

(Please print)

(Witness - sign that he/she has witnessed the process of informed consent)

Annexure F

ASES Shoulder Score

Name: ________________________________ **File No.:**__________________

Answer all the questions, selecting just once unless otherwise stated

1. Do you take pain killers such as paracetamol(acetaminophen), diclofenac?

	Yes
	No

2. Do you take strong pain killers such as codeine, tramadol or morphine?

	Yes
	No

3. How many pain killers do you take on average per day?

4. Is it difficult to put on a coat?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

5. Is it difficult to sleep on the affected side?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

6. Is it difficult for you to wash your back/do up your bra?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

7. Is it difficult to manage toileting?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

8. Is it difficult for you to comb your hair?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

9. Is it difficult for you to reach a high shelf?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

10. Is it difficult for you to lift 4.5kg above your shoulder?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

11. Is it difficult for you to throw a ball overhand?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

12. Is it difficult for you to do your usual work?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

13. Is it difficult for you to do your usual sport/leisure activity?

	Unable to do
	Very difficult to do
	Somewhat difficult to do
	Not difficult

Annexure G

<u>Constant Shoulder Score</u>

Name: ______________________________ **File No.:**_________________

Answer all the questions, selecting just one unless otherwise stated

During the past 4 weeks ………

1. Pain	**(0=No pain; 10=Severe pain)**

0. 1. 2. 3. 4. 5. 6. 7. 8. 9. 10.

2. Activity Level	**(check all that apply)**

	Yes	Unaffected Sleep
	No	
	Yes	Full Recreation/Sport
	No	
	Yes	Full Work
	No	

3. Arm Positioning	**(check all that apply)**

	Up to Waist
	Up to Xiphoid
	Up to Neck
	Up to Top of Head
	Above Head

4. Strength of Abduction (Kilograms)

	0
	0.5-1.5
	1.5-3
	3-4.5
	4.5-5.5
	5.5-7
	7-8.5
	8.5-10
	10-11
	>11

Annexure H

Simple Shoulder Test

Name: ______________________________ **File No.:**_________________

Circle the response that best describes your condition.

1. Is your shoulder comfortable with your arm at rest by your side?

Yes	**No**

2. Does your shoulder allow you to sleep comfortably?

Yes	**No**

3. Can you reach the small of your back to tuck in your shirt with your hand?

Yes	**No**

4. Can you place your hand behind your head with the elbow straight out to the side?

Yes	**No**

5. Can you place a coin on a shelf at the level of your shoulder without bending your elbow?

Yes	**No**

6. Can you lift one pound (a full pint container) to the level of your shoulder without bending your elbow?

Yes	**No**

7. Can you lift eight pounds (a full gallon container) to the level of the top of your head without bending your elbow?

Yes	**No**

8. Can you carry 20 pounds at your side with the affected extremity?

Yes	**No**

9. Do you think you can toss a softball underhand 10 yards with the affected extremity?

Yes	No

10. Do you think you can throw a softball overhand 20 yards with the affected extremity?

Yes	No

11. Can you wash the back of your opposite shoulder with the affected extremity?

Yes	No

12. Would your shoulder allow you to work full-time at your usual job?

Yes	No

Simple shoulder test score: 12/12 = 100%